# eCAADe 2017

# ShoCK!

Volume 1

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eCAADe2017 Logo Contest winners: Mohamed Elgendy and Omar Hadid (1st prize); Valerio Perna (2nd prize).

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# Sh$^{o}$CK!

## *Sharing of Computable Knowledge!*

Volume 1

Proceedings of the 35th International Conference on Education and Research in Computer Aided Architectural Design in Europe

20th-22nd September 2017
Rome, Italy
Dep. of Civil, Building and Environmental Engineering
Faculty of Civil and Industrial Engineering
*Sapienza* University of Rome

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# Theme

## ShoCK! – *Sharing of Computable Knowledge!*

The theme of the 35th eCAADe Conference is *Sharing of Computable Knowledge! – ShoCK!* so, we have invited eCAADe community, members of Sibling Organizations and CAADFuture friends to face this exciting theme.
Why such a strong theme? Mainly for three reasons.
The first one, is that we live in a city that has been witness of several revolutions of the conceptions of architectural space: most turning points of space perception are present here by means of architectural masterpieces as Bruno Zevi stated. I like to quote Rem Koolhaas: "It is a platitude that the presence of history in Rome is detriment to the development and display of modern art. But if that were true, Rome – *a city of successive modernities* – would never happened.".
Secondly, as my DaaD research group states "Rome is an open-air museum of architectural avant-garde masterpieces of an *uninterrupted history* where styles are juxtaposed, intertwined and *stratified* other than culturally also physically…" This concept is very close to the modern concept of cognitive sciences: to think by means of several abstraction levels of intelligence.
And the third reason is that we live in a Faculty founded in 1817 – right two centuries ago - has always had a multidisciplinary approach to understand and solve problems: from the outset Architecture, Civil engineering, Bridge construction, Topography, Geometry and Mathematics subjects were present. As a matter of facts this approach it is not limited to technical aspects as – most importantly – the Faculty, now Civil and Industrial Engineering, lives in *Sapienza* University of Rome – established in 1303 – a university that pursuits the "universal" approach where each discipline enhances the others.

Going back to the theme, it involves in turn several subjects: Internet of Things, pervasive nets, Knowledge 'on tap', Big Data, Wearable devices and the 'Third wave' of AI, ... All of these disruptive technologies are upsetting our globalised world as far as it can be predicted henceforth.
So, academicians, professionals, researchers, students and innovation factories… are warmly invited to further shake up and boost our innovative and beloved CAAD world – we already are in the post-digital era – with new ideas, paradigms and points of view.
I said "*CAAD world*" as I think that it contains and involves several disciplines but it is a new subject it its own that overcomes the former ones.

The underlain idea of this International Conference is that as a catalyst of creative energy it pursuits with determination founders' purposes and to be a shocking vanguard, a melting pot of novelties, in words: to become an "incubator" of innovative and seminal ideas, to generate enthusiasm, to be an occasion for new friendships and to facilitate the establishment of effective researches' networks. The title of the conference reflects well these intentions:

ShoCK! – Sharing of Computable Knowledge!

So the aim of the Conference was to knock our habitual design activities out, to compare the various methodological and technological trends and to disseminate the latest research advances in our community. Will our fine buildings and design traditions survive? Or, will they 'simply' be hybridized and enhanced by methods, techniques and CAAD tools? Obviously, computation is needed to match the ever-growing performance requirements, but this is not enough to answer all these questions we have to deal with the essence of problems: *improve design solutions for a better life*!
Obviously, ***computation*** is needed to match the ever-growing performance requirements, but this is not enough... As life is not a matter of single individuals, we need to increase collaboration and to improve ***knowledge*** and ***sharing***. This means going back to focusing on human beings, and involves the humanistic approach, and the long history of architecture... from handicrafts to thinking to technology... to handicrafts again.
A large spiral of the *architectura* as *eternal* as our city.

**A.**

*Antonio Fioravanti*
eCAADe 2017 Conference Chair

* This first volume of the conference proceedings of the $35^{th}$ eCAADe conference contains 74 papers grouped under 13 sub-themes; both volumes contain altogether 155 accepted papers. The Conference was held at the Faculty of Civil and Industrial Engineering, *Sapienza* University of Rome, Rome, Italy, in via Eudossiana 18, Rome, on $20^{th}$ – $22^{nd}$ September 2017.
In addition to the accepted papers, the first volume contains *Keynote* speakers' contributions concerning the themes of their keynote lectures and the *Workshop Contributions* including the contents of workshops given; the second volume furthermore includes the *Poster Session* contents.

All the papers of these proceedings will be accessible via CuminCAD - Cumulative Index of Computer Aided Architectural Design, http://cumincad.scix.net

# Acknowledgements

Authorities, colleagues, researchers, professors, students, professionals all of you are welcomed to the 35th eCAADe conference, in Rome the *eternal city*.

It has been a long time ago – 31 years – since the previous eCAADe conference was held in this Faculty, hosted by our University - "La Sapienza".
That time, Gianfranco Carrara, one of the eCAADe founders, chaired the $4^{th}$ eCAADe conference in 1986. That time on, there was only one eCAADe conference in Italy precisely in Palermo in 1995 chaired by Benedetto Colajanni and Giuseppe Pellitteri. This Faculty – now Faculty of Civil and Industrial Engineering – inspired by Parisian and Austrian academic models, is quite old as it was funded by Pope Pius VII in 1817, so now it celebrates its Bicentennial!

But it is quite young compared to our mother University "La Sapienza" that was established by the Pope Bonifacius VIII in 1303.

The original idea of bringing the eCAADe conference back to Rome goes rather back in times, I remember it was in 2009 at eCAADe conference in Istanbul. You know things take their time in Italy, so only in 2013 my Faculty approved and on $21^{st}$ March 2015 eCAADe Council granted us the permission to organize the $35^{th}$ conference. Over the last years several people have helped us to make this conference happen. We thank the former Dean of Civil and Industrial Engineering Faculty, Prof. Fabrizio Vestroni and especially the present Dean, Prof. Antonio D'Andrea for their supports.

During the process of organizing the eCAADe 2017 we have had the privilege to experience the supportive, collaborative and frank atmosphere of eCAADe Council, whose members, no one excluded, have helped us with all organizational aspects.

Let us be touched in remembering for his humanity the former eCAADe President, Johan Verbeke, who recently passed away. We all are sad in this moment thinking is no more physically with us now, but at the same time we are grateful to have met him and exchanged ideas on equal terms as his habit. In spirit, he is present so we can tell him: Johan, special thanks for your open-minded support, we warmly thank you! We miss you, and we do not forget you!

How cannot we mention Joachim Kieferle a friend, who is also the eCAADe President, for his encouragement and unswerving support during the last years and his ability to cut up dead-

locks into pieces? A special thanks to the great Bob Martens for his ability in organizing complex tasks and simplifying processes – Dutch origin helps – his daily support was precious and helped us relentlessly. And a “suuppper” thanks to a “super” friend as Gabriel Wurzer for his optimism and silent help in difficult issues.

Also, we wish to thank all the other previous conference organizers, Henri Achten, Rudi Stouffs and Emine Mine Thompson, for sharing their experience and knowledge. A special thanks to more recent conference organisers Bob Martens, Gabriel Wurzer, Thomas Grasl, Wolfgang E. Lorenz and Richard Schaffranek together with Aulikki Herneoja, Toni Österlund and Piia Markkanen!

Quality is the vital issue concerning conference proceedings.

To improve it we used different means: *OpenConf* conference management system that easily ensured that none of the reviewers came from the same institution as the authors; through special relationships between Liverpool University and eCAADe thank to Martin Winchester’s support we were able to overcome program bugs; a second and handcraft check of interest conflicts among authors and reviewers was made during the reviewing phase; a double-blind peer review process; and an accurate reviewers’ selection. The selection was fair, and only extended abstracts with high grades were admitted to full paper phase.

Quality means also typographic quality control in two ways: for printing results and for respecting author’s layout; so, thanks to the well-known *ProceeDings* formatting management system eCAADe could fulfil these two needs.

Authors uploaded their extended abstracts (length of 1000 to 1500 words, two optional images, 5 to 10 references) by 1st of February 2017; each abstract was evaluated anonymously.

Altogether, we received 309 extended abstracts from 46 different authors’ countries, shortly after 5 were withdrawn. Each extended abstract had three blinded peer reviews so 912 reviews were accomplished in a short time and 188 papers were accepted for full paper submission. After a while 11 of these ones were withdrawn and eventually 155 papers were published in the eCAADe 2017 Proceedings.

Let us express our very grateful appreciations for all the 132 reviewers from all over the world for their constructive and thorough comments for each author. A special thanks to reviewers who spent their time to review more than 8 extended abstracts – Joachim Kieferle and Anand Bhatt - not to mention members of “Joker Reviewers’ Team”: Stefano Cursi, Salma Elahmar,

Paolo Fiamma, Silvia Gargaro, Gianluigi Loffreda, Wolfgang E. Lorenz, Davide Simeone, Gabriel Wurzer and me that were able to review abstracts during the last days to accomplish missing reviews on time.

We thank and congratulate all authors for their hard work and support on using the ProceeDings tool and finalizing their full papers carefully in time. In this last phase of editing full papers we want to thank for his "extra-ordinary" work Gabriel Wurzer, the Master of the ProceeDings and Wolfgang E. Lorenz and Ugo Maria Coraglia, who with high sense of responsibility worked with us and to successfully produce high quality proceedings.
We also continued the practice started in eCAADe 2015 conference in Vienna of having all the session chairs to give prospective comments of the papers and to evoke the discourse at early stage between the author and session chair for the 27 sessions of the conference. All the session chairs also participated the peer review process of the extended abstracts.

We owe great gratitude to the session chairs for their commitment and their long-term contribution to the process until the final paper presentations.
We thank the keynote speakers and their contribution of writing the keynote papers concerning their lecture themes: Gianluca Peluffo, Chair in *Exhibition Design* and *Art & Architecture*, IULM - International University of Language and Media; John Gero, Research Prof. in *Computer Science and Architecture*, University of North Carolina at Charlotte and Krasnow Institute for Advanced Study George Mason University; and Gernot Riether, Director of *School of Architecture*, NJIT – New Jersey Institute of Technology, Editor of *DCA Journal*.
Workshops are part of eCAADe conferences, so we thank all the organizers for their workshop and for their contribution of short papers (non-peer reviewed) about the contents of their own workshop.

We are also grateful to Wolfgang Dokonal and the eCAADe Council for organizing the traditional PhD workshop for young researchers and supporting the grant winners with a subsidy for traveling to Rome.

We recovered an old tradition of previous eCAADe Conferences bringing poster session to life again, so during the conference we had 4 free lectures on interesting themes.

This year for the first time we launch an international competition linked to the Conference, the "eCAADe2017 Logo Contest" that helped in disseminate the spirit and values of eCAADe in new areas. We thank the International Jury that was made up by Antonino Saggio (President, Chair in *Information Technology applied to Architecture and Urban and Architectural design*), Eleonora Fiorani (Vice president, Chair in *Cultural Anthropology and Sociology of Innovation*),

Henri Achten (former eCAADe President, Chair in *Computer Aided Architectural Design*), Maria Argenti (Chair in *Architectural Composition* and Editor in chief of *Rassegna di Architettura e Urbanistica*), and Antonio Fioravanti (Chair in *Architectural Engineering*). Two Winners and three Honourable mentions were awarded (see on website https://www.daadgroup.org/result/).
We would like to express our gratitude for the administrative help in organizing this conference to eCAADe council and especially Nele De Meyere that has provided us valuable input and lessons learned from past conferences.

We have also had support from DaaD*group* for managing the conference services, ranging from the registration process to the actual on-site registration services. A big thank you goes to PhD students Ugo Maria Coraglia and Francesco Rossini for their extra-work in critical situations.

Thanks to the sponsors we were enabled to organize an international conference as eCAADe is. Financial supports, apart Sapienza University of Rome, was generously provided by A-Sapiens, AT Advanced Technologies, Autodesk; 3TI Progetti and Bentley Systems International Ltd. Technical support was provided by Epson Italia, Gangemi Editore, Geores, it solution, Noumena and ProceeDings.

We wish to also thank Gangemi Editore in person of Giuseppe and Fabio Gangemi for their very fast and accurate printing process and the high quality of both volumes.

As a special form of sponsorship, all members of the Organizing Team and students of Architecture-Building Engineering M. Course that donated their time to help prepare and organize this conference. Thank you all !!!

Rome, 1st September 2017

*Antonio Fioravanti*

Conference Chair

*Angelo L.C. Ciribini, Gabriele Novembri and Armando Trento*

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The 2017 eCAADe conference
is dedicated to

**Johan Verbeke**

current eCAADe vice-president, treasurer, and previous president and long standing council member, who unexpectedly passed away 6 weeks before this conference.

Johan has not only been very active in the eCAADe community but was also in the EAAE council, board member of ELIA and founding member of ARENA, an enthusiastic leader and promotor of architectural computing, research by design and research through reflective architectural and artistic practice.

He will always be in our hearts and minds.

*eCAADe Council and eCAADe 2017 Conference Organisers*

# Contents

# KEYNOTES

# Keynote Speakers

## Gernot Riether

Gernot Riether is the Director of the School of Architecture and Associate Professor at the College of Architecture and Design at the New Jersey Institute of Technology (NJIT). In his Digital Design Build Studio he and his students are researching new novel computer controlled fabrication and manufacturing methods. He previously taught at Kennesaw State University, Ball State University, ENSA Paris La Villette, Georgia Tech, NYIT and Barnard College at Columbia University and is lecturing internationally.

His Digital Design Build Studio won competitions such as the design of the AIA Pavilion for the American Institute of Architects in New Orleans with a hydroponic spherical enclosure made of environmentally friendly polymers. The studio was commissioned for projects such as a public installation for the Nuit Blanche Festival in Paris where he took cues from biology to digitally create a lightweight structural envelope for a pavilion in which interactive art projects were displayed.

Projects from the Digital Design Build Studio were presented at the Centre Pompidou, featured in books on digital design and fabrication and published in prominent publications such as Architectural Record and DETAIL. Riether's studio has been funded by the AIA, the Austrian government, non-profit organizations such as MainX24, material fabricators, the construction industry and universities. His forthcoming book, Urban Machines, co-authored with architect Marcella Del Signore, explores the relationship between public urban spaces and information technology.

## John S. Gero

John Gero is a Research Professor in Computer Science and Architecture at the University of North Carolina, Charlotte, and a Research Professor at the Krasnow Institute for Advanced Study, George Mason University. He is the author or editor of 50 books and over 650 papers and book chapters in the fields of design science, design computing, artificial intelligence, computer-aided design, design cognition and cognitive science. He has been a Visiting Professor of Architecture, Civil Engineering, Cognitive Science, Computer Science, Design and Computation or Mechanical Engineering at MIT, UC-Berkeley, UCLA, Columbia and CMU in the USA, at Strathclyde and Loughborough in the UK, at INSA-Lyon and Provence in France and at EPFL in Switzerland. Professor Gero is an international consultant in the field of design research.

## Gianluca Peluffo

Architect, founder of the 5+1AA studio in 1995, deals with the theme of contemporaneity in the relationship between city, territory and architecture, as the realization of reality. The transformation of reality is, therefore, the cornerstone of an idea of architecture as a body and enigma, which is both realistic and emotional, pragmatic and sensual, shared and capable of creating amazement as a mechanism of knowledge.
The main research line developed during the years of scientific and didactic activity is linked to the central issue of the architecture project as a tool capable of triggering dynamics of the transformation of the space of the city and the territory. In this line of research, the architecture project is intended as an element of putting in shape and perception Reality and the Context, meaning the Context as a complex and variable set of real and imaginary city and territory. In this sense, the project must be interpreted as a narrative-perceptual process, that is, as a physical, visual and mental sequence of putting in shape and perception Reality and the Context.
In 2003 he was awarded the Benemerito Title of the School of Culture and Art of the Ministry for Cultural Heritage and Activities. In 2005 Silver Lion of the Venice Biennale for the New Palace of Cinema. In 1997 he won the Ph.D. grant in "Theories and Techniques of Architectural Design" at the Faculty of Architecture in Genoa, with a thesis entitled "Beautiful and useful, a superfluous opposition, public elegance and private comfort in the urban residence". In 2001 he will discuss the Ph.D. thesis with Professor Pasquale Culotta and Prof. Paolo Portoghesi. Research grant for the Academic Year 2004-2005 at the Faculty of Architecture of Genoa, Diparc, on the theme "Replacement and modification: building infiltration in the present city". In 2005 he won a competition for the role of Researcher at the DIPARC of the Faculty of Architecture of Genoa. In 2009 he is confirmed as Researcher and assumes the role of a researcher at the Faculty of Architecture of Genoa.

# The Digital Design Build Studio

*Gernot Riether*[1]
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*This talk will present a series of projects from the Digital Design Build Studio. The Studio explores the relation between computation, materiality, tectonics and structure at an architectural scale. The research presented in the talk will have a focus on an investigation on polymers. The talk will also use these explorations to discuss a model of operation for architecture schools in the context of a profession that has been disrupted by digital technology. Talking about some projects in more detail will illustrate the findings of the experimentation with different polymers. The discussion will also highlight the social aspect of these interventions and illustrate how coalitions between non-profit organizations, developers, industry and municipalities may benefit and impact their communities.*

## POLYMERS

Polymers were popular in the 60s and 70s. MIT's Monsato House of the Future was an investigation in using polymers to create a shell structure. The Olympic stadium in Munich was exploring the possibility of using transparent acrylic panels for a cladding system. Polymers used in these projects were fuel based and are environmentally highly problematic. But recently the chemical industry changed the production of durable polymers from fuel based to durable biopolymers at a very large scale. According to DOW Chemical or the Biomass program of the US Department of Energy these polymers are based on synthetic materials, cellulose, starch, sugar cane or food waste. That creates urgency in architecture to think about strategies for reintroducing environmentally friendly polymers to the built environment.

Polymers are also known for the waste they produce. The reason for that is that half of polymers are produced for single use applications such as water bottles. That produces 550 billion pounds of waste per year or twenty-five percent of all landfills. We think that this waste can be used as a raw material

in architecture. Reintroducing polymers to the build environment architects also face an aesthetic problem. The aesthetic of polymers is currently associated as an environmentally problematic material and a material that produces waste. These are some of the challenges that informed a series of studies that explore different polymers such as PE, HD-PE and PP. The scale of the pavilion or small urban interventions has proven to be very productive in providing feedback of material performance, tectonics and structural behavior.

Figure 1
Interior view of the AIA Pavilion, New Orleans, Louisiana.

## PROJECTS

The AIA pavilion demonstrates how the malleability of PETG can be used to respond to program. The project was part of an annual art festival, organized by the AIA, the American Institute of Architects. The goal of the project was to activate otherwise forgotten urban spaces by injecting small pavilions into the city fabric of the French Quarter of New Orleans (fig. 1). Some spaces were hidden and difficult to reach, others were private property. The final pavilion was built in a private courtyard that was for one week - the duration of the event - turned into a public space.

The form of the pavilion adapted to the courtyard. Its dramatic lighting drew people into the courtyard that was located deep inside the urban block, far from the busy street. In order to bring all the building components to the site through a very narrow alleyway the envelope of the pavilion had to be tessellated into small triangles. Each of the PETG triangular panels was shaped to respond to the program of foundation, seating, window, structural elements, water collectors and planting pots. This created a total of 320 different variations.

To do that we used the malleability of the material that is a behavior typical for polymers. We combined the thermoforming techniques of vacuum forming, drape forming and draping. Instead of using 320 different molds to form the 320 modules we developed a flexible mold that allowed us to produce all the different modules with one single mold. That way we were able to save most of the material that would have otherwise been required to produce large quantities of variations.

The Nuit Blanche Pavilion demonstrates how the elasticity of ETFE can be used structurally. The pavilion was developed for the Nuit Blanche festival in Paris, France (fig. 2). The challenge was to develop a display for an interactive video installation by the artist Damien Valero. The skin was using the polymer's strength and its natural elasticity to self-stabilize a structure. This was achieved by building the cell from two parts that once connected to each other formed a double-layered pre-stressed surface.

The skin integrated the infrastructure of the video installation such as projectors, sensors and cables. It was developed as a modular system that could be shipped, easily assembled and reconstructed at different interior and exterior spaces. The flanges of both parts were first bent and then connected to the neighboring cells. In that way the memory effect of the polymer was used to create tension between the modules. The stress that was built up within the surface by all flanges collectively formed the pre-stressed envelop of the pavilion. To optimize the structural performance the size and geometry of the panel were related to the curvature of the overall form. In the final pavilion different densities of hexagons and pentagons were used. This idea was inspired by the structure of exoskeletons of beetles. The parts and edges were numbered in the assembly sequence that allowed for a self-guiding assembly system that didn't require any additional drawings. This also allowed us to ship the unfolded parts to Paris and to involve a local team of students to help folding and assembling them on site in less than two days.

Figure 2
Interior view of the Nuit Blanche Pavilion, Paris, France.

The Underwood Pavilion is exploring the use of Elastan and its integration with a parametric tensegrity structure (fig. 3). The project resulted from a coalition with the Muncie Makes Lab. Its goal was to create a new permanent destination for hikers and cyclists in the postindustrial landscape close to Muncie, Indiana. Rather than rationalizing a given geometry into a tensegrity system the intension of this project was to use simulation tools for a form finding process. Individual modules were linked into a single tensegrity system. The final form emerged from changing the module's proportion or the configuration of the pattern causing a twisting and bending in the aggregate that was used to define the pavilion's spatial enclosure.

With all of the modules assembled on site each individual module was fitted in an elastic fabric. The fabric enclosed the struts defining a minimal volume. Enclosing the compression struts with the fabric that was in tension created a perception of weightlessness, as the volumes visually appeared to not touch each other. Enclosing the modules with a fabric also suggests using the fabric structurally, an idea for future investigations.

The use of a parametric tensegrity structure had proven effective as a temporary structure because of its self-erecting behavior along with its ease and range of adapting its geometry. Simple details were developed to allow for a fast and accurate assembly process while maintaining the possibility of collapsing a mobile pavilion into lightweight bundles of cables and rods for easy transportation.

Figure 3
Underwood Pavilion in Muncie, Indiana.

Urban Blanket explores the possibility to thermoform HI-MACS with the goal to save material in the fabrication process. The project was developed in partnership with SandBox Crew, Midtown Alliance and Modern Atlanta in an effort to increase pedestrian traffic of public spaces in Midtown Atlanta (fig. 4). The project provides a type of physical public space for people using mobile digital devices. More than 20 people can simultaneously occupy Urban Blanket. Another goal of the project was to find new applications for HI-MACS and testing the material that is typically used for interior spaces in an exterior space.

In order to optimize the mold we developed physical and digital models that simulated the material in its malleable condition. These models allowed optimizing the geometry against the mold that was made up of a minimum amount of points and lines. This process was guided by a complex set of different parameters: First the proportions of the human body so that the landscape can cradle the person using digital devices, second enough curvature to create enough tension in the material in its malleable state and preventing it from sagging between the elements of the mold and third the unrolled geometry was nested on the available size of sheets without producing waste.

The individual 6 mm thick sheets were chemically bond and sanded to create the illusion of homogeneous solids. The hygienic properties unique to HI-MACS allowed us to use a white color for an urban surface. The coalition between the school, material scientists at LG Hausys and the fabricators was crucial for the development of a novel fabrication workflow for complex HI-MACS surfaces and for the development of a prototype for a new application for HI-MACS in an exterior space.

Figure 4
Urban Blanket in Midtown Atlanta, Georgia

## CONCLUSION

One of the main aims of Design Build Studios is to bring designers and craftsmen together. The Digital Design Build Studio creates an environment for students to develop an understanding of workflow from design to fabrication and enable experimentation in conceptualizing production and assembly. It is also a collaborative environment where students learn to interact with clients, fabricators or city officials and how to form new types of coalitions. As we believe that innovation does not happen in a bubble, the Digital Design Build Studio connects students to the industry, the city and a network of people that students can draw from as young architects after they graduated. Each of these explorations is used to build coalitions between entities within and outside the university. The coalescing that is formed around every experiment has proven to be beneficial to the public, the private sector, the industry and the school. The research is also not just shared between academia and the industry but also exposed to the larger public.

## ACKNOWLEDGMENTS

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Collaborators: Nuit Blanche Pavilion: Damien Valero, Underwood Pavilion: Andrew J. Wit.

Universities and Partners: Georgia Tech, Ball State University, Kennesaw State University, Muncie Makes Lab, Modern Atlanta, Midtown Alliance, Sandbox Crew, LG Hausys, TOP South, Gail K. Fabrics.

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# Cognitive Design Computing

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*This talk describes the foundational concepts of cognitive design computing and then presents some examples. Cognitive computing is concerned with modeling human cognition computationally and using that model as the foundation for constructing computer models of design activities. Human cognition is based on perception, learning and adaptation. Here we present human cognition in terms of situated cognition - cognition involving interaction with an environment. The talk briefly introduces a set of principles for cognitive design computing founded on the three concepts of interaction, constructive memory and situatedness. It then presents two examples of applications of this approach.*

## INTRODUCTION

Computational design tools aim at encoding knowledge and making it available in an objective manner to the designer. There is an assumption behind this approach, namely that all the knowledge is objective, ie, independent of the user. Examples of objective knowledge include stress analysis, determining the position of the sun, thermal analysis of a building and methods such as linear programming in optimisation. Such objective knowledge tends to be deductive in nature. The most powerful examples of deductive knowledge are those based on axioms from which subsequent theorems have been developed. These theorems map onto the behaviour of the world. In addition, there is a category of knowledge that is based on induction (ie, knowledge learned from examples without causality). Even inductive knowledge is treated as objective, ie, independent of the user. For example, a layout algorithm that utilises some heuristics is used as if there were causality encoded. This has served design computing well. It has allowed for the widespread distribution of computational tools. It has provided the basis of transferable skill development in users. As our knowledge of the world has improved, so we have

been able to update and adapt the knowledge in these programs.

This talk presents an approach that aims to extend our understanding of what kinds of knowledge we can expect our computational tools to have and how systems that have a range of kinds of knowledge might perform differently.

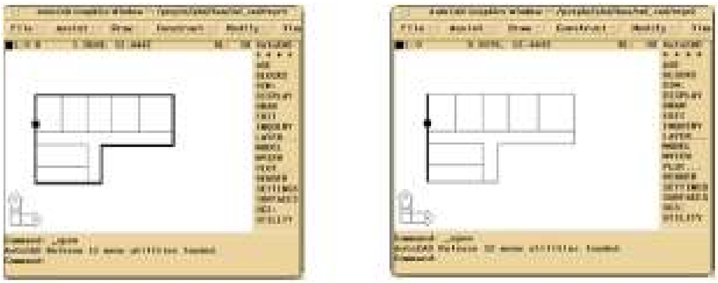
## FIRST-PERSON VERSUS THIRD-PERSON KNOWLEDGE

We call such objective knowledge *third-person knowledge* in that the person who produced the knowledge is not required to be there when that knowledge is used by another person. For example, even though Newton is dead his laws continue to work fine. Whilst it is clear that much of human knowledge is of this third-person kind, in the sense described above, there is a category of everyday knowledge that depends on the person rather than deduction. This kind of knowledge develops through the interaction of the individual and their world and as a consequence is personal knowledge. It is called *first-person knowledge*. This class of knowledge is sometimes inappropriately encoded as third person knowledge and when done so often causes the mismatch between the experience of the person who coded the knowledge and a subsequent user of that knowledge.

A simple example of such encoding of personal knowledge can be seen even in the way objects are represented in a CAD software system. Figure 1(a) shows the screen image of a floor layout. Simply looking at the drawing of the floor layout gives no indication of how it has been encoded. The darkened line is the single polyline representation of the outline obtained by pointing to a spot on the boundary, but that representation could not be discerned from the image. Figure 1(b) shows exactly the same outline but it is encoded differently, as indicated by the darkened polyline obtained by pointing to the same spot.

The issue here is one of interpretation that is often missing in computation. A common assumption is that the external (and even the internal) world is there to be represented, ie, that in some sense it has only one representation. This misses an important step: namely that of interpretation, which depends on the viewer not on the underlying external representation. Before anything can be represented it needs first to be interpreted and it is this interpretation that is represented. This is an example of first-person interaction with the external world that results in first-person knowledge about the world.

How can we build computation systems that encode first-person as well as third-person knowledge? To do this we rely on concepts from cognitive science and in particular a branch called *situated cognition*. Using those concepts we can produce a branch of computing called *cognitive computing* that is a closer analog to how the mind works than general computing.



(a) (b)

Figure 1
The same image has different encodings (a) and (b) that depend on the individuals who created them rather than on any objective knowledge.

## SITUATED COGNITION

Cognitive science is concerned with understanding and representing structures and processes in the mind (as opposed to brain science which is concerned with understanding and modeling structures and processes in the brain). Situated cognition is concerned cognition that is embodied and a consequence of embodiment is an increased focus on the interaction between the computational system and its environment (Clancey, 1997; 1999; Gero, 1998; Suchman, 1987).

Situated cognition is founded on three ideas:

1. Interaction: knowledge comes from encoding and through interaction; in particular first-person interactions with representations, which includes the expectations of the person or system carrying out the interpretation (Agre, 1997; Smith and Gero, 1998; Zhang, 1997);
2. Constructive memory: constructive memory, which is concerned with memory as a process to generate a memory cued on a demand to have such a memory rather than a recall of elements in a location (Bartlett, 1932/1977; Dewey, 1896; Gero, 1999; Rosenfeld, 1988; von Glaserfeld, 1995);
3. Situatedness: situatedness is concerned with being in a particular place at a particular time and how the world is viewed by each individual from that place at that time (Suchman, 1987).

## PRINCIPLES FOR COGNITIVE DESIGN COMPUTING

We can develop a set of principles that form the foundation for the development of cognitive design computing.

*Principle of Effect*: What you do matters
The implication of this principle is that actions produce effects in terms of the production of first-person knowledge. In traditional uses of computers in designing, the computational systems are unchanged by their use. This makes sense if the system only embodies third-person knowledge. However, the use of any system, whatever kind of knowledge it contains, generates first-person knowledge in the system that uses it. This is the first fundamental distinction between traditional design computing and situated design computing. For example, an optimization approach used in the design of layouts could produce first-person knowledge in the form successful strategies. These could then be used next time the optimization program was used for layouts.

*Principle of Ordered Temporality*: When you do what you do matters
In traditional design computing when you carry out a computation plays no role in the result that is produced. Again, this makes sense if the system only embodies third-person knowledge. However, if the system embodies first-person and generates first-person-knowledge as it runs, the chronology of the system's use affects what is used and what is learned. As the boundary condition for this principle consider that if A is carried out before B, then A cannot make use of any knowledge acquired through the execution of B, but B can make of knowledge acquired through the execution of A.

*Lemma of Experience*: What you did before affects what you do now
As a consequence of principles 1 and 2, we can state this lemma: What a system did before affects it does now. This is one definition of experience. Experience has the potential to guide future actions. The effect of this is that cognitive design computing systems are not static systems but are dynamic in terms of their behavior. This concept can be applied recursively, so that previous experiences are used to produce current experiences.

*Principle of Locality*: Where you are when you do what you do matters
First-person knowledge includes not only what happened and when it happened but also where it hap-

pened. The system has to be at the "right" place at the 'right" time for unique events to be interpreted.

*Principle of Interaction*: Who and what you interact with matters
Interaction is one of the distinguishing characteristics of a cognitive design computing system. Without interaction there is no potential to produce first-person knowledge. There are two sources of interaction for a system: other computer programs and users of the system. Conceptually there is no difference between them in terms of interactions. Each interaction has the capacity to use previous experiences and to produce first-person knowledge. Interactions have the potential to change the meanings of experiences.

*Principle of Ontology*: What you think the world is about affects what it is about for you.
This implies that cognitive design computing develops a representation of the situation that provides the basis for any interpretation of what is observed.


## ACKNOWLEDGEMENTS

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# The navel of the world

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"Gianluca Peluffo & Partners" has been founded in 2017, looking at the Mediterranean Sea of the "Italian Riviera" after 20 years of creativity and architectural construction of 5 + 1AA, to propose an idea of architecture as a specific genealogical identity, capable of an international dialogue with any other culture, an idea of non-eclectic architecture, but "Renaissance" as made of physical matter, at the same time of corporeality and soul, and "contemporary", expressed through a language capable of containing more time in the same space.

They designed and are designing, built and are building in Italy and Europe, North Africa, Egypt and Turkey and around the World, housing, villas, university campus, schools, offices for ministries and banks, buildings for Cinema, Music and Entertainment, hospitals and hotels, interior design, art exhibitions halls.

Italian style for a specific reaction to each specific situation.

In Albissola, therefore, on the Italian Riviera, in the Studio where Lucio Fontana with his own hands, made decisive gestures, decided to break two-dimensionality and create space, using over the canvas, an archetypal matter like earth, Gianluca Peluffo with young and trusted partners , collaborators and friends, looking for happiness of human beings through construction, in the rose gradations that start from the shades of the skin and come to the flowers of the bougainvillea, crossing the roses of Spatialism.

If man and the world are made of the same flesh, and the invention of physical and sensory space, is the fundamental theme of architecture, then we must and we can start from the navel of the world.

# WORKSHOPS

# Internet of Homes (IoH)

## *Ambient Displays and Wearable Devices for Eco-feedback in Smart Homes*

*Eiman Elbanhawy[1], Daniel Gooch[2], Theodoros Georgiou[3], Aikaterini Chatzivasileiadi[4]*
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### OBJECTIVES

The increase of home energy consumption levels is a major concern associated with designing smart cities. The use of innovative technology is meant to make our life easier but if not properly designed and utilised, can double our electricity bills. Lack of awareness and the inability to sense the energy being used in homes by tenants, is considered as the main contributor to this matter. Taking a hands-on experience approach, this workshop aims at increasing collaboration and engaging architects, designers, researchers and professionals with the Internet of Things (IoT) at a level where they can design and create prototypes. These prototypes can help them to understand, monitor and better utilise innovative technologies.

### SCOPE

In order to improve design solutions in future cities, deploying participatory design approach is a way to raise awareness and engage the public. This one day workshop aims at running "A Maker Workshop" where the participants will gain hands-on experience designing, creating and installing a simple ambient display or a wearable device to give eco-feedback on their smart home appliances and clean technologies. The workshop works as a Hackathon, to explore new and innovative ideas for implementation.

### SCHEDULE

The workshop starts with a set of short presentations and introductions followed by dividing the participants into groups. Two proposed applications where the participants get to choose which case study they want to work on: Solar Battery System or EV shared residential charging bay. Groups are divided into the following categories: **Group A**: Light Ambient Display. **Group B**: Wearable Device. **Group C**: Sound Device. The following part of the workshop includes thinking about the possible use of the Arduino kit to create a first working prototype. The closing segment of the workshop includes presentations and discussions about the wider context of using wearable devices with some closing remarks and network creation.

### CONTRIBUTION TO THE CONFERENCE

The proposed IoH workshop is in line with the eCAADe theme this year. We are deploying IoT, ambient displays, and wearable devices in the context of smart homes and green mobility.

### EXPECTED OUTCOMES/SKILLS ACQUIRED BY PARTICIPANTS

(1) Be exposed to Human Computer Interaction (HCI) knowledge in smart cities domain; (2) Understand simple Arduino principles (through presentations and making), see figures; (3) Explore various applications of wearables and ambient displays.

## PREREQUISITE SKILLS OF PARTICIPANTS

No particular skills are required; however, this workshop is for those who are interested in physical prototyping. The workshop evolves around IoT and it needs participants to utilize their creativity, work towards solving a given problem, and come up with possible applications. It will involve programming (aided by the organisers) and some electronic connections to make the prototype. Participants will be asked to submit a position paper (500 - 800 words), where they will: Briefly describe their background and why they are interested to participate in this workshop. Mention any particular challenges they might have faced, if they already have experience in designing, developing or using any relevant approaches to engage in smart homes and cities. They will also be asked to indicate if they are interested in giving a short presentation. Papers will be reviewed and the organizing committee will select up to 12 participants according to relevance, diversity of opinions, and the probability of creating dynamic discussion. In addition, we are actively exploring a book or journal special issue based on the outcomes of this workshop.

## LOGISTICS AND TECHNICAL REQUIREMENTS

The workshop mainly includes group-based activities, so we will need a space with three tables, with enough space for each group to work on their ideas and prototypes.

We will provide the necessary technical background and guidance before the activity starts, along with 2 presentations (in addition to a 3rd presentation post the activity), a short demo (using a small table in front of the presenter). Members of the organizing committee will be available during the activity to provide technical support and help to answer any questions that may arise during prototyping.

We are also going to need stationary to assist participants during their team presentations at the end of the activity. This stationary will include marker pens and large, poster size paper. We recommend having a printing facility to print posters A1 size so the groups can present their projects. In addition, we will need four flip chart boards (one for the organisers, and one for each group) for group discussions.

## BIOGRAPHIES

### *Eiman Elbanhawy*

Eiman Elbanhawy, is currently working as a Research Associate in Smart Cities' Technologies and Social Practice at the Open University. Within the remint of the research project (MK: Smart), Elbanhawy focuses on the social practice of the use of innovative technologies and renewable energies in smart homes and green mobility. In Northumbria University, Elbanhawy organized and conducted various symposiums and internal workshops for Ph.D. researchers. The participants were giving presentations and their work was assessed by the organiser, invited speakers, and subject specialist. She participated in organizing one international conference as a part of her role in E-mobility research project in Northumbria University. Elbanhawy continued her success in organizing hands-on experience workshops covering Human Computer Interaction (HCI), visualisation, and IOT in smart cities context.

### *Daniel Gooch*

Daniel Gooch is a Lecturer at the Open University. For the last 2 years, Gooch was principally HCI researcher in MK: Smart project. His research interests are motivated by wanting to understand how we can best design technology to fit within, and where necessary change, peoples practices and behaviour. The work Gooch does is interdisciplinary cutting across computer science, psychology, information science, design and education. As a continuous role, Gooch has been leading the Citizen Innovation strand of the MK Smart project, investigating how to facilitate citizen-led innovation within Smart City projects. Gooch has been involved in organizing community workshops and events with other stakeholders.

Figure 1
The needed surface for each group to work on their prototypes

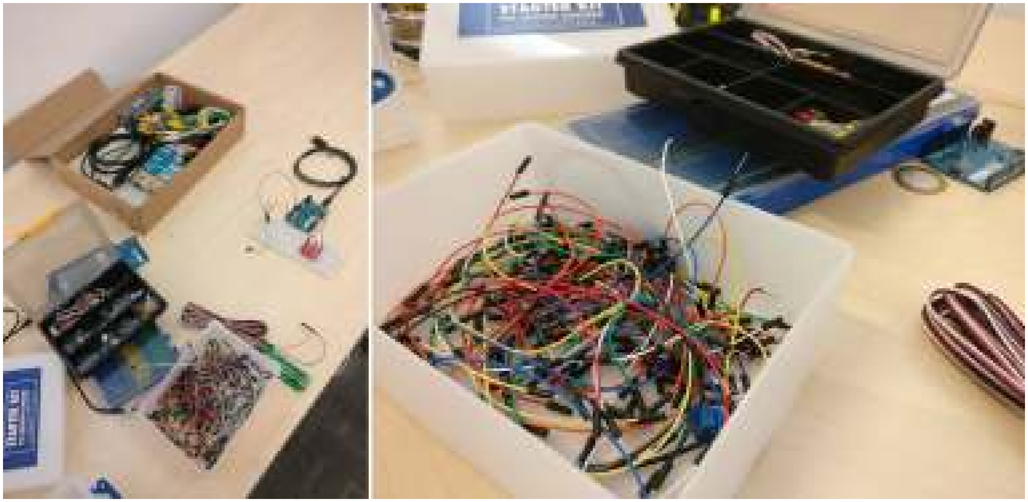

Figure 2
The wired prototypes have to be connected to the participants laptops

***Theodoros Georgiou***

Theodoros Georgiou holds a BSc (Hons) and an MSc in Computer Science, an MSc in Human Centred Interactive Technologies and is currently working towards a PhD in Human Computer Interaction. Theodoros current research focuses on the design, development, testing and evaluation of wearable devices capable of monitoring gait and provide a tactile rhythmic cue to the person wearing it. The ultimate goal of this research is to assist with the gait rehabilitation and training of people who suffer from neurological conditions affecting their gait. He was on the organizing committee of a PhD student symposium at the University of York, and helped to organize the annual departmental conference at the Open University, where he currently works, for the past three years. Theodoros also helped organise numerous hackathon events, including one on prototyping using human-centered design techniques.

### *Aikaterini Chatzivasileiadi*

Aikaterini Chatzivasileiadi is currently working as a Research Associate at the Welsh School of Architecture on a Leverhulme Trust funded project. The project aims at using a technique called non-manifold topology to significantly influence architectural computing and architectural practice and to ultimately improve the experience of people who use buildings. Her previous research was on the integration of renewable energy and battery technologies in buildings. She fully organized a symposium regarding energy use in buildings, as well as a workshop on user-centred design at the Welsh School of Architecture. She also was in the organizing committee of two inter-disciplinary conferences in Cardiff; one on energy and human interactions in the built environment and another one within the broad context of science.

# CoOptimise

## *Exploring human and machine's cooperation in optimisation and design*

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### BACKGROUND

Architecture and engineering have always been inseparable. It is not possible to imagine one working without the other. 2000 years ago, Vitruvius wrote down what had already been acknowledged for ages; architecture is function, stability and beauty. Standardisation and mass-production methods of the second industrial revolution created a gap between architects and engineers that we are still trying to bridge today. With the so-called third industrial revolution - the digital revolution - we now have the opportunity to revert our design traditions and to create holistic solutions for a sustainable future.

### OBJECTIVES

This workshop will provide designers of tomorrow tools to analyse and optimise structural schemes on a conceptual level. We will use the dynamic and scriptable interface of Rhino/Grasshopper with the structural analysis plugin Karamba. With dynamic geometry in Grasshopper, optimisation is made straightforward and the designer no longer needs to set up geometry, loads and supports for each separate model he or she wants to run. It is automated. With Karamba the designer has a FEM solver at hand that is built into the dynamic environment of Grasshopper. The ability to numerically test all your options calls for an optimisation to take place. The most fit option can be found, whether that being the most functional, the most stable or the most beautiful one.

### OUTCOME

We finish the workshop with building and testing a series of designs, to compare digital simulation with real life results.

### BIOGRAPHIES

#### *Kristjan Nielsen*

is a Danish structural engineer with international experience from Paris, London and Berlin. He's applied computational design methods for various scaled projects, from small art pieces and pavilions to world cup stadia and high-rise towers. Since 2012 Kristjan has been running workshops on computational design at conferences as Smart Geometry '14 in Hong Kong and Design Modelling Symposium Copenhagen in 2015, as well as at École nationale supérieure d'architecture Paris-Malaquais in Paris, La Sapienza University in Rome, Technical University of Denmark in Copenhagen, Ecole nationale supérieure d'architecture de Versailles in Versailles and at Contemporary Architects Association in Tehran, Iran.

#### *Mariam Khademi*

is currently studying Building Engineering and Architecture at the faculty of Civil and Industrial Engineering at Sapienza University of Rome and holds a Bachelor's degree in Cell and Molecular Biology from The University of Tehran. Together with Kristjan she has organised two one-day workshops at the faculty of engineering at Sapienza University of Rome, as well as a workshop at Contemporary Architects Association in Tehran, Iran.

## SIZE

The workshop will run for two days, split between 2/3 lectures, tutorials and exercises on the computer, and 1/3 model making.

## SCHEDULE

### *Day 1*

**Part 1.** An introduction to FEM analysis using state-of-the-art FEM program Karamba.

**Part 2.** Students will learn how to assemble their own structural models using Karamba.

### *Day 2*

**Part 1.** Students will be divided into groups and will design their own structure and make small scale models.

**Part 2.** Groups will have found their preferred design which will be further developed, fabricated and tested.

## PREREQUISITE SKILLS OF PARTICIPANTS

Basic modelling skills in Rhino (1) and Grasshopper (2) are required although no specific knowledge of Karamba (3) is needed. Students should bring their own laptops with Rhino (eventually trial version) and Grasshopper installed prior to the workshop. A group license for Karamba will be provided to participants.

## LOGISTIC AND TECHNICAL REQUIREMENTS

A room with a projector and desks for the number of students is required. This workshop requires tools for production of scale models and load tests. Preferably laser cutter with wood or cardboard. We suggest that this will be determined in collaboration with the conference organisers.

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[3] http://www.karamba3d.com/

# Co-Design using HYVE-3D

## *Representational Ecosystem and Design Conversations*

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### OBJECTIVES

The goal of this workshop is to initiate participants coming from different backgrounds to the approach of co-design in a multidisciplinary and collaborative context. The idea is to prepare the participants to actively support co-design activities through the appropriate Representational Ecosystem (Dorta et al. 2016a) ranging from traditional tools as physical models to freehand sketches all combined to digital hybrid immersive techniques via Hyve-3D(TM) (Hybrid Virtual Environment 3D) (Dorta, et al. 2016b).

During this workshop, all the stakeholders of the given project will master the elements of the Design Conversations (Dorta, et al. 2011), namely: the verbal protocols of this particular kind of collaborative ideation. This will allow them to gain awareness of the emergence of collective creative ideas, therefore learning the co-creative steps underlying better performance of the co-design process.

Participants will engage collaboratively to propose creative and innovative solutions to ad-hoc projects. These projects will be realized in immersion, locally and remotely, through interconnected Hyve-3D systems (internationally). Hyve-3D is a multiuser Social VR system allowing 3D sketch creation and embodied interaction with 3D models inside a hybrid immersive virtual environment (Dorta, et al. 2016b). The innovative visualization technique uses a non-intrusive anamorphic image projected on a spherical concave screen. This open fabric screen permits enough space in order to accept many people at once ensuring the needed communication among users.

In addition, the 3D Cursor(TM) technology of Hyve-3D facilitates local and remote collaboration. Using a handheld tablet, users interact with the virtual environment by moving the device and using well-known multi-touch gestures. Every user has a dedicated 3D cursor, enabling for an intuitive navigation in the virtual environment via the 3D trackpad (Fig. 1).

Users will be able to go back and forth, exporting vectors (.dxf) of their 3D sketches to the CAD software of their choice, detailing their projects and importing them back into Hyve-3D (wavefront .obj textures files) for further codesign work. Also, it is possible to import photogrammetric models as large point clouds (.ply).

Figure 1
Hyve-3D and two users with their respective 3D cursors.

### SCHEDULE

#### *Day 1:*

**Part 1.** Co-design rationale sessions in groups (up to 4 groups of 3-5 participants) learning about the representational ecosystem with traditional tools and the design conversations.

**Part 2.** Hyve-3D: Introduction and training sessions. Co-design in immersion.

### *Day 2:*

**Part 1.** Hyve-3D: International remote codesign.

**Part 2.** Refinement of conceptual sketches in personally preferred CAD software and export/import into Hyve-3D for iterative co-design cycles.

**Part 3.** Interconnection with Montreal collaborators for final revisions and open-access presentations.

## PREREQUISITE SKILLS

No particular skills or experience in design are essential as the proposed activity aims to foster the potential of a more open ideation process shared collaboratively by different multidisciplinary stakeholders engaged in the project using a representational ecosystem. Participants are encouraged to bring their personal laptops with any 3D modeller of choice preinstalled, which can export .obj files and import .dxf files. If available, participants can use their photogrammetry software (a point cloud model will also be provided).

## BIOGRAPHIES

### *Tomas Dorta*

Tomás Dorta has a background as a practitioner architect and designer. His research interests include the design process and co-design using new technologies and the development of new techniques and devices of design in the virtual realm. He obtained his Ph.D. (2001), studying the impact of virtual reality as a visualization tool into the design process. As a design educator, Tomás Dorta joined the School of Design of the University of Montreal in 2003 where he is now a professor. Tomás Dorta is the director of the Design research laboratory Hybridlab.

### *Emmanuel Beaudry-Marchand*

Emmanuel is currently a master's student in the Design and Complexity program at the University of Montreal and is working under the direction of Tomás Dorta at Hybridlab. Emmanuel's research focuses on immersive virtual environments and the perception of architectural scenes transposed using affordant digital representations for a contextualized ideation. Coming from a background in graphic design, his projects are driven by a deep interest in the implications of novel forms of mediatic documentation.

## PAST WORK IN RELATION TO THE WORKSHOP

Tomas Dorta demonstrated their system Hyve-3D at SIGGRAPH 2014 (Vancouver) where it was launched, and 2015 (Los Angeles). He organized in collaboration with colleagues of the Victoria University of Wellington (NZ) a workshop about virtual heritage using Hyve-3D in CAADRIA 2016 conference at Melbourne. Hyve-3D is selected as one of the best user interfaces of 2014 by Co.Design. Other mentions on the media include Bloomberg, Tech Crunch and The Telegraph.

## PARTNER

The Design Research Laboratory Hybridlab of the University of Montreal is a research laboratory under the direction of professor Tomás Dorta. It is composed of team of professors/collaborators as well as graduate and undergraduate researchers, designers and programmers focusing on fundamental research and development on new digital solutions supporting the ideation process.

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# Wall.4.all

## *Mass customization of 3d wall design in online environment*

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**Keywords:** *Mass Customization, Web3D, Parametric design, Digital Fabrication*

### OBJECTIVES, SCOPE AND CONTRIBUTION TO THE CONFERENCE

Mass Customization is the new design paradigm that replaces mass production, allowing customers to participate in the design process. Such design paradigm is especially important in the age of parametric architecture, with the increased need for design collaboration and knowledge sharing. Recent advances in cloud technologies allow the parametric design configuration to be implemented via the web environment without additional software installation. It can be done via various Grasshopper plug-in platforms such as Human UI, Speckle.xyz, or ShapeDiver.

The aim of this workshop is to provide basic knowledge regarding web-based parametric platforms and to introduce a workflow for creating a 3d wall design that can be exported for manufacturing production (3d printing or CNC manufacturing). Participants will be trained to design and optimize Grasshopper models of a 3d parametric wall for cloud applications via the ShapeDiver platform. Participants will learn how to create their own web-based 3d wall configurator with the ability to export 3d files and embed a model directly onto a blog or a website.

### EXPECTED OUTCOMES AND SKILLS ACQUIRED BY PARTICIPANTS

### SCHEDULE

Introduction to Mass Customization approach in design and architecture. An overview of contemporary parametric web3D platforms. Introduction to Grasshopper3D. Design strategies for creating 3d walls. Introduction to topological mesh editor Weaverbird, an add-on for Grasshopper. Introduction to Shapediver, add-on for Grasshopper and parametric web3D platforms. Working with design variations and design optimisation for web3D. Creation of web based parametric platform. Export options and embedding models on a blog.

### PREREQUISITE SKILLS OF PARTICIPANTS

Participants are required to bring their laptops with installed 64bit Windows, Rhino5, Grasshopper3D, Weaverbird, LunchBox, and ShapeDiver.

### MAXIMUM NUMBER OF PARTICIPANTS

15

### BIOGRAPHIES

Bojan Tepavčević is a professor at the Department of Architecture and Urban Planning, Faculty of Technical Sciences, University of Novi Sad, where he teaches courses in computational design and architectural representation. He is also co-founder of Digital Design Center and the head of the master's program "Digital Techniques, Design and Production in Architecture and Urbanism at the University of Novi Sad.

He was awarded the International Trimo Research Award in Ljubljana in 2011, for his PhD dissertation about the influence of geometric representation of space on contemporary architecture. He is a co-author of the book "Architectural Scale Models in the Digital Age: Design and Manufacturing" (Springer Vienna 2013), as well as the author of many research papers in the field of contemporary architectural theory of design, computational design and advanced modelling strategies in architecture.

## EXPERIENCES ON CONFERENCE / WORKSHOP ORGANIZATION

Conference Chair at the 4th eCAADe International Regional Symposium 2016, Novi Sad, Serbia (1). Workshop tutor at the 4th eCAADe International Regional Symposium 2016 Workshop topic: Design based on structural performance optimization (2).

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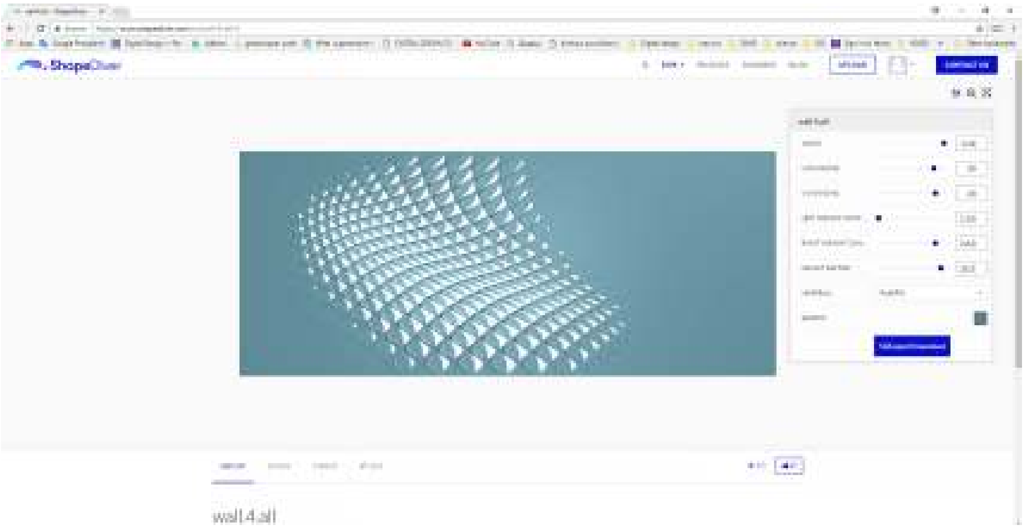


Figure 1
ShapeDiver User Interface

# LightWIRE

## *structurally embedded luminescence*

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### OBJECTIVES

The aim of the LightWIRE workshop is to produce a series of physical prototypes to rethink the structural and ornamental aspects of design, steering one to blur into the other. The former is reached by bending plastic rods at specific angles in order to discretize complex morphologies into linear elements, joined together through edge connections. Thanks to this, a second layer of electroluminescent wires can find its paths through the network and add a lighting attraction to the system while embracing the structural core.

### SCOPE

Throughout the experience, students will apprehend methods from the digital realm to implement into the physical one. Elements such as material properties and physical constraints will be taken into consideration through digital simulations in order to simplify the fabrication and assembling processes. All this, in a constant iterative loop between design and fabrication, to refine construction details and study possible geometries.

The module manipulation will be coded entirely with Rhino/Grasshopper and the Anemone add-on to simulate system feedbacks. The experience will be structured in sequential steps, going from software understanding, to testing new approaches in order to build an architectural prototype in a 1:1 scale.

### EXPECTED OUTCOMES AND SKILLS ACQUIRED BY PARTICIPANTS

Students will have the chance to research multi-scalar design languages and complex geometries in discrete environments exploring Computation through physical prototypes and practical crafting methods in a continuous feedback between digital/-manual. The final output of the workshop will be the result of progressive study steps in which students and tutors will work side by side.

We believe that the LightWIRE experience represents an interesting example of dialogue between the technological and physical bounds of contemporary design. By physically translating digital considerations into physical, it can become an asset for the Sharing of Computable Knowledge conferences.

### SCHEDULE

#### *Day 1*

Introduction to the topic: Design investigation + Proposal + Prototyping

#### *Day 2*

Prototyping + Assembly + Short presentation

### PREREQUISITE SKILLS OF PARTICIPANTS

The workshop is open to all participants, no previous knowledge of Rhinoceros and Grasshopper is required (although an introductory knowledge is welcome). Participants should bring their own laptop with a pre-installed software. The software package needed has no additional cost for the participant

(Rhino can be downloaded as a trial version, while Grasshopper and plugins are free). These software are subject to frequent updates, so a download link to the version used in the workshop will be sent to the participants a few days before the workshop.

## LOGISTICS AND TECHNICAL REQUIREMENTS

One Projector/Screen (32" to 40"), Table for 10 students + 2 Instructors, small laser cutter, small 3d printer.Material (estimated budget 500 euro): METACRILATO PIPE (8mm external radius, 5mm internal radius, about 10 meters per participant). ELECTRO LUMINESCENT WIRE (2.4 to 2.7mm, 1 to 3 meter each, 1 kit per person). HEAT GUN (1 every 4 participants). WOOD BOARD (12mm thickness, 50x50cm, 1 every 2 person, used as base for the prototypes). Zip ties, cutter, sand, gloves

## BIOGRAPHIES

### *Noumena*

Founded in 2011 by Aldo Sollazzo and Matteo Di Sora, Noumena promotes experimentation in every task, pushing its own boundaries beyond conventional design limits.

Noumena is a collective group focused on design, research and education based in Spain, with nodes in Austria, India and Italy. We investigate between the boundaries of new digital paradigms and design strategies applied to architecture, robotics, and fabrication, through a hands-on and experimental approach. Besides that, we provide external services of consultancy, bringing our skills into other environments, offering our experience on computation and fabrication to external projects.

Noumena leads and coordinates several international events and activities such as workshops, competitions and exhibitions, establishing a networking workflow based on open-innovation. We embrace data-driven design, mixing environmental strategies with computational thinking from urban scale to robotic fabrication.

**Eugenio Bettucchi.** Eugenio Bettucchi has a degree in Building Engineering and Architecture from Alma Mater Studiorum, University of Bologna, Italy. He developed his thesis focusing on robotic material deposition based on real-time feedback between digital simulation and physical environment. He is a senior designer at Noumena and his interests and skills lie in computational design, digital fabrication and the way of which these systems interact. During his studies, he assisted several seminar and courses as external faculty at IaaC (Institute for Advanced Architecture of Catalonia) and collaborated in many workshops and research projects in international events related to computational and fabrication topics.

**Iacopo Neri.** Iacopo Neri studied at the University of Florence (UNIFI, Italy) - School of Architecture - and attended a Master in City and Technology at the Institute for Advanced Architecture of Catalonia (IaaC, Spain) after presenting a paper about Swarm Intelligences for crowd-based analysis during the Responsive Cities Symposium (2017, Barcelona). Currently he is studying new areas of dialogue between digital simulations and craftsmanship as computational designer at External Reference Architects (Barcelona, Spain), while he is involved in the organization of international workshops to discuss the role of computer graphics and parametric programming in the field of architecture as a researcher at MTSYSStudio (Florence, Italy).

# Parametric Design of Street Profiles

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## OBJECTIVES

The main objective of this workshop will be to present the CIM-St tool (Klerk and Beirão 2017) to the academic CAAD community, frame it within the CIty-Maker toolset and parametric urban design methodologies and gather user feedback to support further development of the tool. Another objective is to promote parametric design methodologies among the participants, providing them with the necessary tools to achieve that.

## SCOPE

The workshop will be directed to both architects and urban designers but is open to any willing participant.

## CONTRIBUTION TO THE CONFERENCE

In this workshop, we will present and experiment with CIM-St tool for parametric street profile design. The workshop will provide a practical and pragmatic complement to the corresponding paper presentation during eCAADe 2017. Participants will 'dig deeper' into the inner workings of this parametric design tool, which associates semantics with a generative design system, and experience with an alternative and expedite method to design street profiles.

## EXPECTED OUTCOMES OR SKILLS ACQUIRED BY THE PARTICIPANTS

Participants will learn parametric methodologies applied to urban design, more specifically, to the design of street cross sections. They will also learn how to quickly create these designs with the aid of CIM-St, supported by real time analysis of the proposals. After this workshop, participants are expected to be able to use CIM-St without difficulties and generate qualified designs in an expeditious fashion.

## WORKSHOP SIZE

Half day (4 hours).

## SCHEDULE

The workshop will start with an overview of the CIM-St parametric design system and its interface, framing it within the CItyMaker toolset (Beirão 2012) and parametric urban design methodologies; Users will be given an urban design problem, requiring them to propose street profile design solutions for a given area based on a set of constraints. This will require them to become familiar with CIM-St's interface and experiment with it extensively; After the design stage, participants will be asked to complete a questionnaire regarding the usability of the design system; The workshop will close with a debate among participants, where they are expected to share their design proposals for the area and argument in their favour, with the support of CIM-St's real time visual analytics. Besides a comparison between designs, the debate will also focus on the methodologies and tools used to accomplish them, straining their advantages and disadvantages.

## PREREQUISITE SKILLS OF PARTICIPANTS

There are no prerequisite skills of the participants to participate in this workshop. Participants are required to bring their laptops and should have already installed a working version of Rhino 5 (1) with Grasshopper 3D (2).

## LOGISTIC AND TECHNICAL REQUIREMENTS

In terms of space, the workshop requires enough room to comfortably accommodate all participants while using their laptops (with access to energy supply). We will also require internet connectivity for everyone and one projector + canvas.

## MAXIMUM NUMBER OF PARTICIPANTS

25

## BIOGRAPHIES

### *José Nuno Beirão*

José Nuno Beirão is Assistant Professor at the Faculdade de Arquitectura, Universidade de Lisboa - FAUL-Architecture Department. He graduated in architecture from the Faculty of Architecture of the Technical University of Lisbon in 1989. Practiced architecture and urban design since then starting the architectural firm B Quadrado Arquitectos with Miguel S. Braz in 1998. José Nuno Beirão concluded his Master's degree in Urban Design in 2005 at ISCTE and his Ph.D. dissertation entitled 'CItyMaker: Designing Grammars for Urban Design' at the TU Delft Faculty ofArchitecture in 2012. He developed a method and a set of tools to generate alternative solutions for different urban contexts by combining design patterns encoding typical design moves by means of shape grammars. The integrated set of tools, involving analytical, generative and assessment tools have been argued to constitute the basis of the concept of city information modelling whose acronym CIM can be read in the title, CItyMaker.

His research interests are involved in the development of customizable and flexible design systems, focused on housing since 1998 and more intensively on urban design since 2001. His current interests are focused on the development of shape grammars for urban design and on the use of the generative capabilities of shape grammars to support the urban design process and foster design exploration. He is presently Co-Coordinator of the research project 'Measuring Urbanity', hosted by CIAUD. He is responsible for the Parametric Urban Design chair integrated in the Advanced Studies on Computation for Architecture, Urbanism, and Design at the Faculdade de Arquitectura, Universidade de Lisboa.

### *Rui de Klerk*

Rui de Klerk holds a MSc degree in Architecture from the Faculty of Architecture, University of Lisbon (FAUL) since 2012 and is currently a PhD Candidate in Design and Computation applied to Architecture at the same Faculty, with a research on Semantic Design Systems with a FCT Doctoral Grant (SFRH/BD/131386/2017). From June 2016 until September 2017, he was a Research Fellow at the Research Centre for Architecture, Urbanism and Design (CIAUD) at FAUL, integrating the research project "Measuring Urbanity: densities and urban performance of extensive urban fabrics. The Portuguese case" (CIAUD_BI_09/ EAT/04008), with an FCT/MEC grant. From April 2015 to May 2016 he integrated the research project "TECTON 3D - Digital Mockup: Touching the 3rd dimension" (PTDC/EEI-SII/3154/2012) with an FCT grant, working on the development of an application for procedural modelling in immersive virtual reality environments. During 2013, he worked as a research intern in the project "O Lugar da Villa Renascentista na Arquitectura Portuguesa" coordinated by Professor Amílcar de Gil e Pires (FAUL).

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[1] https://www.rhino3d.com/edu

[2] http://www.grasshopper3d.com/

# Structuring of Teaching and Learning Situations in Architectural Education

## *Using and Integrating Digital Analysis within Interactive Genetic Algorithms*

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## BACKGROUND

In the search for a deeper understanding of aesthetic quality in architecture, complexity of a design provides a possible area of comparison. In further detail, varying degrees of complexity may serve as comparable characteristics regarding different design proposals, either observed in the design as a whole or over different scales (fractal characteristics). Thus, using different methods to determine complexities can lead to a deeper insight concerning which role each of them plays in the overall aesthetic quality of a given design. One well established method to describe complexity represented as density and distribution of significant lines of a design across different scales is the fractal analysis method box-counting (Lorenz 2012). The authors propose an additional method, called gradient analysis, as part of a greater palette to aid design aspect-analysis.

### *Gradient analysis*

Gradient analysis is an additional method for architects, designers as well as students and scholars to analyze and subsequently influence the degree of proportion-complexity of a design (Kulcke et al 2015, 2016). This method is based on the assumption that redundancy reduces the complexity of an objects' appearance. However, the reduction of complexity is not a quality per se; the matter at hand is for designers to achieve a balance between redundancy, which provides readability of form, and complexity to sustain interest in it. Moreover, the authors are aware that, concerning this balance, many different levels of comparison exist, including, among others, the variety of material and colour combinations. However, for the moment the authors decided to focus on proportion, expressed by a gradient which is defined by two points (diagonal of a rectangle).

The basic idea of redundancy-analysis by gradient-comparisons led to a computer program called 'gradient analysis', which pairs every significant point of a design with each of the other points, comparing the gradients of the lines defined by each pair. By doing so emphasis is put on similar relations rather than specific relations (e.g. Wagner, 1981). Moreover, relations are not weighted depending on distance and/or visual highlighting e.g. in form of material edges, since Gestalt perception does not necessarily require edges (Kulcke et al, 2015). The weighting of different perceptual relations will be subject of future studies.

The result of the measurement is a list of pairs of points (coordinates of corners or intersections of lines) and their gradients, given as angles. In addition to the angle redundancy quotient a length redundancy quotient is also determined. The angle-redundancy quotient $R_\alpha$ is defined by the number of different angles $C_r$ divided by the total number of angles $C$ (formula 1; Kulcke et al, 2015):

$$R_\alpha = \frac{C_r}{C} \quad (1)$$

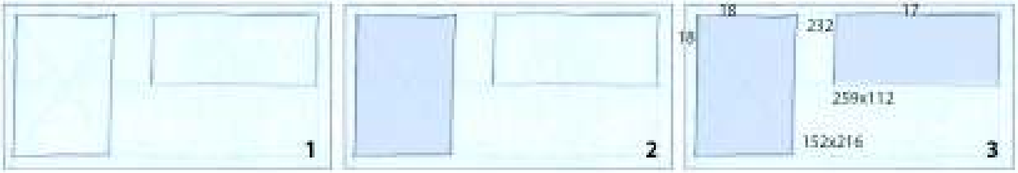


Figure 1
Scan and retrieving rectangle measurements

with $r$ being all repetitions and $C$ being calculated as follows (formula 2; Kulcke et al 2015):

$$C = \left(n \cdot \frac{n-1}{2}\right) \quad (2)$$

with $n$ being all single connections. The length redundancy quotient is calculated in an analogue fashion. In both cases, a tolerance coefficient takes into account that slightly differing angles or lengths may be perceived as similar and that the drawing of the object may not be accurate. The tolerance coefficient includes all angles inside a certain range, i.e. angles that stay within that range are counted as a repetition of the angle they are compared to.

### *Interactive genetic algorithm*

In order to create a responsive system to be used within a design- and/or learning process the gradient analysis has been integrated in an interactive genetic algorithm (IGA). Within the IGA it serves to determine the fitness value of a given object evaluating the degree of proportion complexity and to create variations with an optimized degree of proportion complexity. In principle, the algorithm consists of the following steps:

1. Generating the first population of n parents: Currently two different designs each of which is defined by significant points.
2. Encoding: The coordinates of all significant points are translated into binary code.
3. Crossover: Two encoded parents are cut at a definite point and their parts are exchanged.
4. Mutation: Digits are swapped at a certain position.
5. Fitness values: Angle redundancy quotient and length redundancy quotient are calculated to determine the segment size on Goldbergs weighted roulette wheel (step 7).
6. User-choice: The user can favour a result for Goldbergs weighted roulette wheel.
7. Generating the next population of n parents: The next generation depends on the result of Goldbergs weighted roulette wheel (Coates 2010, König 2010) and another user-choice.

Some of the steps above are determined by users' choice and/or including randomization. The process is repeated until a satisfying solution is reached.

## IGA WITH GRADIENT ANALYSIS IN THE WORKSHOP

In the workshop participants extensively test the interactive genetic algorithm and thus also the integrated gradient analysis in a given framework. Since the software is undergoing a process of permanent evolution, particular attention is paid to the analysis and discussion of the results. Another focus is laid on the discussion of possible integrations into learning environments.

The presented method of analysis to evaluate a certain layer of design quality is used exemplary to test the integration of design analysis via an IGA into a design learning context. Alternative methods for evaluating design complexity, like easy access fractal analysis (Wurzer and Lorenz 2017), may also be integrated into a similar design process. Participants are held to adapt the process to their analytical focus or expertise within their own teaching environment.

### *The process*

The design process as considered in the workshop consists of three phases:

1. Freehand form development by sketching objects into a given rectangular field plus im-

age enhancement and measurement extraction (Figure 1).

2. Evaluating the intuitively chosen proportions by using the gradient analysis IGA (Figure 2) and semi-automatically producing alternative versions on the basis of proportion analysis (Figure 3).
3. Comparing and choosing the final version, thus optimizing or confirming the initial design gained by sketching.

Figure 2
IGA user Interface and first population of n parents (n=2; showing just one of the two parent), displaying fitness values

### *The workshop content*

As preparatory steps the participants are familiarized with the general theoretical approach of proportion complexity and proportion optimization. Then they are taught to use scanning and an image enhancing process allowing to feed the intuitively reached object into the web application to apply the IGA for proportion optimization. The actual task is presented as a design task to develop a prefabricated concrete façade module with two openings, especially focusing on a pleasing design considering the placement and size of the windows or doors. The height and width of the desired element are given, participants are asked to choose the openings boundaries as parallels to the rectangular boundary of the overall object. The participants are advised to draw a minimum of six variations and encouraged to optimize a favoured first design by iteration i.e. by sketching it again with alteration of measurement, but preserving the general idea of the previous design. After choosing two favourite designs from the sketching phase, these are scanned (Figure 1) and opened within the image enhancing software. The sketched and digitalized rectangles receive an overlay of digital rectangles as a means to retrieve the measurements of the openings. These are chosen by the participants who visually control the process, especially regarding if the overlay rectangles still represents or even betters their design aim. The measurements of the favoured two variants can now be entered into the user interface of the gradient analysis IGA to serve as parents (Figure 2), as the starting point for the interactive genetic algorithm. Again in several cycles the proportions of the openings within the facade element are optimized, chosen by the numerical gradient quotient and visual appearance (Figure 3). After several cycles the participants receive an output of the favoured solution of each cycle out of which again two favoured designs can be chosen. These are then put to comparison to the top design solution from the first phase of sketching. Finally each participant presents his or her work and voices the choices he or she has made on the way toward the final design.

### *Advanced Task*

The integration of user choices remains an important focus as the developer intend the tool to be utilized as a cognitive and analytic aid during the design process and not as an automatic design generator. For the workshop the software has been developed further in order to allow users to manipulate elements of the IGA themselves while producing design variations e.g. implementing their own cross over masks (Coates 2010, König 2010).

To gather and evaluate the feedback (of students) a qualitative approach is in development. The status quo is using narrative interview technique and computer aided qualitative content analysis. It is part of the workshop to discuss the optimization of and alternatives to this feedback-process.

Figure 3
Two examples of first cycle and user choice (bottom) for next cycle, displaying fitness values

## PREVIOUS TEST CASES

### *The implementation in the learning environment*

The approach has undergone first testing with students in the winter semester 2016/17. The students' feedback is taken into account to optimize the process and the interactive algorithm (Poirson et al 2010) for further implementation in design education. A crucial point is the carefully adjusted use of different media (sketching in combination with analyzing/choosing within the GUI of the IGA). On the basis of testing the IGA within the learning environment changes have been made to the algorithm to optimize the design process. The comparability of the task is significantly changed by seemingly small alterations, respectively given rules and constraints, regarding the task.

To gather and evaluate student feedback a qualitative approach is in development. The status quo is using narrative interview technique and computer aided qualitative content analysis. It is part of the workshop to discuss the optimization of and alternatives to this feedback-process.

## DISCUSSION

Allowing participants to use edges that are not parallel to the boundaries of the rectangle, using rounded corners or organic freeform is of course possible. But this should be done in a way that every participant is aware of that possibility, to ensure comparability for later discussions of the results. A possible variation is also to allow for teamwork and to propose to participants to marry their own favourite design from sketching to one chosen from a colleague, thus building the initial pair for the IGA.

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# Dynamo: Applications for Design and Optimization

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## OBJECTIVES

Workshop participants will learn to use Dynamo for Revit, Dynamo Studio, and the Dynamo Customizer on the web to enable architectural design and workflow automation. We will begin by developing a common understanding of the mechanics of Dynamo, then move on to build a set of scripts together that will include geometric and Revit applications. On day two, emphasis will be placed on extracting the most value from your Dynamo scripts including Industry best Practices, tips and examples for building robust scripts for sharing, and adapting scripts for optimization. We will conclude with a look forward to Autodesk's Project Fractal and Project Quantum.

## SCHEDULE

### *Day 1*

**Part 1 & Part 2.** Build common Dynamo understanding

### *Day 2*

**Part 1.** Learn to Develop Dynamo Scripts for sharing, and adapting scripts for optimization.

**Part 2.** Get peek into Autodesk Future Generative Design Tools.

## BIOGRAPHIES

### *Colin McCrone*

Colin McCrone (@colinmccrone) is a product manager with Project Quantum at Autodesk in San Francisco. He teaches BIM and computational design at California College of the Arts, and he is a Lynda.com author. Colin was previously the Director of Design Technology at Safdie Architects in Boston and the Computational Design Evangelist for the Dynamo product team at Autodesk. He has also just returned from a summer-long solo cycling trip across the United States. Previous Workshops led: ACADIA 2014 and 2015, eCAADe 2014, USC BIM Symposium 2014, Facades Plus 2014, 2015, 2017, BILT NA 2017

## PREREQUISITE SKILLS OF PARTICIPANTS

To get the most out of the workshop, participants should have a basic to intermediate understanding of visual scripting including Dynamo. Bring your questions and your challenges.

Participants have to bring their own Laptop and have Revit 2017 or newer, and Dynamo Studio Installed prior to the workshop. To access Autodesk Software for students and educators use Autodesk website under the section education (1). For Participants who want to take a look upfront into Dynamo you can access Autodesk´s Visual Programming Guide (2).

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[1] http://www.autodesk.com/education/free-software/all
[2] http://dynamoprimer.com/en/

# AGENT-BASED SYSTEMS

# Extended modelling

## *Dynamic approaches applied to design reef habitats at Sydney Harbour*

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*This paper outlines a critical approach to computation in architecture by using multi-agent systems and dynamic simulation tools. Such methods reinforce viewing design as a data-driven process, whereby a problem is analysed to a set of agents and their properties. The related actions assume extensive modelling techniques, recursive experimentation and testing to assist design since the early stages until completion. In reflection, similar methods are employed to tackle problems of content other than architecture. The experiment being discussed is Bio-shelters. It involves designing artificial coral reefs to be placed at the Sydney Harbour, aiming to improve the living conditions of seashell and other endangered organisms. This paper first describes reefs as highly sophisticated ecosystems; then, it proposes methods for designing and constructing ones, further commenting onto their shape, fabrication, materiality and on-site placement, consequently reinforcing that extensive modelling techniques currently applicable in architecture may also respond to different scenarios about our settlements and the environment.*

**Keywords:** *Dynamic simulation, data-driven design, multi-agent systems, computational tools*

## INTRODUCTION

With the advancement of digital tools approximating behaviours, phenomena and influences, it is currently possible to apply an all-encompassing approach about architectural design seen as a performative process (Hensel and Menges, 2007). Extensive data inputs and recursive processes are main applications of computation supporting form-finding techniques. As such, computation may assist in managing a set of agents acting as self-organizing principles during morphogenesis (Weiss, 1999; Weinstock, 2004). Advanced parametric tools have been used to break down a problem to multiple agents described by their properties in preparation for interactions. The related operations assume producing models that are suitable for testing ideas since the early steps until final resolution.

This paper draws upon critical applications of computation in architecture, whereby design is approached as a data-driven problem, first analysed agents and their properties, then interacting via dynamic simulation to produce various schemes. The appointed techniques assume advanced modelling techniques based on recursive experimentation and testing leading towards increasingly sophisticated outputs. A case study experiment has been developed to test the efficacy of such methods in responding to problems of content other than architecture. The task particularly involves the analysis and further designing of artificial coral reefs to be placed at the Sydney Harbour, an area of rich biodiversity that is also heavily populated. Ideally, the proposed schemes would be informed by reefs' remarkable complexity and sophistication invested onto their shape, structure, behaviour, materiality, fabrication and on-site adaptation. In assessing the results, it is suggested that extended modelling techniques making use of advanced computation such as those currently applied in architectural design research are suitable to tackle problems about our broader environment, artificial and natural alike.

## A NEW POTENTIAL FOR EXTENDED MODELLING VIA MULTI-AGENT SYSTEMS

Multi-agent approaches have been employed in architecture in order to explore the influences of different contextual factors. Initially developed in the 1960s with reference to Cybernetics (Pask, 1969), the underpinning idea has been that a design problem may be described by a set of influences interacting with each other as part of a dynamic system. Same as in nature, elements of an artificial setting may not be seen in isolation, but rather as integrated components of the broader environment in which they belong. Agents pursue goals or carry out tasks in order to meet design objectives, which may be supplementary as well as conflicting to each other. In effect, multi-agent systems have helped to understand, manage, and use distributed, large-scale, dynamic, open, and heterogeneous computing and information systems (Weiss, 1999) rendering those systems more resilient, robust and reliable in relating and managing variable inputs and their influences to proposed schemes.

The tentative list of agents in architectural design includes the sum of contextual factors as traits making the architectural system (Ballantyne, Kawiti, Schnabel, 2016). These may be about the site, proximities and surroundings, energy flows, movement, connections and traffic with entry points, regulations, restrictions, enduring and changing conditions, social behaviours, economy and culture, existing and proposed activities, functions and the program. The agents are introduced via a set of data, properties and rules, along with their intensity of impact. They express behaviours, characteristics and properties, as ways to outline potential relationships manifested in the result. Design is viewed as a problem of complex relationships between agents; moreover there is direct connection between the inputs and the form that occurs from the related actions and vice versa.

Relating agents via a system offers alternative ways to describe data patterns, iterative processing and progressive assessment as opposed to aesthetic-driven operations mostly relying on intuition, talent, or subjective judgement. Advanced computation combined with systemic views on architecture makes a synergy in resolving design. With software currently available, data inputs may interact with each other by controlled operations even in real-time. In effect, multi-agent approaches assist to describe a design problem in analogy with science and engineering; then, the outlined functions are interpreted, processed and adapted to answer the problem via digital methods of high accuracy and control. Considering the breadth of applications in engineering, multi-agent approaches such as those described above may be applied to resolve a wide range of scenarios. For this case, advanced computational methods are employed to tackle problems of environmental concern. Specifically, data from marine biology inform prototype models for artificial reefs. It is aimed that the outputs meet the needs of specific organisms as they are also conditioned by the data taken from different environments.

Early schemes may be produced directly as the agents are introduced in a design platform to interact with each other. In architecture, these operations are typically manifested in the context of drawing. The architectural drawing may not be limited to provide technical information or to document design. The drawing is a transitory element, offering modes of systemic association of the data it depicts in a mode being varyingly diagrammatic (Allen, 2000). It shows information about the design factors altogether as topographical data (Vidler, 2010). It further aims to initiate dialogue among all agents and their interaction as in a real-time experiment, as opposed to being strictly a visual statement about the design outcome (Frazer, 1995). Such an operative conception of the drawing is reinforced by generative functions related to the computer seen as an iterative also relational device (Rahim, 2009; Schumacher, 2009). The use of advanced computation to calculate and to visualize the results of interactions has invoked readdressing the significance of the drawing as an experimental tool where design is performed, rather than one driven by aesthetic operations (Zavoleas, 2014 and 2015). Being supported by the digital, the drawing has been updated to a dynamic simulation model constructed to relate the various agents of design.

The simulation model has operational analogies with scientific ones commonly described as experiments set to reach greater validity. The model in its extended form becomes an active element. Evidently, the main difference between current computational approaches and former ones executed exclusively at the drawing board may be addressed in the tools appointed for modelling and processing the problem. These have departed from the analogue framing with its character and functions often being intuitive to embrace the capabilities of dynamic simulation and real-time interactions, as those performed in experimental settings and contemporary design packages. In the simulation model, multiple agents interact as they are being related to spatial and formal effects. The model - or the drawing in its updated form as a means to visualise agents and interactions - is the collective scene where agents perform together and the technical basis to frame a design proposition.

## EXTENDED MODELLING APPLIED ON ARTIFICIAL CORAL REEFS

This paper proposes that advanced computational methods employed in architecture as dynamic techniques to produce schemes are equally capable of responding to design problems of other areas (Spuybroek, 2009). The project being presented is Bioshelters: Design Reef Habitats at the Sydney Harbour, an interdisciplinary research study between architecture, computational design and natural sciences. It has used a multi-agent approach with data from marine biology and bio-engineering to model prototypes for coral reef structures. It is aimed that the produced outputs are designed to meet the needs of specific sea organisms and to offer variations that are suitable to different topographical and environmental conditions. For this purpose, negotiating with existing natural settings has been a critical factor in shaping design schemes.

### *The project and its motivation*

Designing habitats for non-humans is proposed as a way to test extended modelling techniques applicable in sensitive natural environments. Artificial coral reef colonies are aimed for locations of diverse marine ecology such as coastlines being under potential threat, since there is also where rapid urbanisation occurs. Evidence for this was given in an article published recently in The Ecological Society of America Journal stating that “some estuaries in Australia, the United States and Europe have had more than 50% of their natural coastline modified with artificial structures” (Dafforn et al., 2015). In the same article, the researchers argue for a “conceptual framework for designing artificial structures with multiple functions,” pointing towards that at present “while the design of artificial structures remains linked solely to engineering goals, their multifunctional potential may not be fulfilled.” The present paper aligns with the prospect of a ‘multifunctional potential’ by a data-driven design output that can cater for all involved participants. Consequently, designing reef habitats for oysters, barnacle, seaweed and kelp, sets the case study to test the “extended modelling” approach expressed above.

Sydney Harbour has been chosen as Bio-shelters’ site. Sydney Harbour is an area of remarkable biodiversity; still, due to urban development along the harbour foreshore and due to the industrial heritage of the harbour particularly west of the Harbour bridge, water quality and marine biodiversity are at risk. Traditionally a rocky shoreline, many of the species living underwater are complex systems that expand as colonies of seashell organisms such as clams and oysters (Figure 1). These organisms are filter feeders, whose primary contribution in sustaining environmental balance is to clean the water by removing excess nutrients and pollutants. Those systems are extremely versatile, agile and vital in maintaining environmental balance, meanwhile being very fragile and threatened under the existing conditions. Due to disturbing factors (Dafforn et al., 2015) such as human population increase, also pollution and climate change, the ocean is becoming a stressful environment for seashell organisms living on rocky locations as well as for underwater plants. If those systems are continuously subjected to numerous stresses especially those related to human factors, the strain is too much to endure and so they will perish. In response, the project proposes alternative structures aiming to improve the conditions of seashell organisms and alike of plants whose survival is crucial for the ecosystem.

## *Approach*

The study involves a large list of specialisations from bioengineering science, marine biology, engineering, computer science and advanced manufacturing working together with designers and architects to apply a computational design-driven strategy. The aim has been to link architecture with engineering and science through a compound understanding of various processes related to computational design.

In analogy to a hypothetical problem in architectural design, this case includes collecting data from biology to describe typologies of marine habitats about the living conditions of various organisms, also information about the site concerning landscape, topology, soil, temperature and sea currents. Sufficient data sets were collected from colleagues of sciences and engineering to establish a three-fold iterative process potentially leading to a site- and organism-specific design outcome. As the project suggests, key parameters influencing the viability of clams and oysters also of underwater plants as

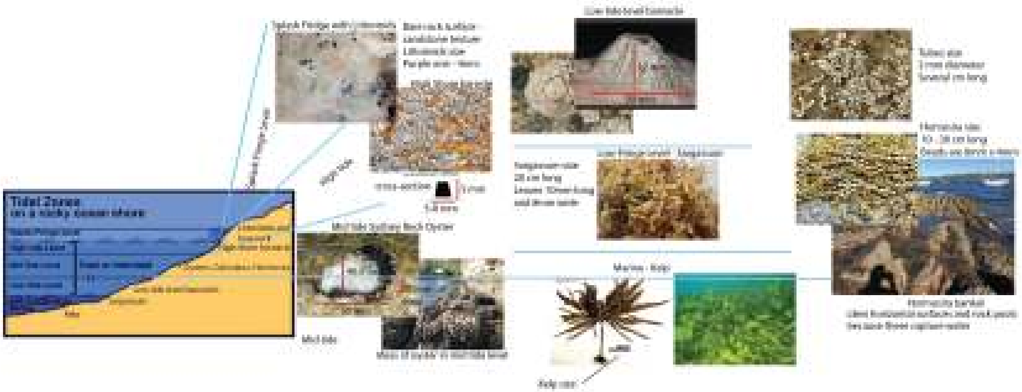

Figure 1
Cross section of rocky shoreline inhabitants inhabiting all relevant information about marine organisms.

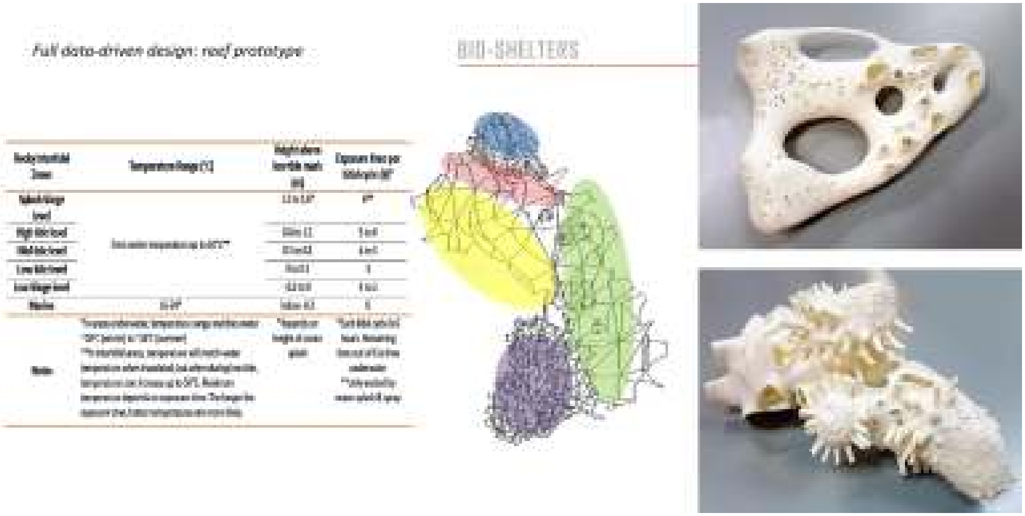


Figure 2
Data-driven design process with different physical outcomes.


Figure 3
First virtual models and renders .

the various occupants are translated to design structures being then prototyped. The process showed a macro- a meso- and a micro- dimension for the project as outlined below:

* MARCO. As macro- input, the team has defined variables and data sets that respond to site location (geospatial data) such as positioning, orientation, exposure to sun and wind, wave impact, topography and material consistency of the shoreline, etc. This data assisted to define early sketches of artificial coral reefs also of seawalls with similar function. As so far the designs have not been site-specific, this input has been set aside for later, until a decision for the site is made causing to adapt the design to a specific location.

* MESO. This has been arguably the most signif-

icant input, directed by the marine biologists of the team to inform the core data sets for this project. The aim has been to define habitat requirements of oysters, barnacles, seaweed and kelp as specific typological features (Figure 2).

* MICRO. The micro- dimension is concerned with questions of materiality for final reef / seawall production. By following upon earlier experiments with seawalls, it has been argued that high PH-level consistencies such as those being similar to concrete could hinder populating the structure. Thus, the material requires special consideration, which is yet to be defined as a mixture made of clay and crushed oyster shells combined with paper particles to add extra porosity as these will eventually be dissolved. 3D printing is chosen as the most reliable fabrication technique to produce same copies of the designs directly from the digital source.

### *First experiments*

Given that the marine biologists could provide various data sets within a very short period (in fact, these had existed already as in cvs. format from previous research) the design team could start modelling to produce the first results during the one-week workshop (Figure 3).

In retrospect, interacting with specialisations of diverse background has provided the designing team with valuable insight on how an optimised 'living quarter' for oysters, barnacles, seaweed and kelp might look like. Yet, the marine biologists could understand instantly parallels to formations they have experienced in their day-to-day work and hence they provided feedback on how close the data-driven design approach was, compared with nature's precedent structures. The first designs were designed digitally, then prototyped in miniature size by using 3D printers, as this process was informed constantly by specialists' feedback. As a start, physical objects were printed using PLA filaments, helping to better understand the produced geometry and shapes. From these series of models of 250x210x100mm, it was clear that a high level of complexity was actually attainable (Figure 4).

Figure 4
First 3D printed results.

Figure 5
3D printed model using Z-corp printer. Prints shown with their support material (top row); Z-corp print, whole model and detail (bottom row).

Then, one of the models was scaled up to an approximate dimension of 700x350x350mm and printed using a Z-corp dimension printer and ABS material. Overall manufacturing time had extended in this scale to several days of non-stop printing and the process required large quantities of support material as well. This experience provided with an indication on what to expect during fabrication at physical size with materials defined in the micro- dimension. Consequently, the team currently investigates digitally controlled fabrication processes with the use of a CNC mill with custom-made funnel pipe to distribute a clay / oyster shell mixture (Figure 5).

## CONCLUSION. MULTI-AGENT SYSTEMS AND DYNAMIC DATA INPUTS INTO DESIGN

This study aims to reinforce the idea that employing advanced computational techniques such as dynamic simulation and real-time testing currently applied in architectural design research is suitable for a wide range of scenarios including our urban environment and the broader ecosystem. For example, there are many analogies and similarities between human settlements and colonies of marine organisms, particularly in the established relationships with the environment, whether natural or artificial, or both. The analogies are revealed as soon as a design problem is approached via systemic logic, described by data inputs and the relations between them. Especially with the aid of advanced computational tools currently available, design of any kind, whether of an architectural, urban or environmental focus, may be analysed to a set of variables represented by agents interacting with each other and so having their influences registered onto form.

In examining the above, this paper discussed the recent findings of Bio-Shelters, an interdisciplinary project being about the development of reef habitats and the applicability of architectural methods combined with advanced computation to inform the design process. First, it identified the conditions allowing marine ecosystems to survive. These have been translated to their attributes concerning typological features, relative positioning and materiality. Dynamic simulation techniques have been employed to test artificial reef structures as multi-agent systems whose formal and other characteristics are driven by real-like scenarios. Then, the paper presented a series of alternative design structures providing a safe environment for these organisms to breed and to thrive. In assessing the results, this paper has acknowledged the efficacy of extended modelling techniques to drive the process from the early until the final stages of design. Due to full parametrising, it has been possible to adapt the produced schemes to different conditions by performing tweaks of the initial data to affect the outcome. Additionally, dynamic simulation and real-time testing have offered accuracy in each phase of development. Later, prototype models scaled and at physical size will be built and placed at natural locations of Sydney Harbour. The designs will be further examined with regards to feasibility and performance, as this will assist to finalise shape, fabrication techniques, materiality and on-site placement methods.


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for digital and robot fabrication: Dr Kate Dunn, Melinda Wimbourne, Marjo Niemela;

for advanced 3D printing: Dr James Gardiner.


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# Emergent order through swarm fluctuations

## *A framework for exploring self-organizing structures using swarm robotics*

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*In modern architecture, construction processes are based on top down planning, yet in nature but also in vernacular architecture, the shape of shelters/nests is the result of evolutionary material processes which takes place without any global coordination or plan. This work presents a framework for exploring how self-organizing structures can be achieved in a bottom up fashion by implementing a swarm of simple robots(bristle bots). The robots are used as a hardware platform and operate in a modular 2D arena filled with differently shaped passive building blocks. The robots push around blocks and their behaviour can be programmed mechanically by changing the geometry of their body. Through physical experimentation and video analysis the relationships between the properties of the emergent patterns (size, temporal stability) and the geometry of the robot/parts are studied. This work couples a set of agent based design tools with a robust robotic system and a set of analysis tools for generating and actualising emergent 2D structures.*

**Keywords:** *Multi Agent Systems, Generative Design, Swarm Robotics, Self-organizing patterns*

### INTRODUCTION

Unlike the modern architects' fascination with machines and simplicity, digital architecture has developed a fascination for complexity and has drawn inspiration by freeform shapes found in nature. The first digital age in architecture celebrated geometric complexity which was enabled by digital tools but also created a gap between the materiality of architecture and the immaterial logic of digital design. This initial gap was bridged by the application of digital fabrication techniques and industrial robotic arms (Gramazio and Kohler, 2014). Additionally, the mature use of digital tools has led architects to consider computation as an alternative for solving complex design problems rather than merely using it as representation tool (Kalay, 2004). Although the advent of information age and the digitalization of the building industry have radically changed the way we conceive and construct building structures in the recent years, in many cases digital technologies are used as means to express designers' formal aspirations and as extensions of long established design

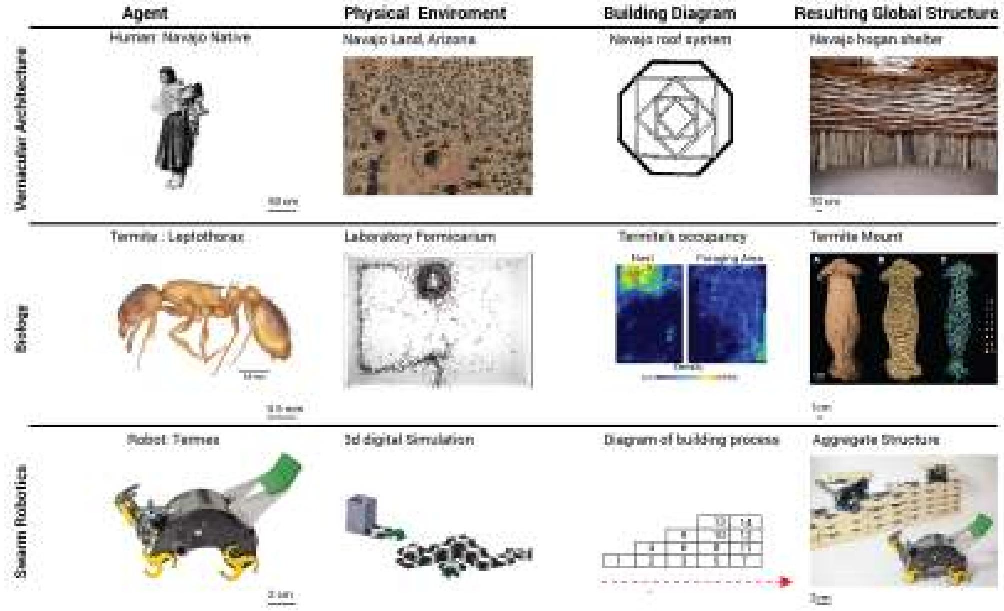


Figure 1
Table with bottom up construction processes from the field of vernacular architecture, biology and swarm robotics. From left to right we illustrate in different scales a builder, the environment it operates, different building diagrams and the resulting global structures. Image sources from top to bottom: Navajo Nation, Wikipedia.org google.com/maps(top), Perna & Theraulaz / Journal of Exp. Biology / http://jeb.biologists.org (middle), Petersen K.H & Werfel J./ Wyss Institute (bottom)

paradigms instead of fulfilling new ones (Bechthold, 2010). However, at a time when the complexity of building design goes beyond the cognitive capacity of a single design team and digital design systems become so intractable that designers can no longer fully understand and therefore control them, the question arises on how to develop new design paradigms and tools based upon complexity and emergence. More specifically how we can develop generative design methodologies which are coupled with evolutionary models and swarm robotics. The motivation of this work is to merge agent based design approaches with research from complex systems. Work from the latter has shown that the linking of computational models which describe social insects' coordinating mechanisms at the particle/individual level with quantitative data can explain pattern formation at a higher collective level (Fouquet et al., 2014).

Visionaries such as B. Fuller acknowledged as early as the 1970's the necessity of looking at design from a scientific perspective and emphasized the importance of updating existing design models by embracing nature's complexity and not by reducing it (Fuller, 1975). Pask and Frazer envisioned the use of computation in design not merely as developing drafting aids that improve descriptive design methods but as a way to redefine design based on the nature's metabolic and evolutionary processes (Frazer, 1995). This approach is now more relevant than ever because of the increasing computational capacity which offers new ways for formalizing algorithmic design thinking and tooling methods. In the second digital age that we are currently going through, more than any other concept, understanding and accommodating complexity via computational means appears to be the core design issue (Oxman, 2006). Although work has been done towards managing complexity from within the fields of Architecture Engineering and Construction (AEC), there are alternative approaches and scientific techniques that can be disseminated from different fields such as experimental biology, computer science, engineering and complexity theory . The study of complex adaptive systems, has gathered a lot of attention as it offers an alternative way of designing intelligent systems, in which self-organization, emergence and distributed behaviour can replace control, programming and centralization (Bonabeau et al., 1999). By closely examining the behaviour of complex systems, scientists try to defer bottom up rules and build stochastic models to investigate how non linear systems achieve order (Heylighen, 1989).

In digital design, Coates and Miranda, Snooks and Leach have focused on investigating swarm intelligence as an alternative to established design paradigms and have applied it to problems which range from urban to architectural design(Miranda and Coates, 2000,Leach, 2009, Snooks, 2011). Menges has explored how agent based design models can be used for generative design purposes and how they can be implemented materially (Baharlou and Menges, 2013), while Scheurer has investigated how self-organization can be applied for the design and optimization of real design applications (Scheurer,2005) . Big part of these research efforts have been based on algorithms that have been developed in fields of computer science and engineering (i.e. Reynolds' swarm behaviour algorithm, Reynolds, 1987) and have been appropriated for architectural design research purposes. However, in their early manifestations such agent based models were decoupled from physical constraints until the later stages of design and in many cases the design outcomes have proven to be challenging to materialize even in small scales (i.e. size of a pavilion). Trying to address this issue, Tibbits among others has been focusing on how to program matter directly in a bottom up fashion by controlling geometric properties of materials which can allow them to self-assemble into emergent forms(Tibbits, 2011).

Additionally, research in the field of robotics, inspired by the concepts of biomimicry, focuses on how autonomous robotic systems can be used for reducing engineering and construction complexity of large scale structures (Werfel et al., 2014). The application of robots in real construction sites during the 90's in Japan has shown that there are issues of communication, control, maintenance cost and reliability which significantly increase the complexity and makes their actual application in the building industry harder(Warszawski and Navon, 1998). Understanding the behaviour and mechanisms which characterize nest building of termites and transcribing the flexibility, robustness and self-organisation of such processes is considered crucial for developing distributed robotic systems which can achieve tasks that may be too complex for one robot to accomplish (Beni, 2004). Werfel has shown the potential benefits of using multi agent systems for reducing computational complexity by combining software and hardware platforms and by using distributed swarm robotics for achieving complex global behaviours and structures (Werfel et al., 2014) . By using local information and basic sensing mechanisms such systems can remain simple even when they scale up. Current work suggests that designing and fabricating several task specific robots which can operate autonomously for performing building tasks can be more reliable and less complex than programming and controlling multiple industrial robotic arms (Petersen, 2014). For instance, explicit robot-to-robot communication rapidly becomes a big issue when the number of robots increase: such an issue can be eliminated by controlling robot-to-robot communication implicitly via the geometric conditioning of their interactions and the interaction with their environment (embodied behaviour). Moreover, when dealing with multiple robots, the reliability and robustness of the system as a whole increases because the failure of one or several robots won't prevent task completion, while when using a single robot an error can be preventive for the task completion.(Figure 1)

Despite the fact that research in the field of engineering suggests that distributed robotic systems can be more flexible and fault tolerant and therefore more suitable for the unpredictable and dynamic

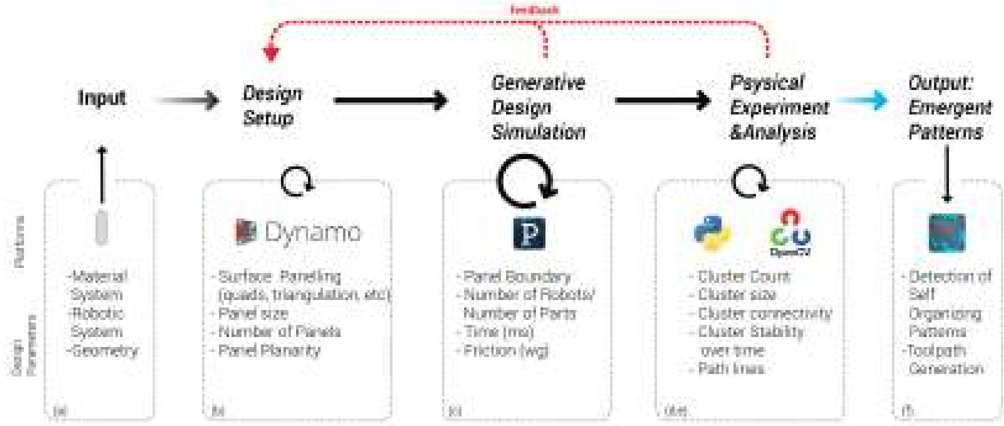


Figure 2
Workflow diagram illustrating the design steps, parameters and implmented platforms

environment of the construction site, academic research in the field of architectural robotic construction so far has been mainly focusing on the use of industrial robotic arms (Gramazio and Kohler, 2014). Another gap is that although generative design techniques are becoming more popular for design exploration using local rules in a bottom up fashion (i.e. agent based models, genetic algorithms), material constraints and design optimization are applied at the later design stages and their construction is done using strictly top down techniques. Consequently, the generated geometries in many cases are the outcome of the arbitrary manipulation of a number of parameters which condition a specific digital model and not the result of an evolutionary material process (Jencks, 1997).

On the contrary, if we refer to nature, in the case of termite colonies for instance, each construction act from an individual termite changes the stimulus of the whole swarm which is operating collectively and therefore affects the outcome of the global structure(Perna and Theraulaz, 2017). Similarly , vernacular architecture offers a large variety of examples where the generation of design alternatives is the direct result of evolutionary material processes which are influenced by environmental conditions, social parsimony and iterative construction processes (Rudofsky, 1964). Unfortunately, vernacular architecture has been largely overlooked and only in few cases there has been interest in computationally implementing vernacular building techniques as in the case of reciprocal frames (Larsen, 2008). Although biologists have been able to study termite colonies in depth, by conducting physical experiments in laboratories and by building computational models using the gathered data, evolutionary design patterns of vernacular structures have yet to be rigorously studied under the light of computation and digital design models are often not coupled with vernacular building wisdom. While the complex geometry of termite mounds has fascinated architects formally for biologists it is considered as the result several evolutionary parameters which include: physiology of the termites' body, environmental conditions, speciation, available resources, the longevity of the colony (Bonabeau et al., 1999) (Figure 1).

## METHODOLOGY

This study builds upon the hypothesis that we can reconsider agent based modelling methods in architectural design by combining them with robust hardware platforms which are based upon autonomous robotic systems. The coupling of generative design approaches with the close observation of natural systems and the constraints of distributed robotic construction methods can lead to formally complex results with built in efficiencies previously unattainable. Via the mechanical encoding of design intentions and realistic constraints into the behaviour of swarm robotic systems, the objective of the study is to: a) effectively bridge the gap between agent based design generation and design materialization using low level autonomous robots, b) to use a rigorous physical testing and analytical process for developing design behaviours and c) make use of design data visualizations to detect emerging patterns in order to inform decision making of future design iterations (Figures 2 and 3).

Figure 3
Images illustrating each of the design steps of the proposed workflow: a) Geometric setup and design analysis of environment b) Parametric design of the robotic body and physical prototypes, c) Simulation of the generative behaviour d) Physical testing in different arenas e) Analysis of the experimental runs using computer vision and f)tool path generation based on robots motion

## *Experimental Setup*

To explore our hypothesis, we have developed a design methodology and designed an experimental case study which enables us to study the emergent self-organizing behaviour of simple robots and the appropriation of such system for architectural design purposes. In this case for reasons of simplicity, the design methodology includes the exploration of emergent 2d patterns based on the mechanical programming (embodied behaviour) of a swarm of simple robots(bristle bots). The experimental setup is based upon a workflow which was initially implemented at Smart Geometry conference 2016 (Andreen et al., 2016). It includes a reconfigurable two-dimensional environment (Arena) in which simple robots (Agents) move around passive building blocks (Parts) for specific time intervals (5-45min) or until they reach a state of an equilibrium. The shapes of the arena in which the robots operate can be considered as the boundary of an architectural panel to be designed. The design parameters which determine the geometry of the generated patterns, include the shape of the boundary, the geometry and number of the robots, the shape and number of blocks, the ratio of area to number of blocks (i.e. degree of transparency) and the runtime. The motion of both agents and blocks is tracked using a high definition camera (GoPro) and analyzed using a kit of custom developed computer vision tools (Python, OpenCV, Matplotlib) which allows for the performative evaluation of the emerging structures and behaviours. The robots are cheap and commercially available (www.hexbug.com/nano) and can move at an approximate speed of 11mm/s by combining a simple vibrating motor and 6-14 angled soft legs. The way the robots move is affected by the friction of the surface and obstacles they encounter (Figure 3f). Based on the variability of the ground surface and obstacles they encounter they can move relatively straight or follow random trajectories. In this case, we "program" the robots by altering their body geometry and the environment they operate. The body geometry of the robots is altered by adding covers with variable geometry(Figure 3b). Initial experiments showed that big and/or front heavy covers severely alter the locomotion of the robots and consequently the patterns they generate. We develop different covers to test how robots can grab and move blocks around the arena and how we can achieve specific swarm behaviors. In conjunction with the robot cover geometry we develop design alternative geometric configurations for the passive blocks (Figure 5). For simplicity purposes we start by selecting two primitive shapes such as circle and hexagon and develop different types of blocks by topologically altering the shapes. The robots operate in a modular arena, which can be reconfigured in different shapes (Figure 4).

### *Design Simulation Tool*

An agent based generative tool was developed in order to explore different design alternatives based on the physical setup described above. Unlike existing agent based tools that implement swarm behaviours and are not connected to the physical world, the developed tool is modelled after our experimental setup and is used as a platform to see how different boundary conditions and geometries of the agents can lead to different self-organizing configurations. The tool was implemented in Processing (Reas, 2007) using Box2D as a physics engine and allows fast design iterations, which can then be tested physically. Additionally, the tool enables the designer to test the scalability of different configurations and to observe what the global impact of local rules is when a large number of agents interact in the environment. The aim is to be able to easily adjust the parameters of the tool to match the behaviour of the robots and their interactions in the physical world and explore how we can design control different swarm behaviours. The tool consists of a 2d environment which is populated with active agents and passive building blocks. The designer can parametrically alter the design of both the boundary geometry as well as the robot/-part geometry using Dynamo visual scripting editor (DynamoBIM.org) and import them directly into Processing as a .json file. To achieve more realistic simulation of the locomotion, apart from their geometry, the designer can control the: a) ground friction, b) object-object friction, c) object density and the d) coefficient of restitution. The vibrating motor which propels the robots to move forward is modelled as an applied vector force on active agent with some noise to account for the variable ground friction that affects the trajectory of the robots. The robots are placed randomly in the arena and their position (x,y coordinates) at specific time interval is exported as a .csv file for visualization purposes.

### *Design Analysis*

In order to be able to detect clusters and characterize emergent patterns that form over time from the interaction between robots and blocks, a tool has been developed which analyzes the videos of the experimental runs. The video data is processed using blob detection algorithms, which have been implemented using a computer vision library in Python language (Open CV). The aim of the analysis is to see how the geometry of passive blocks, robots and shape of boundary affects: a) the trajectory of the robots in the arena b) the formation of larger clusters of blocks through physical interlocking c) the collective transport of blocks by the robots. By fine tuning geometric parameters of the blocks we test how can we affect the behaviour and size of the emergent clusters. By changing the geometry of the robots, we can affect how they interact with the passive blocks (i.e. grab and push one block at a time) but also with other robots (i.e. form chains).

Figure 4
Isometric drawings and top view photos of the three experimental environments (arenas) where the robots interact with the parts

## CASE STUDY

A case study has been developed to test our workflow and experimental setup. We investigate how the emergent clusters can be translated into openings of a panel and therefore alter its level of transparency. By controlling the ratio of blocks (i.e.number of blocks * area of each block) in relation to the area of the arena (i.e. panel area) we can define the level of transparency of the generated panel, while the interaction of the robots with the blocks can define the position of such openings. Our case study consists of the following steps (Figures 2 and 3): a) we consider a design surface (i.e. planar or curved façade surface) b) discretize the surface in panels using 3 different methods (circular, triangular, rectangular panels) c) one typical panel is selected from the surface for each panelisation method and its boundary is used to form an arena for the robots d) perform experimental runs with 20-100 robots and 2 different types of block geometries.

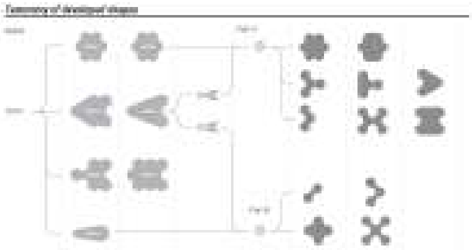

Figure 5
Taxonomy of generated robot and part designs

Figure 6
Time lapse photos of different behaviours of a single robot obtained by different conditions : a) the robot is moving freely in the arena, b) the robot is moving freely in the arena while pushing a block c) the robot is pushing a block following a path described by a soft boundary (textile)

The design parameters which affect the behaviour of the robotic system are: a) shape global boundary b) block geometry c) robot geometry d)introduction of obstacles within the arena e) initial configuration of blocks f) the time the systems is interacting (runtime). The experimental setup presented by Andreen, Napps , Jenning and Petersen (Andreen et al., 2016) is extended by introducing different types of part and boundary geometries and study how those affect the formation of the patterns. As a first step we study a small swarm of 20 robots and investigate the level of clustering that different part geometries can achieve and how the robot geometry can affect the manipulation of the parts and the locomotion of the robot. Although the research is at a very initial stage we hereby provide a set of both qualitative and quantitative observations:

### *Design of robot's body & motion*

The robots' motion is influenced by the weight and shape of its body and total number of parts (blocks) in the arena. Different speeds and level of agility can be achieved by changing the inclination of the body relative to the hexbug. Depending on whether the robots have grabbers or not it can engage with a block (grab it) and push it in a straight line until an obstacle is met, move along with it or simply hit it and change its trajectory. Cardboard robot bodies slow down the robots but provide more stability when they move. Robots with grabbers can align with each one is pushing one block or multiple robots are pushing a cluster of parts. Robot Designs that had no grabbers and had the same geometry like the parts, became one with the part cluster and move together along with it (Figure 8c). Robots with "grabbers" proved to be good in enabling the robots to consistently engage with one part at the time and push it forward in relative straight line (Figure 5). However, in many runs the robots clustered with only other robots and the lack of directionality of their shape resulted into one counteracting the motion of the other and therefore not moving. From the different robot body designs that were developed and tested the best ones proved to be the lighter ones with grabbers (Figure 6). A main design parameter for directing the robot is altering the friction level of the ground floor. By adding a more textured material we were able to direct the robot through a specific path until it reaches an endpoint (Figure 5). Another important parameter which affects the locomotion of the robots is the frequency of the motors rotation per minute (rpm). When the robots' batteries wear out, the motor's rotation slow down (rpm) and makes the robots run in circles thus changing its behaviour. Lastly, the robots cannot move if the inclination of the ground is more than 15% and they cannot push a single part if the inclination is more than 8%.

### *Design of part*

As far as the part is concerned two different types of geometries were tested along with their topological variations: a) one set of designs is based on the hexagon and four different types of block designs are created, b) the second set of geometries is based on the circle and fours different types of blocks based on the topological variation of 2,3 and 4 circles are created (Figure 6). The geometrical and topological variation is driven by how the parts can form bigger and more stable clusters by creating connecting points with higher friction. The main design parameters are the weight and the contact surface of the part to the ground which affects its friction. Moreover, the number and length of edges of the part affect the way it can connect with other parts. Hexagonal parts form more stable structures due to the friction of the sharp edges while circular parts are transported easier by the robots as they can allow for multiple grabbing points. The pushing of parts make the robots move in more straight trajectories also. Lastly, the topological transformations of the shapes help the creation of bigger clusters but constrain the flexibility of the robots to move around the arena. We calculate how the parts occupy the arena over time as well as the size and number of parts in clusters to see how the boundary of the arena and the robot-part geometry affect the formation of clusters (self-organizing patterns)

Figure 7
Images showing implemented robot behaviours, namely: a) Single robot navigating on a path defined by variation of friction, b) Robots forming a chain by pushing parts in synchronous motion, c) Emergent clustering of hexagonal robots parts and collective transportation of the cluster

### *Arena Occupancy and Clustering*

For each experimental case there is an entry point for all the robots and different initial configurations for the parts were tested namely: random placing in the whole arena, placing as one cluster in the middle of the arena and at the edge of the arena. Independent from their geometry, robots tend to gather towards the boundaries and can draw constant trajectories following the boundary of the arena, unless it has sharp angles (90 or smaller) which tend to trap the robots.The introduction of fixed parts (obstacles) in the arena reduced the variability of the clusters and depending on the number of obstacles (1-3) constrain the motion of the swarm. This led to the convergence towards of clusters that the robots could not alter within the experimental run and the swarm was stuck. In Figure 7 we plot the level of clustering of experimental runs of 30 robots and 60 parts, in different arenas. By analyzing the graphs we can observe that in all cases we start with a high number of small clusters (1-2 parts) that evolves into a lower number of clusters with bigger size(20-25). In the rectangular arena we can observe that at different timestamps medium (Figure 7a) and large size (Figure 7d) clusters are created for a small duration. Additionally, the hexagonal components form medium and large clusters for longer duration (1-2 min) unlike the circular components (<1min). In the triangular arena we can observe the formation of bigger clusters with the hexagonal parts(ca 20 blocks) which persist for the whole duration (Figures 7b and 7e).

## CONCLUSIONS AND NEXT STEPS

In this study we have investigated the generation of 2D self-organizing structures using a swarm robotic system. By changing the geometry of the robots, the parts and the environment (arena) where they interact we can achieve different swarming behaviours. We extend an existing approach proposed by Andreen D. and present a series of experimental results in which we explore how changes on the shape of robots and parts as well as on the boundary and ground friction of the environment affect the behaviour of the swarm. By working with a simple and cheap robot, we can physically test the interaction of a large number of entities and implement different swarm behaviours. By keeping our robotic system robust and by controlling a set of input parameters namely: population size, geometric shape of part and robot, shape of boundary and ground friction we can test which parameters have a greater impact on the emergent structures. The behaviour of each individual robot is simple and its motion appears random, but the modulation of friction(Figure 8a) and the geometric interaction with passive blocks affect the motion of the robots and can lead to complex global structures and synchronous behaviours (Figure 8b) .The initial results show that we can obtain control over the motion of the robots by creat-

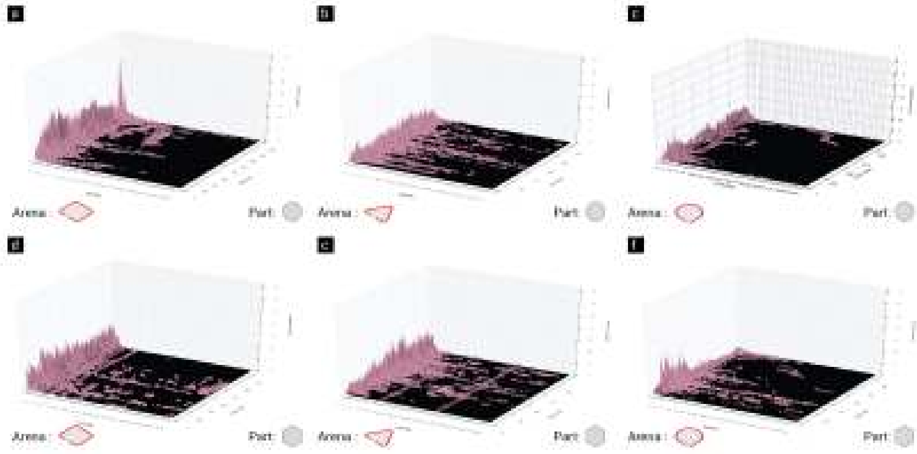

Figure 8
Plots of the number and size of clusters (between robots and parts) over time in 6 experimental runs . The top row shows results of the experimental runs with circular parts in the 3 different arenas while the bottom row shows results of the runs with the hexagonal parts.

ing soft boundaries which have higher level of friction (i.e. textile). Moreover,lightweight body modifications can improve the behaviour of the robots for pushing and grabbing parts without reducing their agility.

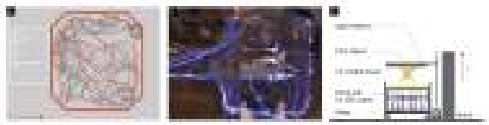

Figure 9
Generation of robot's toolpath using the developed tool in Processing(a), tracking of the motion of 5 robots interacting with parts equipped with UV lights in a rectangular arena(b) and diagram of the additive manufacturing platform currently under development (c)

The developed robot-bodies can transport circular parts for longer distances in almost straight lines. The creation of clusters is closely related to the design of the parts: curvilinear geometries (circular parts) are less likely to create stable clusters while the hexagonal parts can form bigger and more stable structures (Figure 8c). If the arena entry point remains open after the robots enter, then the robots navigate and/or push material outside of the arena by themselves

The limitations of the experiment include that we operate in a 2d environment and that we have not yet tested a very large number robots (>100). Additionally, no feedback mechanism is yet implemented into the robots in terms of identifying where they are positioned in relation to other robots or the arena boundary.Our future steps include to improve the simulation of the robots using the data collected from the videos, and provide a User Interface so that the designer can easily change robot and boundary designs and easier explore alternative designs. We also aim to test feedback mechanisms on the robot (electromagnet, proximity sensors) so that we can obtain more control over their behaviour. More importantly, we need to run multiple experiments with different number of robots and parts to test if the patterns and clusters persist independently of the size of the swarm. Our objective in studying whether these behaviours and robots' motion path persist in various scales is to use them for the development a distributed additive manufacturing platform where the trajectory of the agents over time is used as a printing tool-path for the curing of UV sensitive resin. The design of this platform is illustrated in Figure 9 and its design is based on the adaptation of open source 3d printer for curing UV sensitive resin (Calderon et al., 2014). The overarching target of the work is to connect digital agent based simulation techniques with the physical world by investigating distributed fabrication platforms based on swarm robotics and to explore how such strategies can be utilized in generative architectural design.

## ACKNOWLEDGEMENTS

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# Modelling Buildings and their Use as Systems of Agents

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*This research investigates the development of a new modelling and simulation approach for building design - defined as Agent-Based Building Modelling - that moves from the current object-oriented representation (such as in BIM) to an agent-based one. In the proposed approach, the representation domain is extended in order to include users and hosted activities, and the static modelling of the building is integrated with the dynamic simulation of its functioning. For this purpose, this paper presents a general template of the agent that ensures homogeneity of formalisation of the different typologies of entities (building components, spaces, V-Users, activities) and support the virtual simulation of the use process.*

**Keywords:** *Agent-Based Modelling and Simulation, Behavioural Simulation, BIM, Game engine, Agent-Based Building Modelling*

## RATIONALE

In AEC design processes, modelling and simulation have been generally considered as two distinct, sequential activities aimed at defining the different key aspects of configuration - both formal and technological - and performance of the design. The sequencing of these two actions, although recursive in the analysis-synthesis-evaluation cycle of an architectural design process, relies on the concept that the output of the modelling is the input (or at least a part of the input) of the simulation (Koutamanis, 1996). This sequence inevitably generates delays and many resources are wasted in modelling the different versions of the building, as it usually happens in trial and error design processes. The advent of Building Information Modelling has even bolded these criticalities: the forced accuracy and coherence of a building information model, as well as the tendency to over-detailing the design for documentation purpose, has pushed - at least conceptually - simulation later in the process. Even when a direct link between the modelling environment and the simulation one has been conceived, there is still the necessity of a well-detailed design in order to successfully perform simulation activities. The introduction of parametric design - in particular in its declination towards the performance-based design - has partially overcome this issue, conceptually and technologically fusing modelling and simulation actions to generate, control and optimise shapes and configurations for specific phenomena such as shading, visibility, energy consumption etc., although in a very qualitative way. More recently, Agent-Based Modelling and Simulation approaches have progressively introduced in the AEC field as a way to represent and control complex systems that can be decomposed into a set of autonomous, interacting entities (for instance people egress during a fire), in order to predict possible emerging phenomena and explore the effects of design variations (Gerber, 2017). As previously proposed by Smith ( 2003), a shift is possible in virtual architectures modelling by moving from an object-oriented approach to an agent-based one, overcoming the definition of static places that do not respond to the intended use. In particular, while some effort have been made in the integration of modelling and simulation actions regarding some specific aspects such as daylighting and shading, energy balancing or structural behaviour, few works has tried to enlarge the representation domain in order to include operations, use processes and users' requirements (Wurzer, 2010; Simeone and Kalay, 2012, Simeone 2015). In fact, while in literature buildings have been often compared to the concept of living systems, even from a computational perspective (such as in the "patterns" proposed by C. Alexander in 1977), current modelling systems are only centered on the virtualization of design and do not consider users and their activities as "part of the model".

## THEORETICAL FRAMEWORK

The integrated definition of the building and of its performances (in particular its use by its inhabitants) has been a hot topic since the introduction of digital technologies to the CAAD field. With the progressive increase of computational power, as well as the development of new paradigms, different approaches have been presented to the CAAD scientific community and some of them are now used in the architectural practice to evaluate specific aspects of human behaviour in buildings such as fire egress or pedestrian movement. From a brief study of the state of the art in this particular sector of CAAD, we can recognise three different main approaches oriented to the simulation of people movement and behaviours in the building:

1. Cellar automata systems;
2. Agent-based systems;
3. Activities-based systems (sometimes known also as Process-driven or Narrative-based).

The first difference between these approaches is the allocation of Artificial Intelligence among the different entities representing the building and its users. The cellar automata approach, that is maybe the older among them, principally rely on the modelling of the built environment as sets of active entities (defined cellar automata) provided with simple algorithms to control specific variables. For instance, in a simulation of people's movement in a building, the users' entities are actually passive and their passage from one cell to the other is actually controlled by the cells themselves. Specific variable -such as occupancy or movement speed - are stored both in the cells and in the users and support this computation that is, in fact, distributed. Among the others, cellar automata experimentations in the CAAD field embrace different applications as generative design tools (Herr, 2016) or simulative tool to predict and visualise pedestrian activities (Dijkstra, 2001).The introduction of Agent-Based Modelling in the simulation of people's behaviour in the building has actually inverted the AI distribution perspective of Cellular Automata. In fact, the core of this approach is the autonomy of the agent, provided with a set of behavioural rules able to interrogate the surrounding environment, make decisions and performs actions that change its status as well as the built environment in a continuous perception-decision-action cycle.
In this approach, the built environment is mainly passive and the use phenomenon emerges from the combination, iteration and interference of the behaviours of the n agents.
The introduction of this approach has represented a big shift both in the research field and the professional practice: many of current tools that are currently use to predict people's movement in specific buildings as stations, airports, shopping malls (such as Mass Motion by Arup and SmartMovement by Buro Happold) (Cenani, 2008; Yan, 2004), as wells as simulating evacuation processes (Gwynne, 1999), rely on this approach.More recently, research has proposed a new approach, partially derived from industrial production planning and management, that re-

lies on the “smart” formalisation of use processes in terms of a sequence of activities, organised and scheduled by means of a temporal-logic approach, and their simulation in a 3D virtual environment.
This approach, particularly effective in representing more articulated use processes rather than the simple people’s movement, is at the base of different modelling and simulation methodologies such as the USSUU system proposed by Tabak (2010) and the Event-Based Modelling (Simeone and Kalay, 2012, Simeone et al., 2013, Schaumann et al., 2015). In terms of AI distribution, this approach assigns AI resources to a process engine (as in the USSUU system) or to autonomous process entities (the events) able to coordinate and simulate multi-actors activities performing in the built environment.

## AGENT-BASED BUILDING MODELLING

In this context, we propose to shift the current BIM methodology towards a new user-centered perspective, in which the building is defined not only in terms of mere constructive components but also in terms of use and performance, including the representation of how it will work and how it will be used and experienced by its inhabitants. The development of an innovative system based on the integration of both modelling and simulation is indeed at the core of this research. In this system, entities are not passive databases for data storage (as in current BIM) but active agents provided with their own “intelligence” and behaviour. This modelling and simulation approach - defined as Agent-Based Building Modelling (ABBM) - differs from current ABM applica-

Figure 1
The BIModel of the case study - a hospital - that shows initial discretization of the building in terms of elements, provided with their own semantics (not yet agents because of the absence of behavioural rules).

tion to the AEC field for the fact artificial intelligence is distributed among V-Users (the virtual computational entities representing the various users of the building), the entities that compose the building (i.e. floors, doors, furniture), spaces, and process entities (activities, organized through temporal logic). To obtain a homogeneous multi-agents system, we conceived a general ontology for the agent, meant as a self-contained AI entity capable of controlling its own decision-making and acting based on its perception of its environment, in pursuit of one or more objective (Wooldridge and Jennings, 1995). In the proposed MAS system, the agent embeds three different components, applicable to all the different entities of the Building + Users + Use model:

- ID;
- Properties-Status;
- Behaviour Engine (meant as a set of decision/action rules).

The role of the first component, the ID, is clear: it supports the identification of any single entity within the model, from its generation to its elimination, and allow the agent to feel and recognise the different entities that surround it. ID are conceived as an alphanumeric code where the first part represents the class of the element and the second part indicates in a unique way the instance number within the model. The second component, the properties/status, represents both configuration and status during the simulation of any entity. While in a BIM system the properties component describes the static features of the building entity (i. e. topology, materials, construction information), in the ABBM system it embeds all those variables that 1) add use semantics and 2) represent the status of the agent/entity during the simulation. In the case of the technological components of the building, as well as of spaces, the properties formalisation is very similar to the usual BIM-oriented one. In fact, in building information models classes already embeds some semantics related to specific construction and production aspects. In the proposed model, this semantics is enlarged in order to formalise information related to usability and use,

Figure 2
The Agent-Based Building Model of the hospital case study (in the game engine Unity3D), where any entity - Building elements, V-Users and activities - are agents with their own set of properties and rules.

both to enrich the static model and to support data access, variation and evaluation during the simulation of the building+users+use system functioning. These properties - the static and the dynamic ones - clarifies the twofold feature of the proposed Agent-Based Building Modelling. The static properties, that are defined by the architect, represent invariant features of the elements such as materials, etc.. The dynamic properties, instead, represents the status of the elements during the simulation of the building use and embeds all those features that can actually vary during the process of use of the building. For instance, a door embeds a static property that clarifies which users are allowed to pass or a Boolean property that describes if it is open or closed. In a similar way, space entities can store information regarding the maximum number of users allowed at the same time while a dynamic property (controlled by a measurement algorithm) can store the number of people actually present in the room during the different stages of the simulation. By operating on these primitive properties, other properties (i.e. the temperature related to the room occupancy) can be derived through specific calculation algorithms. The memorization of the variation of this kind of properties is particularly effective during the evaluation of the simulation results since it allows designers to estimate particular phenomena such as overuse or underuse and consequently optimise the design. In a similar way, static and dynamic properties are useful in representing V-Users and their features. Static properties can be used to define the specific profile of the Users in terms of role (i.e. a patient in a hospital), physical features (age, sickness typology etc.), specific abilities and all the other aspects that can be considered and modelled during the design process. Dynamic properties, instead, can be used to represent the status of the V-User during the simulation: a walking_speed property or tiredness_level, for instance, can describe the specific condition of the V-User at a certain time of the simulated use-process. In the case of activities entities, the properties (both static and dynamic) embeds all those information necessary for a correct representation and simulation of its system of actions. Static properties can formalise the kind of V-Users necessary for its performing, while dynamic properties such as performing_time or influence_radius can represent both efficacy and influence of the activity performing within the built environment and in accordance with the use process. During the simulation, the sum of the status of the different entities - representing the building (and its spaces and components), the V-Users and the planned and unplanned activities - as well as its variation, represent the state of the entire system at a certain step of its intended use process, allowing even quantitative estimation of different aspects of the use phenomena.Compared to current BIM representation schema, the proposed model, in its static formalization of entities, represents both an extension and a "deepening": on one side, in fact, it enlarges the representation domain in order to include Users and Activities; on the other, the classes-subclasses-instances schema allows to build more deep taxonomies if compared to the family-type-instance schema typical of BIM, ensuring a better accuracy in the definition of the entities and of their features.As in usual Agent-Based Modelling and Simulation Systems, phenomena emerge from the interaction of different agents behaviour, as well as their mutual combination and interference.

For this purpose, it is necessary to conceive the third component of the agent, defined as the Behavioural Engine, a set of rule that allows the agent to 1) understand the surrounding environment 2) make decisions by comparison of the system status with its objectives 3) perform actions and 4) update the status of the environment (and of the agent itself). In the case of a V-User, the Behavioural Engine controls its actions during the simulation, as well as updates its status for each simulation frame. In a similar way, the behavioural engine of a building component can control some usability aspects and measure particular conditions, in order to provide specific feedbacks to designers. For instance, a door entity will be enriched with semantics about its usability and it will be able to know which people are allowed to open it and

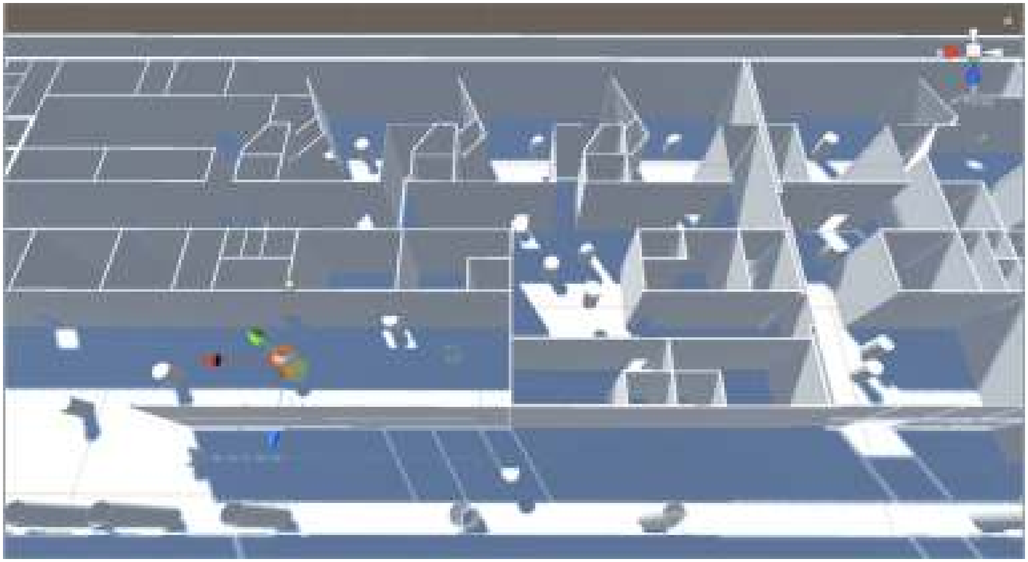

Figure 3
A screenshot from the case study experiment in Unity 3D, showing the functional simulation of the outpatient services area

how. The AI-enriched door will check any usability issue during the modelling phase and the door will perform accordingly to these assumptions once the simulation of the building use will be running. Even the process entities - the activities - are provided with a Behaviour Engine: in this way, they can coordinate different V-Users involved in the same activity, in order to manage complex collaboration that would be particularly difficult to manage only with mutual interactions between V-Users agents. Temporal logic relationships among activities, as well as their organisation on different priority levels, also drive the simulation in accordance with the previously defined use scenario.The conception of this abstract schema of the agent, potentially applicable to all the typologies of entities that are part of the Building+Users+Use system, ensures both homogeneity and extendibility of the model. In fact, different classes of agents, belonging to any of the three domains, can be included in the model if they are constructed according to the proposed schema. This is actually an advantage of ABMS systems that could not be reached in simulation systems that rely on a central simulation engine. This model prerogative is also very well suited to a BIM-oriented architectural design process since it integrates the definition of objects - typical of BIM - with the specification of its functioning/behavioural dynamics. From the implementation perspective, we chose to rely on a game engine (Unity 3D) in order to integrate building modelling and use simulation in a single platform. In fact, the game engine allows to conceive and develop smart entities representing the different building components (as in a BIM environment) and provide them with both the properties/status component and the Behavioural Engine. At the same time, in the game engine provides the technology and the Artificial Intelligence resources that are necessary to simulate the building use processes and the behaviour of a large number of agents. In addition, specific third-party applications ensure good interoperability with BIM software such as Autodesk Revit, in order to support design documentation and additional detailing. Currently, the Agent-Based Building Modelling approach is under application in the field of hospital design, where operations and use processes assume a particular relevance. In particular, current experiments are focused on the functioning of diagnostic and ambulatory units of a newly designed hospital in Rome, as well as the people's behaviour within the public spaces of the hospital (see Figure 1).

Those services, in fact, are the more affected by a number of potential patients, as well as by the kind of services provided and the availability of human resources and machinery (Cohen, 2010) (see Figure 2). In particular, waiting rooms occupancy was measured, as well as medium waiting time for the generic patient. In addition, mobility within the public areas was evaluated, particularly measuring the access to both relax areas or commercial services. To improve users' experience and hospital resources management, different allocations of human resources were tested, considering different time shifting. Although these tests are still under development, the proposed Agent-Based Building Modelling is showing good potentials in giving a new dimension to the hospital design process, integrating the definition of the building in its parts and the configuration of the services that it will provide, and the behaviour of the users it will host (see Figure 3).

## CONCLUSIONS

The result of this distributed intelligence approach is a modelling and simulation platform that will support architects, engineers, managers and all the other specialists to conceive the building and its articulation by predicting and understanding how it will interact with its inhabitants and how they will behave in it. While current BIM approaches mainly provide construction and assembly coherence, the Agent-Based Building Modelling will ensure also functionality and use quality, allowing designers to virtually conceive, model, test, and optimise the design without even stepping into the construction process. At the same time, clients will be actively involved in the design process: the simulation platform allows them to understand how their building is going to work and operate after its construction. The anticipation of use evaluation will increase designers' awareness of the impact of their design decisions on the future users of the building, enhancing the overall quality of the building and, consequently, the quality of the life of its inhabitants.

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# Saving Lives with Generative Design and Agent-based Modeling

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*The increasing number of crowd disasters has awakened the need to evaluate the evacuation performance of buildings. However, the information available in building design guidance documents is insufficient to efficiently address safety requirements and official metrics do not take into consideration crucial factors for the success of emergency evacuations, namely the people's dynamics. Although modeling human behavior is not trivial, the recent approach of Agent-Based modeling has been facilitating this task, thus being a suitable tool for evacuation simulations. Nevertheless, the potentialities of this approach are still quite unexplored. Although Agent-Based modeling is already being applied in security analysis tests, its use in combination with Generative Design (GD) is still very limited. In this work, we show how a combination of both approaches improves the safety of buildings.*

**Keywords:** *Simulation, Agent-based Modeling, Agent, Evacuation, Performance-Based Design*

## INTRODUCTION

Lately, architects have been taking advantage of programming to either extend the capabilities of their tools, or create new ones entirely (Kilkelly 2014). Generative Design (GD), a design approach that produces designs through algorithms, along with analysis and optimization, promote considerable advances in the design exploration process, and in the improvement of buildings' performance across different metrics, including structural, thermal, and environmental. While these metrics are important regarding the building's common use, there are others that also need to be considered in special situations, such as the case of an emergency. In these events, the way people behave and move constitutes a determinant factor, in addition to the local spatial characteristics. Nowadays, with the increasing number of crowd disasters, safety performance in public buildings becomes an important concern when designing a building. Realistic simulation of evacuations has been helping architects to understand and improve the buildings' safety measures. However, modeling human behavior is a complex task and the traditional simulation tools are not prepared to deal with it (Janssen 2005). Fortunately, the recent paradigm of Agent-Based Modeling (ABM) can handle complex systems, thus being a valuable tool for simulating human systems (Bonabeau 2002). For this reason, ABM is an important tool for modeling evacuation scenarios. Nevertheless, its application in architecture is still limited, being only applied at later design stages, when major changes are difficult to make. Although ABM has already been used as a GD method (Puusepp 2011), in this paper we use it in combination with GD, where GD generates the simulation scenarios, ABM is used to evaluate them, and the results used to influence the GD process, in an iterative cycle to improve a building's safety.

## PERFORMANCE-BASED DESIGN

The design task is interdisciplinary, as each architectural project must integrate and satisfy the requirements from different fields (Turrin et al. 2011). Traditionally, only few of those requirements were considered in the conceptual phase of design, which mainly addressed aesthetical and functional performance criteria, postponing other disciplines to later stages of the process (Turrin et al. 2011; Shi 2010). However, it has been shown that decisions made in the initial phase have a great impact on the final solution performance. Moreover, at the final stage of the design process, there is usually not enough room for maneuver in order to efficiently address some of the requirements (Shi 2010), limiting the performance of the result.On the other hand, Performance-Based Design (PBD) is a design approach that combines the building's quantifiable performances with the functional and aesthetical requirements (Shi and Yang 2013). PBD arises from the integration of design synthesis with design evaluation processes, enabling the design process to diverge from a traditional paradigm - where the human subjectivity and rationality guides the process, and the performance evaluations are left for final stages - to one in which the design generation is oriented by analytical performance evaluations towards the objective of optimizing the design (Oxman 2008). Even though PBD only became successful in the last two decades, this concept is not new - it goes back to 1970, when Negroponte presented the utopian theory "Architecture Machine". Although research on Negroponte's concept was continued by other authors, it was only towards the end of the 20th century that PBD gained a boost of attention and application. This resulted from, firstly, the rise of sustainability awareness in the Architecture, Engineering and Construction industries (AEC), which encouraged the implementation of green building standards (Shi 2010). Secondly, from the proliferation of simulation tools. On the other hand, the advancements in GD have also played an important role in making PBD more accessible to architects. GD creates models that are based on associative geometry, i.e. a model with defined relationships between its elements that implies the establishment of a hierarchy of dependencies, where some attributes are independent - models' inputs - and others are dependent (Turrin et al. 2011). This chain of dependencies is responsible for the propagation of changes in a coherent way, a fundamental ingredient in the advancement of PBD. GD automates and accelerates the generation of design iterations, covering a larger design space, while replacing manual adjustments of the design geometry (Gerber et al. 2012).

## EVACUATION

Panic behavior in crowd situations can be disastrous. Recent examples include girls being stampede in a stairway in Afghanistan in 2015, and the fire in a nightclub in Brazil in 2013. Mass events are a reality of our time and stampedes occur even without any physical trigger. In these situations, safety measures are determinant for the success of the event's outcome. While some measures are obvious, like the presence of fire doors and emergency exits, others are context-specific, such as the best location for those doors. Unfortunately, the traditional evaluation of different evacuation scenarios is either empirical or expensive (Wagner and Agrawal, 2014). Simulation through computation has the potential to overcome this problem since it allows the evaluation of different scenarios with less expenses. A simulation can be defined as an imitation of a real-world system (Banks et al. 1984), which requires the development of a simplified model of the system according to the investigation subject (Law and Kelton, 2000). Observing the model, we can estimate what would happen in the system and, by changing either the inputs or the geometric characteristics, we can also evaluate the effect of those changes. In fact, simulation is one of the most widely used tools in operations-research and system analysis, and it is also valuable for design (Banks et al. 1984). Initially, simulation programs were only developed for research, requiring a deep understanding, and, therefore, rarely used by architects. Nowadays, they have become more accessible and, aware of their advantages, architects and engineers started to integrate them into their workflow (Shi 2010). Currently, there are some simulation programs that cover several disciplines and, in this work, we are especially interested in simulating and evaluating the evacuation performance of public buildings.

## AGENT-BASED MODELING

Agent-Based Modeling (ABM) is a simulation modeling paradigm that started gaining popularity in the 90's (Heath et al. 2009). Its attractiveness relies on the fact that it allows the simulation of systems that have complex interdependencies (Macal and North 2009). In ABM, systems are modelled as a collection of individuals, known as agents, which behave following a set of rules. Actually, the key factor of ABM is the ruled interaction between the agents (Janssen 2005), since the system's global behavior emerges from it (Bonabeau 2002). The sophistication of the model depends on the given rules - the agents' behavior can range from the most primitive to the more complex ones that already include learning and adaptive algorithms (Macal and North 2005). Through these, agents behave in accordance to their specific context, which allows the simulation to consider a heterogeneous sample instead of forced generalizations.ABM is becoming widespread, being the subject of intense study and development, and is also being applied to a vast variety of subjects, covering human social, physical, and biological systems (Macal and North 2009). Examples include the modeling of ancient civilizations (Chliaoutakis 2014); air traffic control (Conway 2006); and also land market (Filatova et al. 2011). ABM is a suitable approach to deal with crowd and evacuation systems and, combined with the advances in computational power, it has been enabling the simulation of more complex systems. Some of the recent studies include crowd evacuation of buildings and urban roadways (Wagner and Agrawal 2014), evacuation from a foot bridge (Carroll et al. 2012), or from a train station under a bioterrorist attack (Wei et al. 2011). Nevertheless, due to the variety of potential disaster environments that may occur, the use of ABM in emergency planning remains an open research area (Jain and McLean 2008). The main difficulty found when dealing with ABM is acquiring the appropriate data to construct the models. Regarding human behavior, most of the research in matters of panic is of empirical nature (Helbing and Farkas, 2002) and, in relation to the overall system behavior, there are not yet systematic studies or quantitative theories (Helbing et al. 2000). This lack of information makes the model's calibration and validation difficult to achieve. Still, there are already some important contributions to the field. Helbing (2000) modeled the collective phenomenon of escape panic based on socio-psychology literature, media reports, and other indirect methods. More recently Bellomo et al. (2016) made an overview of the study of human behavior in evacuation, where they also addressed the validation that most authors dismiss.As shown by Bonabeau (2002), ABM is a valuable tool for simulating human systems, and Procházka et al. (2015) demonstrated that programming pedestrian and crowd dynamics is relevant, specially, when its overall success has a lot to do with the users and their behavior. ABM appears to be a promising tool to solve circulation problems, in which agents represent the individual dynamic behavior in a built environment. In fact, pedestrian movement, evacuation and crowding models have been the main focus of ABM's in architecture (Puusepp 2011).

## ABM-GD FRAMEWORK

Even though most agent-based models are analytical, there are applications of this paradigm with GD processes: Puusepp (2011) studied the use of multi-agent systems for generating circulation diagrams; Reffat (2003) developed a model where agents generate new design concepts by exploring two-dimensional sketches.Nevertheless, although ABM has been used as the driver of a GD process, it has not yet been explored as being driven by a GD process. By this we mean a PBD approach that combines GD and ABM, which is opportune at different levels. Firstly, GD is appropriate to generate complex designs in which the performance is difficult to predict, especially when considering the human behavior. Thus, a simulation tool that can encompass the GD paradigm is convenient. Secondly, GD has been mostly used in public buildings, such as stadiums, office buildings, and museums, where safety requirements are especially relevant, including the emergency evacuation performance. Therefore, a tool for safety performance evaluation is particularly valuable, which is the case of ABM. Finally, instead of only using ABM to analyze the obtained solutions in terms of evacuation safety, we propose that ABM can also be used to improve the design towards a better solution regarding its safety metrics, while considering its geometric and aesthetical basic requirements. This possibility is enabled (1) by the capability of ABM to simulate and evaluate the evacuation times of several design variations, and (2) by the flexibility of GD, which allows changing the model in an automated way and according to the information acquired from the simulations.

## CASE STUDY: PARAMETRIC SHOPPING MALL

In this work, we present a combination between GD and ABM in a Performance-based approach. Based on it, we developed a case study using GD that allows the generation of several instances to be then evaluated through a simulation process - in this case the simulation of an emergency evacuation. Our goal is, firstly, to compare the input parameters of each evaluation and its corresponding results - numerical and visual results - and, secondly, to acknowledge trends and behavior patterns through this balance. Thus, this allows the subsequent generation of new variations for the model through an optimized perspective, by repeating the cycle *generation-simulation-evaluation* and, therefore, achieving improved design solutions.

### *Geometric Definition*

We started by developing a GD model of a simplified shopping mall. The model corresponds to a single story quadrangular building in which the stores are placed in concentric rings around a central atrium. From this atrium, a set of main corridors breaks the rings and gives access to the building's exits. A concentric ring corridor is also placed between rings of stores (see Figure 1). Figure 2 summarizes the model's parameters, which are:

- number of corridors;
- corridors' width;
- size of the stores' doors;
- size of the mall's exit doors;
- number of shop-rings;
- area of the central atrium.

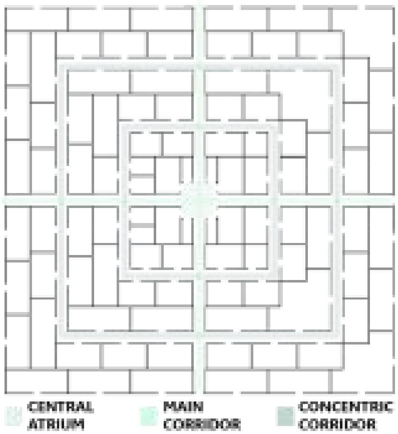
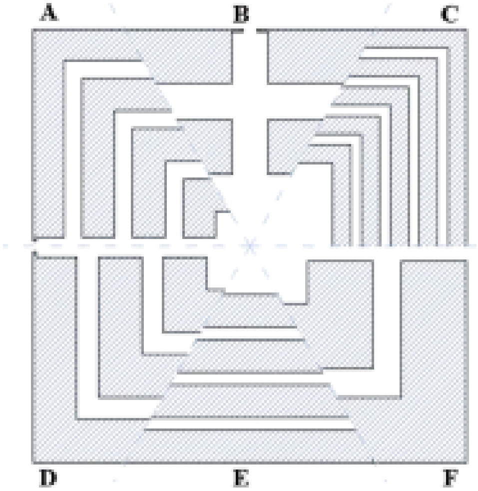



Figure 1
Instance of the parametric model with its basic structure marked.

Figure 2
Potential automatic variations of the model: number of concentric corridors (as an example, A has three concentric corridors, while B has one); width of corridors (for instance, C has the smallest width value of all, whereas B has the biggest); area of the central atrium (C has the largest central atrium of all examples); and the number of main corridors (the vertical axis in example E is closed, i.e., it does not have a main corridor connecting the outside with the mall's central void).




## *Simulation Process*

The next step was generating a representative solution space. Since we were only considering safety requirements, namely, evacuation times, and the number of parameters was not extensive, we were able to make an exhaustive analysis for each variable. Supported on the GD capability to easily create a substantial solution space, we evaluated variations of one parameter, while maintaining the others unchanged, and repeating this process for all the parameters. An additional variable was included in all simulations - the number of people inside the mall. Since higher values of human concentration inside public buildings are usually related with emergency evacuation disasters, if we increase the number of users, the geometric implications on the evacuation performance will become clearer. This method also allows us to evaluate the maximum number of people that the building can afford.

To evaluate the models, from the current available simulation tools (Cuesta et al. 2015; Peacock et al. 2010) we selected *Pathfinder*, as it adequately satisfied the requirements of our scenario.

## *Emergency Evacuation Results*

Finally, after executing all the simulations, we organized the simulation results into a set of graphs - see Figure 3. The vertical axis in all the graphs correspond to the evacuation times in seconds, whereas each horizontal axis corresponds to the input variable being considered - width of corridors, shops' doors, and exit doors; number of concentric ring corridors, and main corridors; size of the mall's central atrium. Finally, the curves of different colors correspond to different numbers of users.

Figure 3A shows the outcome of the variable *number of concentric corridors* for the values 1 to 4. It shows that this variable's variation has impact in the evacuation times, even though it can be quite smooth in certain situations, as is the case of smaller numbers of users. However, as this number increases, the evacuation times also increase, and more significantly regarding higher numbers of concentric corridors. Regarding the second analysis in Figure 3B, which evaluates the variable *exit doors size*, it is possible to understand that this is a critical variable in this model, since its variation causes meaningful changes in the performance results - except in the case of very few users, where the evacuation times remain almost constant. Figure 3C presents the results of the variable *number of main corridors*. This variable received three different values as input: 2, 3 or 4 main corridors. Since these are the corridors that give access to the mall's exit doors, it means that, by decreasing the number of corridors, we are automatically decreasing the number of exit doors. As it is visible in Figure 3C, the evacuation time increases with the decreasing number of main corridors, and it gets more accentuated with higher numbers of user densities. Otherwise, all evacuation times seem to converge as the number of corridors increases. Figure 3D presents the evaluation of the *central atrium size* variable, from which it is possible to conclude that it almost does not interfere with evacuation times for all user density values.The results regarding the "corridors width" variable are shown in Figure 3E. The width varied between 2.5 and 5.5 meters, with incre-

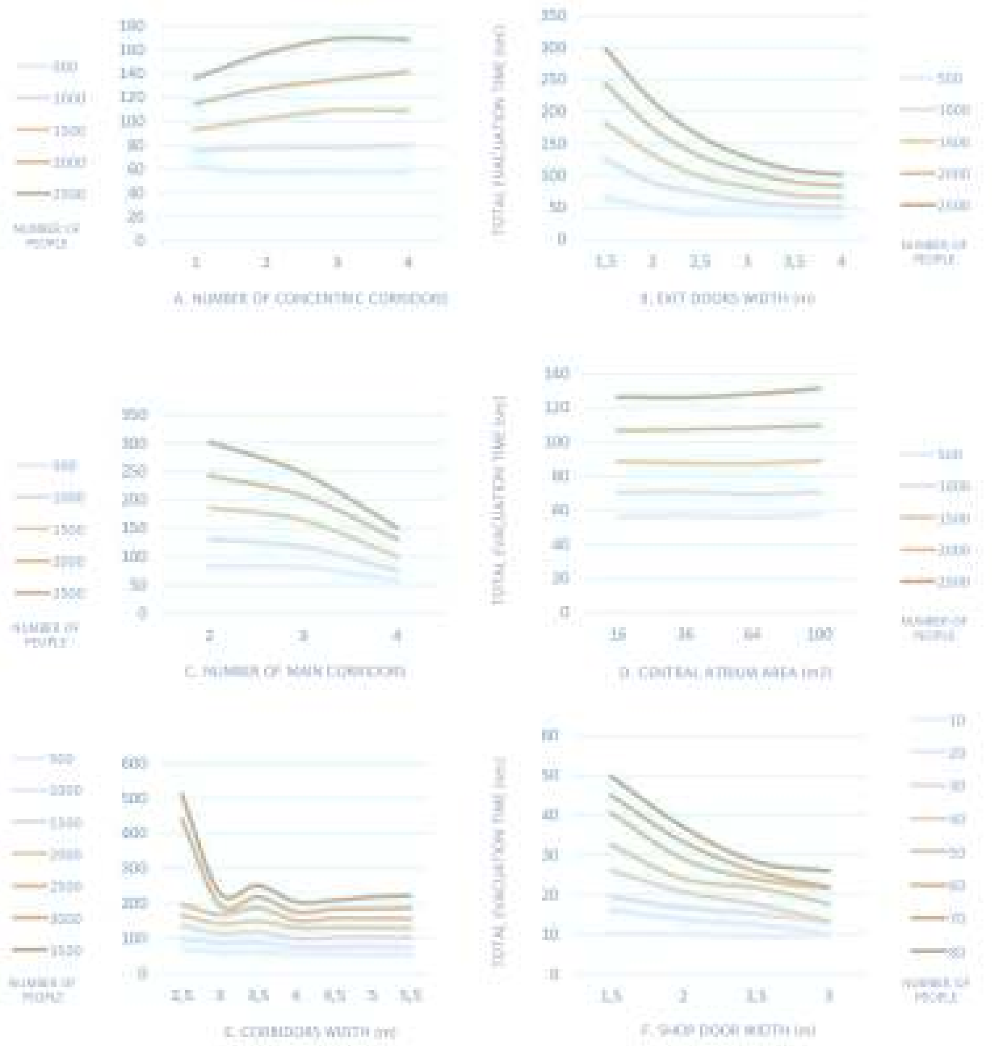



Figure 3
A. Evacuation time for different numbers of concentric corridors; B. Evacuation time for different widths of exit doors; C. Evacuation time for different numbers of main corridors; D. Evacuation time for the central atrium different areas; E. Evacuation time for different corridor widths; F. Evacuation times from a single store with different door widths (the number of people inside the store varies between 10 and 80).

ments of 0.5 meters. Even though the width variation has almost no impact in evacuation times for smaller numbers of people, as this number grows, the graph's behavior becomes irregular - it does not decrease linearly, instead it grows and decreases with consecutive values. Finally, we tested the effect of changing the *stores' door size* between 1.5 and 3 meters (Figure 3F). This simulation occurred in slightly different conditions comparing to the previous examples, since it measured the time people took to get out from a single store, instead of the whole shopping mall. To maintain the user density, we simulated a smaller number of users. Nevertheless, as previously demonstrated by the evaluation in example B, door widths are key points on emergency evacuations, especially with higher concentrations of people.

## RESULTS

From an overall analysis point, we can make significant conclusions regarding higher numbers of people. Globally, as the number of people increases, their effects on evacuation times are accentuated. Moreover, by the slope variation between different concentrations of people, it is possible to understand the relevance of each parameter. As an example, Figure 3B shows that the exit doors' size has a great impact on the evacuation performance, whereas Figure 3A reveals that the variable *number of concentric corridors* only becomes relevant after a certain number of people is reached. Finally, Figure 3D shows that the variable *central atrium area* has almost no effect on the evacuation times. Although some variables revealed trends in behavior, such as the variables visible in Figure 3 B, C, D and F, others have a more complex and unpredictable behavior, as is the example of Figure 3E. This can be a result of the associative geometry of the parametric model: as the model is adapted geometrically, the combination of different and, sometimes, contradictory impacts on the evacuation performance leads to unexpected results. Therefore, the designer should consider these non-linear phenomena in order to gradually improve the design solution. In the next sections we analyze two of these situations.

### *Corridors Width*

Changing the corridors' width seems a sensible action to improve the evacuation performance but one should also consider that when we increase the corridors' width, their lengths also decrease, meaning that two geometric characteristics are changed instead of one. Moreover, although changing the corridors' width may help alleviate intersection areas, it can also create obstruction problems at the exit points, since the users reach these areas more rapidly. Analyzing the results, it is possible to understand that when the corridors are too thin, people get jammed in the intersections and, thus, do not reach the exit doors (Figure 4A). On the contrary, when corridors are too wide, people get stuck in the exits (Figure 4C and 4D). In intermediate situations, such as the case of Figure 4B, there is a balance between people getting stuck in the intersection points and exit doors. This divided flow rate allows a better coordination between users' evacuation routes and, thereby, a better evacuation time. In addition, the length and thickness of the corridor that connects the two critical points contributes to the balance of the flow rate.

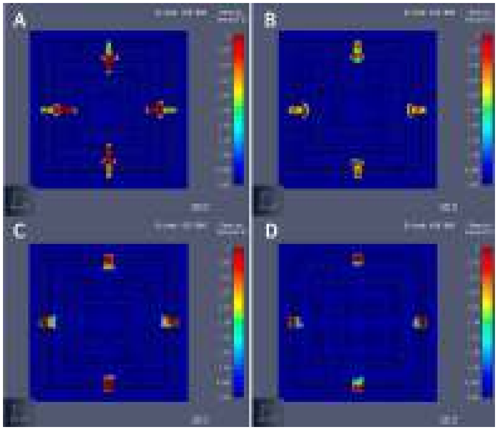



Figure 4
User density levels (for 1500 visitors) at 45 seconds of the evacuation time. Each diagram corresponds to different corridor widths: A=2,5; B=3,5; C=4,5; D=5,5 m. Colors show the density of people.

In the previous example, the corridors' width was varied while the size of the exit doors was kept unchanged. Considering the critical influence of the exit doors' size in this balance, we decided to further analyze the impact of varying the corridors' width accompanied by exit doors' of the same size. The results are visible in Figure 5, from which we could conclude that when the exit doors size have the same width as the corridors, the evacuation performance turned out to be more linear.

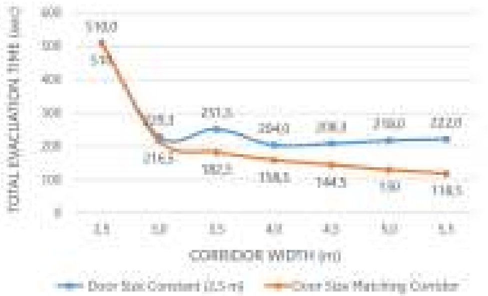



Figure 5
Comparison between changing the corridors' width using fixed exit doors' size and using exit doors whose size matches the size of the corridors.

| CORRIDOR AND DOOR SIZE (m) | | 3 | 4 | 5 |
|---|---|---|---|---|
| N CONCENTRIC CORRIDORS | 2 | 156 | 123,8 | **101** |
| | 3 | 157,3 | 125,8 | 103 |
| | 4 | **160,5** | 129,8 | 103,3 |

Table 1
Evacuation times for different number of rings, corridor widths, and exit door size (for 2500 visitors). The results are in seconds. The values in bold represent the maximum and minimum evacuation times.

### *Number of Concentric Corridors*

We also analyzed the results obtained from the *number of concentric corridors* variable (Figure 3A). As shown previously, there is an irregularity in these results, regarding the number of rings and the corresponding evacuation times of different numbers of people. In practical terms, the effects of increasing the value of this variable has impact on the evacuation times because (1) it increases the number of intersections areas, which can work as filters so that people are not all in the same place, decreasing the evacuation times (see Figure 6), (2) it decreases the length of the corridors that cross the stores - long corridors can distribute people, whereas short corridors concentrate them, and (3) it narrows the corridors - small corridor widths potentiate the obstruction of people, thus increasing evacuation times.Moreover, as shown in the analysis of Figure 3E, when corridors are too narrow, the intersection areas become critical points (see also Figure 6B). In that line of thought, we further explored the relation between the number of concentric corridors and different corridor widths (visible in Table 1), and, based on the previous analysis (Figure 5), the exit door's size matching the corridor's width. This analysis shows that the evacuation performance is better for a smaller number of rings.

Regarding the modeled shopping mall, the simulations allow us to conclude that we should:

- Minimize the number of concentric corridors;
- Maximize corridor's width;
- Use exit doors with the same width as corridors;
- Maximize transversal corridors;

## CONCLUSIONS

Architects are increasingly more interested in designing safe architectural solutions. PBD is a design process that emphasizes the building's performance. It consists of cycles of *generation-evaluation-analysis* from which the architect can gradually achieve better performing solutions. It is an iterative process in which each cycle requires the generation of a solution whose evaluation and analysis is the basis for the next iteration. For the analysis to be successful, it is necessary that the generated and evaluated solution space is substantial in terms of number and quality, and the acceptable number of cycles depends on each model complexity. In this paper, we demonstrated the feasibility of the combination of GD and simulation in a context of PBD, where evacuation performance is the focus. The relevant role of human behavior implied the integration of ABM in this study. To evaluate the combination GD-ABM, we developed a case study based on a generative approach - a shopping mall - and, then, we produced several evacua-

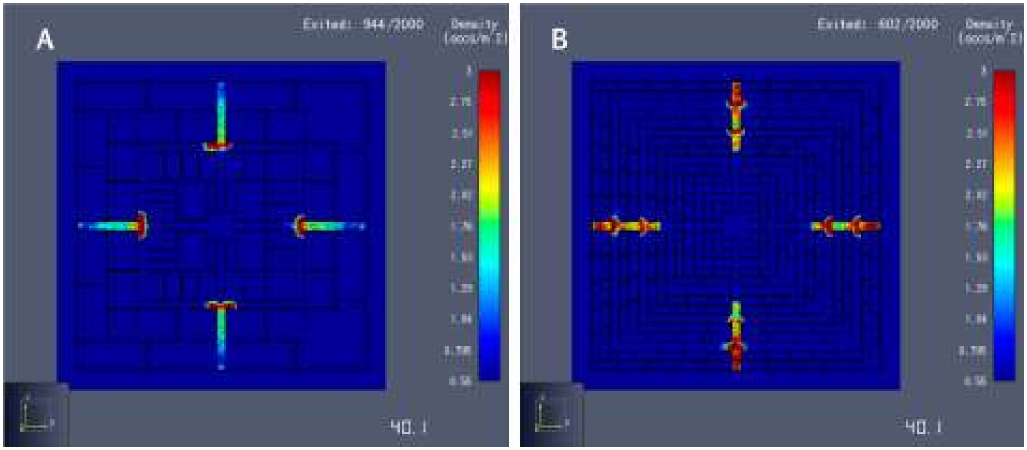


Figure 6
Densities for different number of rings.

tion simulations regarding different parameters, such as doors' width, area of the central atrium, and number of corridors. The use of GD enabled the generation of different instances of the model more rapidly and in an automated way - by changing the parameters, the model was automatically adapted - allowing us to cover a wider design space than if we used a traditional design approach.The case study demonstrated that the use of GD potentiates PBD. By allowing the consideration of wider solution space, it potentiates better results. Based on the results' analysis it is possible to make more pertinent combinations of parameters for future iterations, thus accelerating the search for improved solutions. Even though the simplicity of our case study, it could already demonstrate that the influence of certain parameters in the building's performance is not trivial to predict, revealing the relevance of additional tools to support the decision-making process. In real scenarios, where the scale and the complexity of the building increase, there are more inter-dependencies between parameters and, thus, the architect intuition might not be enough. Hence, it will be even more necessary to resort to a design process that is based on numerical evaluations and analysis.

## ACKNOWLEDGEMENTS

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# Improving Proactive Collaborative Design Through the Integration of BIM and Agent-Based Simulations

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*Traditional design paradigms take into account phases as the process were subdivided rigidly in boxes to which pertain specific building entities, actors and LODs. In reality the process of design, a building f.i., it is not so much organized in series, nor designers deal with just a specific LOD. The process is intertwined and actors mix various type entities with different accuracy. To manage these problems, we need a new paradigm and new tools able to take immediately into account satisfied/unsatisfied constraints, to trig on consequences of choices made as far as it is possible and to link fluently and bidirectionally a 2nd layer of building abstraction (BIM) with a 3rd one of knowledge abstraction. An on-the-fly link has been established between BIM and a swarm of agent-based simulations.*

**Keywords:** *Agent-Based Modelling and Simulation, Behavioural Simulation, BIM , Agent-Based Building Modelling*

## DESIGN SCENARIO

Huge phenomena have arrived from last century: most population lives in cities from 2008 [1], energy released in the atmosphere increases temperature, pollution is more dangerous that car accidents, connections - any connection - physical and informative ones run more than capacity to understand context and information itself.

That gives huge responsibility to designers: they should understand in deep problems and boundary critical conditions, they can be able to modify event courses and Planet safety and address projects toward success or failure (Meadows 1972, Diamonds 2011).

The building design process has become through the years more and more complex: indeed, it involves a huge amount of information that describes the complexity of the process and the context, in the wide means of the term. Furthermore, this complexity is evident in case of interventions on historical buildings and buildings of our current digital era are said to be more complex by information structure because of the complexity of shapes and the difficult to conduct the process in a coherent integrated way.

As other industrial sector, AEC sector presents a growing complexity, following the even higher performances required by users, the urgent need is to optimize design choices avoiding unexpected delays and cost-dangerous project variations (Dehghan et al., 2015).

Designers, in addition, need to untangle this intertwined complexity due to an increasingly extensive and detailed regulatory framework, related also with a parallel increase of requirements express by users. Finally, the designer itself is involved in a deep transformation, in favour of large design companies with hundreds of designers, belonging to specific different domain, often spread in different parts of the world (Chen and Hou, 2014) that often even work concurrently on the same entities.

In a changing world - in nature and humans needs - we need very clever tools to speed up the design, all types of design - architectural design this case, as W. Morris stated.

Managing these extreme problems means "designing". In our CAAD world, we should adhere to strategies nature did, particularly one of most successful example of adaptation: the human behaviour.

What humans do? Optimise. Optimizing thinking especially. The following study reports how a new paradigm can support architects making their choices more aware - and satisfying - in a proactive way.

## STATE OF THE ART

From the outset of the Informatics Era, designers felt the need to use informatics tools to satisfy their necessities. Thus, the attempt envisioned by Nicholas Negroponte to replace the Designer (Negroponte, 1973) regarded as a "elitist middlemen" (Llach 2015) appears today differently achieved, at least partially, in practice.

Starting from the Sixties, when the digitalisation started to make its way, many tries were made toward the definition of support tools for the design activity. The experiments developed to this aim belong essentially to the set marked by two methodological opposite approaches, which have characterized CAD tools development starting from first times. These were carried out when the vision of Yona Friedman and Nicholas Negroponte were opposed to Skidmore, Owings and Merrill (SOM) approach based on Building Optimization Program (BOP) or, in other words, the "Perfect Slave" approach. (Llach 2015).

Friedman and Negroponte, in different but conceptually close studies, hypothesized a cohabitation between two intelligent species in a symbiotic relationship among them. Following the Friedman and Negroponte's perspectives, complex support systems have been developed in order to simulate the behaviour and performances achieved by building objects (and systems), allowing designers to choose design solutions to be adopted among those that match the stated requirements. That time onward, research has applied to two different challenges: to improve performance of a singular aspect of design, the "tools by tools" approach; or to have an "overall vision" of design process. Obviously, these two philosophies have had in times different outcomes, and that the edge between them has been blurred, as well as the "singular aspect", the "limited scope", is relative to a certain extent.

Another aspect to be taken into consideration since the birth of the early CAD systems, technologies and instruments is that designers act in two distinct phases: "mechanical" and "creative" ones. The former has evolved radically until to the current BIM systems, causing a radical transformation of operating methods of the design activity. The latter, in contrast, today appears practically negligible as the number and effectiveness of tools conceived. Some difficulties in giving to computer systems human-like attributes, such as curiosity and judgment, and due to the belief that fundamental design parameters escape from an objective definition hence they are hard to be represented and managed.

Nevertheless, all of these experiences are based, more or less explicitly, on the Coons paradigm (1966) were design was considered as an iterative process that alternates a creative stage" to a "mechanical stage," in which design choices are tested with respect of "performance metrics"(Llach 2015).

This lack is mainly due to the undervaluation of several aspects that, instead, were central since the early experiments developed in the 70's: the flexibility, defined as the ability of a system to cope with problems of any size within a specific domain and adaptability, defined as the ability of a system to deal with problems pertaining to different domains.

The challenge to provide designers support systems with the required flexibility and adaptability became clear from the beginning. "Each designer is creating His Own library of services out of the problem-oriented language. Once created, note that these operations are no less rigid than the predefined package of design commodities."(Negroponte 1973).

Some experimental systems have already shown the possibility to create advanced representations of building objects flexible and adaptable, based on the knowledge engineering, allowing the design choices verification against a system of constraints. In this way, only acceptable solutions are guaranteed. These experimental systems and, even more, the current support tools offered to designers by the market, cannot assume proactively behaviour modifications and, consequently, integrating autonomously the designer choices in order to identify solutions that can optimize the performance achieved compared with stated requirements.

## CURRENT SOLUTION FOR AN ANCIENT PROBLEM

To deal with these tasks designers and researchers extensively explored the collaborative design paradigm (Kvan 2000, Carrara et al. 2009, Achten and Beetz 2009) and turned out that to be effective it should be overcome: inconsistent data by means of BIM tools, incoherent semantic entities by means of representation of Ontologies (OWL), and the missing relationship between them by a "bridge" that links these two layers (Fioravanti and Loffreda 2015, Beetz et al.2006).

The inconsistent database management problem has been treated by J. Gray the Google Earth inventor and now it is no more a taboo to deal with inconsistent entities, f.i. different interpretations of an archaeological site entities by means of ontologies belonging to different archaeologists (Cursi et al. 2015), or putting together ontologies and shape grammars (de Klerk and Beirao 2016).

We already explored in a previous study the possibility to realize a partial "proactive" design tool (Carrara et al. 2013), but with traditional ontologies it is possible to treat only entity property incoherencies (2nd layer) not to treat fuzzy entities.

Although the current BIMs provided a multidisciplinary platform, and the possibility to develop the design phase in a concurrent way among different-located work set, the design activity request a real software environment, composed by a huge number of digital tools, often with lack of interoperability (Miettinen and Paavola 2014), forcing designers making many data-transfer operations among different forms and tools. Consequently, this intricate process results time-consuming and error-prone. Evidently, the envisioned mutual complementary improving, and role interchanges between computer and designer that, nowadays, are getting closer to the dream of human-computer co-operation.

To attain these aims, the DaaDgroup at Sapienza University of Rome, is developing some experiences aimed at overcome present days' paradigm and building design systems by an Agent-Based development environment integrated with current BIM systems system to link the 2nd layer (building abstraction - BIM) with the 3rd one (knowledge abstraction). This solution is capable to offer the required flexibility and adaptability, taking a proactive role able to complement 2nd with 3rd reasoning layer, respecting to the "first-order logic" [2] and leverage the designer activity through the identification of near optimal design solutions.

## INTEGRATING BIM AND AGENT-BASED SIMULATIONS

To smooth the design process, we addressed to the agents' representation that can dynamically adapt solution (if any) to an ever-changing context (physical and cultural). Other two important assumptions are: a frame representation able to change its superclass and to structuring its entities in subset; an adjacency network that takes into account not only spatial relations (rooms, loggias, etc.) but also proximity of preferred orientations or links (cultural sites, sightseeing, panoramas) or, in a closer Project Management point of view, the viability and related time and costs related to building realization at construction phase.

We have a quite powerful paradigm as the Collaborative design one that has proven to deal with these aspects, but nothing regarding intelligent classes or subclasses of entities we can group for a goal. Moreover, if we changed the orientation of a building, these tools (BIMs and ontologies) can rotate the building and just put in evidence not satisfied requirements.

The proposed system is founded on a new paradigm by means of an Agent-based Model approach (Novembri et. al. 2015) with two fundamental assumptions: modularity and flexibility ones. This system can effectively be achieved by adopting an on-demand concurrent-computing technique. The agent swarms, indeed, are highly modular as numerous the technical domains (architecture, HVAC, structures, etc.) are; and the system is so flexible as allows swarms of agents (or a single agent of them) to hot-swap when they are required at the moment. These agents can be distributed (also geographically) and can operate concurrently. However, this process is normally avoided by BIM systems because a concurrent access to the instance of the model can easily generate situations where designer choices and the proposed systems actions can cause rat race condition conflicts. A rat race, however, is an endless, self-defeating, or pointless pursuit. It brings to mind the image of lab rats racing through a maze to get the "cheese" much like the single project domains tries to get an optimal design solution but, when integrated with other domains, is useless.

These agents can be modelled by means of an old-new language (Lisp) linked to the lower ontologies layer. This way we are free to customize agents according to our needs and allow them to call libraries, different languages, external functions, ontologies and BIM programs at will. Another interesting characteristic is its nature of the interpreted language that can trig immediately consequences on related entities.

Thus, an interesting development environment called BIM Work-Bench (BWB) can match desired synchronous characteristics with BIMs limit need by means of an embedded communication mechanism. There, every project change, (f.i. updating or adding components, characteristics, spaces, etc.) made by designer into the BIM environment gets Actors (in terms of messages to be executed), that is transferred immediately to the correspondent Agents. Consequently, this 'intelligent' system uses the event-input to elaborate action(s) to realise choices into the BIM system. This is made possible by means of modelling Actors (Hewitt 1973) that manages effectively communication among them. The system has been implemented by AKKA.net tool, that improves the actors' effectively modelling through a message-based and asynchronous process, avoiding involving a huge quantity of computational power. Furthermore, this tool provides a hierarchic structure with the creation of a Supervisor-Actor, that can manage several data belonging to different domains. Another challenge to be dealt with is the simulation of a cluster organization of actors, like the human approach to create task-groups for complex problems.

To deal with these objectives we applied two ideas: a very large use of default values even if on jeopardized knowledge at different abstraction layers; an extensive use of adjacency in different domains, not only on i.e. climate, public infrastructure,

So these agents (Mei et al. 2015) should be coupled with Graph theory and complexity models, as like is for IoT to suggest the designer which is the proper windows to choose in respect with the several constraints that characterize a project as the suitable path for a car that takes into account traffic status in an automotive navigation system.

Going back to the example of changing building orientation, in a façade modelled by Agents differently that previous situation it reacts to that event, trigs for an adaptation of former solution to a newer suitable for new context. Context in a broader sense like we explored in a previous research (Gargaro and Fioravanti 2014). That in turn trigs other agents in the agent's network as far as possible with information system has.

## PROACTIVE DESIGN SYSTEM AS A COLLABORATOR OF THE ARCHITECT

The system we are developing is a "design partner" able to dialogue with humans as, like humans, concurrently thinks at different abstraction layers and takes into account different partial solutions of different design phases. The usefulness of this approach is that agent-based systems have a complementary ability compared whit humans,

If they change an element all the reasoning network is activated as far as it will be possible. That means they extensively use their defaults (architectural components, plants, details, shapes, context conditions, etc.).

So, we are developing a system able to take into account heterogeneous entities of different knowledge abstraction layers (each of these ones with several levels of detail) in domains full of default entities, that in real time explores entity networks and puts in evidence consequences and side effects. That can be considered a true pro-active design system.

## ACKNOWLEDGEMENTS

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[1] http://esa.un.org/unpd/wup/unup/p2k0data.asp

[2] https://plato.stanford.edu/archives/win2013/entries/logic-classical/

BIM

# BIM-based Multiuser Collaborative Virtual Environments for end user involvement

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*This paper examines the potential of utilizing virtual mock-ups in end user involvement processes. To access if virtual mock-ups can optimize existing processes, current workflows using physical full-scale mock-ups on several projects are explored. Requirements regarding the traditional workflows are captured through a series of interviews and observational studies. The identified use hereof is then analyzed and consolidated into system requirements and visions of a potential virtual supplement. Based on the identified requirements, a live prototype is developed supporting multiuser experiences in interactive environments through multiple and various devices such as CAVEs, HMD´s and touch devices supporting multi touch co-creation. Finally, the prototype is tested together with end users in ongoing projects to validate the potential of virtual mock-ups and to further detail the requirements to such a system.*

**Keywords:** *User Involvement, Virtual full-scale Mock-ups, Virtual Reality, Co-creation*

## INTRODUCTION

Reliable and accurate feedback from end users in any construction projects is critical to ensure that the final facility meets actual user needs. In complex projects, it becomes even more imperative since ensuring that user needs are retrieved and obtained during the user involvement process becomes correspondingly more complex and the consequences from failure to do so increases dramatically. A building that meets even budget, quality and deadline is still in risk of being both worth-, and useless if not compliant with user needs.

Complex construction projects usually involve a large span of different actors with sometimes opposing agendas, which makes the capturing of user needs and communication critical, in order to make decisions based on actual user needs and to prevent misuse of unclear information. Advanced decision and illustration tools are needed to enable end users to understand presented design proposals and thereby being able to contribute with their valuable input, and to support sufficient argumentation of the decided solutions to intermediaries and decision makers.

In hospital projects, the use of full-scale mock-ups is a widely used method to enable user input and for general communication purposes between the different stakeholders (Dunston et al., 2011). This method allows users who are not building industry professionals to understand and interact with complex design proposals, enabling them to share knowledge and contribute through interaction.

Despite the obvious need to involve the diverse stakeholders in the process, and the increasing and widespread adoption of 3D-modelling, BIM software and use of VDC-technology within the AEC industry, only few solutions, and with limited functionality, support user involvement processes and collection and communication of the complex data that is accumulated during these processes.

This paper examines existing processes and tools for end user involvement in complex healthcare projects utilizing physical full-scale mock-ups to fit and extend user needs regarding the user involvement process itself. To improve the existing processes of end user involvement this paper proposes a BIM-based virtual environment system supporting utilization of virtual mock-ups.

## METHODOLOGY AND EMPIRICAL DATA

To collect empirical data regarding the use of physical mock-ups for end user involvement in complex construction projects, the researchers have used the methodologies of Contextual Design (Beyer et al., 1998) and Interaction Design (Preece et al., 2011). This method enabled the researchers to investigate the use of physical mock-ups in a wide perspective, from the hands on use of artifacts to the complex communication between the large number of stakeholders.

Throughout the research period, a series of contextual interviews and observational studies were undertaken to collect empirical data, both in the users' environments, as well as in laboratory like surroundings.

These data were analysed and prioritized using the tools in Contextual Design to interpret and consolidate user needs, leading to optimization opportunities. To validate these opportunities, various levels of prototypes and test with users were carried out and the results from the preliminary tests were then reconsolidated into system requirements, which finally led to live test of prototypes with end users. Figure 1 shows an overview of the development process.

To understand the comprehensive communication and politics between the diverse stakeholders involved in these complex projects, the researchers have interviewed and observed user involvement facilitators, AEC consultants, as well as the end users themselves (in this case only hospital employees).

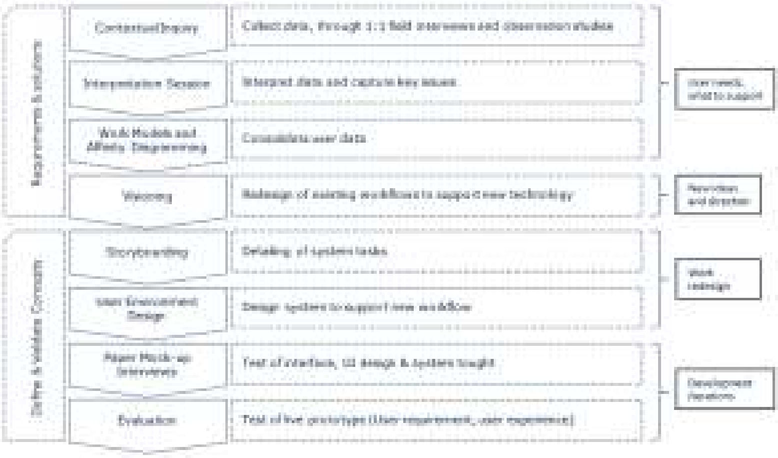
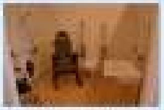
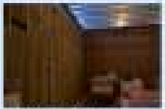



Figure 1
System development process inspired by Beyer et al. (1998).

Table 1
Four levels of full-scale mock-ups supporting different purposes.

| Scale 1:1 Physical Mock-ups | | | | |
|---|---|---|---|---|
| | Level 1 | Level 2 | Level 3 | Level 4 |
| |  |  |  |  |
| [illegible] | Establish basic principles of the general design and interior planning. | Design proposals is concretised. Tests are conducted using roleplaying. | Test of proposed solutions in realistic settings. | Test of technical solutions and constructability. |
| [illegible] | Rapid prototyping/validation of allocated m2 in the early stages of a project. | Test of assigned m2, equipment and work/processes/environment in the proposed design. | Detailed test of proposed design e.g. self-reliant toilet visit. | Detailed test of technical solutions e.g. ventilation, or constructability issues. |
| [illegible] | Very high | High | Low | Low |
| [illegible] | Low, e.g. artefacts could consist of cones and tables | Medium, artefacts could consist of mobile walls, and real equipment like hospital beds. | High, e.g. build up room from plywood and gypsum with wall mounted equipment. | High, e.g. with fully functioning ventilation system, insulation etc. |
| [illegible] | Users move artefacts to create and test new design alternatives. | Users move artefacts to create and test new design alternatives. | Users interact with the design proposal by using the room as they would in the final building. | Users interact with the mock-up by replacing / installing parts or experiencing installation during operation. |
| [illegible] | Fotos, videos, sketches, notes. | | | Documentation: Measurements, fotos, notes. |
| [illegible] | Lectures, reports, 2D plans, 3D renderings. | | | |

## PHYSICAL MOCK-UPS IN END USER INVOLVEMENT

Through observational studies and contextual interviews on several on-going healthcare projects utilizing physical full-scale mock-ups to involve end users, the researchers gained an in depth understanding of the complex dynamics, which such mock-ups support.

The studies outlined several findings important to the use of physical mock-ups in end user involvement, which the researchers divided into 6 main categories.

### *1. Utilization of physical mock-ups in user involvement processes*

The first and most important finding was understanding the reason to and how users are involved in the projects since the purpose of user involvement outlines the overall requirements of a future virtual alternative or complementary solution.

The physical mock-ups were used throughout the process from the early design stages and continued even after the beginning of the construction phase and included conceptual design, quality assurance and pre-use training. Users were involved in interior design to extract user experience and to assure quality of planned designs and based on the final results, pre-use training was executed.

Since the applications, in which the physical mock-ups are used, vary depending on the nature of the issue that is being investigated, so does the mock-ups themselves. Depending on the project stage and purpose of the user involvement process, the mock-ups, the artefacts used in the mock-ups, and the type of interaction with the mock-ups vary. In the studied cases, the researchers found at least 4 levels of full-scale mock-ups, which outlines the wide spanning application hereof.

The levels listed in Table 1 illustrates that physical full-scale scale mock-ups are being used throughout the different stages of a project, and that the need of more detailed mock-ups with real-life interaction increases as the projects progress.

To make the end users able to fully understand the complex material they are presented to, it is important to simplify the means of communication. This is the overall idea behind involving them in the process based on full-scale mock-ups, as full-scale mock-ups let the users experience the spaces as they do in their everyday life.

In the earliest stages of a project, geometric shape of specific rooms and distribution of square meters might not even be assigned yet, which makes detailed mock-ups like level 3, and 4 as illustrated in Table 1 hard to achieve with physical mock-ups. By using virtual mock-ups as a supplement, we could potentially close that gap and provide the users with a more realistic environment even in the early stages of a project, enabling them to better understand the mock-ups they are testing, and co-creating.

Since the level of abstraction influence the degree to which the end users are able to comment and give feedback to specific mock-ups, using virtual mock-ups might bring great value to the user involvement process in the early stages of a project just by improving the communication alone.

Furthermore the physical full-scale mock-ups also have to fit into a physical facility and are thereby limited to fit that facility´s natural boundaries. This makes it difficult to create mock-ups of entire levels of a project, and to test logistics between areas that a not in near proximity. Viewing a full-scale section of a large project displaced from its context creates a need for alternative ways of displaying the immediate surroundings to the user. To that extent, the physical mock-ups have to be accompanied with additional tools to provide the users with the information needed.

## *2. Use of additional tools*

In the projects studied, several tools and artefacts were used to support the user involvement in different stages of the process. To support debates about overview topics related to logistics and context related matters in general, which cannot be tested without a more comprehensive context, board game style miniature mock-ups and large printouts on wax dew were used as illustrated below.

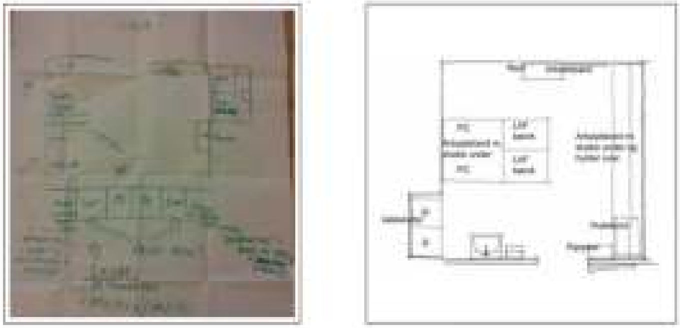
Board games were used to create an overview of larger areas to place full-scale mock-ups in their context, and in a Lego-like manner enabling the users to move walls and interior in co-creation with other users. The board game served the purpose of communication of logistics relations and as a compensation for limitations due to the lack of physical space in the full-scale test-facility.

Figure 2
Example showing the difference between the artefact in use, and the actual real-life counterparts.

In relation to this, physical full-scale mock-ups of different level of detail, in different project stages, were constructed and tested by the users, allowing them to explore and test design intents in 1:1 scale from fully customizable low level mock-ups to constrained high level mock-ups. These diverse levels of mock-ups enabled the users to investigate alternatives to space utilization and interior equipment freely, as well as, the result of previous mock-up iterations, e.g. decided designs - limited by its actual dimensions and equipment. The full-scale mock-ups therefore enabled the users to interact with and in real-time experience the resulting change of their interaction with either objects or other users. The full-scale mock-up acts as a design tool as well as a training facility, where learning by doing supported by role-plays and scenarios can ensure quality and usability of the future healthcare facilities.

To prepare users for their future workspace and thereby ensuring as smooth a transition to the new facilities and organization as possible, both full scale mock-ups of smaller areas and large printouts displaying entire wards were used. Accompanied with Lego objects the large printouts supported training sessions to prepare users for their future workplace utilizing roleplays described in scenarios prior to the sessions by a facilitator. The pre-use training was used to prepare the users for logistical aspects of the

Figure 3
Data collection from a user involvement session using physical full-scale mockups.



new facility as well as new ways of working caused by use of new technology and new organizational structures.

To support the above-mentioned tools, traditional drawings, 3D-visualizations and walkthrough videos were used to explain and communicate complex details, which were not possible to visualize in the physical prototypes.

The observational studies made the researchers aware of the following aspects:

- Volumetric realism is key to gain trustworthy input from end users
- Understanding the context is important and necessary for training purposes, but can be difficult to communicate in full-scale due to limitations of physical space.
- Multiuser interaction and Co-creation in the physical mock-ups is essential to enable user input in a quick and dirty manner, and
- Facilitated plenum discussions in full-scale environments are effective ways of bringing forth profession based knowledge.

When trying to supplement these complex work processes with a system enabling use of virtual mock-ups, the aspects above should be considered as the basic requirements of such a system.

## *3. Artefacts and realism hereof*

In more than one occasion it was observed in the studied cases that the lack of present artefacts led to the use of less realistic artefacts as illustrated in Figure 2, which counteracted the purpose of involving users through physical full-scale mock-ups by increasing the level of abstraction leaving the perception of design intent to the user imagination. In other cases, too much detail impeded the user involvement process, since the users couldn´t abstract from the details presented and the actual focus of the session at hand.

In a BIM based virtual environment, there problems would potentially no longer be an issue since the number of available objects would no longer be limited by the possibility to obtain the actual piece of equipment. In a virtual environment object libraries could be vast and support different levels of detail pr. object supporting multiple requirements in terms of presentation quality e.g. textures and geometric details.

## *4. Interaction with the artefacts and users*

The user involvement processes were in all the studied cases highly dominated by the presence of multiple users and highly influenced by the co-creation and roleplay methodology used, the user involvement processes also stated the need for multiple and simultaneous interaction with objects.

When analysing the users' interaction with the mock-ups, it became clear that the virtual supplement would have to support different types of interaction from different devices, which comes down to interaction with:

- The full-scale mock-ups in the virtual environment
- Other users in the virtual environment, and

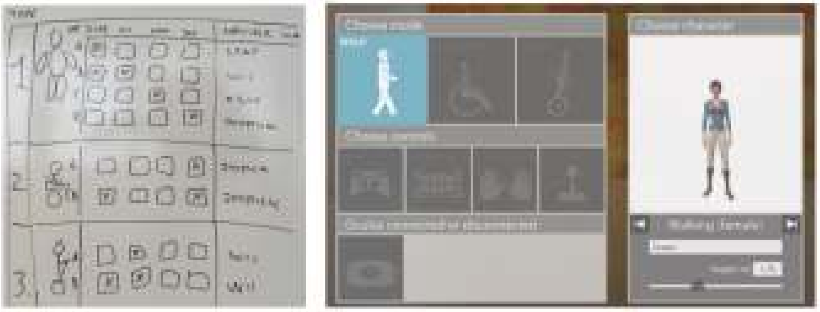


Figure 4
Snapshot of whiteboard from discussion of navigation and interaction functionality with end user representatives (left). Resulting user interface for entering the system (right).

- A top down representation of the full-scale mock-up including the context

Each of the above furthermore have a connection to the others.

In the case of utilization of the overview tools (e.g. the board games and large printouts) the tool was linked - in practise by duplication of some parts to the full-scale mock-up and in case of the training session carried out from the large printouts these scenarios were supplemented with 3D interactive models to demonstrate the vertical dimension and to help communication of the area presented to the users.

In parallel, the full-scale mock-ups were supplemented with additional tools to communicate information about the surrounding context of the specific mock-up.

A virtual mock-up would be able to combine these by supporting different types of displays and interaction:

- Head Mounted Displays combined with interaction devices to support detailed manipulation with the virtual environment
- CAVEs to enable group participation and debate of activities within the virtual environment, by still having a full-scale representation of the environment.
- Touch devices to support overview through 2D-plan views, co-creation

To better support the work processes already observed through the use of physical full-scale mock-ups, the virtual supplement should synchronize events between the three, to achieve the potential synergies by combining them.

## *5. User roles and facilitation of the user involvement process*

During the user involvement process, different user roles were needed to perform the tests. Besides the end user, a facilitator and representatives from the advisors were present. The end users were divided into different user-roles corresponding to different professions within the healthcare facility, the facilitator of the process oversaw and supported the co-creation and roleplays and the consultants pitched in to answer questions - mainly concerning third dimension uncertainties to the end users.

A shared need for all of the above, was the need to observe one another. The facilitator especially had a need to be able to oversee the users actions, and ideas which in a virtual environment is not automatically given. To provide this functionality, the virtual environment should support a spectate functionality and also multidevice connectivity to that environment.

If the solution could be be made online, it would be possible to participate in user involvement sessions remotely - thereby potentially minimizing the need for transportation of users to specific test facilities.

### *6. Data collection and communication hereof*

Data produced during the user involvement sessions were mainly captured on hand-drawn sketches and photos (see examples in Figure 3), although the facilitators mentioned that video recordings had also been used in the past.

To help the facilitators and architects to understand the identity of the sometimes abstract artefacts, and the reason for their placement and necessity to the end users work, post-its and whiteboard markers were used. The data captured were then re-entered into the BIM-tools and distributed to non-participating users/colleagues through traditional 2D-drawings and 3D images.

This process could potentially by optimized be linking object databases, the BIM environment and the virtual mock-ups to centralize the user inputs minimizing the risk of data loss and repeated tasks.

## SYSTEM DEVELOPMENT

Based on the above-mentioned case studies and literature studies, e.g.: "Patient Rooms of a California Based Hospital: Benefits of Physical Mock-ups vs. Virtual Mock-ups" (Johansson, 2012), the researchers found a considerable potential for optimization through the use of digital counterparts.

In order to verify the benefits from utilizing virtual mock-ups, prototypes were developed and tested. The aim was to develop a multi-user distributed environment, supporting real-time co-creation and interaction with BIM-based models allowing users to experience the design intents in settings as realistic and easy to percept as possible. In this way supporting the same workflows by combining various tools, the use of drawings, 3D-visualization, board games and large printouts into one system.

To mimic and extend the capabilities of previously used methods of communication within the end user involvement domain in a new digital solution, the proposed and evaluated prototype was created with a combination of different display technologies. These included CAVE-technologies, Head Mounted Displays, touchscreens and additional motion tracking devices to enable more natural ways of interaction with the virtual environment than traditional joysticks, and to further improve and investigate potentials found in previously developed prototypes for virtual mock-ups in user involvement (Svidt & Sørensen, 2016). Based on comments from users of the first prototype, different ways of interaction with the virtual environment were discussed. Figure 4 shows on the left, notes from discussion of relevant combinations of avatars and navigation devices and to the right the resulting user interface for entering the virtual environment. Similarly, based on user demands, a touch screen interface was designed featuring a floor plan view with rotatatable menus for selection of preloaded items to insert into the virtual environment as well as a customizable 3D view (Figure 5).

## TEST OF SYSTEM

The system was tested in a case where end users were involved in furnishing of a university building for 150 employees and 450 students. A group of 20 end users representing management, employees, students and maintenance staff, as well as representatives of the furniture providers took part in a 1.5 day workshop which led to decision of all furniture acquirements for 9 different room types in the building. The results of this test are reported by Petrova et al. (2017) and Rasmussen et al. (2017). They found that despite the different professional backgrounds of the users, they managed to achieve a common understanding of the rooms and a broad acceptance of the VR system as an easy-to-use technological solution. It was found valuable and time-saving that end users could test their ideas by directly manipulating the models in an intuitive way instead of explaining their ideas to a CAD operator. However, some limitations were also identified. In the current version of the system, users could not save different design proposals for later comparison and negotiation. Consequently, a number of 2D printed design proposals were the ba-


Figure 5
Touch screen interface with floor plan and rotatable menus for inserting artefacts into the virtual environment.

sis for discussions and final decision. Rasmussen et al. (2017) also found that a few users were reluctant to start using the technology, especially when they needed to wear the Head Mounted Displays to enter the virtual environment. The authors of the present paper observed in other cases that users felt less discomfort in experiencing the virtual environment in a CAVE than by using Head Mounted Displays.

## CONCLUSIONS

Studies of existing work processes based on physical mock-ups underlined significant improvement potentials in terms of development costs, scalability, level of abstraction, availability of artefacts and ultimately data-gathering and further re-use of data.

To reach the potential benefits from the virtual mock-ups, they should enable users to understand and interact with the environment in intuitive ways similar to the physical counterpart. Evaluations of the proposed BIM-based virtual environment showed that end users were successfully involved using these, bringing new possibilities to the end user involvement domain, including location independent involvement, more comprehensive mock-ups, improved realism and availability on artefacts and a more unified link between user involvement and the project planning.

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# H-BIM and web-database to deal with the loss of information due to catastrophic events

## *The digital reconstruction of San Salvatore's Church in Campi di Norcia (Italy)*

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*Nowadays , we are able to produce geometric models of historical buildings at different scales of detail, using photos and measurements. This is true when you are observing something that is still under your eyes. We are faced more and more with lack of preservation actions and maintenance activities, policies framed without foresight, unexpected natural events, etc., that are forcing professionals and researchers to operate without usual data. In such cases, we need a consistent repository to collect and distribute data to produce information.Furthermore, we need to ``give intelligence'' to these repositories, in order to query them with respect to geometrical instances, topological issues, historical features, etc. This last aspect, (archives and databases connected with geometrical aspects), lead our digital model to a new dimension, the informative one (where spatial, temporal, historical and building parameters work together), that should always characterize speculative actions towards the constitution of a wealth of knowledge. We need to work on the efficiency of the process to reach effective methodologies of survey.*

**Keywords:** *cultural heritage, Structure from Motion (SfM), loss information, H-BIM, web-database*

### IDEAS FOR RECONSTRUCTION

The work proposed is a part of an ongoing research focused on the application of H-BIM approach for the management of historical building heritage (Murphy 2009; Murphy et.al. 2013). In particular, with regard to the catastrophic event consequences, both the acquisition phase and the archive research process are of great importance, for protecting our undefended building heritage. Following the latest disaster in Italy (Aquila, 2009; Amatrice 2016), most of the historical sources were lost and the artefacts themselves were in a state of total ruin. This fact has lead the scientific community to wonder which approach can be used in this particular case, when all the specific information (survey and historical sources) were unavailable or lost.  If the information are missing, it is necessary to gather information through non-coventional methods and reasoning for deduction or analogies with other existing cases: a possibility could be to use the Structure from Motion (SfM) for recreating the digital model from images archived from the network or granted by the local population. Inspired by a similar work of virtual geometrical reconstruction from historical pictures of the Bamiyan's Buddhas (Grün 2004), that were destroyed in March 2001 by the Taliban, we have revised the methodology described in this work and extend, adding the possibility of semantically enriching the model and extending the knowledge beyond the purely metric 3d reconstruction aspect.The mesh model obtained with the SfM techniques can be used as reference for developing an H-BIM model.  Although the system seems to be one of the best approaches for managing data and driving the decision-making process, several difficulties arise, due to the amount of effort required in modelling the initial phases (Volk 2014). One of the main issues, still not resolved in the field of H-BIM, is the establishment of the maximum deviation levels from geometrical data survey into the parametric elements that, for their nature, are simplified models, as compared to the complexity survey mesh models achieve with TLS or SfM approach (Lo Turco and Santagati 2015).The model has the dual function of communicative media but, is at the same time, a "virtual prototype" to conduct additional simulation and analyses, which have the primary objective of not endangering the historicity of the monument.In our case, the starting information (amateur sources and material collected from the world wide web) will produce an error, greater than that of a professional topographic approach.  In that sense, the procedure should not be interpreted as a method for obtaining forms with a topographic precision but, a qualitative way to rebuild shape and elements.  We must be aware that the H-BIM model will include a level of uncertainty.

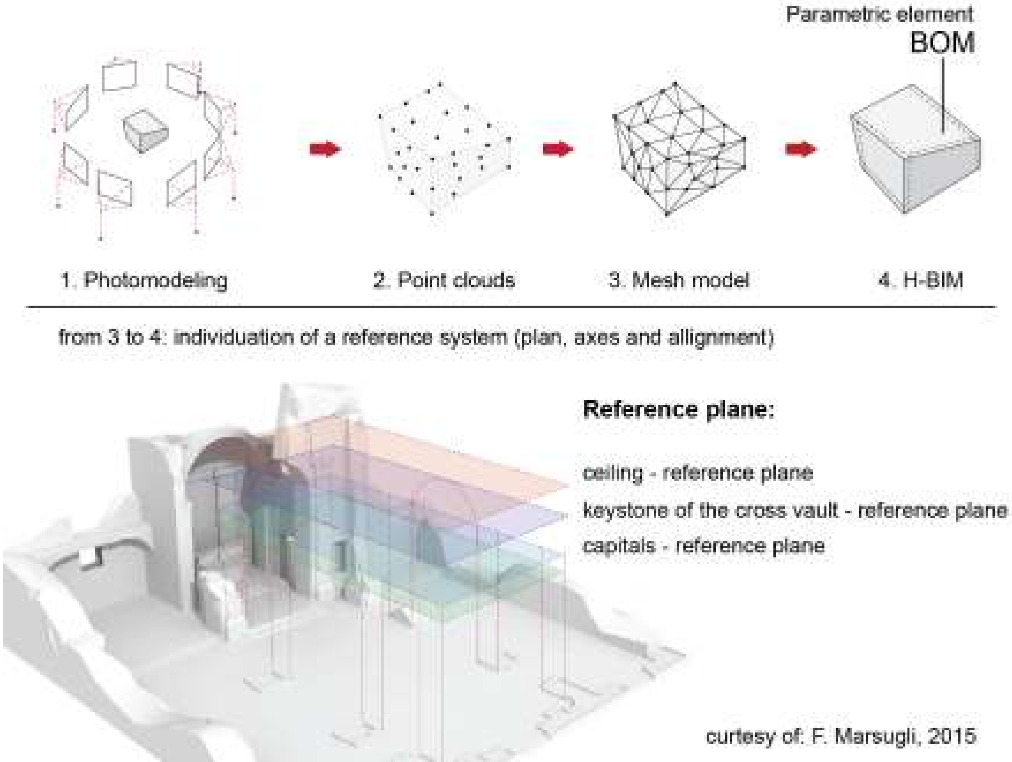
## A POSSIBLE METHODOLOGY

The novelty of the method is to gather, elaborate and rebuild missing information from unconventional procedure.  The general idea that prompted this work was to find a process that can overcome a lack of access to the ruins and achieve the most accurate digital model from the information available. Moreover, a fundamental aspect is to create a platform where it is possible to manage the information that will vary during the time. The methodology that we are going to present is based on the definition of two main strategies: the modelling strategies (1) and the gathering information involving the local population (social participation) (2).

### *Modelling strategies*

A possibility for gathering or restoring information could be using SfM and extracting metric information from the pictures.  The process has been well documented in literature (Lichti 2002, Apollonio 2010, Lo Turco and Santagati 2016), especially when the images are taken by professionals or specialist operator who has knowledge of photographic parameters which vary in accordance with different conditions.  Instead, less work has been conducted when the reference material is scarce or has been downloaded from the World Wide Web.  The process that we propose starts with the interpretation of the mesh model achieved from SfM that can used as reference for setting the macro element of the preliminary H-BIM model. This model is characterized by a low level of detail and information (LOD 100) and is composed of several main spaces individuated by function (defined at the gross volume of the masonry, floors and roofs).  In particular, in the architectural domain, it is necessary to highlight the reference plane and the height of trusses, beams, ceilings, columns, frames, pilasters, niches, tabernacles and other building and all the architectural elements that will characterize the building (Marsugli, 2015) (see figure 1).   After exhausting the first phase of modeling, the digital model needs to be enriched by additional, new information.  In many cases, not all historical buildings

Figure 1
Methodology: form SfM to H-BIM




have been archived in official historical archives, as in our case, where an earthquake destroyed all the information (material and immaterial). For that reason, we propose a "campaign of sensitization" of the population: several items of information can be gathered from pictures, documents and historical sources, not published or not stored in official archives. All the information can be collected through a web platform where people can have a registered access. All the information will be uploaded using a logical and quality criteria for organizing and predisposing the material for digital elaborations. This platform is undergoing formalization and will be applied also for a case study in the Norcia area, affected by the earthquake (see figure 2). Once the information is uploaded through the platform, the operator must interpret it and understand how to use it for a semantical enrichment of the H-BIM model. This process will influence the building subsystems that are defined as Building Object Model (BOMs) in literature (Biagini and Donato 2014). The process of their creation could be time consuming, due to the missing of shared libraries available and due to the unstandardized form and shape (Volk et.al. 2014). It is necessary for the users to declare the level of accuracy. There are two main aspects for enriching the element within a H-BIM model: the first relates to the process of converting survey data into parametric ele-

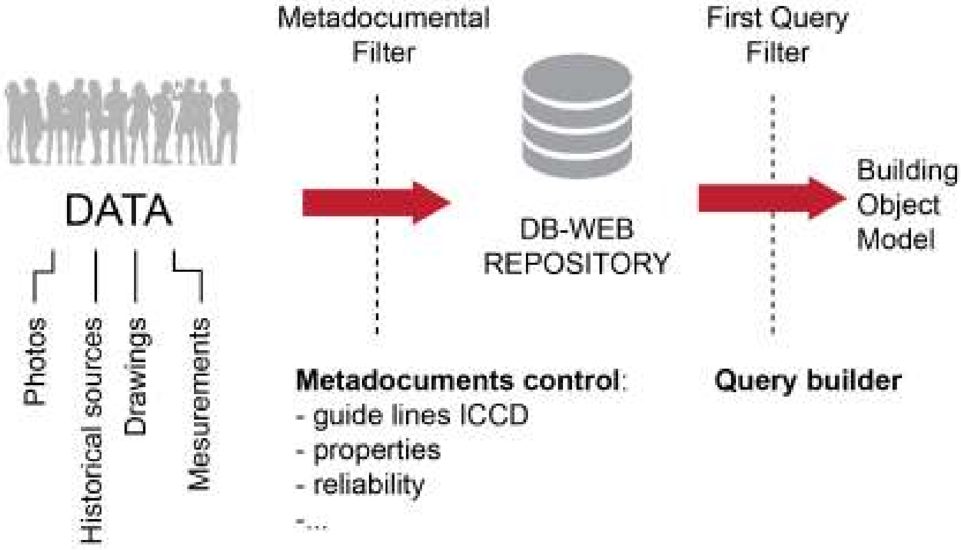


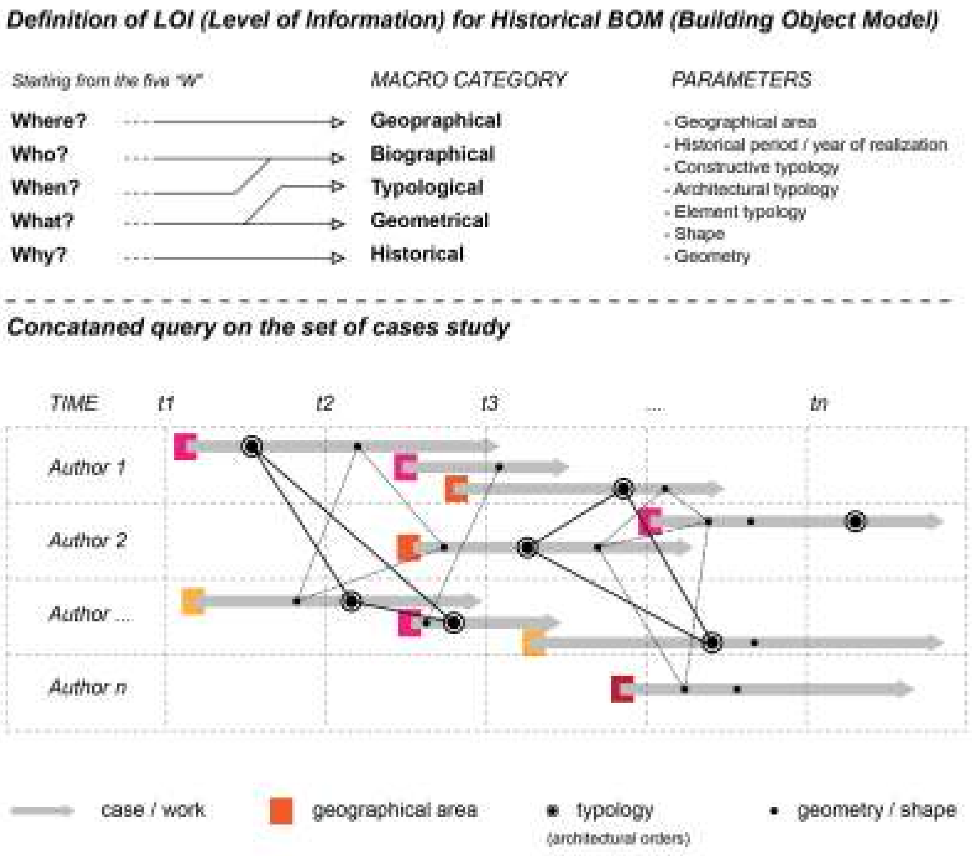

Figure 2
Call for sensitization: data gathering from social participation

ments, parsing the model semantically and decomposing the same, inserting a separation in an element that by its nature does not exist, whilst the second relates to the definition of BIM use that will heavily influence the modeling stage (Kreider 2013). The modeling strategies of BOMs (Building Object Models) could be diversified: if a point clouds is available, it is possible to achieve metric information and trace the elements; otherwise, in the case of missing information, we must use reasoning for analogy and use a deductive process. The information in this last case can be achieved from manuals and historical treatises or from deduction, comparing the information with similar case studies that present similar characteristics (typology, type of construction, era, year of construction, etc) (see figure 3).The LOD (Level of Development), that is expressed by two components: the level of information (LoI) and the level of geometrical detail (LoG); these must be calibrated as a function of the final purposes and if the model is used for analysis purpose, it can only be pure documentative. This can be chosen individuating the goal of the model that can be defined as the "BIM use". Currently, the LoD information is not a normed concept, and will be inserted in the new Italian legislation UNI 11337-2017.

### *Social crowd-sourcing and Web 2.0 for data management*

Representation and its techniques play a fundamental role in the transmission of knowledge. We specifically join the geometrical model to a clever archive of historical data (families of structured and well known elements, intended as the minimal logical part of the whole building). After having put into an interoperability mode a relational database with a repository of "intelligent objects", we create a procedural path that allows users (researchers and professionals) to: (a) interactively select an element of the repository (thanks to a query builder); (b) import the BIM family into the BIM project; (c) associate the elements (BOMs) to the digital geometrical model; (d) link other parameters to elements (alpha-numerical and iconographic documentation; conjectures, other sources); (e) perform a semantic validation of the H-

Figure 3
Tool for research and comparative analysis based on rules on a population of case studies: identification of elements analogous or similar on the basis of search criteria




BIM. We have also considered the possibility of distributing database and query builder starting from a web app, using computer technology ordinarily used for social internet site platforms (see figure 2). This digital model was used as a reference to develop an H-BIM. This article demonstrates the feasibility of a whole H-BIM approach for complex architectural shapes, starting from TLS point clouds. In order to improve the framework for 3D modeling, the experience will show the challenges of using integrated procedures to rebuild the historical documentation, when the information has been totally lost.The proposed web platform must consider several aspects: the creation of complex databases of the building must follow the guidelines set out by the Central Institute for the Catalog and Documentation (ICCD) of the Ministry of Cultural Heritage and Tourism; the platform must be user-friendly, to facilitate participation by an enlarged public (institutions, scholars, professionals, citizenry); raising public awareness of the need to supply historical data archives through accessible and transparent tools; the ability to interrogate databases differently, according to different search filters that can be combined (Wei Li et al. 2016).

From the above-described requirements framework, the following operational tools (in a prototype version) have descended on the verification of the methodological approach we have outlined. In particular, this platform, which will be operated on distributed computers and on the web, includes two spaces of interaction: one dedicated to the inputs of the database, open to a widespread, appropriately accredited public, and the other turned to certain profiles that work on the digital reconstruction of the building.The open virtual public square provides archiving tools of various types of materials, meta-documented according to what is foreseen in the catalog of cultural goods. It allows the correct sorting of digital materials, functional to the consistent questioning of the sets (Sloane 2011).

The main objective is creating an inter-operable and queryable "speaking" three-dimensional models of the built heritage, where the scholars can access and conduct comparison between similar case studies, directly or by analogy, and then associate the results of the document search with specific parts of the model.In more detail, those who work on the building information system provide appropriate parameters for the objects of the model library (general, geographic, and typographical, typological, geometric, topological attributes); The input of these parameters allows their conjunction with "and" and "or" constructs in a query string that is made up of a specific hypertext parameter called "search".The search parameter is compiled within a relational database that has the specific purpose of integrating specific data operations, which are not possible within the building information model (BIM) processing environment. Specifically, the system interacts with model library objects (BOMs) or with their specific formalizations (areas, volumes, or masses).

## THE H-BIM FOR SAN SALVATORE CHURCH

The case study that we are presenting is the "Church of San Salvatore" in Campi di Norcia that was affected and extensively damaged by the sequence of earthquakes of 26th-29th October 2016 (see figure 4). At the moment, the church is in ruins, with a few remains of the outer walls standing (in particular the southern wall, which was reinforced following earlier earthquakes), and a few sections of the vault near the back walls. The rest - the vaults, the frescoes, the facade and almost all of the ponte (iconostasis) - was all lost. Initial research in the archives of the Diocese of Spoleto-Norcia and the Superintendency of Cultural Heritage did not uncover any surveys of the state of the buildings before the earthquake. The only information available are some photographs and studies of the church, but no drawings. From an architectural point of view, it is clear that a huge amount appears to have been lost: not just the materials, which are currently being gathered, but also the form: the architecture's geometry.This study, starting from the situation described above and with the clear objective of digitally reconstructing the church as it was, involved exploring the outermost boundaries of knowledge of the relevant science, sometimes reinforcing them, and at other times going beyond them.In any case, this research is only the beginning of a process that is not only much longer, but also much wider in scope. The application outlined here could be repeated to produce an increasingly accurate reconstruction of the collapsed building, and also extended to other parts of the building and to other sites that have suffered the same fate, unfortunately all too common in the region struck by this earthquake.As mentioned before, at the starting point of our work, the only material available was: some spherical panoramas made public on google maps through a virtual tour. No other source of information was available.The first topic was to recreate a geometrical reference (axes, alignment, plane of references) for tracing the geometry of all the building elements. For instance, in the case of the gothic cross vault digital reconstruction, it is necessary to

Figure 4
The San Salvatore Church: before and after the earthquake - the spherical panorama: the only information available


highlight the reference horizontal planes for capitals and the keystone for the transverse arches and the diagonal buttress but, at the same time, it is also necessary to highlight the vertical position of the reference planes for the arches. All the geometrical information were extracted by a 3d mesh model achieved form SfM approach (in particular with the software Agisoft Photoscan) that allows us to extract information from the panoramic photographs.The 3d mesh model was scaled as a function of a topographic measurements taken on site from the surviving masonry, as well as a photo-grammetric survey conducted using a drone. In that sense, the 3d mesh model was geometrically validated.The main issue was that from the photo modelling, using just the panoramic photos, the entire left-hand nave and part of the right-hand nave were recreated with a certain level of detail (approximately one point every 5 cm). However, the extracted model is lacking in other areas, especially the right-hand nave.In this particular case, ad-

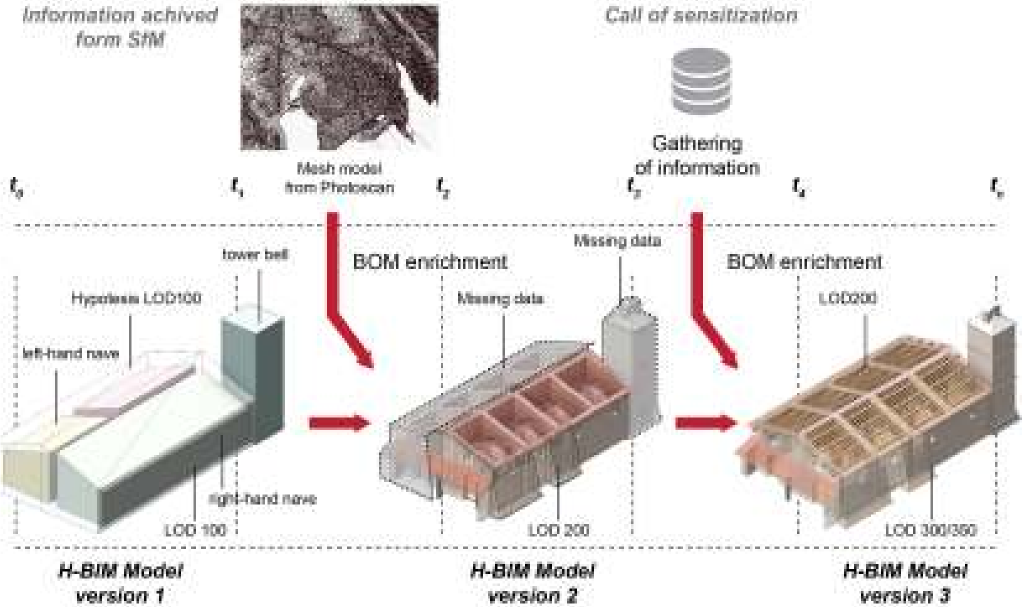


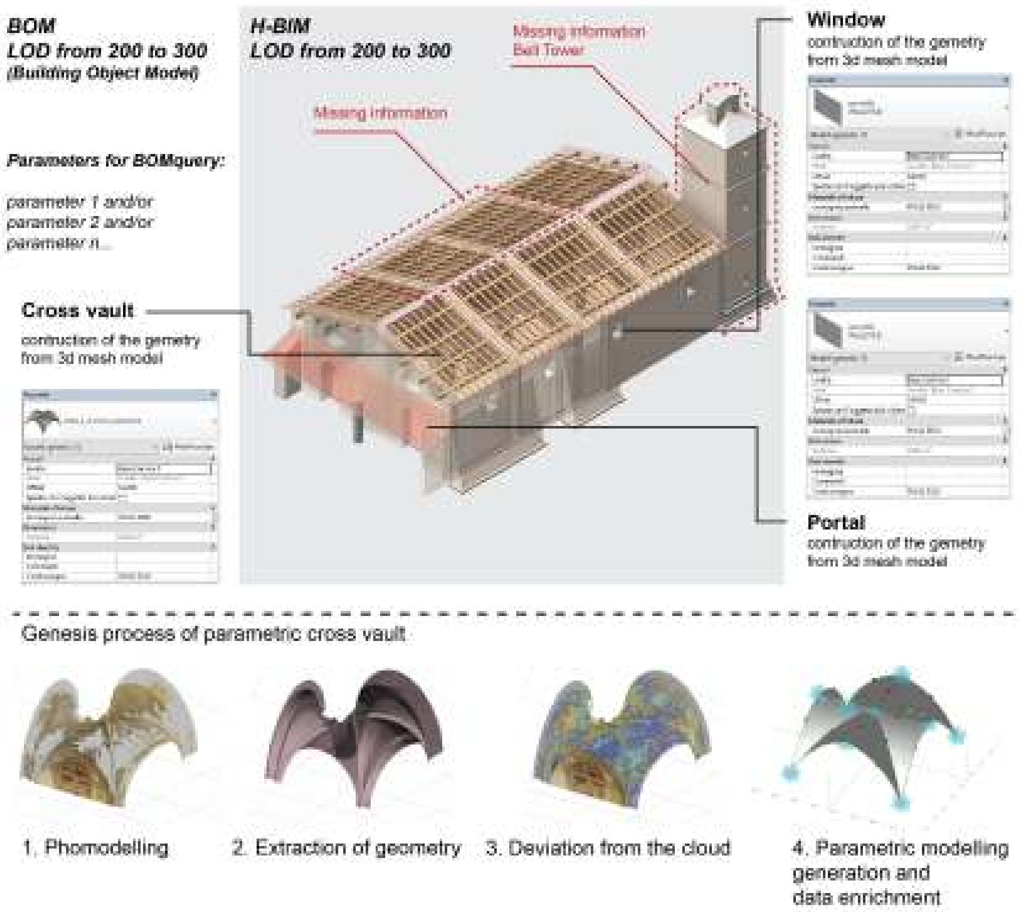

Figure 5
Process of data enrichment

ditional photos could help to fill the voids left by the starting process. Only through a consideration of the original historical measurements and with a recent study of the authors, the 3D mesh model was scaled up and the necessary analysis carried out to reconstruct the creative process.The model was decomposed in the subsystem, starting from the load-bearing element, going till the roof and defining the rib vault and hypothesizing the traditional composition of the roof made by the main beams and secondary beams. This information can be obtained by observing the internal spherical panorama that allow us to look in the left nave. Unfortunately, due the low level of detail of the images, is not possible to extract metric information.Another step was the definition of the vaults. Before the earthquake in October, both naves were covered by raised rib vaults, with the keystone of the ribs higher than the arches surrounding the vault. Another observation is that the centre-to-centre distance of the aisles is not consistent, and they are laid out along a straight line, which is not parallel to the floor. These characteristics, typical of Italian Gothic architecture, should not be attributed to haphazard building techniques, but rather to an artisanal approach typical of mediaeval architects.For this, we have developed a parametric rib vault that can be adapted on the mesh model, inserting 9 control points (4 for the lower level of the arcs, 4 keystone of the arcs and 1 keystone for the vault).For this research, as a case study, the left-hand nave was modelled at the LOD200. Other parts of the church were modelled based on the picture extracted from google maps at the LOD100 due to the absence of information. Proportional relationship between elements were obtained through the inverse perspective method.

## CONCLUSION

The research conducted until now demonstrates the potential of H-BIM applied for driving the process

Figure 6
H-BIM model for the San Salvatore Church - model version 2 towards version 3




of reconstruction after the seismic event due a loss of information. Although the procedure shows high potential in general, from another perspective, it shows limitations, especially the difficulties of populating a virtual library of case studies (churches, for instance) and elements (BOMs for historical building heritage).Further work will be conducted in presenting the platform officially in the town of Norcia and starting with the phase of "sensitization" and gathering of information for developing the third version of the model. The final objective will be to achieve a complete "as-it-was" model, including all the architectural and technical notices necessary to guide the reconstruction phase of the church.

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# Spatial Typology for BIM

## *Preassembling for Synthetic Architectural Design*

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*Contemporary Building Information Modeling (BIM) software provides basic component types such as bathtubs, desks, windows and walls that are available in many varieties of kinds and ready for drag-and-drop into a design project. However, the software is unlikely to provide higher level constructs such as bathrooms or offices as types, and these spatial concepts are largely unframed in the ontology of the building system. This paper looks at these spatial concepts left unframed in BIM as important fabric in the design process, examines how they are represented typologically in conventional design resources such as Neufert Architects' Data, and discusses strategies for embedding them in BIM. Together with abundant published cases of architectural designs, the examples of spatial forms in these resources play a role of Big Data. The paper then demonstrates a prototype of parametric office building typology embedded in BIM and illustrates how such a tool helps an architect to study volumetric layout on a given site. The approach tested leads to an idea of BIM imbued with a massive taxonomic library of preassembled spatial types and takes us a step closer to a symbiotic or synthetic architectural design process.*

**Keywords:** *Building Information Modeling, Architectural Typology, Design Representation, Big Data, Synthetic Design*

### INTRODUCTION

What is BIM? This question continues to be answered in many ways by people who find different stakes in it. In the preface of the BIM Handbook (Eastman et al. 2008), Laiserin gives a historical account and shows that many ideas such as simulation, database, and automation play important roles in forming BIM. The present study looks at architectural design as a composition of types and specifically focuses on the symbol system as a critical ingredient of BIM.

Geometric modeling applications such as Rhino provide primitives such as cylinders and boxes along with tools to manipulate them. An array of cylinders can simply be positioned on a thin rectangle box. In a typical BIM application, the same step can be carried out by placing an array of columns on a floor that they attach to. A column is a symbol for a type of architectural part, whereas a cylinder is a symbol for a geometric primitive. A column has parametric properties such as height and material and can be associated

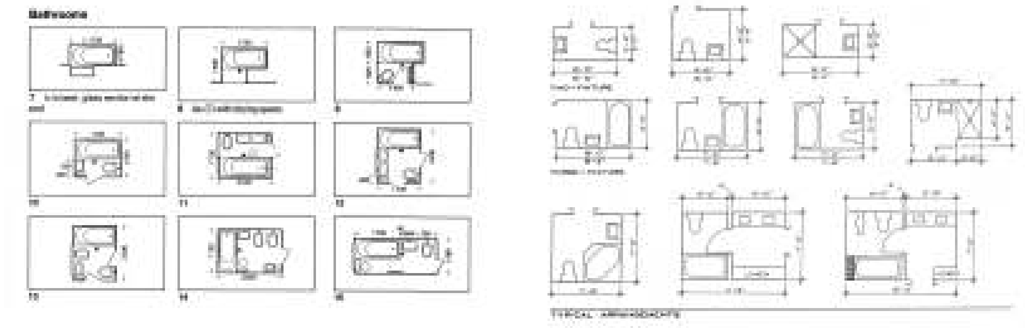


Figure 1
Some bathroom types documented in Architect's Data (left, Neufert 1970) and Architectural Graphic Standard (right, Ramsey and Sleeper 1932).

with specific geometry such as a cylinder, rectangular extrusion, or H-section, which can be interchanged. One piece of column that is inserted in the drawing is said to be an instance of the column type. A column also knows how its instance relates to instances of other symbols, such that a column attaches to a floor at its bottom and intersects with a beam.

In this way, a BIM application provides an environment where an architect drags and drops various types of architectural parts such as columns and walls, edits them, and assembles them into a building. A huge number of instances of these types are included in the design, and the spatial relationships between them are simultaneously recorded as the design develops. The resulting model is a giant web of building information.

The foundation enabling this process is its symbol system of architectural parts. A typical BIM application today comes with the basic tectonic vocabulary necessary to document a building, including wall, window, floor, column and others. The application also embeds floor level, grid, room name, section line and other elements as special symbols, each with its own properties and embedded ways to relate itself to other symbols. A window is hosted in a wall. The floor level can be used to set the relative vertical position to a floor instance, and a column instance may be located with reference to a grid intersection.

All of these features are important concepts for any architectural design process. To build intelligent software for a shared domain of discourse, the specification of its representational vocabulary as an ontology is a known strategy (Gruber 1993). However, not all familiar spatial concepts are readily available in a typical BIM application. For example, it likely provides no bathroom or office building as built-in types. Instead, an architect is expected to assemble basic components such as bathtub, sink, wall and floor one by one and create a bathroom or office building design. These spatial concepts are largely left unframed in the ontology of the building system. The present study aims to fill this gap by using existing design resources as a "Big Data" of credible examples and by mining a useful body of disciplinary knowledge that has already been compiled.

## PRECEDENT AND METHOD

The idea of types in architectural design is deeply tied with that of composition throughout history. The classical order, for example, is described by many books, from the Four Books of Architecture (Palladio 1570) to A History of Architecture on the Comparative Method (Fletcher 1905). Figure 2 shows William Mitchell's coding scheme of classical order (Mitchell 1977). In this case, the lines between named elements represent two different essential relationships between types in a somewhat confusing fashion. The line between Order and Doric represents type and subtype relationship, often referred to as "kind-of"

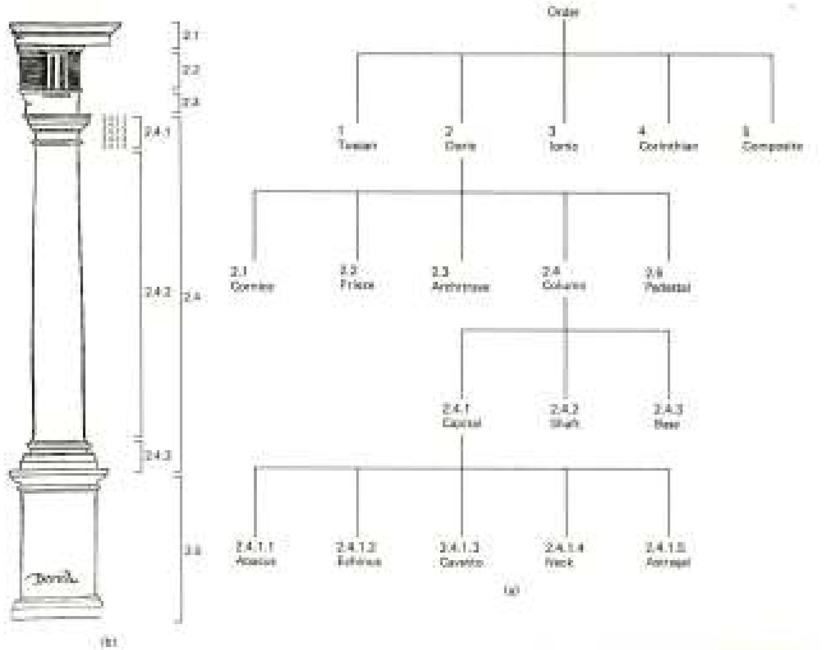



Figure 2
William Mitchell's coding scheme of classical order (Mitchell 1977).

in computer science. Tuscan, Doric, Ionic, Corinthian and Composite are sibling types that belong to Order, their parent type. The line between Doric and Architrave represents the composition and component relationship, often referred to as "part-of." Cornice, Frieze, Architrave, Column and Pedestal are all component parts that belong to the Doric order composition. Spatial relationship between components can be more specifically described. For instance, a column shaft attaches to its base, and a wall hosts its windows in a facade.

These relationships can be nested in a hierarchy. The Doric subtype may further be classified down by Greek and Roman subtypes and makes a tree-like taxonomy of types. Mitchell's illustration also shows compositional hierarchy with Doric at the highest level, Column and Shaft at the next two levels, and Neck at the lowest level of this breakdown. His team proposed and demonstrated Topdown (Figure 3), a software toolkit that allows encoding of such taxonomy and composition of types and provides visual navigation through their hierarchy (Mitchell et al. 1990).

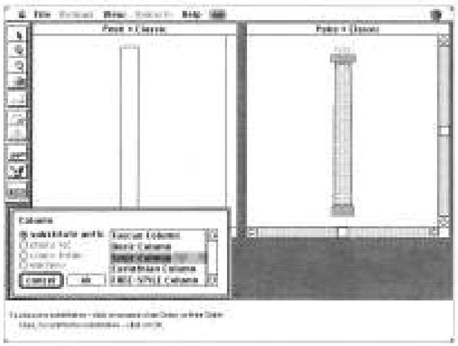


Figure 3
A screenshot of Topdown showing a generic column replaced by a classic Order composition (Mitchell et al. 1990).

In a scheme with the entire building regarded as the top level of compositional hierarchy, a typical BIM application provides elemental types near the bottom of the hierarchy, such as wall, window and floor. The wall taxonomy is rich with tectonic subtypes such as brick, stud and curtain walls and describes each subtype as a composition of finish, substrate, insulation, sweep, etc. The vocabulary still lacks some peculiar types such as dome and vault, but efforts to collect and embed industry standards are on the way (Sharif 2015). On the other hand, the BIM application does not say much about how these elements can be assembled into meaningful architectural compositions. For example, a variety of sink, bathtub, and shelf are there as built-in types, but an architect still needs to assemble them with wall, window and floor into a bathroom design. Because the bathroom is a most frequently used and documented concept of spatial type, as exemplified in Figure 1, one strategy to help this bathroom designer is to study them and embed bathroom as an available type in BIM.

Similar to Mitchell's diagram of classical order, the bathroom type in BIM would include various layout options as sibling subtypes and describe each as a preassembled composition of sink, wall and other elements that are already embedded in BIM. A bathroom is a spatial type near the bottom of the compositional hierarchy. On the other hand, each spatial concept found at a higher level hierarchy is a composition that includes other compositions as its component, in which case the use of abstraction becomes convenient. For example, the lounge type for airport design may include a waiting area and a bathroom as its components. Because the bathroom itself is a composition, the lounge may represent it in an abstract form without revealing the detailed composition of sinks and compartments inside. For tool development, such abstraction allows the lounge type to be framed as some composition before the bathroom type composition is fully framed. For an application, it is more computationally efficient to process representations without unnecessary details in the context of design. For architects, sketching out a design idea for the lounge at an early design stage benefits from omitting the bathroom interior and postponing its design until the overall lounge layout is fixed.

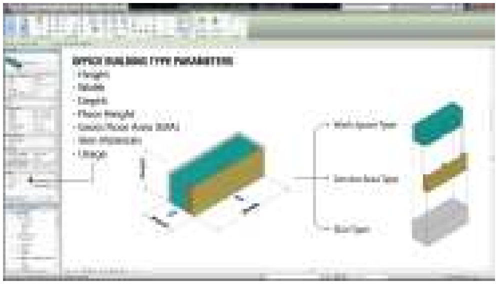


Figure 4
Office building type. Gross floor area (GFA) is computed from width, depth, height of the building and floor height. While the GFA value is locked, dragging the triangle handle of the building and changing its width interactively adjusts its depth so the floor area adds up to the given GFA value. This aids in the volumetric study for a specific site and program.

## OFFICE BUILDING PROTOTYPE AND TEST

To test the idea of preassembled spatial compositions as types in BIM, an office building typology that architects widely use to study building volumes on urban sites was prototyped using Revit and its SDK. A generic office building type was defined as a composition of work space, service area and skin types. Figure 4 shows its major properties with interdependency. The component types are represented as abstraction in colored primitives.

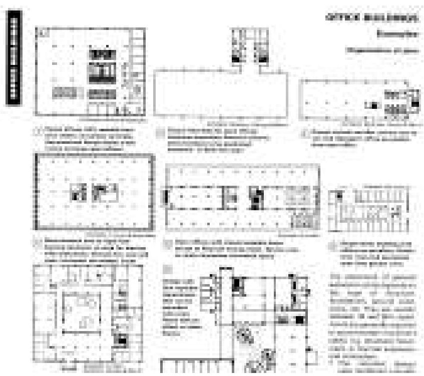
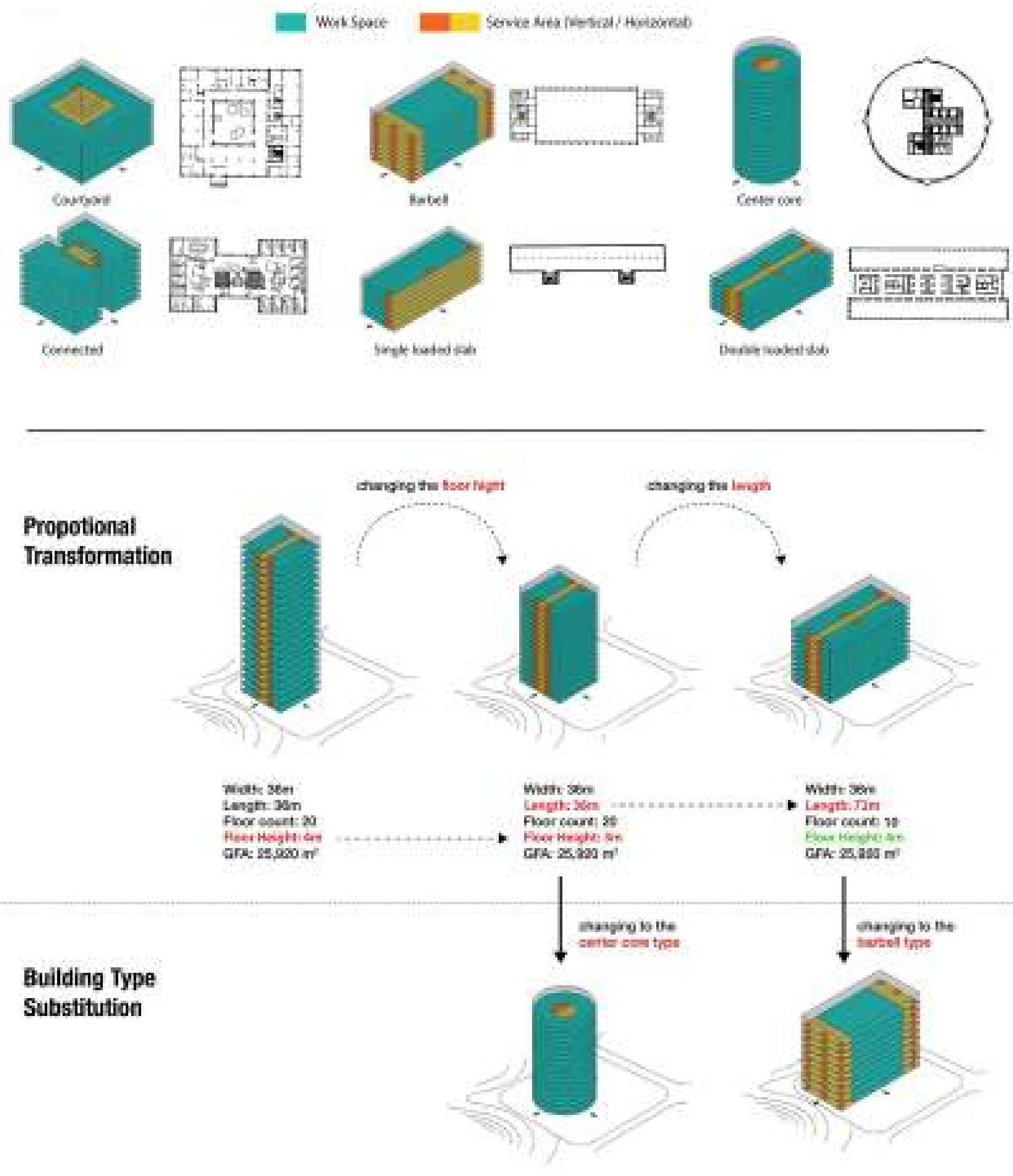


Figure 5
Examples of office building typology documented in Architect's Data (Neufert 1970).

Figure 6
Top: Office building subtypes prepared: single loaded slab, double loaded slab, center core, courtyard, barbell, and connected types. Bottom: Proportional transformation of a double loaded slab instance and its substitution to an instance of center core or barbell types while the GFA value is locked.



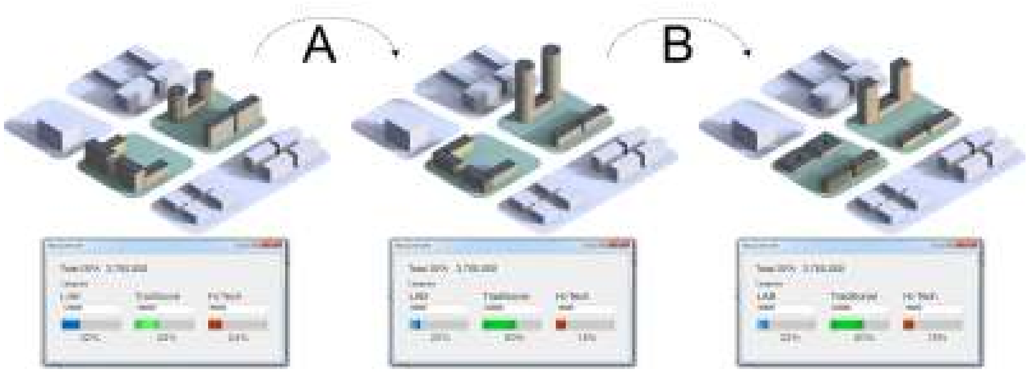



Figure 7
Variations of office complex designs made by a subject, who categorized a number of office buildings into high-tech (red), traditional (green) and lab (blue) uses. During the design study, the total GFA of these use categories was locked. A: The GFA value for each use was adjusted by the slide bar, and the building proportions were adjusted. B: The GFA value for each use was locked, and building types were altered while some buildings are repositioned.

To prepare a small typology of office building, the examples of large office buildings from Architect's Data (Neufert 1970) were referenced. The chapter on Office Buildings (Figure 5) lists principles in terms of program, lighting, mechanical, desk, construction and other issues and explains how changing work styles transformed office building typology from the 1950s to the 1990s. Our implementation focused on the formal composition of work space and service area and simplified and configured the examples in this chapter, instead of directly using the office typology provided there. Six office building subtypes were prepared (Figure 6 top).

Substitution and parametric transformation of a building instance on a site works interactively similar to the substitution and transformation of a typical window in a wall but with special attention to its Gross Floor Area (GFA) value, which can be locked during transformation (Figure 6 bottom). Furthermore, an interface was added to lock the total GFA value of a group of buildings while modifying the GFA value of each building in the group.

A test and observation was made by asking architecture students to use this BIM plugin and to design an arrangement of an office building complex on an urban development site (Figure 7). The small and simple office building typology enabled a swift generation and modification of compositions of design schemes. Interviewed subjects commented that being able to drag and drop a pre-assembled building and transform it by the preset parameters allowed efficient evaluation of different possibilities because attending to ordinary generative steps of gradually composing elements was not needed while solving an architectural program. In addition, flipping one building form instantaneously to another reportedly brought a novel sensation.

## CONCLUSION AND SPECULATION

Many architects today think of BIM software as a production tool and dismiss it from the context of design creation. They note its look and feel of functionality as well as interface and recognize its usefulness for making presentations and running simulations, yet prefer other software for shaping architectural forms during their creative process.

The goal of the present study is not to question if the current BIM implementations can be made to operate more intuitively for designers or to intervene in the quest for architectural creativity. Instead, an opportunity is presented to inquire about a type of tool imbued with new intelligence, to question whether a tool that understands various spatial typologies helps architects design, or to ask what spatial concepts can help make a good design and how these concepts can be framed and embedded. The

Figure 8
A search result for "Kitchen layout" in Google.

initial office building typology deployed in this experiment was based on small samples identified in a widely used architectural resource book and regarded as credible. The targeted spatial concepts were shown to be deployable in BIM software, and tests of their use with subjects demonstrated their effectiveness in producing design studies.

Further investigation has multiple possibilities. An immediate one is to expand the typologies to include more spatial types and compositions. For instance, in office building typology, the service area type may have further subtypes, with each representing a different composition of lobby, bathroom, staircase, and elevator types. In an ultimate scenario, the software will implement typology of a general office building with known subtypes and all details. Dragging the building type onto a site could immediately show an example of a fully complete design of architecture ready to be built, with parametric and substitutable composition of parts. Spatial types are studied and categorized in widely used treatises and resource books such as Fletcher's one and Neufert, where hotel, hospital, restaurant, school and many other building types are documented. Any of these are available targets for implementation.

Besides these carefully investigated and compiled typologies, an enormous number of architectural designs have been created through the history of civilization. Although many are neither documented digitally nor online, we already have Big Data for mining architectural typology. Just searching "kitchen layout" in Google alone produces millions of plans (Figure 8). Therefore, another future possibility is to develop a synthetic tool to explore this Big Data, identify architecturally meaningful spatial compositions, and frame them as types. The tool would read these images, sort them into patterns, and formulate typologies, similarly to how precedents are studied and interpreted when an architect designs a kitchen. Such a Google-minded strategy would require rigorous employment of computer vision and machine learning algorithms.

Also, the subject of sampling spatial concepts left unframed in BIM may be expanded from formal vocabulary to qualitative one. For example, architects rely on ideas such as open, enclosed, divided, and connected as means to classify and characterize architectural space. Embedding such concepts into BIM helps the process of selecting and evaluating design variations. Online crowdsourcing is a way to help train software to learn these qualitative spatial concepts; the software learns by presenting examples of spatial design to people and by asking which concept applies to each presented design. A similar approach has been tested recently in urban and architectural design contexts (Naik 2014 and Obyedkova 2013 [1]).

These lines of investigation built on the symbol system of BIM will lead to a massive database of parametric typology of spatial concepts that are useful in developing an architectural design. The more BIM applications know about these concepts, the more dialogue it facilitates with architects who share them. In the long run, a BIM system imbued with such an intelligent database and appropriate interface will have a chance to work symbiotically as a designer's partner and take us a step closer to an autonomous and synthetic architectural design process, especially in combination with other generative methods and simulation tools.

## ACKNOWLEDGEMENT

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[1] http://cat2.mit.edu/4.566/_archive/12f13s/katya/index.html

# BIM Tools Overview

## *Target group- and process-oriented examination of free BIM tools*

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*In Germany, 90% of architectural and engineering companies employ less than 10 employees. The profit generated there is often insufficient to legally exploit the cost-intensive BIM software solutions of IT companies. This is one reason why the BIM method is not widespread in Germany. In the context of BIM, there are free-to-use tools that are either developed in research and open source projects or also offered by IT companies. Within the scope of this research project, such tools were evaluated and assigned to BIM processes. The results are published on a website and the companies concerned can use these to extend their own BIM competence.*

**Keywords:** *BIM survey, open source, AEC, tools, usage sceanrio, evaluation*

## INTRODUCTION

The application of integral planning methods requires a high degree of cooperation and integration. This applies to both actors and competences, as well as information and tools. In order to ensure an efficient process-oriented application of integrated planning and optimization tools, the approach of model-based planning (Building Information Modeling BIM) has already proven to be a purposeful method with great potentials (Both 2011). A virtual semantic building model forms the basis of this integrative approach, which provides the participating stakeholders with building information throughout the entire lifecycle. It also serves as the information basis for cooperative team, simulation and optimization processes within the planning process.

However, current surveys reveal (Both 2013) that the German construction industry, is far behind the Nordic countries in terms of the implementation of this BIM methodology. There are also deficits in comparison to the global trend. It is proved that the method is suitable and both the public sector and the political side see its necessity (Koggelmann 2013). However, with the exception of some pilot projects, the impact is still limited and the method is rarely used in smaller building projects.

The reasons for this are, among other things, the small-scale corporate structures in Germany and the relatively high-priced structure of commercial BIM software solutions. Because of this, they are hardly accessible to smaller companies (Braun 2015). Inadequate technical interfaces and the lack of quality of exchanged BIM models hamper model-based collaboration with other companies and lead to loss of efficiency. Especially for the small companies in the planning and construction process, which are forced to cooperate strongly with partners, the question arises: Which tools are available to support these processes at reasonable costs?

Small companies in particular benefit from the cooperative and cross-company processing of virtual building models. An improvement in the situation of this group of companies is expected to lead to a quality gain in the overall BIM process chain.

Research projects as well as IT companies have developed various freely available or open source based BIM tools, which seem to offer potentials for a wide range of applications. Access to such free and cost-effective BIM tools can create competitive advantages for small companies even in international competition.

However, the relevant target group in the construction industry often does not know these tools because they have often been developed in other contexts and their usability has so far hardly been evaluated.

In an one-year research project at the Department of Building Lifecycle Management at the KIT, existing free and open source BIM tools were examined and evaluated. The project and a summary of the results are described in this paper. First, we give an overview of the project. As we employ usage scenarios to classify the tools into BIM processes, we describe one of these scenarios as an example. We briefly describe the investigated BIM tools and explain the evaluation criteria. We then summarize general statements about the quality and the availability of free tools and how we made the results publicly available. The paper closes with an outlook.

## OBJECT OF THE RESEARCH PROJECT

The research project was divided into the following steps:

- Research of BIM processes and development of usage scenarios
- Search for free tools and derive software classes
- Definition of evaluation criteria
- Testing the tools and classifying them into usage scenarios
- Prepare the results for the public on a website

A Wiki system has been set up in the work preparation. Above all, the research was efficiently documented. It turns out that by far more sources had to be searched than free tools were found. The use of the Wiki system prevented redundant searches. A version management system was also used to document the progress of the project.

The BIM processes have been researched in the current literature, BIM guidelines and standards. An important document in this context was the Devlivery Manual (Wix 2010). Although it was not possible to derive relevant processes from this, it underlined that the data exchange is essential for every BIM process. Other sources such as the BIM Guidelines for Germany (Egger 2013), the BIM Reference Process, and (Scherer 2014), (Tautsching 2014), (Borrmann 2015), (Hauschild 2010), (Hausknecht 2016) provide arguments for BIM by showing potentials and objectives. However, there were no practical usage scenarios, which could be applied directly to the target group. The BIM reference process was too extensive. Furthermore, the document does not describe any BIM processes in detail, which require a concrete use of tools. The usage scenarios finally used were based on the suggestions of (Hausknecht 2016). Six scenarios were developed and formalized in the BPMN notation. Later, the tools found could be assigned to the activities in the BPMN notation, see Figure 1.

The search for the tools was partly carried out parallel to the development of the usage scenarios. This was necessary in order to be able to estimate which usage scenarios are relevant at all. The search was essentially done online. Criteria were defined which the tools had to meet in order to be considered. A considered tool ...

1. ... had to be available free of charge.
2. ... did not have to be limited in time.
3. ... could request a registration for use.
4. ... had to run on a current operating system.

According to these criteria, about 80 tools could be identified. They were assigned to 13 software classes

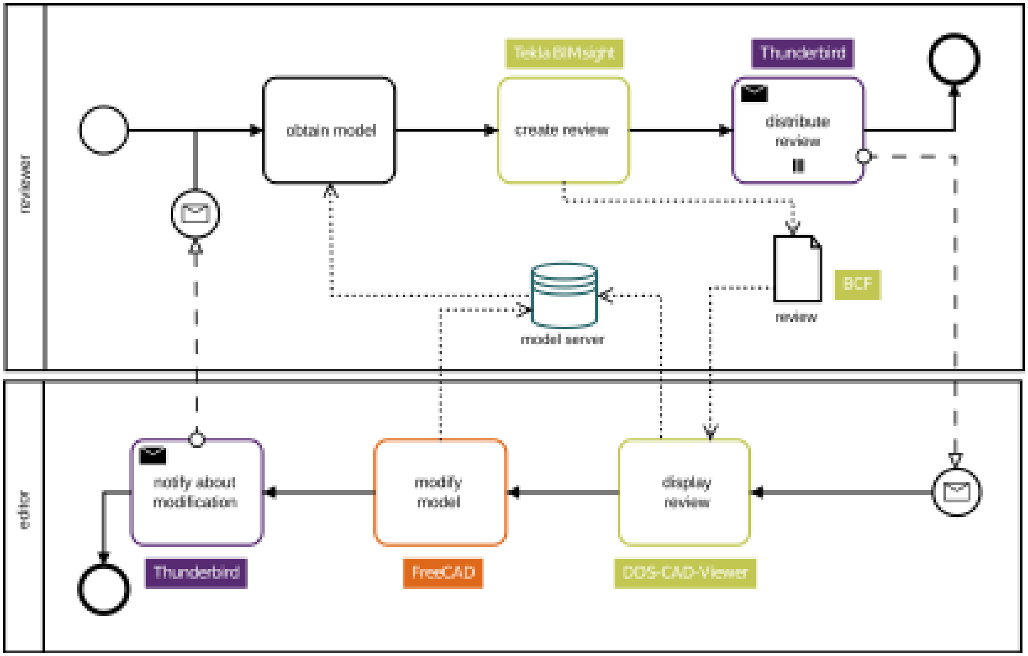


Figure 1
Usage scenario "Merge and Coordinate" with associated tools in a BPMN diagram.

and written down together with a short description in the wiki system. From this set, 19 tools were selected and evaluated according to a criteria catalog.

## USAGE SCENARIO

To impart a usage scenario to the target group, we explain each in three sections. The first section gives a more general overview and introduces the context. The second section explains an ideal scenario that we believe should be implemented in a BIM process. The last section describes a possible scenario, which is supported by the tools found by us. One of the scenarios, the "Merge and Coordinate" scenario, is described below as an example in the manner described above. The other scenarios are "Construction Schedule", "Simulation and Computation", "Presentation and Visualization", "Release" and "Pricing".

### *"Merge and Coordinate"*

If several disciplines are involved in a construction project, the disciplines usually work in their own specialist models. By combining these models in a coordination model, it is possible to check the model at specific times and to perform collision checks. The collision check is only one method that is carried out within regular reviews of the current planning stage. In addition, semantic checks can also be carried out using so-called model checkers. They serve to clarify the completeness of the modeling or to check compliance with the customer information requirements. These activities fall within the scope of the so-called BIM coordinator. Thus, coordination and modeling errors can be detected before the construction phase and subsequent costs avoided.

The review of the coordination model can always be combined with a joint meeting. Nowadays, as digital communication channels are available in order to be able to make arrangements between the planning parties, even without a dedicated appointment, the review should be carried out continuously.

**Ideal scenario.** For this, it is necessary to use a common data storage, on which regularly current versions of the specialist models are uploaded by the different disciplines. Anyone affected by a change to a model will be informed by email. In order to carry out the review, the BIM coordinator takes advantage of the coordination model, which has already been integrated in a central location. The model can now be tested for collisions or other technical aspects. For the sake of simplicity, it is also possible to access the filtered views or selected sub-models from the coordination model.

The result of the review is then communicated to the responsible persons of the respective discipline, so that the latter can understand the comments and make the necessary adjustments quickly.

**Supported scenario.** For data maintenance, the BIMserver offers the possibility to separately and cen-

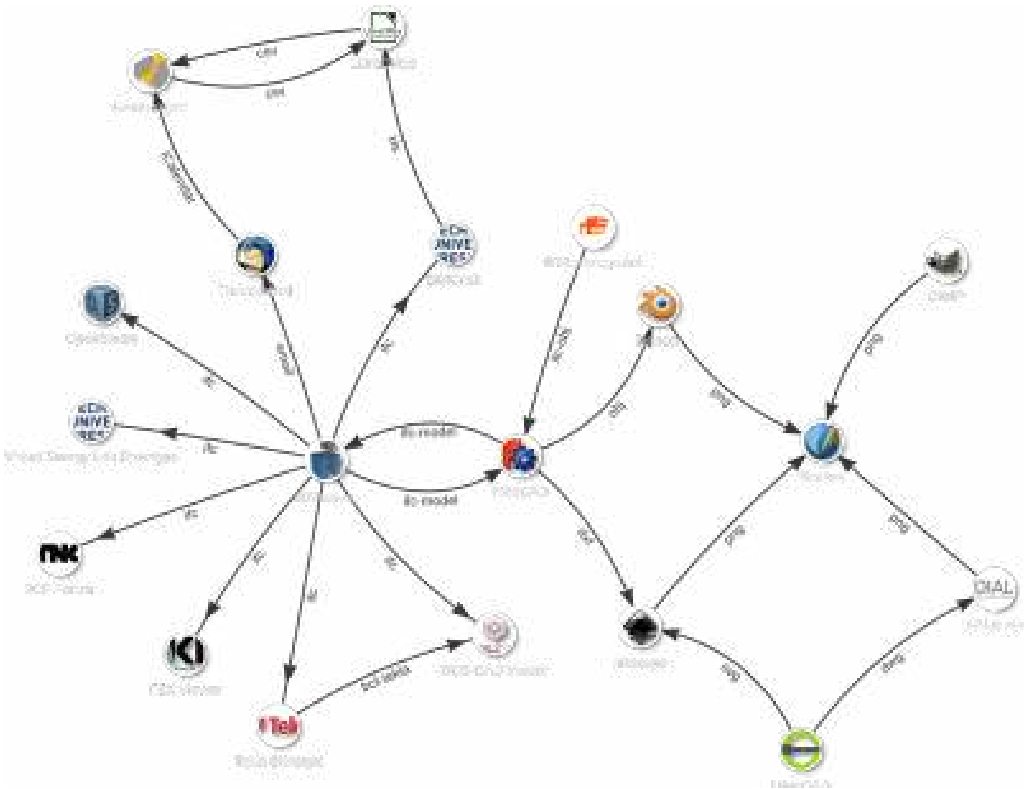


Figure 2
The overall process via tool interaction describes reasonable data exchange points.

trally provide IFC-based models by version. Once a new version of a model has been uploaded, the interested parties will be automatically notified by email. All subject models must then be stored locally and loaded and superimposed with the Tekla BIMsight tool - unless a coordination model already exists. Afterwards, a collision check can be carried out with Tekla BIMsight as part of the review.

The results of the review are stored in standardized BCF format. This format contains the model references, comments, and the view settings on the coordination model. Afterwards, the BCF file is sent to the person responsible for the model, who then open it again with Tekla BIMsight or the DDS-CAD viewer. These two tools restore the view stored in the BCF and display the associated comment. If the editors are able to solve the problem described in the review, they adapt their respective model and upload a new version to the BIMserver.

## TOOLS

Not every tool was suitable and could fit into a reasonable usage scenario. Therefore, only the following tools were examined in detail. There is an extensive review for each of these tools. This contains a detailed description of the functions, and sets the tool into the context of the target group. If a tool is not very sophisticated, some information has also been given on how to use it. The following list is limited to a brief description of the tools.

*FreeCAD* [19] is a stable 3D CAD tool that supports parametric modeling. In combination with the IfcOpenShell project, the tool supports the IFC file format that is important in the AEC domain. The tool includes workbenches for the architecture domain and finite element modeling and calculation.

*BIMCraft* [12] has been developed in a research project. It provides graphical programming of filter rules for building models. Quantities can be derived using the filter rules. The quantities can be exported as room books and parts lists to Excel files.

*BIMcatalogs.net* [16] is a web-based product catalog from which product models in various formats can be downloaded after registration. The catalog sorted by manufacturer has interesting search functions. Instead of using text search, the catalog can also be examined using uploaded STL files or sketches.

The *BIMserver* [20] is a simple model server which processes versioned IFC and CityGML models and whose functionality is expandable with plug-ins. The models are visualized in the web browser. The models can also be downloaded and new versions uploaded. Since the tool uses the standardized BIMSie API, the model-based data exchange with FreeCAD or OpenStudio is possible.

The open-source tool *OpenStudio* [7] supports energetic building simulation based on EnergyPlus. By connecting the Radiance simulation core, daylight simulations are also possible. The geometry and topology of a building model can be edited using a SketchUp plug-in. The building model can also be downloaded directly from a BIMserver. The calculation according to EnergyPlus is valid in the US as a proof of the energy performance of a building.

*LibreOffice* [17] is a collection of tools that forms an office suite. It includes application for word processing, spreadsheets and presentation. In addition, an application for creating simple drawings and a database management system is included.

*DIAlux evo* [8] is a free lighting design tool. First, the functions of the tool must be used to build a 3D model into which lighting systems from product catalogs are subsequently placed and configured. In addition, the integrated ray-tracing engine creates photorealistic renderings from it.

*GanttProject* [18] is used for project planning and is similar to the commercial counterpart Microsoft Project. However, it has fewer functions. With this tool it is possible to create Gantt diagrams, link tasks to resources, and leverage the critical path.

*LibreCAD* [13] is an open source tool designed specifically for editing 2D CAD drawings. It runs on all common desktop platforms. The stable tool can read DWG and DXF, write DXF and export SVG and raster graphics.

*FZK Viewer* [14] is a free tool for semantic and three-dimensional visualization and overlaying of IFC, CityGML and gbXML models. In addition to the possibility to use web-based mapping services such as OpenStreetMap, some functions are offered for analyzing these models.

*Thunderbird* [15] is a sophisticated email client with address management and extensible through add-ons. For example, the Lightning add-on adds calendar functions to the tool.

The *BCF Forum* [5] is a research prototype and uses a BIMserver to visualize building models. The second component of the tool is a forum in which comments for these models can be created in the BCF standard and visualized over the course of the project.

The *Virtual Energy Lab Prototype* [11] is a research prototype and provides an energy demand calculation based on an IFC building model. Furthermore, rules for the reconciliation of the building model with German standards are implemented.

The free *Tekla BIMsight* [9] can load several models at the same time and superimpose them for the purpose of coordination in the planning process. Any number of elements can be checked for collisions. Subsequently, the collisions found can be commented along with adjustable views on the model. The tool can export this to the BCF format and is also able to import BCF.

*DDS-CAD* [4] is a feature-enhanced BIM viewer. It provides various viewing modes, as well as reading and writing BCF-based communication. It is possible to change certain parameters of a loaded IFC model and then save the enriched model.

*Blender* [2] is a powerful open-source modeler to create 3D content. Besides the extensive functions for editing geometry, it is also possible to create animations and render them with the integrated engine. The tool contains a game engine with which interactive worlds can be created. It also implements video processing and object tracking functions.

*Inkscape* [6] is a tool for creating 2D vector graphics that are used for screen and print media, logos, and banners to provide sharp, scalable visualizations of information.

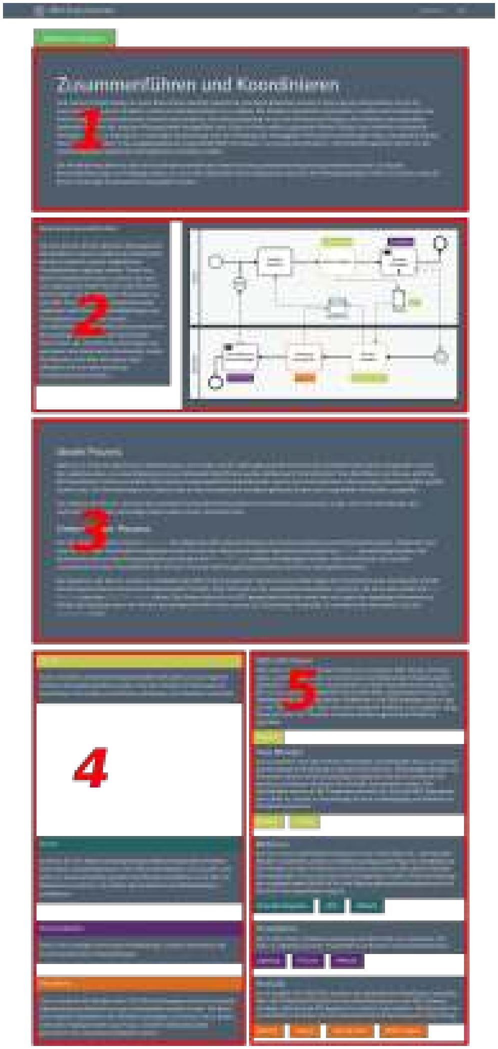


Figure 3
Screenshot of the scenario “Merge and Coordinate”. The layout consists of fife parts: Overview(1), BPMN diagram(2), Ideal and supported scenario(3), Software classes(4), Associated tools(5)

*GIMP* [10] is a tool for editing raster graphics. Besides the functions for correcting photos, it is also possible to create animations and to draw freely.

*Scribus* [3] is a tool for the layout of digital portfolios or for the production of professional printouts.

## SOFTWARE CLASSES

Assigning tools to the software classes was important in order to quickly identify suitable tools in the subsequent assessment and classification into the usage scenarios. The software classes used are listed below. The number in brackets indicate the number of tools identified per class.

- **Services** are free web services, which can be used with a browser. (6)
- **Catalogs** are online repositories from which models can be download. (5)
- **Servers** are systems that support collaborative work and are centrally managed. (4)
- **Viewers** are tools that display building models without enriching the models. (17)
- **Modelers** are tools with which 3D models or CAD drawings can be created. (13)
- **Mobile** are tools that are explicitly intended for use on mobile devices. (5)
- **Checkers** are tools with which the quality of 3D models can be checked. (1)
- **Management** are tools that focus on project organization and planning. (3)
- **Simulation** are tools with which input models can be read, parameters can be defined and simulations can be carried out. (6)
- **Communication** are tools that do not generate new model content, but support the cooperation of the project participants. (3)
- **Publish** are tools whose output is solely for presenting and imparting something. (3)
- **Query** are tools with which certain quantities can be derived from building models. (1)
- **Utility** are tools that can not be classified into any of the already listed categories. (13)

## CRITERIA

For the selection of the tools, the possibility of data exchange played an essential role. A graph was drawn which relates the relevant import and export functions of the tools, see Figure 2. A tool has only been evaluated in detail if it has some form of meaningful data exchange with other free tools. This made sense since the greatest value added by the BIM method is the reduction of manual inputs (Both 2012).

The other criteria describe the usability and functionality of the tools. In total, there are 30 criteria, whereby not every tool has been evaluated according to each criterion. Due to the BIM context, some of the criteria refer to the modeling or enrichment of semantic building models. If the tool is just a viewer, it was not necessary to fill these criteria. The criteria are listed below.

- *Visualization:* Display the geometry of models and customize the view of the model.
- *Comment:* Leave comments in different forms and, if necessary, their further processing.
- *Selection:* Select individual elements and display their meta data.
- *Edit:* Modify the properties of the elements of a model.
- *Create:* Add new elements to a model.
- *Overlap:* Load multiple models simultaneously and display them in a single view.
- *Collision:* Functionality that allows a collision check based on the geometry of the elements of a model.
- *Communication:* Connects to services that allow communication with project participants directly through the tool.
- *Mobile:* Assess whether the tool is also prepared for use on mobile devices.
- *Language:* Which languages are supported by the user interface?
- *System:* Which operating systems are supported by the tool?
- *4D:* Does the tool have certain functions with a reference to the concept of 4D planning?

- *5D:* Does the tool have certain functions with a reference to the concept of 5D planning?
- *Support:* Are there any ways to contact experts? (This includes commercial support and open communities.)
- *Architecture:* Will the tool be used on a server, desktop or mobile device?
- *Share:* Can the tool use data from remote sources? Here, also implementations of standardized APIs such as BIMsie are relevant.
- *IO:* What file formats can the tool read and write?
- *Convert:* Can the tool save a readable file format to a different file format?
- *Activities:* Evaluates the current activities of the related project to make an assessment of the relevance and future development of the tool.
- *Setup:* Evaluates the effort and knowledge required to install and maintain the tool.
- *Domain:* Specifies the target discipline.
- *Documentation:* What support is available to learn how to use the tool (tutorials, videos, manuals)?
- *Stability:* Evaluates the subjective reliability as well as the known errors of the tool.
- *Alternative:* With which more well-known commercial tools the tool can be compared to or serves as an alternative.
- *License:* Is the project open source or freeware and which licenses are available?
- *Expandable:* Can the basic software be supplemented by plug-ins or add-ons, thereby expanding the range of functions?
- *API:* Does the tool provide an API that allows a developer to access an instance of the tool?
- *Fault tolerance:* Is there an undo / redo functionality?
- *Source:* Is the source code freely available?
- *HOAI:* In which phase of the Official Scale of Fees for Services by Architects and Engineers can the tool be classified?


Figure 4
Screenshot of the Blender tool review. The layout consists of three parts: Short description and important links(1), Properties based on the criteria(2), Complete review(3)

## RESULTS

It was possible to make general statements on the quality of tools from commercial suppliers, from research prototypes and community projects. Thus on the commercial side mainly viewers without functions for model enrichment were found. The research prototypes were underrepresented and rarely functional. Especially in the non-classical BIM context the range of tools from community projects was very large. For this reason, tools found in community projects allow for modeling and have a good usability.

The evaluation of the tools was carried out, as far as possible, in virtual environments. The evaluation should be encapsulated and better assigned to the scenarios. Many of the tools have either complex installation procedures or the installation influences the installation of other tools. This conflicts and incompatibilities between tools could be avoided by using virtual environments.

For each tool a detailed review was formulated in addition to the evaluation criteria. For the preparation on the website [1], a model was developed that allows the formal assignment of the tools to the usage scenarios. The form of the website was thus separated from the content. The website has three views. A welcome page on which the underlying motivation and a brief description of the structure of the website is formulated. For each usage scenario, a description is displayed together with the BPMN diagram with which the tools are linked, see Figure 3. In addition, an ideal and a supported process are described based on the process description. The tools are presented one behind the other. For each tool its list of evaluation criteria and the complete review is displayed, see Figure 4. The target group of the research project are companies in Germany, therefore the results on the website are in German.

## CONCLUSION & OUTLOOK

The aim of the research project is to provide public information on free tools and their use in BIM processes. These are intended to help small companies to avoid falling behind with the introduction of BIM in their planning process. Initially, research prototypes were expected to be a viable source of such tools. Unfortunately, this could not be confirmed because these tools are either not available or are not commercially available and are often hardly usable. In contrast, the community projects demonstrated transparency and quality assurance measures to ensure that free tools are also feasible and useful in the context of BIM processes.

A few functional subprocesses could be found, but we could not fully cover a usage scenario with the identified tools. Thus, the results on the website are to be understood as an incentive and practical introduction to the topic of BIM. It will not be possible to implement a digital planning process alone with the free tools identified here. Nevertheless, interested companies should take the results as a basis to carry out their own experiments. The results were explicitly prepared for smaller companies in Germany and justified by the special situation regarding the average company size in Germany. If it is found that similar situations are also present in other countries, it might be worthwhile to translate the website into English.

We have started with the assumption that it is sufficient to evaluate the tools with the help of our criteria. It turned out that the tools and approaches are too different. We can not make a robust statement about their practical suitability. A further investigation, which this time considers more the cost reduction and the time savings, would be the logical next step. This would then involve the companies concerned. Thus, a more reasonable comparison of commercial software products with the free tools would be possible.

To support the development of free tools, a concept for improving interoperability between the tools should be developed. The concept would specifically target data exchange between the tools and could establish a common strategy between the different projects, research facilities and IT companies developing free tools. The difference to the establishment of a standard such as e.g. IFC, is that the data exchange points are aligned along realistic usage scenarios. This would result in a considerable added value in the practical application of free tools and the establishment of the BIM method in general.

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# The uptake of BIM

## *From BIM teaching to BIM usage in the design studio in the Bachelor studies*

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*This paper is about the uptake of BIM in the design studio in the Bachelor studies. In the current study year at our school we have the first cohort of students that have followed integral education of BIM from the very start of their study programme. We assess the usage of BIM in the final project work. The final data are not in yet, but we can observe a slight increase of the use of BIM in the design studio work.*

**Keywords:** *Building Information Model, Education, BIM Pedagogy*

## INTRODUCTION

At our institution BIM was introduced for the first time in 2004. Throughout ten years the course was offered to an increasing number of students. Because it was an elective course in the second year of studies, it did not have a firm anchoring in the remainder of the curriculum of the faculty. In the study-year 2014-2015 BIM was offered integrally to all first-year students. Right at the start of the year they can choose from three software packages: AutoCAD (no BIM), Revit (BIM), and ArchiCad (BIM). For the education at our school this was quite a large leap forward. First of all, it increased the number of students who got education in BIM-based software in contrast with previous years; second, it meant institutional acceptance of BIM as a subject; and third, it meant that BIM-skills could be reasonably expected as basic skill from students.

Figure 1 shows the options students have in their choice of software education at our Faculty, from the study year 2014/15 onward. Each course takes up one semester. Students have the possibility to take BIM for four semesters, leading them to "expert" level either in Revit or in ArchiCad. A decreasing amount of students choose AutoCAD and 3DStudio Max as their track, turning them into AutoCAD experts at the expense of BIM.

Figure 2 shows the changes in amount of groups (roughly 15 people per group) that take particular courses throughout the study program. From this graph we can conclude: **Demographically there is a decreasing amount of incoming students (which happened after the transition of Czech Republic to democratic system), particularly notable since the year 2015.** In the study year 2014/15 we can see a sharp change in trend what the students choose from the very start of their studies. **General decrease of interest in AutoCAD, 3dMaxDesign and Rhino.** Increased interest in BIM-based software Revit and ArchiCad.

The absolute amount of students are listed in Figure 3 and Table 1. We can observe an increase in the amount of students that choose a BIM-based software.

As can be seen from Figure 3, roughly half of the students choose the non-BIM approach through Au-

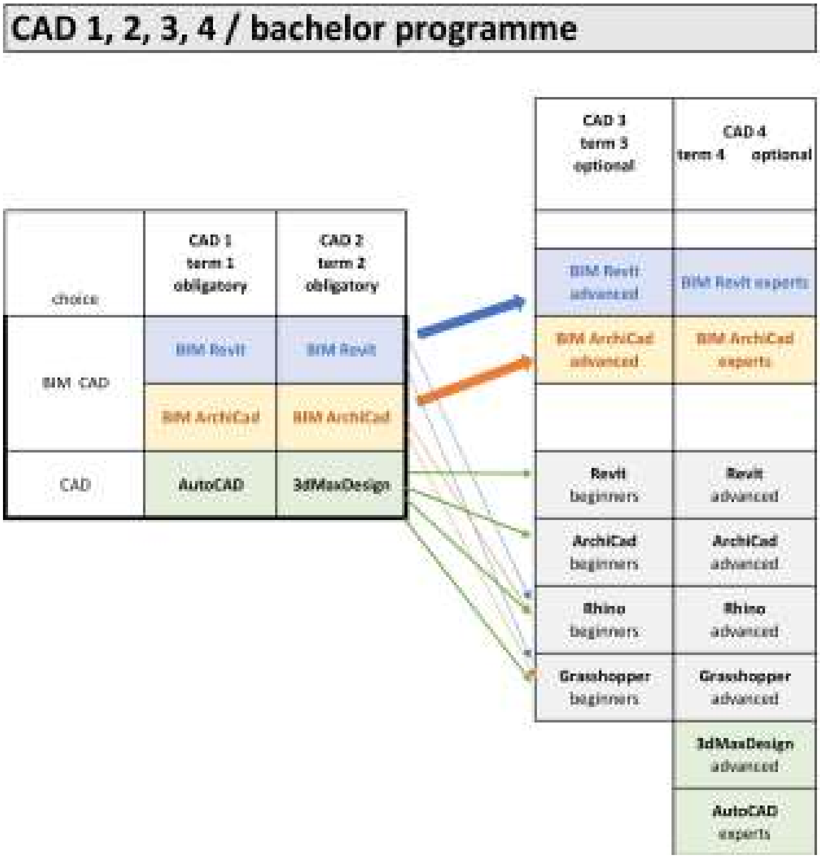


Figure 1
Schema of CAD education in the first 2 years (4 semesters) in Bachelor programme, since study year 2014-2015

toCAD as CAAD package. BIM adaptation is on the rise in Czech republic, starting from a low level of adaptation reported earlier in Vinšová, Matějovská and Achten 2014, compared with other European countries (Russell and Elger 2008; Boeykens et al 2013; Kocaturk and Kiviniemi 2013; Ibrahim 2014; Dieckmann and Russell 2014). An increasing amount of parties in the building process are able to produce BIM documents, but because these operate in a fragmented process (architect to documentation to permission to constructor, each with own fee system), there is no incentive to pass on BIM models between the parties. The large construction firms mainly operate on BIM, but many architects and smaller construction firms still make do with AutoCAD.

## DEMAND FOR BIM GRADUATES

Table 2 shows in more detail the amount of students taking the BIM-courses at the Faculty.

Table 2 shows the amount of students that successfully completed the course (in WT: Winter Term the basic course on Revit and ArchiCad; ST: Summer Term the advanced course on Revit and ArchiCad). Where available, the data shows number of registered/number of successful students


Figure 2
Situation before 2014/15 and after

At the end of the summer term 2016 we had the first cohort of students that took all four courses on BIM during their Bachelor studies. To be more precise: 15 students following Revit, and 23 students following ArchiCad. The latest results we do not have at our disposal yet. BIM education has a long tradition at our Faculty; ArchiCAD from year 2004, and Revit from year 2006. In fact BIM education preceded the demand for graduates with BIM capabilities at Czech firms. This situation was different however for larger Czech firms that worked with foreign developers (for example the architect's office of Cígler&Marani in 2010). Those offices eagerly welcomed graduates with BIM skills.

Today, mainly due to the pressure of large Czech developers (in particular Skanska a.s., Metrostav a.s. and HOCHTIEF CZ a.s.) and the application of BIM in large construction companies (e.g. VPÚ DECO PRAHA a.s., Metroprojekt Praha a.s., Obermeyer Helika a.s.) there is a high demand for graduates from Civil Engineering who are capable to work with BIM, while there seems to be a surplus of BIM-skilled graduates from Architecture. The reason for the latter surplus may be that in Czech Republic, the laws and implementing regulations for designing in preparatory phase in architectural firms do not require the use of BIM. Additionally, due to a number of inappropriate marketing campaigns, there have been several unsuccessful projects with BIM that disheartened undecided architects to go "BIM."

## HISTORY OF TEACHING, EXPERIENCES AND RESULTS

In 2015 we reported on our experiences of first time education of BIM in the first year of Bachelor studies (Vinšová, Achten, Matějovská 2015), and diverging from the standard approach of teaching AutoCAD in the first year. The first cohort of students who had four semesters of BIM education, are the ones that can apply their BIM skills in their graduation project. We feel that this phase is in particular important to assess, because it is in the integrated application of design studio that students learn to appreciate the advantage (and limitations) of BIM (Techel and Nassar 2007, pp. 635). The graduation project at our institution in the Bachelor studies has a particular setup. It runs over two semesters. In the winter semester the students make a design for a particular task. This is a regular task as can be seen over many schools of architecture - design a house; housing complex, offices, sports facilities, and so on.

The winter semester is dedicated to the concept design (so-called "study"). Students design the main volume, internal organisation, basic material decisions, and create visualisations of the project. In the summer semester they have to produce all the materials and documentation that are required to obtain the so-called "building permit." This means that they have to produce plans, floors, sections, and details as in a realistic project, as well documents about structural calculations, HVAC systems, electricity, and regulation schemes as required by the municipality. The whole set of documents comprises the work that has to be handed in for the final diploma work. At the defence of their work, students typically show the results of their "study," a scale model, and a projected presentation about the design and most significant results from the detailed documentation. Usually an architect from practice is assigned as external critic to detailed assessment of the diploma work.

It is precisely due to the character of the graduation project, that we were able to introduce BIM in

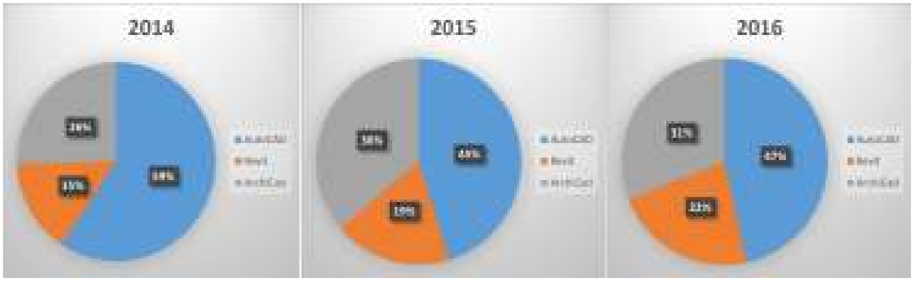


Figure 3
Distribution of first-year choice of students of CAAD-package.

| Year | AutoCAD | Revit | ArchiCAD |
|---|---|---|---|
| 2014-2015 | 168 (58%) | 43 (17%) | 72 (25%) |
| 2015-2016 | 120 (45%) | 49 (18%) | 96 (37%) |
| 2016-2017 | 108 (47%) | 52 (21%) | 72(32%) |

Table 1
Distribution of first-year choice of students of CAAD-package.

the first year of Bachelor studies. The school had obtained finances from a two-year OPPA grant that enabled us to offer extra-curricular workshops and lectures to educate students in the third year to work their graduation project (BP) as a BIM model. This was necessary as extra effort, because we found that due to high learning curve and time pressure, students ultimately reverted to AutoCAD to produce their documentation. Using BIM required more organisation and was more complex than in traditional production mode. The graduation project is not realistic, it does not undergo major changes, and it does not require coordination of many specialisations. Thus the normal advantages of using BIM were not applicable, and the use of BIM was seen as additional load. In order to ease the learning curve, it was decided to teach BIM from the first year, and offer four semesters of BIM-based courses. The model is limited to the architectural and civil part of the model. We do not have the ambition to model also technical installations, nor control of the structural design; students do need to check for collisions between parts of the building design - thus we are positioned somewhere between BIM level 1 and level 2, however with the requirement that the use of 2D software is out of the question.

Through the OPPA project we found it was easier to follow the students in their own individual design studios where they choose to do their graduation project, then to concentrate all “BIM students” in specialised design studios. Students have the possibility to consult their BIM model throughout the whole year for production of their graduation project. We do not have the final figures of the actual graduation projects, but it is already clear that there will be a large number of BIM models. The winter semester, in which the students produce the “study” concept model, 90% of the students who passed have done the “study” as a BIM model. For the summer semester, in which the students make their final graduation project, we estimate that it will be 70% (this number may actually change). In order to reward the students for their additional effort, we have set up for the successful students a so-called “BIM Ready Certificate.” To obtain this certificate, the model must pass a number of criteria “BIM rules,” which also acts as a motivation. We found that the students work the whole year and throughout the whole school with BIM, and that the supervisors of the design studios do not have an issue with this.

Table 2
History of teaching BIM software

Revit

| history of teaching BIM - Revit software on FA CTU (number of students, SW Autodesk Revit) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 2010/11 | 2011/12 | 2012/13 | 2013/14 | 2014/5 | 2015/16 | 2016/17 |
| Revit - BIM & basic skill | WT | 64 | 87 | 43 | 40 | 69 | 43 | 49 |
| Revit - advance skill | ST | 21 | 31 | 37 | 18 | 41 | 38 | 23 |
| BIM - Revit in 1st year | WT | - | - | - | - | 43/35 | 49/45 | 52/47 |
| | ST | | | | | 35/29 | 45/40 | 45/39 |
| BIM - Revit in 2nd year | WT | | | | | - | 20/15 | 32/22 |
| | ST | | | | | - | 16/15 | 19/9 |

ArchiCAD

| history of teaching BIM - ArchiCad software on FA CTU (number of students, SW ArchiCad) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 2010/11 | 2011/12 | 2012/13 | 2013/14 | 2014/5 | 2015/16 | 2016/17 |
| ArchiCad - BIM & basic ski | WT | 79 | 93 | 78 | 99 | 69 | 21 | 26 |
| ArchiCad - advance skill | ST | 43 | 56 | 45 | 52 | 28 | 17 | ? |
| BIM - ArchiCad in 1st year | WT | - | - | - | - | 68/48 | 96/84 | 72/63 |
| | ST | | | | | 41/33 | 81/67 | 62/49 |
| BIM - ArchiCad in 2nd yea | WT | | | | | - | 49/28 | 37/22 |
| | ST | | | | | - | 32/23 | 20/? |

Table 3
Number of hours of obligatory courses in the Bachelor programme.

| term | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Number of hours per week | 30 | 30 | 28 | 28 | 29 | 23 |

## FURTHER CONSIDERATIONS

The greatest obstacles in BIM education are found in the established practices of drafting building structures. Although the drafting regulations are taken as recommendations (some of which are even not accepted in practice), the school insists on strict adherence to these standards. For students this means additional work, because Revit is not yet fully localized for Czech situation. A standard stumbling block in case is the depiction of staircases, which yields problems for all students. We did find that supervisors and reviewers of the graduation projects done in BIM greatly appreciate the ability of BIM software to create 3D axonometric sections, as well as 3D worked out details or shaded axonometric sections through the floors.

We also found that with increasing knowledge of BIM, the overall level of the design studio work becomes even better. There is a growing number of shared student's models, in particular when multiple people in a design studio are working on the same location, as for example in creating an urban block with shared underground parking. We can observe team collaboration through the creation of such shared models, with the students using Dropbox, BIM server, and transfer of IFC-models. Thanks to this, the models of the individual work are more explorative in shape and material. Students have access to more advanced technologies already at the start of their study, as they start to use 3D printing and Virtual Reality more easily. So far we have not been able to extend the application of BIM to other areas, such as sustainable design, analysis and simulation, and in general all other kinds of calculation that are possible on the basis of a virtual building model. We decided to focus on intensive teaching of BIM software Revit and ArchiCad, as for the basic production of a 3D model. We are aware that this is only a prerequisite for further use and development of BIM and the design. A high quality 3D-model that is well prepared for working together with other BIM project parties does not yet guarantee a high quality process or result during the design, realisation, and ultimate use of the building. Throughout the Bachelor programme, (additional) BIM education has to compete with the rather high amount of obligatory courses (Table 3).

The introduction of a separate course dedicated to principles of BIM is in this context highly unlikely. Therefore we are looking rather at an option to offer existing courses additional lectures on BIM, and thus to update their curriculum. This concerns in particular:

- Construction
- Structural systems
- Building materials
- Installations and HVAC
- Management and economics of buildings.

We have found that it is important to set up and maintain a systematic and steady terminology for the BIM education. Thus BIM is also something that should appear in foreign language teaching. We can state that general introduction of BIM in education is something that effects the whole curriculum. Through the CAD education, students learn the basic alphabet for architectural design. At our Faculty, the graduation project needs to be worked out on the level comparable to obtaining a "building permit." If they are able to realize this project using Revit or ArchiCAD, then the Faculty for sure will appreciate this. BIM in practice is a long-term practice that is difficult to approximate or simulate in the semester teaching at our school. For this reason, students have difficulty grasping the practical advantages of using BIM. We are currently preparing practical workshops outside regular curriculum workshops, that would allow combination of various branches within the university, so that architecture students can work together with for example students from structural engineering, building construction, HVAC, economics, and realisation, so that they actually verify the realism of their projects. In practice we see clear trends at successful architecture offices an increased effort of all parties involved to work together. This collaboration already starts in the early phase and continues to add quality and functionality later in the process as well. We see a definitely positive contribution of BIM to these processes.

## ACKNOWLEDGEMENTS

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# An Automated Code Compliance system within a BIM environment

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*The present paper presents a framework for an Automated Code Compliance (ACC) system within a BIM environment. We begin by introducing the concept of ACC and its applicability in contemporary practice in general and BIM in particular. We proceed by introducing the mathematical method of Multi-Dimensional Data Fitting (MDDF) to develop singular structural design equations from multi-dimensional datasets of structural design equations employed in international design codes. We follow this by demonstrating how the MDDF output has been implemented in BIM-based software, to achieve code compliance. Finally, we demonstrate the overarching framework and how this can be implemented on a wide scale to achieve full ACC.*

**Keywords:** *Automatic Code Compliance, BIM, Timber*

## *INTRODUCTION*

Building Information Modelling (BIM) has been the dominant digital paradigm in the Architecture, Engineering, and Construction (AEC) sector the past decade. Indeed, researchers have focussed on BIM to such an extent that it could be argued that today the term acts as a synonym for any Information Technology advance employed in some AEC fields. This emphasis, however, is not shared across all disciplines. A survey of the leading journals of the various specialties reveals that, while BIM has appeared dominant in fields such as Construction Management and Quantity Surveying, and has gathered significant attention in Architecture, it is far less prominent in other major AEC sectors such as Structural Engineering. It can be argues that this restricts the impact BIM has in the design and implementation of buildings and prevents it from releasing its full potential.

The present paper presents a framework for an Automated Code Compliance (ACC) system within a BIM environment. We begin by introducing the concept of ACC and its applicability in contemporary practice in general, and BIM in particular. We proceed by introducing the mathematical method of Multi-Dimensional Data Fitting (MDDF) to develop singular structural design equations from multi-dimensional datasets of structural design equations employed in international design codes. We follow this by demonstrating how the MDDF output has been implemented in BIM-based software, to achieve code compliance. Finally, we demonstrate the overarching framework and how this can be implemented on a wide scale to achieve full ACC.

The particular domain in which we employ this approach is structural timber design; this is partly due to our research backgrounds, which emphasize sustainability and innovative materials, and partly due to the inherent challenges involved in structural timber design which make ACC particularly beneficial. The BIM environment in which we have implemented the MDDF output is Autodesk Revit(C); this is largely due to the popularity of the software with UK designers. However, our greater approach is domain-agnostic and platform-independent. As such, it can be implemented equally effectively in any structural engineering problem and any BIM-enabled platform.

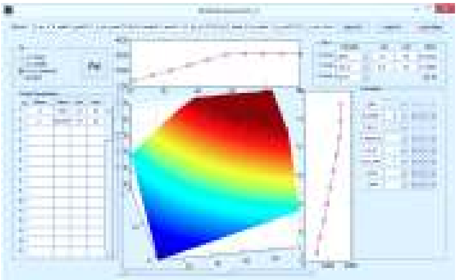


Figure 1
Screenshot of fitting software

## *AUTOMATED CODE COMPLIANCE*

Automated Code Compliance has drawn considerable interest in the BIM community (Tan, Hammad, and Fazio 2010; Zhang and El-Gohary 2015; Solihin and Eastman 2015). Generally, it refers to digital design tools that allow only the design of elements that satisfy legal or physical requirements, such as those set by national or international Building Codes. This is typically achieved via databases of code-compliant elements, the automatic calculation and adjustment of any non-compliant user decisions, or the automatic checking of all design elements for compliance, providing the user with the respective information. Theoretically, ACC should be applicable to all aspects of building design that rely on specific regulations. However, so far the main focus of ACC has been mostly the design of the building envelope, in order to correspond to set parameters of environmental building performance.

The potential of ACC for the structural engineering aspects of building design are self-evident. The design of the structure is a core component of the building design process; it requires close collaboration between architect and engineer, and it has a significant impact on the building form as well as the implementation of its function. Thus a well-designed ACC environment could improve significantly the productivity of the design team, reducing the required amount of interaction between designer and engineer for easily addressed design decisions.

Moreover, an appropriately validated and verified ACC package could, theoretically, remove altogether the requirements for expert structural engineering advice, at least in more standardized buildings, thus achieving actual automation in design and construction.

The obstacles for ACC, however, are significant. Contemporary structural design relies on elaborate theoretical models, extensively validated experimentally. These are typically codified in respective design standards, which are applicable either on a national (e.g. the American Society of Civil Engineers codes) or international level (e.g the Eurocodes). These design standards are of high complexity and require a certain amount of expert interpretation. Though obviously a range of software is available, the assumption is always that this simply automates the calculation part of the work and the actual design remains the domain of the engineering expert.

Theoretically, this is exactly the sort of cross-disciplinary challenge that BIM is meant to address. However, integrating advanced structural analysis and design in a BIM comes with significant restrictions: most advanced structural software packages already push the limits of the computational state-of-the-art for analysis purposes alone. Introducing the additional ontological, organisational, and analytical complexity of a BIM infrastructure means, almost by definition, that the requirements are above the state-of-the-art. As such, today's BIM packages either avoid state-of-the-art analysis altogether or interpret BIM as data Input/Output (I/O) [1]. This, however, both remains outside the ACC concept (an expert is still required to check compliance) and limits the effectiveness of the BIM process, with all the well-documented issues of I/O interoperability (Volk, Stengel, and Schultmann 2014).

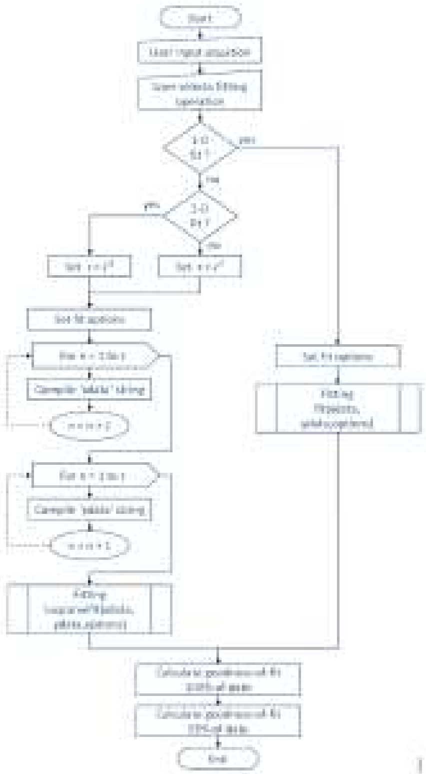


Figure 2
Fitting software flowchart

Some aspects of structural ACC allow for direct conversion from the analogue to the digital realm. Look-up tables and structural design heuristics have long been a common practice in structural engineering, with various resources available for practitioners (Cobb 2014). Such rules and tables can be easily converted to "Smart" BIM components, allowing for immediate benefits in those fields that rely on standardization and repetition such as offsite manufacturing (Patlakas, Livingstone, and Hairstans 2015).

However, for more ad hoc applications, this is less likely to be the case. In contrast to domains such as industrial and mechanical engineering, structural engineering aspires to analyse and deliver outputs (typically buildings or infrastructure) that are designed ad hoc and with a relatively limited amount of available experimental verification. Mechanical and industrial outputs, from cars to smartphones, rely on prototyping and extensive testing before moving into mass production. By contrast, buildings are in their majority delivered without experimental verification, but relying on the structural design codes which prescribe generic processes. The price for this achievement is the aforementioned complexity of the codes.

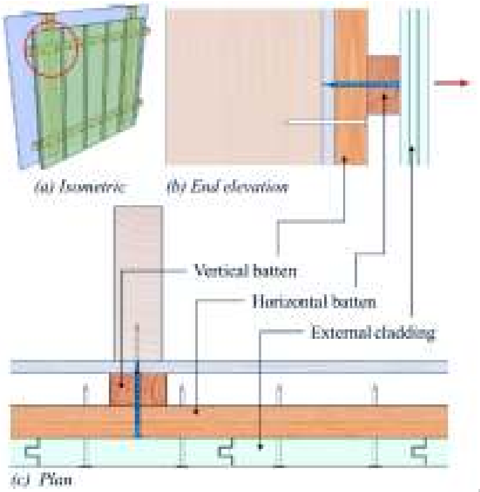



Figure 3
External timber cladding

This mathematical and computational complexity means that structural ACC faces considerable challenges. Achieving actual automation within the context of the capabilities of a contemporary BIM environment would require a way to "compress" the process of structural calculations. In order to achieve this, we have utilised Multi-Dimensional Data Fitting (MDDF) to simplify structural calculations.

## *MULTI-DIMENSIONAL DATA FITTING*

MDDF refers to the mathematical process that allows the fitting of datasets with 'n' number of dimensions. For n = 1, this is effectively the basic one dimensional (1-D) curve fitting, allowing the derivation of a mathematical equation from a collection of data points. For n = 2 it is typically referred to as surface fitting; a mathematical surface is generated so as to pass through or close a 2-D dataset. Generalising for n-D is the MDDF concept, which is widely used in a variety of fields such as population synthesis (Abolfazl, Joshua, and Kermit 2009). However, it has not been widely applied for either structural engineering or BIM applications. By utilising MDDF, we can simplify extremely large datasets derived from either existing calculations or experimental data to a singular algebraic expression that can be integrated into a "Smart" BIM component. Thus we can achieve ACC within a native BIM environment.

**Development of a multi-dimensional data fitting interface.** In order to apply the MDDF process, we developed a customised fitting application in Matlab. This uses inbuilt Matlab fitting routines, such as non-linear least-squares solvers, and extends their functionality to run in more than two dimensions. In addition, the application includes a Graphical User Interface (GUI) that allows visual inspection of the data, including goodness-of-fit, for every step of the fitting process (see Figures 1 and 2). Naturally, numerical outputs of the goodness-of-fit are also included.

A flowchart of the fitting process is given in Figure 2.

## *ACC IN SMART BIM COMPONENTS*

**A Proof-of-Concept Structural Design Case.** As a proof-of-concept for the system, the ACC process was applied in a typical structural timber connection: a cladding detail where a fastener would be required to be checked against axial withdrawal (Figure 3). Besides its architectural ubiquity, from a structural perspective this reflects the majority of the standard checks against ductile failure of fasteners under axial loading, and thus has been deemed a suitable case study for addressing the requirements of Eurocode 5, currently the state-of-the-art code internationally for structural timber design (CEN 2014).

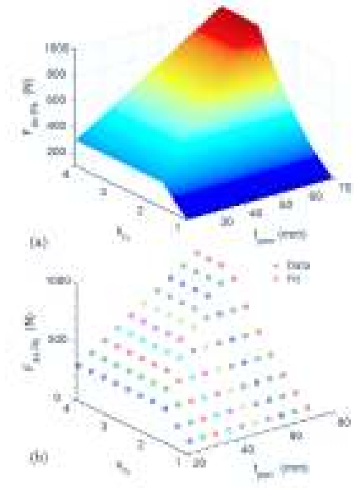


Figure 4
Screenshot of fitting software

Despite the apparent simplicity of the design problem, the identification of a single fitted equation poses considerable computational challenges. The variables that affect the axial withdrawal capacity include both geometrical (thread point-side penetration length; screw head & outer thread diameters) and material properties (pull-through and pointside strengths, as well as associated densities for the connected timber members). From a mathematical perspective, this is an eight-dimension problem, which is solvable given a suitable sample dataset and relevant boundary conditions. Such a dataset was developed using nested loops and utilising the native Eurocode 5 equations. The boundary conditions were chosen so as to reflect typical real-world conditions (e.g. between 21 and 70 mm for the thread point-side penetration length, between 290 and 460 kg/m3 associated densities etc). Using ten iterations per variable, the compiled dataset had a total of 108 data points, thus allowing for a sufficient number of source data on which the fitting process could be applied.

**Surface Intersection Fitting.** The fitting process depends on the progressive fitting of surface intersections. At first instance, two dimensions are fitted, while keeping the rest fixed. The next iterations progressively add each individual dimension, so in a total of seven iterations the fitting process is completed. Figure 4 shows an example of the dataset and fit for two dimensions, as visualised by the fitting application.

Figure 5
Generic Revit wall component

**Algebraic Validation and Experimental Verification.** The final output of the fitting process is a single equation that takes into account all 8 of the initial design variables. In order for this to be acceptable as a substitute for the current Eurocode 5 (EC5) equations, both algebraic validation and experimental verification would be needed.

For the purposes of this work, suitable algebraic validation was undertaken utilising the point of intersection, where the axial withdrawal capacity point-side would be equal to that head-side.

Experimental verification was undertaken at Edinburgh Napier University. A series of tests of the withdrawal capacity perpendicular to the grain were carried out, testing five different types of screws, at forty tests per type, with an additional ten tests without a pilot hole. The total sample size of 210 is in line with structural engineering practice for such a design case.

The algebraic validation showed 100% agreement between the EC5 equations and the fitted equation. The experimental verification showed that 95% of the data points were within 29.9% of the fitted equation, an agreement similar to that obtained from EC5. As such, the fitted equation was deemed suitable for implementation in a Smart BIM component in order to achieve ACC.

The mathematical and experimental work in this section is explained in detail in different work by the authors (Livingstone et al. 2016).

**Integration in a BIM platform.** The development of the Smart BIM components was based on the following process:

- Geometry modelling

A Generic Family component was built in Revit, which hosted the construction detail (Figure 5)

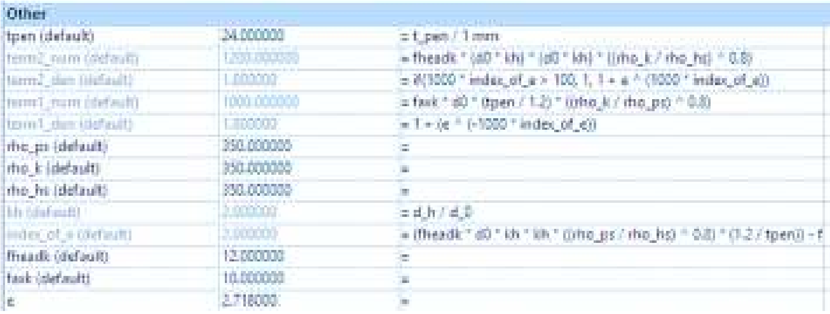
- Parametrization of the component

In order to keep conceptual coherence with standard Revit workflow, the parameters were separated in two categories. Parameters labelled macroscopic referred to the geometric properties of the entire wall system; these would be the parameters typically utilised by the architect during the design of the project. Parameters labelled microscopic referred to the geometric and physical properties of the structural detail.

In current practice, such parameters would be more likely to be specified by a structural engineer. However, by maintaining the boundary conditions identified earlier, a non-expert user could simply choose from a range of values and thus produce an ACC output.

- Derivation of intermediate parameters

The component is programmed to generate new parameters, at both the macro and micro level, which are of interest to the designer, either because they involve quantities (e.g. number of studs) or because



| Other | | |
|---|---|---|
| tpen (default) | 24.000000 | = t_pen / 1 mm |
| term2_num (default) | 1200.000000 | = fheadk * (d0 * kh) * (d0 * kh) * ((rho_k / rho_hs) ^ 0.8) |
| term2_den (default) | 1.000000 | = if(1000 * index_of_a > 100, 1, 1 + e ^ (1000 * index_of_a)) |
| term1_num (default) | 1000.000000 | = faxk * d0 * (tpen / 1.2) * ((rho_k / rho_ps) ^ 0.8) |
| term1_den (default) | 1.000000 | = 1 + (e ^ (-1000 * index_of_a)) |
| rho_ps (default) | 350.000000 | = |
| rho_k (default) | 350.000000 | = |
| rho_hs (default) | 350.000000 | = |
| kh (default) | 2.000000 | = d_h / d_0 |
| index_of_a (default) | 2.000000 | = (fheadk * d0 * kh * kh * ((rho_ps / rho_hs) ^ 0.8) * (1.2 / tpen)) - f |
| fheadk (default) | 12.000000 | = |
| faxk (default) | 10.000000 | = |
| e | 2.718000 | = |

Figure 6
Sample of intermediate terms utilised

they are utilised in the calculations (e.g. the head-to-thread diameter ratio).

- Programming of the MDDF output via a series of intermediate terms

Recent versions of Revit have provided a small range of calculation options for parametrization. However, implementing an equation as complex as the output of the fitting process is still cumbersome. As such, a number of intermediate terms were developed to simplify the calculation process (Figure 6). This also included the introduction of approximations of mathematical constants not currently included, such as the base of natural logarithms. For the purposes of this work, these terms were left visible to the user for debugging purposes. A commercial version would be likely to exclude those, as will be discussed in a later section.

- Final output

The final output of the calculation is the characteristic axial capacity Fax,Rk , which is provided automatically to the user.

**Limitations of the proof-of-concept.** The proof-of-concept example described above demonstrates the capacity to achieve ACC within a contemporary BIM software application. However, being a research prototype, it contains a number of limitations:

- Usability Restrictions


Figure 7
Schematic representation of the generalised process

As this was intended as a proof-of-concept version, some usability restrictions are imposed on the user. For example, the wall member is not designed as a base family wall element, but as a generic component. Similarly, the timber studs are generic components and not base family column elements, thus limiting the actual design usability. Moreover, various "debugging artifacts" have been left on the component to allow debugging. A commercial version of such a platform would either eliminate this altogether (as a proprietary "black box" solution) or only make them accessible as supporting documentation (as a Console object), thus not weighing down the design process with information unnecessary to the designer.

- Automatic Georeferencing for Pass/Fail of Design Checks

As mentioned above, the proof-of-concept example provides the characteristic axial capacity $F_{ax,Rk}$ , which is typically the desired output of the structural engineer's calculations for such a component. However, the interpretation of this capacity still requires a degree of expertise. A commercial version would be likely to rely on georeferencing of the project and draw on a database of local building regulations to provide Pass/Fail feedback of the design.

- Automatic Redesign

It can be argued that, conceptually, full ACC would imply not just informing the user if the design is compliant, but also redesigning the project automatically, so as to be compliant. This has not been attempted in this proof-of-concept.

The first two limitations are justifiable by the focus of the project: the concept that we intended to prove was the implementation of the MDDF equations in a BIM system, and the demonstration of the workflow in a BIM package. The usability restrictions and lack of georeferencing described above can be easily overcome with additional development utilising existing solutions. As such, they do not impede the applicability of the example as proof-of-concept.

The third limitation raises more important concerns. While automatic redesign is possible for a small-scale proof-of-concept example such as the one given here, the feasibility of this approach for the entire building scale is debatable. The state-of-the-art in structural analysis and design at the entire building scale would create a problem of vastly different order of magnitude to solve via MDDF, at least with the currently available computing power (including supercomputers). It can be argued, of course, that this will change in the future. However, this does raise two different questions. Firstly, with regard to usability, how would such a system make design decisions, i.e. the trade-off between automation of the design process and restrictions on the design intent. Secondly, it raises questions with regard to the semantics of ACC, and if it should stop at informing the user of the compliance of the design, or extend to changing the design so as to be compliant. Both of these questions deal with fundamental issues in domains such as Human-Computer Interaction and Artificial Intelligence Philosophy which are, however, outside the scope of this work. As such, they have not been explored here.

## *GENERALISATION INTO AN ACC BIM SYSTEM*

Despite the limitations discussed above, the approach presented in this paper allows for a coherent process that can be generalised to introduce ACC for many engineering problems of up to medium complexity (e.g. up to 25 dimensions), into a BIM system, relying solely on the inbuilt capabilities of current systems, and without the development overheads introduced by programming with Application Programming Interfaces (APIs). A schematic representation of this generalised process is given in Figure 7.

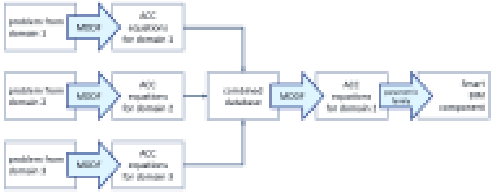


Figure 8
Moreover, the MDDF practice can be nested; namely, MDDF equations can be developed for individual domain problems, then those analysed further for a new, combined MDDF equation. This process is presented schematically in Figure 8.

It is interesting to note that the "engineering problem" node does not have to be domain specific, e.g. a structural engineering problem, a geotechnical engineering problem, a quantity surveying problem etc. Unlike the current "standard" domain-based practice, the approach presented here is domain-agnostic and applicable to any quantifiable problem. As such, it allows for interesting multi-disciplinary solutions which are not handled by current approaches: for example, a generally structural engineering problem could include cost; a services engineering problem could include whole lifecycle data, etc.

Moreover, the MDDF practice can be nested; namely, MDDF equations can be developed for individual domain problems, then those analysed further for a new, combined MDDF equation. This process is presented schematically in Figure 8.

They key element remains that the output of this process is still a single equation which can be introduced as elements of a parametric family in current BIM software. Theoretically, this allows the development of libraries of Smart BIM components handling multi-domain problems, enabling simultaneous ACC for different domains.

Furthermore, this can move beyond ACC to allow input of individual user criteria (e.g. cost controls or maximum serviceability criteria) beyond the local building code prescriptions. In principle, the MDDF front end could be expanded to a commercial web platform, allowing immediate reprogramming of the Smart BIM components based on the user input criteria.

In addition, MDDF equations could also be derived directly from experimental data. Given the increasing importance of post-occupancy evaluation monitoring (Patlakas, Santacruz, and Altan 2014) and whole lifecycle performance (Khasreen, Banfill, and Menzies 2009), libraries of Smart BIM components relying on monitoring data could be updated automatically on a periodic basis, reflecting the additional knowledge gained from this data collection.

## *CONCLUSIONS*

The present paper intended to demonstrate how higher-level ACC can be achieved in a BIM environment, using currently available native usability, without the overheads of programming into an API. For this purpose, the computation-heavy requirements of the structural design code where processed using MDDF to develop a single equation, which was then integrated in a Smart BIM component in a popular BIM-based software application. The resulting component provides the user with the component's axial withdrawal capacity, thus facilitating ACC. Given that this was a proof-of-concept, some limitations were applied to usability and interaction in order to streamline the process and focus on the core problem.

Current work is concentrating on applying the approach on a separate structural design problem of even greater applicability, the lateral loading of fasteners in timber-to-timber connections, as well as trying to develop benchmarks to evaluate the relative performance of the MDDF processes from a computing perspective.

Future work will look into two areas: firstly, extending the concept to problems with significantly greater number of dimensions, by breaking it down into nested MDDF processes as mentioned above. Secondly, considering similar techniques from machine learning to develop Smart BIM components from datasets of monitoring data.

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# Theory of Games and Contracts to define the Client role in Building Information Modeling

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*This research focus on the application of Theory of Games and asymmetry information to the AEC sector underling the impact of these theories to the supply chain and in particular on the evolution of the client role in a Building Information Modeling process. The mentioned theories used to be applied to macroeconomic fields, but allowed the researchers to understand the evolution of the sector and the internal behavior of the team. This analysis of team behaviors permits to grasp how the contractual frame could hold up the natural trend of the market to collaborate, which leads the sector to improve itself. The Theory of Games could be adopted as a hermeneutic tool for understanding actions and agreements to which the various parties achieve. The research provided a global analysis on the evolution of the client role in a cyclical process. Further development of the research will be the application of the theory to a real case study to catch the real team behavior in a collaborative environment.*

**Keywords:** *Building Information Modeling, game theory, contracts theory, hermeneutical approach*

## INTRODUCTION

In spite of the strong technology innovation process in AEC sector and the increasing influence of automation (and automatization) and of-site production of building systems and components (e.g. façade components, MEP, drilling construction) no productivity increment in the last half century is detected and moreover a growing cost and time overrun is registered. According to Eastman research (Eastman and Sacks), the AEC fragmentation is leading the sector to stagnated period, comparing it with the manufactures, we understand that sector has to change direction. From the 1964 the gap created between the two sector is increasing a lot. Analyzing the index of production in the early sixty, it remains stuck at the same level, at present we have a gap over a hundred percentage points. The reason could be appointed to di difference in the in the corporate structure, which changed a lot in mechanical industry. In particular, the partnering, happened in the sector, imposed an optimization of their products both in term of quality, cost and time.

Recent analyzes of the major economic think tank (i.e. McKinsey, Ellen MacArthur Foundation) or national data (CRESME) describe the construction sector as inefficient and with a low inclination to innovative processes and especially to the relational systems between the players. This last point leads to a continuing loss of value of investments defining the sector as the one with the lowest benefit index per output unit. ISTAT (Istituto Nazionale di Statistica) data confirm the statement, in particular they underline the number of self-employed workers is increasing in the last period. The fragmentation, instead of the internal cooperation, is leading the sector to paralysis.

Building Information Modeling (BIM) development implies new and fluid relations between the different actors compared to conventional processes and it is possible to identify how these relationships should be modified. UK government in its strategy (UK Cabinet Office) for the next five years requested a mandatory BIM level 2 maturity, in which the collaboration is one of the core points. Also at European level in the IDDS report (International Council for research and Innovation in Building and Construction) the structural change wished to the AEC sector request a joint response to obtain a new integrated process to deliver projects.

## THE EMPLOYER'S ROLE EVOLUTION

The definition of the employer, set for the first time by the European Union in EU directive 92/57/CEE and then in the D.Lgs. 81/2008 Titolo I art 89, is "the subject for whom the whole work is carried out, regardless of any fragmentation of its realization" he has the task of architectural, technical and organizational choices, in order to plan the various works. The employer's role evolution is associated to the alteration of the process itself. In particular, a traditional process is linear. It starts with the expression of needs up to the validation of each step. Due to the workflow itself, the connection between the employer and the project is just the request of an asset with some requirements and specifications. On the contrary, in an integrated process, such as the BIM methodology, the project team continually engages the connection and inputs.

BIM methodology introduces collaborative forms of contract that allow a hermeneutical interpretation through the Game Theory and Contracts of the different actors in the building processes especially for the Client. According to PAS 1192:2 (British Standard Institution (BSI)), which describe the BIM workflow, we can understand that the employer has a key position in the process. The document, which represents their requirement, is the Employer's Infor-

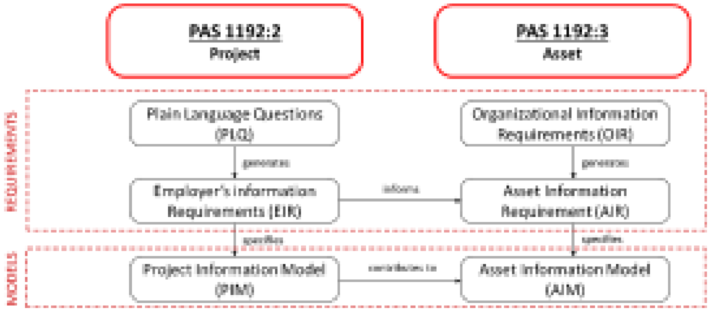


Figure 1
Shared information in a BIM process (source: PAS 1192: 2, modifyed)

mation Requirement (EIR). As explained in Fig. 1, it has the double scope of (i) specifying the ultimate aim of the asset, therefore the Project information Model (PIM) has to be developed, (ii) informing the Asset Information Requirement (AIR). The Organizational Information Requirements (OIR) - the compensation of the Plain Language Questions in the Asset Information Model (AIM) -generates it, all merged in the AIM.

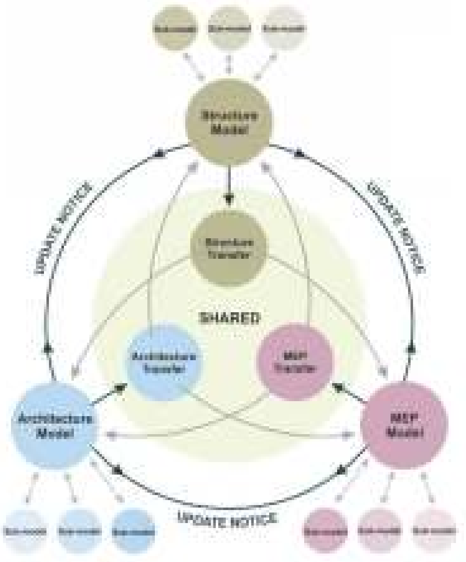


Figure 2
Shared information in a BIM process (source: AEC(UK) BIM Technology Protocol)

The initial contract can be located in the documents' sphere drawn up by the client, with which relies on professional management work BIM aspects. This document is used each time to validate the evolution of the project also verifying it with the Employer themselves. Quoting Barbara White Bryson, who entrusts to the Client a key role in the entire process: "But it is owners who can impact the industry most deliberately and aggressively. Owners can drive innovation on their projects and create profound change in the industry. In fact, owners are uniquely positioned to innovate and participate to it. By planning the design and delivery process, becoming team leaders, collaborating deeply throughout the industry, and applying key elements, owners can summon meaningful and lasting change."

Thus the relationship/negotiation between Client/Sponsor-Designer-Manufacturer-Manager might be addressed with the available methodologies/technologies in the perspective given by game theory and contracts, in order to accurately define the scope within the economic, legal and financial field defining the bargaining power of the parties. This analysis allows the reconstruction of the signifier from the meaning that each of the contract parties historically hold, considering the impact, the temporal presence and cognitive processes contextualizing the relationship.

The back-warding (Fig.3) of the choices involves a reduction in costs for obtaining the same result, this consequence is caused by an increasing level of information and decision in the early process stage, which guarantees a maximizing level of resource exploitation.

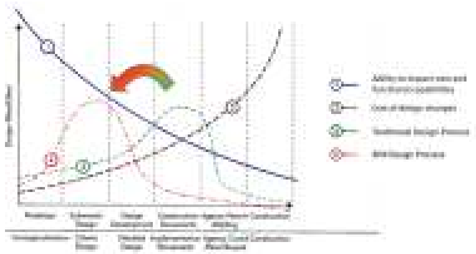

Figure 3
Backwarding decisions in a BIM process (source: MacLeamy's curves, modifyed)

Accordingly, increasing attention to the relationship of the parties will be empowered because of the significant shifts of responsibility that the new contracts and funding frameworks (as exemplified by the Public/Private partnership model). It is evident that the subjects' behavior, even in the presence of "complete contracts" will be oriented to the increased ownership of benefit shares.

The issue of relations between the parties belonging to the building process has never developed in terms of the economic, regulatory and funding situation would have needed, but almost exclusively in terms of conflicts that constantly judicial chronicles delivered.

The debate on BIM needs the combination with new relational forms between the subjects involved in the construction process, which constitute the basis of a new conceptual paradigm. The last decades registered an evident reduction of investment in public infrastructures and buildings and the attempt to reshape, reduce in number and increase the qualification of Contracting Stations. This stresses a new strategic management of relations between AEC subjects becoming an essential condition to achieve advantages in the medium and long term with a new relational approach rather than transactional one, which should analyze the contractual practices in terms of efficiency and reconstruction of internal cognitive processes defined into the request-offer relationships. In this direction, the games and contracts theory is the appropriate analytical tool to analyze the relationships between AEC subjects, inasmuch it addresses the decisional issue and contractual relationships of many players, whose actions derive from their expectations regarding the opponents' moves. As originally formulated, the theory of games traditionally is used as a forecasting and monitoring instrument to examine the equilibrium condition and find out the best solution of a stated problem. In fact, a certain problem might present a multiplicity of equilibria that are not always optimal, but satisfactory.

## THEORY OF GAMES

Through the Theory of Games are studied all the situations of strategic interaction, where the usefulness of an individual depends not only on his actions but also on other agents. One of the most exemplificative example is the Prisoner's Dilemma, an imperfect information game, in which two players have to make decisions without knowing what will be taken on the other hand.

The Theory of Games is a vast discipline the aim of which is to analyze the strategic behaviors of the decision makers (the players), i.e. studying the situations in which several players interact by pursuing common, different or conflicted objectives. Aforementioned theory deletes the individualism principle, placing the benefits of group above the individual ones, in fact according to this theory the highest behavior is not derived from what is best for the individual but from what is best for the community.

Given a game, the player is entitled to choose the strategy that he prefers in the whole of possible strategies: the player will choose the strategy that maximizes his benefit and therefore, the same strategy will be chosen from several players, only if this one will maximize the avail of each player when all implement the same solution.

The well-known solution of the Theory of Games is the Nash Equilibrium, according to which each gamer has at its disposal at least one strategy from which he has no interest in moving away from if all the other players have done their choice.

In the Prisoner's Dilemma (Fig. 4) game there are two possible strategies: (i) to confess: it represents the dominant strategy as it is the best regardless of what the other will do; (ii) to not confess: it represents the more convenient strategy if and only if also the other will not confess. The Nash Equilibrium for the Dilemma is (to confess, to confess) but this is not absolutely the best result: if the players had canned to communicate they would choose to not confess. When the equilibrium is reached, no player can improve is own result only changing his own strategy and therefore he is bound by others' choices.

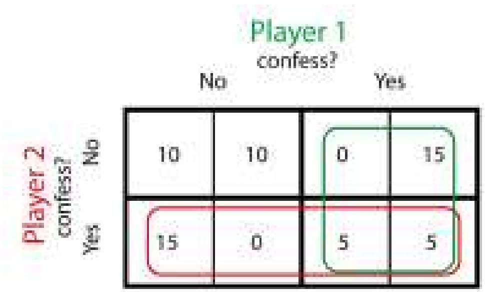


Figure 4
Prisoner's Dilemma

Having said this, it follows that in the process of choosing a strategy to be adopted the operators are confronted with a conflict between: (i) individual rationality: to pursue the maximization of personal interest; (ii) efficiency: to pursue the best possible result, both individual and collective. Against this backdrop, it will refer and describe tests made under the economic market and under the Research and Development sector, in which the forms of interaction between people and the conditions (that allow some strategies instead of others) were analyzed (specifically under what circumstances the operators are willing to cooperate or not). The first experiment it will be described applies the Prisoner's Dilemma to the study of endogenous transfers that can lead to cooperation and coordination mechanisms between market operators. Therefore, it will be studied the compensation mechanisms that arise to promote the cooperation, the test carried out consider couples of players and they are composed of two steps [4]. Step 1: the players establish an offer of a payment for the counterpart in order to cooperate. Step 2: know the amount, the gamers play choosing to cooperate or not. The identified couples of payment participating in the game guarantee the mutual collaboration and convert the game into a coordination game; for this reason, in the second step the players are able to choose the mutual cooperation or the mutual waiver, as described in Nash Equilibrium. Choosing to mutual cooperate it's more likely when payment couple are identical as they lead to the grant of similar results for both sides.

However, this choice is rather rare in Prisoner's Dilemma in which, even though it's possible to get high profits through collaboration, non-cooperation remains the dominant strategy for each of the players.

The solution to this test is discernible into Qin's theory (Correia-da-Silva) according to which the necessary and sufficient condition to induce players to cooperate is to provide the other with the minimum amount necessary to convince him to cooperate.

During the investigation, it was found that cooperation levels are different if: (i) transfers of payment are permitted, otherwise (ii) if transfers of payment are not possible. The first condition is due to Nash Equilibrium's one and where the transfer of reward can deliver results due to the cooperation for both similar or different parties.

The results of the test show that cooperation levels are higher when payment couples moved among the players are identical and when the transfer gives similar results for both sides.

Is possible to adapt the previously explained experiment to a real situation, namely real estate and AEC sector. In these, both the parities request a fair compensation for the service they are going to offer to the other, this reward is just a guarantee deposit or a re-entry in case of greater commitment. In this way, new collaborative contractual theories lead to a review of the structure of the process. As will be explained later, the insertion of a contractual part within it leads to a different view. However, in many cases, individuals tend to get the best out of their own, not considering others, however, this approach does not produce either a global gain or the team or even the project that will be damaged due to selfish behavior.

## INFORMATION ASYMMETRY

In a market the possibility of developing perfect competition mechanism and resource allocation is conditional upon the occurrence of a symmetric information condition; for this to be achieved the information have to respect the characteristics of completeness and accessibility without any cost. Unlike the mentioned hypothesis, in real life information is considered to be like an economic asset and for this reason it is not accessible without any cost, and moreover it is likely that not all the requisite information is available while making economic transactions.

So it is possible to define the existence of an asymmetric information when, within economic process, an information is not entirely shared between people belonging to the same one; this configuration enables one part of the involved agents to possess a higher number of information than the rest of the competitors, out of which they would have a competitive advantage.

In fact, as part of a perfect competition, information symmetry is taken for granted and within the market, the operators argue about endogenous factors caused by each companies' management abilities such as prizes, quantities, strategies and expertise. On the other hand, information asymmetry is an exogenous variable which corrupts those aspects in a way that the financial and economic markets' results are influenced by them (Billett, Garfinkel, and Yu).

Among the different types of problem caused by information asymmetry, this document is focused on analyzing the adverse selection which consists in an operator that has much more information than the one is going to pledge an agreement with. In this situation it is reasonable to assume that during the trades the operators are not aware of the quality of the other's products as well as theirs own because they are given lacking and confusing information (Correia-da-Silva).

Due to this informational confusion and heterogeneity, the business-men are keen on using clever behaviors, which consist in competitive actions that lead to achieve their own interests.

Based on the work environment, the kind of profit achieved by the results and the possible stimulating influence, both parts can choose to act or not to act in a cooperative way. However, the strategic interaction is represented by the Theory of Games and situations attributable to the Prisoner's Dilemma are well described in this document.

As an example of adverse selection, at the beginning the document shows the Akerlof's Lemon Market Theory (Akerlof), then it present other examples of the same subject but in other situations such as the translation industry and the financial one. Next, the article analyses the problem which Akerlof had to cope with and it reconsider them as a modern problem, and then move on to behaviors strategies that take place in the economic market and in the Research and Development industry when information asymmetry is present.

## THEORY OF GAMES AND ASYMMETRY INFORMATION APPLIED TO RELATIONAL CONTRACTS

As described before, over the recent decades, some traditional project delivery systems have emerged claiming to fill the gap between the design and construction projects, but they have shown to be not efficient enough. In this context, some collaborative contracts were developed in a lot of countries (e.g. US, UK and Italy), but they have mainly the same characteristics. Due to their structure and composition, traditional contracts create unavoidably a conflict of interest, which cannot be solved and they impose a rigid division of stakeholders' works. These new working organizations allow achieving the final scope, which is the optimized project. These complementary approaches meld in report (Smith, Mossman, and Emmitt), which concluded that the optimal project delivery method, would be an integrated approach executed under Lean principles.

Following the tripartite division of the knowledge provided by Habermas, game theory could be adopted as a hermeneutic tool for understanding actions and agreements to which the various parties achieve.

Despite their structural diversity, the parties involved in AEC sector reveal the typical conditions for the application of game theory, such as: (i) conflict, (ii) strategic interaction, (iii) strategic options and (iv) set of rules. The former point is conflict, envisioned as a requirement of each of the parties to maximize the potential economic resources to the most convenient conditions for himself. This aspect is caused by a selfish behavior that in a team can cause a sequence of inconsistency due to the desire of the single to provide as less information as possible to provide a work without incur in the liability risk. A problem, each party has, is to decide how much he can trust on the others, they have the possibility to believe in the others, but they could incur in sharing too much information which can advantages others.

The second one is strategic interaction and interdependence of the choices, based on a net of conflicting or collaborative actions in which each of the parties shall take account of others before making their own moves. Strategic options, which are sets of decisions in a given context defining the contractual history and its development paths. these mechanisms could cause a series of consequences of skepticism in the team.

Also set of rules, sanctions, conventions and behavioral habits which motivate operators, for economic exchanges to take place. Relational contract applies this theory to align the interest of the operator, in fact a sharing pain and gain act is used to let people improve the scope and its final result.

## CONCLUSION

The study the relationships of AEC Subjects by game models within the hermeneutical approach means to emphasize the strategic interaction character and conflict in the choices based on the significance that individuals ascribe to action in a specific operative context. The game is "a human paradigm" resulting from the subjects' characteristics, their bargaining power and operative context in which they operate; participation in the game does not put all parties on an equal situation (non-neutrality of the game), and even there is not a general consensus on all the rules (contestability of the game). In production activities management, the actors establish agreements with content, possibly minimum and with standard rules, if, through them, are able to "control" the relational instability level and, at the same time, maintain a degree of freedom to realize their goals protecting their competitive advantages. The hermeneutical approach of the games allows to interpret the competitive dynamics of a contractual relationship between the AEC parties according to a perspective that accepts the existence of a multiplicity of meanings, shares and solutions that all equally possible for the relative advantage position, giving up the idea of arriving at definitive solutions.

In this context, the proposed future scenario is carried out using an approach that aims to deepen the strategic interaction processes existing between the participants in the construction process. According to this approach, the theory of games and contracts can be used as a tool for understanding the parties' agreements, the reasons and their cognitive processes, and despite the needed simplifications, this representation would assume a normative value in a meta-decisional vision. This means providing a systemic vision of the relationships complexity that permits an implemented understanding of decision-making processes.

The paper also outlines the situations defining the interaction processes, underlining the following requirements: essentiality, irreplaceability, interdependence of subjects and the bargaining power modulated by opportunistic or collaborative interaction processes which may be treated, respectively, as not cooperative (incomplete opportunistic contracts) or cooperative (collaborative complete contracts) games.

Based on the abovementioned articles, the drawing of experiments and related issues, it is possible to understand how the issue of adverse selection is important and how its presence in different sectors of our society influences the performance and results of the same. Against this background, in order to reduce the information asymmetry and improve the efficiency levels in which markets operate, many institutions have decided to invest in activities such as (Siegenthaler): (i) reporting and (ii) screening. The first activity involves aspect of market management. The agent, who owns the information, uses means such as guarantees, quality certifications and advertising to demonstrate and ensure both the company's characteristics and the state and characteristics of the good or service it offers in the market. The second activity involves aspect of the administration. The agents carry out market regulation, information evaluation and quality control over the good or service on the market, in order to prevent the reduction of the average quality of the products. In addition, in order to restore market functioning, institutions require to agents engaging in social activities requiring additional costs, this means that the reduction in informational asymmetry requires the parties concerned to define new cost margins. The uncertainty aspect has also been studied also for the Theory of Games, where a player must choose a strategy of action to maximize the global profit, knowing that the results of the same do not only depend on it, but also from the strategy chosen and pursued by the counterpart that is unknown to Initial player.

The player's tendency is to choose a strategy that leads to the maximization of their profit, at the expense of the community. The player is willing to change his strategy when he is aware of the strategy of the other, through free communication mechanisms, and the expected result continues to increase. Thus players' cooperation mechanisms are encouraged when they can communicate and share information about the strategies they intend to implement, aware that the end results will have similar entities for both parties. In conclusion, collaborative contract - and more in general co-operation mechanisms - are the way to mitigate the adverse selection phenomenon, such as the persecution of an informative and efficient communication between the various operators.

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# BIOMIMICRY

# Biofilm-inspired Formation of Artificial Adaptive Structures

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*Todays design researchers are beginning to develop a process-based approach to biomimicry. Instead of merely looking at static natural structures for inspiration, we are learning to draw from the underlying organic processes that lead to the creation of those structures. This paradigm shift points us in the direction of adaptive fabrication systems that can grow through processes of self-assembly and can reconfigure themselves to meet the contours of local environments. In this study we examined the structural growth patterns of bacterial biofilms as a basis for a new kind of artificial, self-assembling module. This demonstration of bio-inspired design shows how contemporary technology allows us to harness the lessons of evolution in new and innovative ways. By exploring the dynamic assembly of complex structural formations in nature, we are able to derive new resource-efficient approaches to adaptable designs that are suited to changing environments. Ultimately we aspire to produce fully synthetic analogues that follow similar patterns of self-assembly to those found in bacterial biofilm colonies. Designers have only just begun to explore the tremendous wealth of natural form-creation processes that can now be replicated with computer-aided design and fabrication; this project shows just one example of what the future might hold.*

**Keywords:** *Biofilm, Adaptive Structure, Formation, Quorum Sensing, Parametric Condition*

## CONTEXT AND RESEARCH GOALS

Today's technology has allowed architects to draw inspiration from the natural world in new and innovative ways. Recent work has begun to explore the possibilities of using biological systems either as a model for design algorithms (Duro-Royo et al., 2015; Kalantari & Saleh Tabari, 2017) or as an actual component in fabrication processes (Araya, Zolotovsky, & Gidekel, 2012). Evolution has produced brilliant arrangements that are ideally suited to the natural and physical environment, and if we attend to their lessons these natural systems can teach us how to create strong, durable, adaptable, and flexible structures with a minimum of waste (Discher, Janmey, & Wang, 2005; Philp & Stoddart, 1996; Vincent, 2012). Our own efforts in the field of architecture have not yet begun to approach the level of sophistication that is seen in the natural world (Benyus, 1997; Oxman et al., 2012; Vincent, 2012), and there is a tremendous amount of potential still to be found in improving our designs through lessons learned from nature. In this project, the researchers analyzed bacterial cellular growth as a basis for new human-created architectural processes. We examined various patterns of bacterial growth, including their use of responsive membranes and scaffolding structures, and then combined this knowledge with the exciting new potential of digital fabrication technology to investigate new architectural assembly methods. The creation of self-assembling structures modeled on bacterial growth has the potential to replicate the tremendous structural advantages and resource-efficiency of this organic process.

## BACKGROUND: BIO-INSPIRED STRUCTURES

"Morphogenesis" is a term used in the natural sciences to describe how structures develop in geological formations and biological organisms. Architectural designers have become increasingly interested in studying morphogenesis as a way to inform human-created structures, particularly as technological advancements have opened new frontiers for replicating these natural processes. For example, Kreig and colleagues (2012) drew from biomechanical studies of the sea urchins to develop a new type of jointed structural system. Ortega-Sanchez and colleagues (2000) used the model of organic tissues to develop new materials that are "self-healing" and tolerant of structural faults. Using advances in "soft" robotics and nano-engineering, some researchers have begun to develop a process-based approach to biomimicry. In other words, we are no longer simply looking to the static design-solutions of the natural world, but are now taking lessons from the organic processes through which those solutions are created. This approach focuses on how natural processes achieve effective designs to fit the contours of a specific local environment and its structural requirements (Tibbits, 2012; Raviv et al., 2014)

Bacterial cellulose structures are a fascinating model for this cutting-edge biomimetic design research. The small scale and rapid duration of bacterial growth patterns makes them relatively easy to study, and the use of bacterial cellulose in industrial, scientific, and medical applications has led to a burgeoning amount of data on the topic (Fernandez et al. 2013; Mohite et al. 2014). Previous studies have focused on analyzing and manipulating the growth patterns of bacteria. For example, foundational work was carried out by Araya, Zolotovsky, and Gidekel (2012), who demonstrated that digital tools and technologies could be combined with living bacteria systems in a controlled environment to induce specific biological functions leading to desired structural patterns. Derme, Mitterberger, and Di Tanna (2016) similarly developed bio-fabrication and scaffolding techniques to control the development of bacterial cellulose, with the ultimate goal of enhancing biomaterials science.

In the current research, we were more interested in reviewing the data on bacterial growth as a model for new types of artificial self-assembling structures. The concept of self-assembly refers to a process by which small building-blocks, on the basis of their local interactions, come together to produce elegant and effective structures tailored to the contours of the environment. This type of assembly is extremely widespread in nature (Widesides & Grzybowski, 2002; Pelesko, 2007). In recent years a variety of researchers have made strides in theorizing the components of self-assembly, taking lessons from observed features in the natural world. The most common model acknowledges four defining features that affect self-assembly-the building blocks (cells, molecules, component structures, etc.), the forces that connect the blocks together (chemical bonds, connective tissue, electromagnetic interactions), the features of the surrounding environment, and the driving force that energizes the assembly process and prompts it to occur (Pelesko, 2007; Tibbits, 2012). Some researchers distinguish between self-assembly processes that approach a static equilibrium in their environment vs.

those that remain in a state of perpetual dynamic growth and energy exchange in relation to their surroundings (Whitesides & Grzybowski, 2002).

The use of self-assembly approaches in artificial architectural fabrication is an extremely new field, but investigations in this area have yielded exciting results. Schoessler and colleagues (2015), for example, demonstrated a system that allowed for constructive assembly, disassembly, and reassembly using passive building blocks. Mairopoulos (2015) similarly developed a component-based system that allowed for a highly autonomous local assembly to fit the contours of the environment. The current research contributes to this innovative direction in architectural assembly by analyzing lessons from bacterial growth. By learning more about the morphogenesis of bacterial structures, designers can eventually produce fully synthetic analogues that follow similar patterns of adaptation and development, thereby harnessing the lessons of countless years of evolution.

## BIOFILMS AS AN INSPIRATION FOR STRUCTURAL FORMATION

Biofilms are arrangements of cells or microorganisms that stick together, typically along an external surface. The cellular arrangement of biofilms is known to confer specialized functions and properties that are not otherwise demonstrated by the individual components of the film (for example, by free-floating forms of the same microorganisms in a fluid medium) (Flemming & Wingender, 2010). Organisms embedded within a biofilm matrix gain specific advantages to nutrient flow and architectural integrity (Oliveira & Cunha, 2008; Tolker-Nielsen & Molin, 2000; Sutherland, 2001). Biofilm formation is typically a multi-step process, beginning when individual cells adhere to a surface using electromagnetic or chemical bonds. After this initial attachment, three-dimensional growth begins to occur, leading to complex microcolonies that may be comprised of multiple types of organisms. Once the biofilm matures and its structural matrix is established, it typically begins to release individual cells, which regain a free-floating planktonic lifestyle and may eventually colonize other surfaces (Flemming & Wingender, 2010; Rendueles & Ghigo, 2012) (Figure 1).

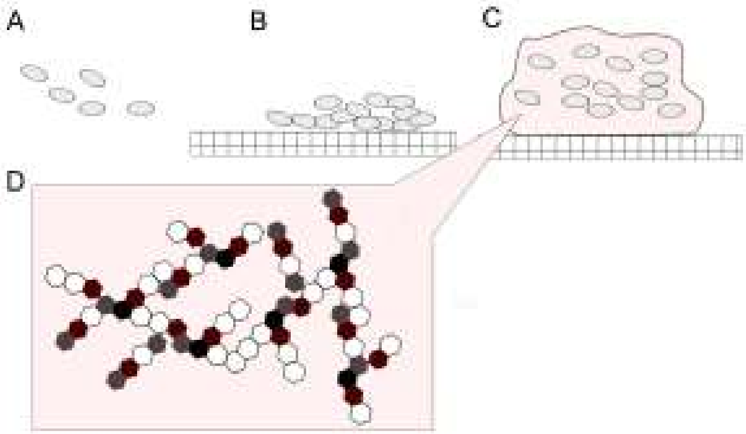


Figure 1
Stages of biofilm formation.

In this study, we examined the natural formation of E. Coli bacterial biofilms as an inspiration for developing an artificial, self-assembling system. The features of bacteria cells were studied as a model for designing architectural units (or "bricks"), and the attachment processes between the cells in bacterial biofilms were studied as a model for developing a smart adaptation system to combine and recombine the individual units together. The selection of E. Coli biofilms as a model for this architectural research was made on the basis of the extensive, pre-existing empirical knowledge that we have about their formation, as well as the complexity of the biofilm structures, their demonstrated environmental fitness, and the relevance of that knowledge to potential design applications.

We reviewed the scientific literature to discover how biofilm structures are formed. One concept that we quickly learned is that cell-surface polysaccharides play a crucial role in mediating the attachment process among individual units. In addition to serving as a barrier between the cell wall and the external environment, these polysaccharide molecules provide much of the structural connective tissue of biofilms. The way in which the connecting polysaccharides are produced by the cells during biofilm formation is mediated by a process called quorum sensing (QS). This is a kind of cell-to-cell communication, mediated by an exchange of signaling molecules, that affects the way genetic instructions are expressed in individual cells. QS allows the individual cells to receive feedback about the density and relative positioning of other nearby bacteria cells. Based on this information a variety of process may be adjusted or initiated within each individual cell, ultimately leading to the formation of effective structural attachments to specific neighboring units (Federle & Bassler, 2003; Vasudevan, 2014; Walters and Sperandio, 2006; Miller and Bassler, 2001; Whitehead et al., 2001) (Figure 2).

Considering the QS system as a form of communication, we investigated what type of information is exchanged among neighboring cells to allow for the effective biofilm formation. Using contemporary architectural language QS can be understood as a kind of distributed "smart system" that adapts to local environmental conditions. The units that are activated by QS can be involved in:

- Processes in which individual units request assistance and communicate their needs, such as the initiation of a larger solid structure.
- Processes that require individual responsive-

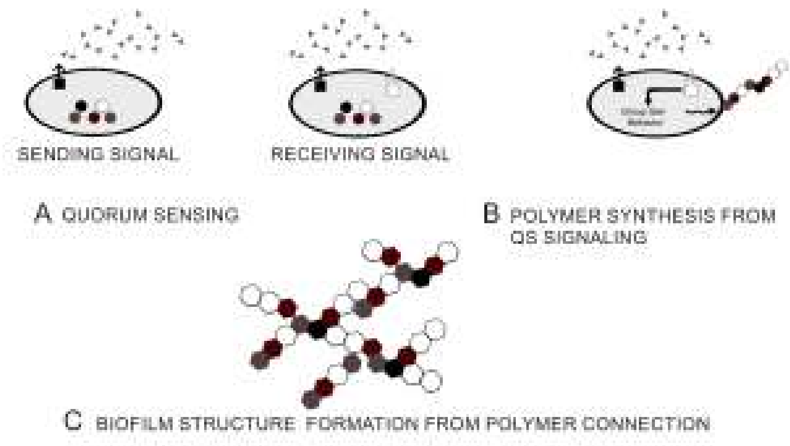


Figure 2
Quorum sensing as a communication mechanism.

ness to environmental variables, such as production of optimized light for each unit.
- Processes that favor the colonization of new territory and the development of expanded, complex communities after local structures are stabilized.

To identify potential configurations among the building units, we analyzed the topology of the connective matrix, in particular the O-antigen repeating units of cell-surface lipopolysaccharide. This typology varies depending on the number and positioning of sugar residues that are present in each O-antigen, varying from two to seven nodes (Brade et al., 1999; Stenutz et al., 2006) (Figure 3).

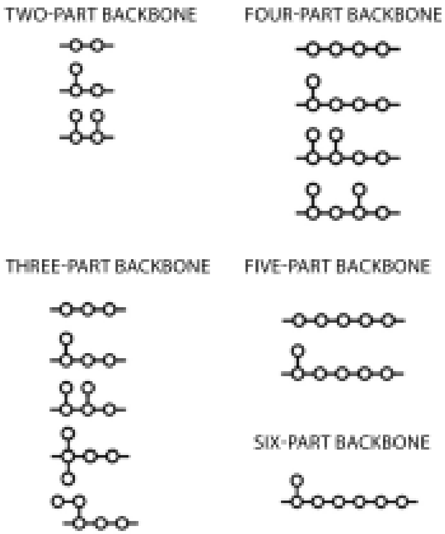


Figure 3
Topology of connective polysaccharides in E. Coli biofilms.

## RESULTS

The assembly models that were developed in this study are based on the features of biofilm formation and the QS communication system as described above. The result is a smart, self-assembling structure that is adaptable in its shape depending on the local environment. The basic cell or building-bock of the structure is a truncated tetrahedron. It has four hexagonal faces which can link to other units, plus four additional triangular faces that do not form links. The structure allows for two basic types of compact colonies consisting of five or six units each (Figure 4).

Once cells create a basic colony in one of these two shapes, they begin to engage in QS communication with other nearby colonies. As a result of this information exchange, the individual colonies may adjust their shapes and link up with each other. Based on the needs of the environment and the available topologies, each of the two colonies can assume a variety of shapes (Figures 5 and 6).

In a manner similar to bacterial polysaccharide branching systems, adjacent cell colonies can link up into different arrangements. Some of these connections will be structurally stronger than others. The stronger connections will generally be favored by the colonies, depending on the environmental parameters and the overall structural goal of the units, which are defined by QS inputs. By specifying the available cell colonies, the possible assembly typologies, and the environmental needs, a unique structural arrangement is formed. (Figures 7 and 8). When needed, this final structure can be easily disassembled into its component colonies and/or reconfigured into a different overall shape.

## CONCLUSIONS AND FUTURE WORK

This project studied E. Coli biofilm formation as a potential basis for computer-mediated "smart" architectural assemblies. The resulting simulations demonstrate how the morphogenesis of biofilms can be used as inspiration for developing new types of environmentally responsive structures. This demonstration is intended to inspire designers to make use of biofilm formation concepts in their work, and to provide practical tools for this purpose. The 3D models produced in the research provide concrete examples of how biofilm logic can be used in the design of innovative and adaptive forms (Figure 9). Ultimately, the ultimate goal of abstracting biological formation

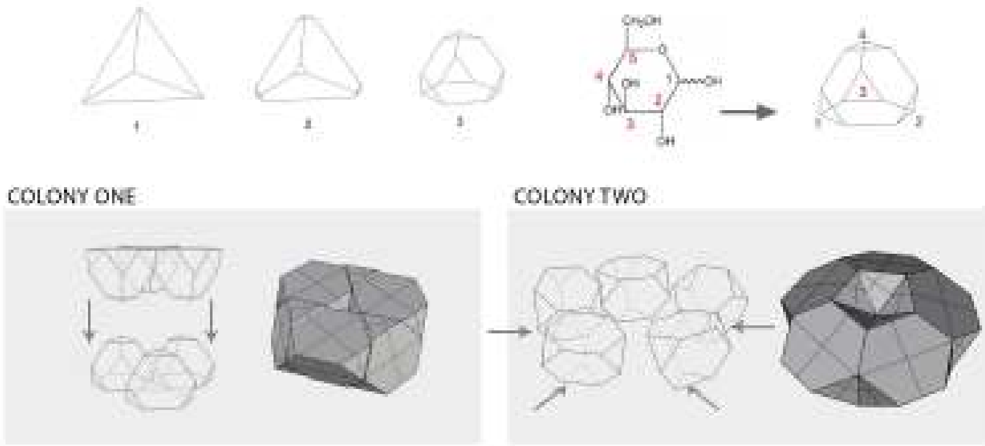


Figure 4
Compact colonies consisting of five or six cells.

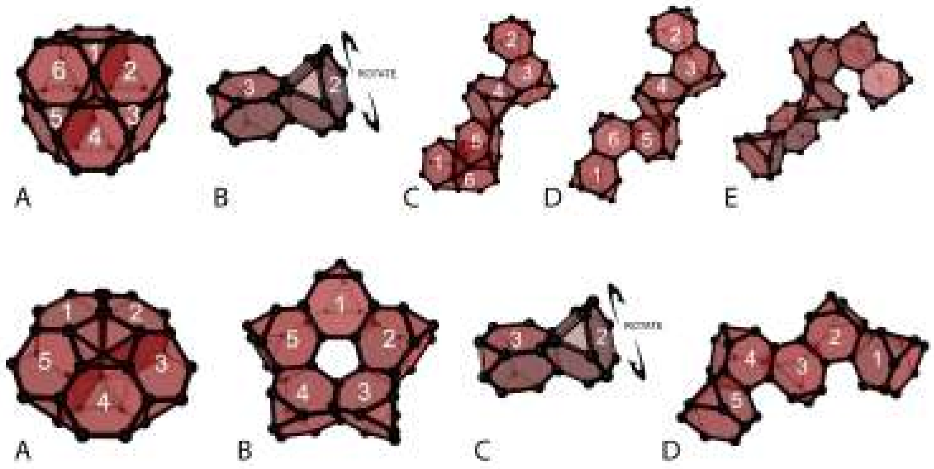


Figure 5
Each colony can assume a variety of shapes.

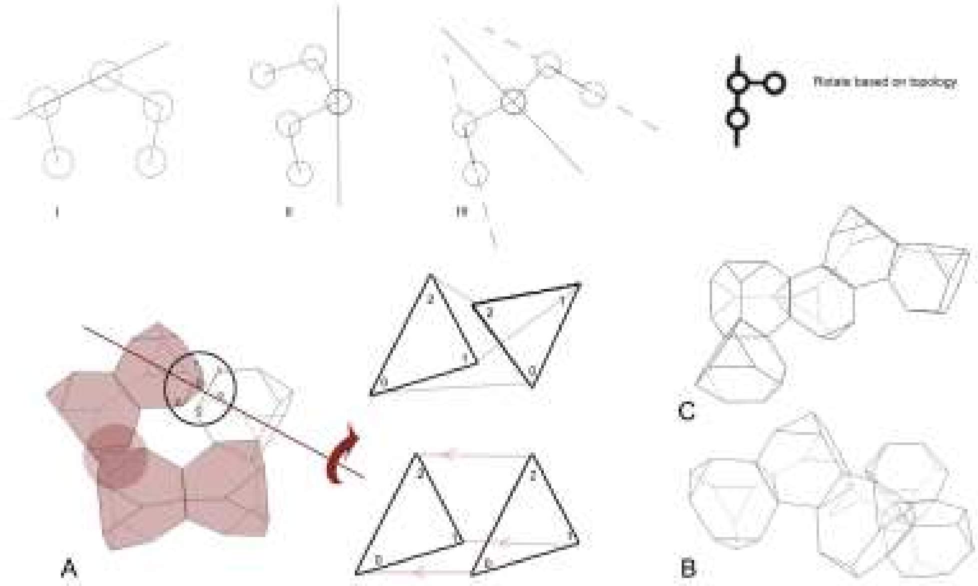


Figure 6
Cell colony rotation and formation based on E. Coli topologies.

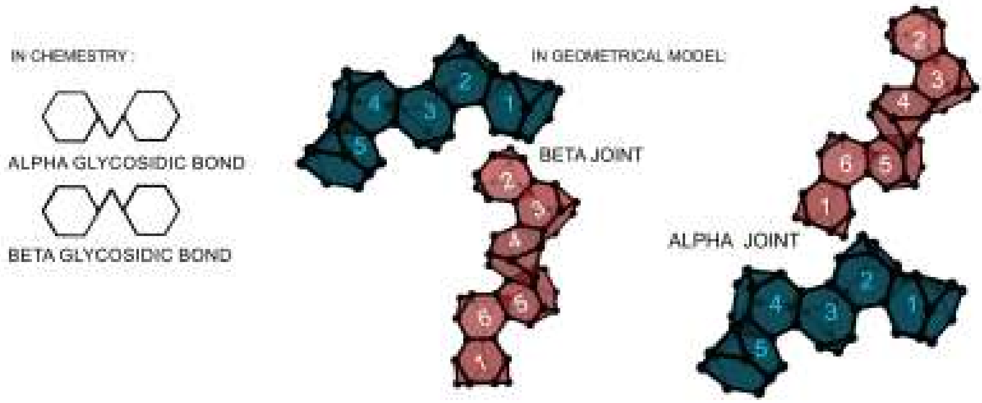


Figure 7
Colonies link together to form larger structures. The “Alpha Joint” identified here will be a stronger link that the “Beta Joint” and will thus be preferred during the self-assembly process.

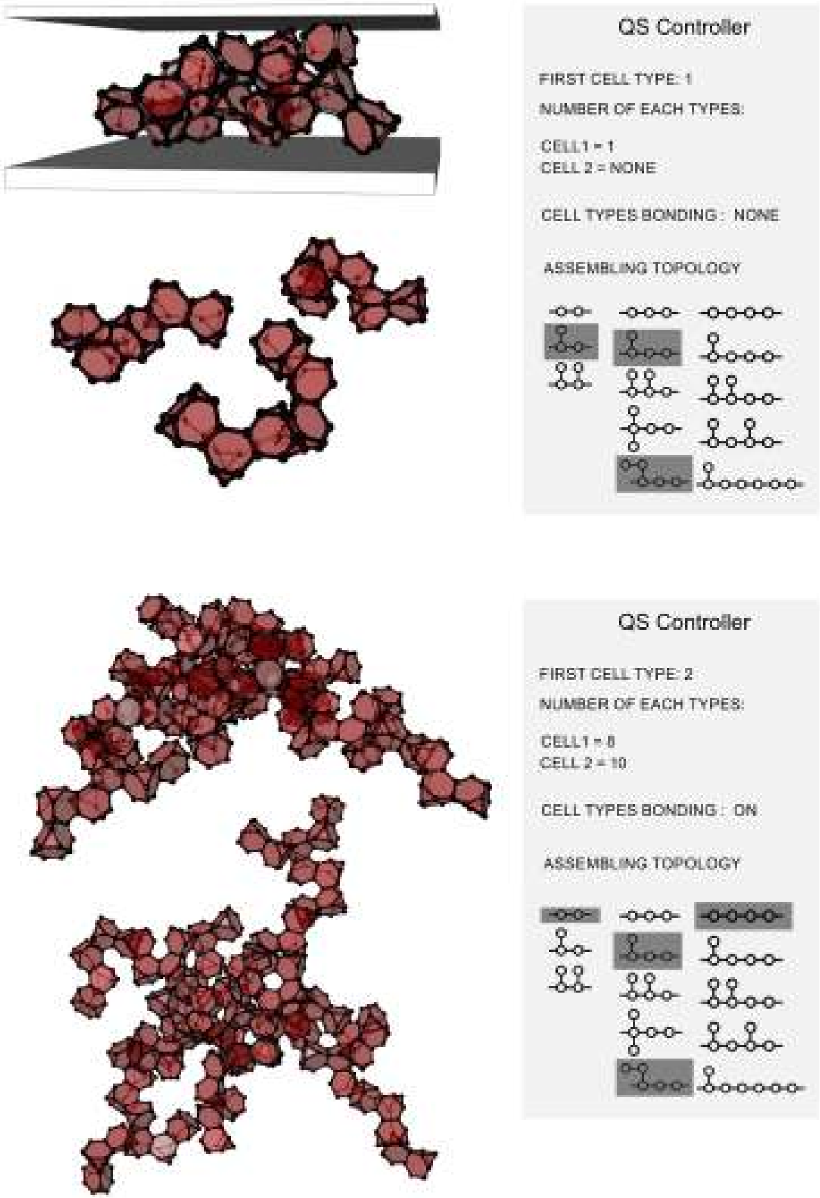


Figure 8
Formation of larger structures based on QS communication among colonies.

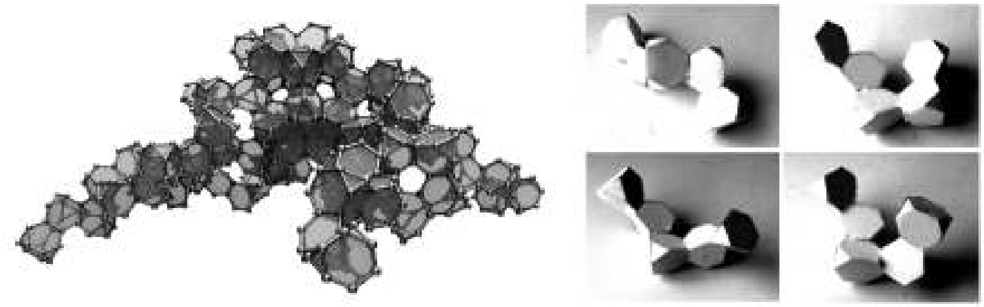

Figure 9
An example of a complex structural formation based on environmental parameters and QS communication among individual cell colonies.

procedure into code-driven models and tools is to gain new insights into how nature deals with physical dynamics, environmental parameters, and feedback within cell and tissue structures. The potential applications include novel designs for responsive surfaces, new fabrication processes, and unique spatial structures.

While this study presents a first step toward simulating biofilm formation in computer-aided design, there remains a tremendous amount of opportunity for analyzing various organic assemblages. By linking the biological sciences to the computational design process we can open significant new horizons for organically inspired design. The next step in this project is to fabricate these cells as "robotic bricks" with embedded sensors. By creating physical examples of this adaptive structure we can further explore its potential applications and verify the effectiveness of our approach. Future work may seek to combine bio-inspired formation directly with established software algorithms, leading to new design tools in parametric modeling.

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# Feather-inspired social media data processing for generating developable surfaces: Prototyping an affective architecture

## *Prototyping an affective architecture*

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*This paper presents the development of an interactive installation intended as a prototype of experimental affective architecture connected with social media data processing. Social moods and emotions are now spread more widely and faster than ever before due to pervasive uses of social media platforms. We explore how data processing of users' expressions and sharing of moods/emotions through social media can become a source of influences on shaping the form and behaviour of interactive architecture. The interactive prototyping method includes (1) a feather-inspired data-to-shape rule system together with the ShapeOp Library for generating strips as developable surfaces, (2) a physical computing platform built with Arduino micro-processor and shape memory alloy springs for actuation, and (3) physical model-making. As a prototype of social media aware affective architecture, an interactive installation design is proposed for a campus space where the actuation of the strip installation is linked to data processing of Twitter messages collated from users on campus. We reflect on the prototyping methodology and the implications of an architecture affected by people's expression of moods/emotions through social media.*

**Keywords:** *social media data processing, developable surfaces, interactive prototyping, shape memory alloy, elastic morphing, ShapeOp*

## INTRODUCTION

Natural feathers found in birds are made with components of different forms and functions (Lovette and Fitzpatrick, 2016). In Plumology, the side branches of a feather vane are called barbs and are linked together by two types of microscopic filaments called barbules and hooklets. The upper barbules contain a series of hooklets catching the lower barbules of neighbouring barbs along the feather shaft. The barbs and barbules form strong flexible surfaces with the interlocking linkages, without which the barbs or hooklets may become separated from each other, losing their integrity. Feathers comprised of barbules and hooklets are termed "pennaceous". Feathers without barbules and hooklets, such as down feathers, are called “plumaceous”, which form layers of insulation next to the skin, trapping air to protect the bird from heat and cold. We observe in bird’s feathers that the existence of an element in the microscopic scale can control the form and function of an element in the macroscopic scale. In this paper, we present some rules derived from the organization of bird’s feathers and demonstrate how these pattern-forming rules can be applied to social media data processing that drives morphological transformation of datascapes into developable surfaces.

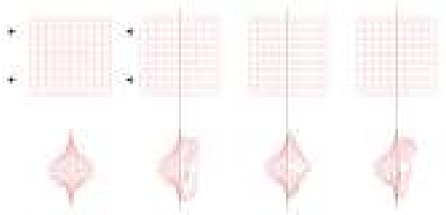


Figure 1
2D parametric modelling of a feather-like pattern

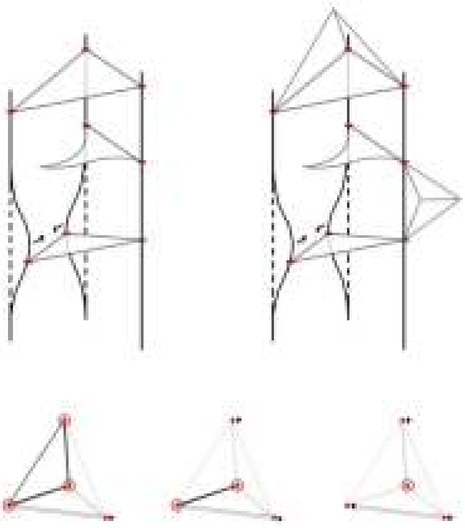


Figure 2
3D parametric modelling of a feather-like pattern

From the rule of the arrangement inside feather branches, the control points of the vane can be parametrically modelled as key points in the model space, mimicking the hooklets structure of feather. We then have a shape/form that can be transformed by these control points. The concept of ‘control points’ taken from the micro-structure of the single feathers is the barbs in the connection parts between barbules, which also control the density and morphology of entire single feathers because of its location and density. In our preliminary computational design experiment, a 2D grid is used to construct lines and intersections, and then set the number of the intersections and layout to control the density of lines. In this case, the 2D grid of different versions are applied with forces in Rhino-Grasshopper (Figure 1).

Extended to 3D modelling, triangles are introduced. The triangle allows changing the control points from (a) controlling two lines to (b) three control points controlling multiple lines, with reference to the stereoscopic model of feathers (Figure 2). In so doing, we see more changes and possibilities. In addition, the stability of the triangle is also used to make the model stay unchanged when the relative distance between the control points is fixed. Because a triangle may share an edge with another triangle in a solid space, the model of a triangular prism can be grown into a triangular polyhedral structure.

## SOCIAL MEDIA AND AFFECTIVE ARCHITECTURE

The rapid rises of social media platforms and smart phone technologies have brought unprecedented changes in communication and information production/consumption. Contemporary uses of mass social media have also evidently affected how architecture is designed, reported, experienced, evaluated, and serviced (Hussien, 2014). We can argue that aspects of (re-)imagination, conception, construction and operation of architecture are increasingly conditioned by social media. The Rotterdam-based practice MVRDV is one of the forerunners of tapping into the potential of planning and design with social data. Indeed, “Datascapes” is identified as one of the key elements of their design philosophy (MVRDV, no date). As more sophisticated models and processing (min-

Figure 3
Twitter API objects value and its conditional relationship

| DATA VALUE | DESCIPTION | TYPE | RELATIONSHIP | CONDITION |
|---|---|---|---|---|
| created_at (time) | The UTC datetime that the user account was created on Twitter. | String | Time | Range / Length |
| text | [illegible] | String | Characteristic | Keyword |
| protected | [illegible] | Boolean | Privacy | Boolean |
| followers_count | The number of followers this account currently has. | Int | Activity level | Amount |
| verified | When true, indicates that the user has a verified account. | Boolean | Status | Boolean |
| friends_count | The number of users this account is following. | Int | Activity level | Amount |
| listed_count | The number of public lists that this user is a member of. | Int | Activity level Visibility | Amount |
| coordinates | [illegible] | Coordinates | Density | Location/Range |
| hashtags | [illegible] | Array of Object | Characteristic | Keyword/Boolean |
| lang(language) | [illegible] | String | Characteristic | Keyword/Boolean |
| favourites_count | [illegible] | Int | Activity level | Amount |
| statuses_count | The number of Tweets (including retweets) issued by the user. | Int | Activity level | Amount |
| place_type | The type of location represented by this place. | String | Function | Keyword |
| withheld_scope | [illegible] | String | Privacy | Boolean |
| filter_level | [illegible] | String | Interaction Level | Boolean |
| retweet_count | [illegible] | Int | Interaction Level | Amount |

ing) methods are being developed and applied to social media data (in particular, to location- aware social media), we propose a definition of social media conditioned affective architecture-the performativity of an architecture that is intrinsically linked to the fluxes of social media data analytics reflecting social moods/emotions in real-time. Social media conditioned affective architecture can be as large as a city or as small as a bench in a neighborhood park. The temporal dimension of the conditioning (sustained linking) can also be varying - from seconds to decades. The manifestation of such architecture can be virtual, physical, or overlay of virtual and physical.

The complex social networks define our experience of the urban environment in addition to the physical architecture (Christian and Liang, 2011). Its framework represents the macro- and micro- simulation of social data through different locative data analyses. The foreground displays classified characteristic information at a local level, while the timer contexts provides the other dimensional comparison. Social data status can explore the immersive space that may respond to or contradict the physical architecture, even allows for the real-time streaming data analysis (Christian and Liang, 2011).

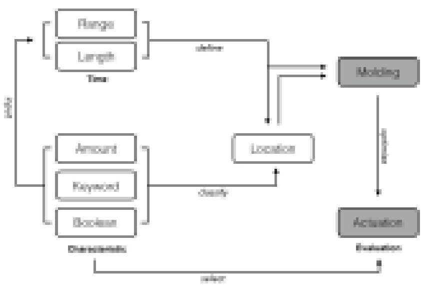



Figure 4
The system diagram of 'data-to-shape' process

The freeform surface will transform to the shape of hills and valleys under the feather-inspired rule which represent the areas with high or low densities or other characteristics of social data as it be accrued. The outcome will be on a coordinates surface reflecting space attributes and activity over time (Christian and Liang, 2011).

According to the Twitter streaming connection process diagram, it receives streamed Tweets as they occur, performs processing and stores results, which means that we can collect real-time space users' characteristic, or we can store it over a specific period of time to conduct a cumulative study of a space ithrough time.

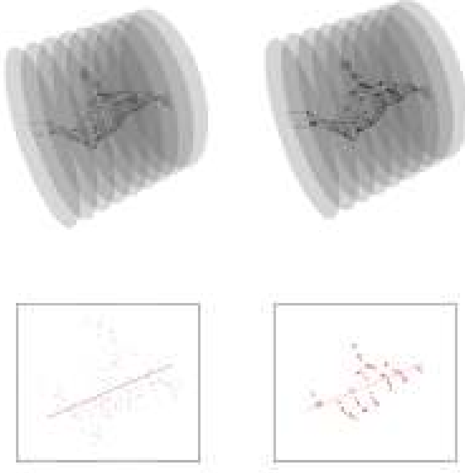


Figure 5
Processing Twitter sample data with a feather-inspired pattern generation system

We classify the Tweets data value stored in excel file according to its type (string, Boolean, int, coordinates, array of object) and the relationship to space (time, characteristic, privacy, safety, activity level, density, function, privacy, publicity, interactive level) as the conditions to define the actuation command (Figure 3).

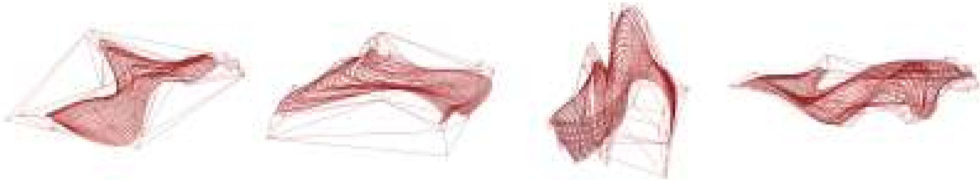
In the proposed 'data-to-shape' process (Figure 4), we use 3 elements-amount, keywords, Boolean as the data characteristic to classify its coordinates, and input it to the other control condition-time to define the location in the period of time. Therefore, a virtual space can be shaped to show its interactive level or other characteristic in a period of time or act as a movable shape related to its real-time data.

## FEATHER-INSPIRED TWITTER (FIT) DATA PROCESSING

Following the SMCA proposition, we explore how Twitter data can be processed to produce 'datascapes' through the feather-inspired modelling method presented in Section 2. In general, social media data can be modelled through characteristic data points with multi-factor controls. An intermediate method is required if the interest is to generate 3D form from 1D or 2D data points (sets) as in the case of typical Twitter data. We explore such a transformation rule mimicking the micro-organization of bird's feathers: the generative interlocking structure with a varying density which could allow changes in the control points in response to a changing environment.

We tested one type of spindle control points leading to stepwise progressive solutions, but they also correspond to each other. The design challenge here is how to extract the key elements from the natural feather-form studied and how they might be converted to 3D models. A Python script was developed to extract Twitter data (tweepy) into Excel, and then into Rhino-Grasshopper, turning the coordinate data into x, y. In our project, tweepy contains user geo location, user gender, keywords, mood, and other characteristics data. These features also provide the basis to determine the attributes and control levels of the control points (Figure 5). We also used other characteristics data as inputs to different control point levels, so linking the model to the Tweeter data feed. In doing so, we can have different states of control points: controlled, random, semi-random and other states. Triangles are used to connect the

Figure 6
Space forming in the same place defined by different time zones and characteristics



X and Y axes, and they are stretched with Kangaroo, so that the user location density is reflected on the Z axis.

The trend of these points suggest an axis as the main control line, and the intersection points on both planes which are found on the main control axis. The triangle network is to play as the second level of control points, so these will be like a feather main branch. Location data can also be used to control the form of dependent variables filtered by gender or a selected keyword which would be more like the organizational form of 'down feathers' that lack of balanced control, leading to a uncontrollable or free form. Through these processes on transforming, it will shows the different virtual spaces which is depends on different time zones and characteristics (Figure 6). It can help us understand the situation of existing building and benefit to create a new way to design or upgrade architecture.

## PROTOTYPING AN INTERACTIVE INSTALLATION AS AFFECTIVE ARCHITECTURE

We applied the feather-inspired social media data processing to a studio design project that aims to produce a prototype of an urban transformable furniture for a University campus site. Sampled Twitter data was used to generate the initial 3D form which was inserted into the site. We are exploring two possibilities: (1) Augmented Reality Furniture (AR-F) exists in an augmented reality application (Figure 7); and (2) Real World Furniture (RW-F) to be realized in the real physical world (Figure 8).

## STRIP AS A DEVELOPABLE SURFACE

Our RW-F scenario suggests a strip-based architecture that flows through the spatial-user context as a bench-shelter-pavilion installation. By modeling the strip, we could develop the surface elements

Figure 7
Virtual Strip surfaces related to the social moods data on site

Figure 8
Physical 'Strip Shelter with Bench'

into 'controllable' and 'uncontrollable' panels. The ground-up portion of the furniture body is controlled in accordance with a specific function, such as a seat changed by the shape of the human body, while the sky-down portion can be perceived to change in accordance with the pedestrian flow which the installation has no control. Modern architecture employs different kinds of geometric primitives when segmenting a freeform shape into simple parts for the purpose of building fabrication and construction. (Pottmann et al., 2008). The next stage of this project is to approximate the initial conceptual surface into discrete fabricable strips-namely single curved developable surfaces.

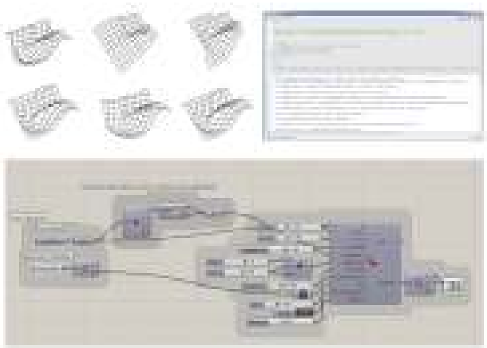


Figure 9
Shape rationalization and consideration of constraints by using ShapeOp

We use ShapeOp (Deuss et al., 2015) for shape rationalization and consider constraints such as mesh face planarity, vertex closeness and Laplacian fairing to explore the final output. The relationship between each group of points is controlled by a series type of constraints like the rule of the FIT-processed pattern. We then tried different combination of these constrains to explore a suitable shape optimization on the freeform strip surfaces, leading to developable surfaces that can be digitally fabricated.

## *GEOMETRIC DISCRETIZATION OF FREEFORM STRIPS*

A simple definition of a developable surface is a surface can be flattened onto a plane without distortion. We use the quad-dominant with planar faces under the feather-inspired pattern to produce a developable strip surfaces. D-strip models as semi-discrete surfaces can be applied to form PQ meshes (i.e., Quad meshes with planar faces) (Liu et al., 2006): the intersection of the row and column polygons produces a smooth curve network that leads the entire mesh converge to a D-strip surface. It is also shown that a semi-discrete representation of a series of conjugate curve network in a surface can provide a computational model to the fabrication of strip surfaces (Pottmann et al., 2008). We use ShapeOp to reconstruct the FIT-generated freeform surface such that each face of the quad-mesh is driven to be planar us-

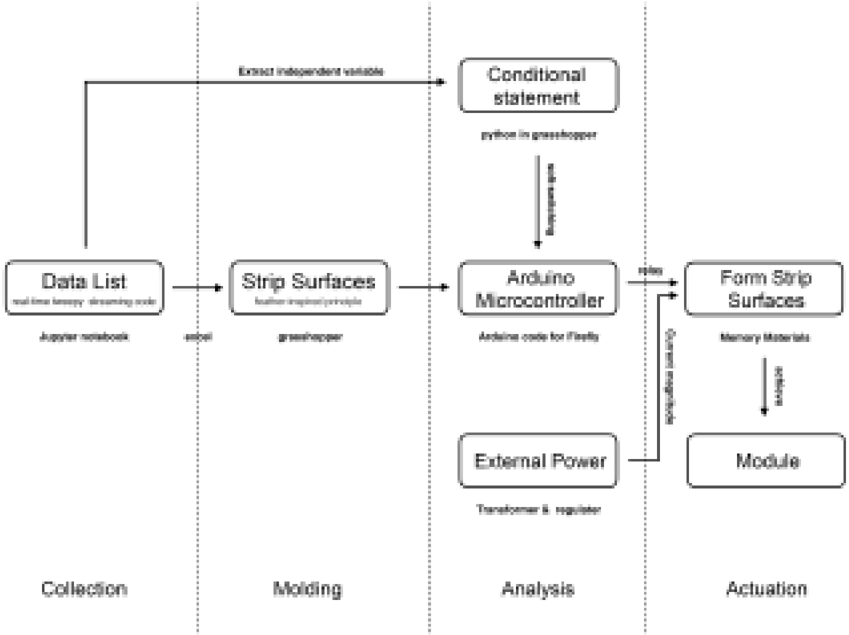



Figure 10
The generic system diagram of FIT process

ing the plane constraint, satisfying the semi-discrete rule as limits of discrete models (Figure 9). And another constraint is the closeness constraint that constraints each vertex to its initial position to maintain the shape of the mesh (Deuss et al., 2015).

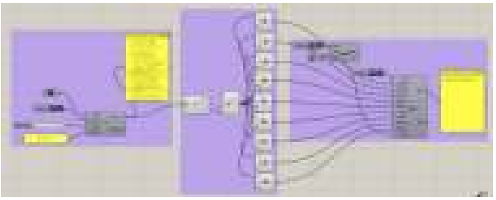


Figure 11
The generic conditional control system diagram

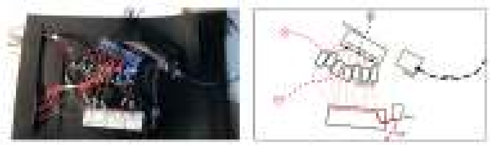


Figure 12
Conditional controllable circuit diagram

## ACTUATION OF INTERACTIVE STRIPS BY SHAPE MEMORY ALLOYS

Apart from being a developable surface, the strips in our prototyping installation design need to be actuated through social media data processing. The generic Feather-inspired Twitter (FIT) morphing system contains four stages: collection, molding, analysis and actuation (Figure 10).

It is connected by social data route under the feather-inspired rule and performs automatically to reveal the relationship between space/location and social elements (i.e., words expressing moods/emotions). The collection stage is operated using real-time tweedy streaming Python code on the Jupiter-Notebook platform presented in Section 2. And the molding step which transforms the data list to strip surfaces under the feather-inspired principle in Rhino-Grasshopper is presented in Section 3. The step of conditional statement for the stage of anal-

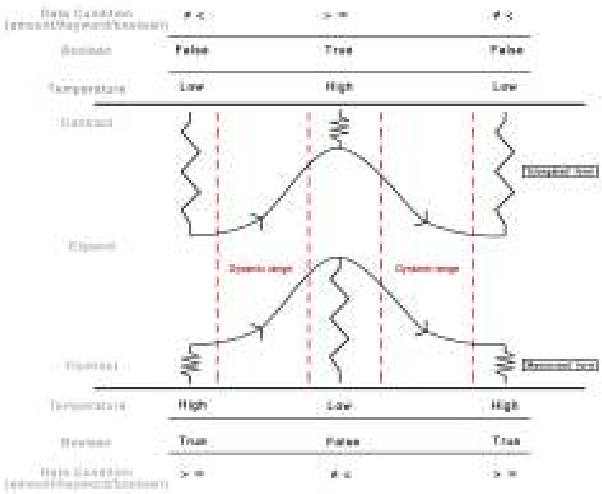



Figure 13
Form property of SMA is stretchable by applied force related to data type

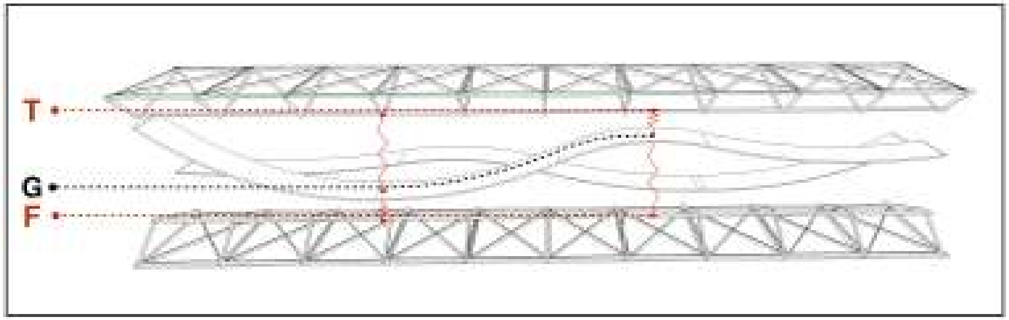



Figure 14
3-Pins controllable simulation unit framework

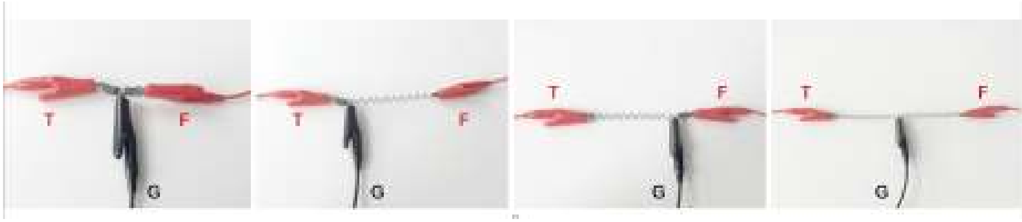



Figure 15
Deformation of SMA springs occurred when heated by different electric ending stimuli

ysis (Figure 11) is organized in Rhino- Grasshopper by the conditional code using Python script. After the step of conditional choose (Figure 11), the output data list will be send to the "Uno Write" component of Grasshopper-Firefly, and then upload to the Arduino board from computer through the Firefly code in Arduino.

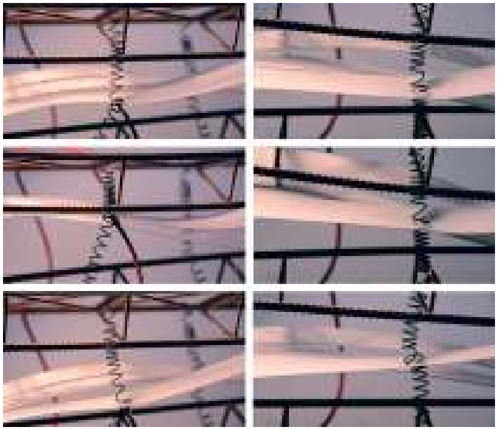


Figure 16
Interactive strips controlled by an array of SMA springs

Figure 17
Conditional controllable framework

The actuation system of conditional controllable circuit consists of two parts - external power system and Arduino conditional control system (Figure 12), connected by a multiply-relay. In the external power system, the power is come from alternating current transformer. Then the power is separated to multiply current routes to transform again by regulators to reach the needed current that leads to thermal effect of electric current. In this step, we can control the parameter of regulator to control the current which leads to different levels on actuation and kinetic transformation. Next, we input the multiply current into multiply relays to make the choices which pin it would be lead to (T/F, G is ground) (Figure 12). In the Arduino conditional control system, we input the social data from excel file into grasshopper, and write the conditional code to make choices automatically transforming the characteristic data to True (T) or False (F) signal, then upload these signals to Arduino Board through FireFly (Figure 13). Finally, we connect the Arduino Board to the multiply-relay that send these T/F signals to the Decision maker. Therefore, the multiply current could controlled by these multiply characteristic data, then flow the shape of shape memory alloy and developable strip surfaces (Figure 14).

For the actuation morphing module, we use shape memory alloy (SMA) as the main deformation material. They are usually shaped as wires or springs that could return to 'memorised' states when they are heated over the 'transform' temperature (60°C) (Figure 15). When programmed, the SMA-driven actuation system can pull the strip surfaces up or down. The thermal effect of the electric current offers the needed 'transform' temperature on the SMA components. We use 5V for a 3A current to heat the SMA springs to trigger elastic morphing lasting about 7-8 seconds. Figure 16 shows the use of regulators to control the ampere of current flow through a series of SMA springs. This process performs a dynamic range such that the SMA spring wires expand and contract in line with social data flows (Figure 17). Therefore, the SMA-based actuation design aims to perform in the prototype simulation for reliability, flexible and safety (Khoo et al., 2011).

## CONCLUSION AND FUTURE WORK

In this study we use public social media data to generate dynamic architectural form and behaviour as manifested in prototyping an interactive installation design. The social media data processing produces inputs to a feather-inspired form generation system which in turn generates freeform strips. We employ the ShapeOp Library to transform the freeform strips into developable surfaces such that they can be digitally fabricated. Movements of the developable strips can be actuated with a Shape Memory Alloy (SMA) driven kinetic framework. We close the loop by linking the social media data processing to the actuation control mechanism implemented on the SMA framework. The outcome from this study suggests a new proposition of affective architecture - an architecture capable of being affected by the moods/emotions expressed among social media users who also share relational experiences with that architecture. The implication is that future architecture can perhaps become more reflective of users' social awareness or consciousness of state of affairs or conditions such as well-being or sustainability. It will be no longer a person sitting in the control room who manages the building, but those living in the building or walking in the city, who use social media to show their moods, emotions and other things.

Architecture has always been an important boundary to define space. With the development of information technology, people develop virtual social boundaries with reference to physical spaces, and also endow the original space with a rich array of spatial attributes. Our digital design experiment explores new possibilities for social media data processing for form and behaviour finding. A series of design tasks were carried out using various technologies of collecting and analyzing social media data, 3D modelling under a new rule-based system, conditional scripting and electrical morphing module making. The design experiment also points to possibilities of future buildings built with an elastic morphing module plugged into to social media networks for occupants to change the space they live in. Future work will include further experiments to test the real-time morphing module using live social media data feed as a site-specific development.

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# Optimization of Facade Design for Daylighting and View-to-Outside

## *A case study in Lecco, Lombardy, Italy*

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*Minimizing the impact of shading devices on the view to the surrounding view is essential for indoor spaces that overlook exceptional scenery and views. Building facades that overlook such views require a special care not to obstruct the view to the outdoors. At the same time, poorly designed shading devices can result in high solar penetration and glare probability affecting the ability of the users to enjoy the outdoor view. In this paper, we analyze the effect of adding different shading devices and configurations to a south façade for a workshop space in Lecco, Italy. A parametric model of five types of shading devices was analyzed for the daylighting, glare and view performance. The trade-off between the objectives and the cases that achieved satisfactory performance in all three criteria were presented.*

**Keywords:** *Computational design, Daylighting, Optimization, View to outside*

## INTRODUCTION

This paper presents the result of an evidence base design project, for the Sustainable Building Technologies (SBT) course and studio of Architecture Design (AD), a mandatory course in architecture and building engineering master degree in Politecnico di Milano, Lecco campus. The multi-disciplinary design project aims to understand the integration between architecture, energy efficiency and construction technology, to apply innovative construction technologies and critic it per architecture design requirements.

The project's goal was to design a multi-functional building located in La Piccola area, in the historical industrial area of Lecco city, in Lombardy, north of Italy. The building's site is in front of the new campus of Politecnico di Milano. Site reconfiguration and the absence of residential complexes left the site with an unobstructed panoramic view of the surrounding mountains. The proposed design consists of three floors plus a ground floor with various functions related to the Politecnico di Milano, such as: sports center, library, study areas for students, auditorium, food court connected to the Lecco Market, and space for workshops with 150 m2 area. The workshop space covers most of the fourth floor. In order to provide a 360° panoramic view of the surrounding mountains, the fourth floor has floor-to-ceiling


Figure 1
Project Location and Building configurations in the site. the diagram shows the orientation of the third floor with the sun altitude

windows in all four orientations. This left the space, however, vulnerable to direct sun penetration. (see Figures 1 and 2)

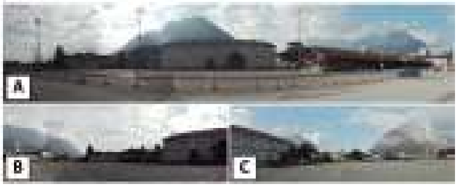



Figure 2
Panoramic view from the project site. Image (A), toward the south direction. (B, C) toward south west and east

Therefore, the biggest challenge facing the proposed project was to keep the view from inside to outside with minimum obstruction in all the directions while providing sufficient daylighting and minimal glare. The studied floor had a rectangular shape with the long sides having a North-South axis with a tilted angle of 10°, and the short sides facing East and East. While the North, façades don't receive high sun exposure for most of the day, the South façade is subject to high exposure for most of the day, throughout the year. East and West facades had a small impact on the daylighting performance of the space due to their relatively small area and being separated than the working space by the staircase and elevators cores.The four façades, especially the south, overlooks the best landscapes of Lecco since it looks directly on historical Lecco's mountains, Resegone, San Martino, Monte Moregallo, Grigna Settentrionale e Meridionale and Monte Barro. Hence, the importance of creating a 360° panoramic view while providing enough daylight for the workshop space. (see Figure 3)

The city of Lecco has a humid subtropical climate, with hot and humid summer and cold winter. The highest sun altitude in winter is of 20.8°, while in summer 67.4°. Moreover, the solar radiation can rise to 1600 kWh/m2 per year. The temperature rarely goes far below zero Celsius, the winter conditions nonetheless require non-negligible heating systems for the comfort. On the other hand, in summer, the high humidity and temperatures (often rising over 25° Celsius from June to August) require an equally important cooling load. As the air flow rate through the year is not adequate to provide natural ventilation, special attention for cooling and heating loads is necessary. Conventional design methods of passive techniques such as shading devices like horizontal shades, Venetian blinds and screens were historically used especially in south facades to reduce the sun exposure, provide adequate daylight and to reduce the glare probability.The concerns in using this kind of shading device are that it doesn't implicate the view factor to outside as a driving force for the design. Therefore, a trade-off between the different measures has to be reached in order to achieve a visual comfort and preserve the view of the surrounding alpine landscape. This paper discusses the relation between the two parameters (daylight and view) by applying daylighting and glare analysis as well as view assessment of different shading devices.


Figure 3
Visualisation for the case study. showing the usage of the interior space beside the southern facade.

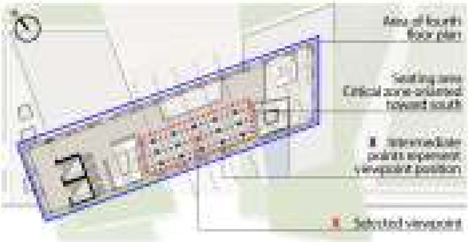



Figure 4
Third-floor plan. As shown the “critical” area of investigation - the workspace - with applied grid for setting intermediated points of examination.

## PREVIOUS WORKS

Shading devices were historically used to reduce the negative effects of direct sunlight and solar radiation inside buildings during cooling period and to permit heat gains during heating (Platzer, WJ.,2001). The impact of using traditional shading devices such as horizontal louvers and solar screens on daylighting, energy use and thermal comfort was studied by several researchers in different locations and climates. Yoo S, et al., (2011) investigated the usage of fixed shading devices on decreasing the thermal loads in addition to increasing the visual comfort and decreasing the glare, and, it was found inevitable to use it on the south facades, especially in Mediterranean climates. In a similar approach, Datta G. (2001) studied the thermal performance of a building with external fixed horizontal louver with variable slat lengths and tilts. LIGHTSCAPE software and PHOENICS Computational CFD package for natural ventilation were used by Hien and Istiadji (2003) to study the effects of 6 different shading device types on thermal comfort in a residential building in Singapore. Hammad and Abuhijleh (2010) analyzed the energy consumption of external dynamic louvers integrated to office building’s facade in Abu Dhabi. The impact of using different shapes of solar screens on daylighting and energy performance in hot arid climate was investigated by Sherif et al. (2012). Parametric and generative design tools allowed the creation of shading devices with a higher degree of geometrical complexity. El Ahmar et al., (2015) used a double skin facades inspired from nature to design a porous and folded façade for reducing cooling loads while maintaining daylight needs of office buildings in hot climatic regions. The possibilities of different arrangements of folded modules had been also examined to create environmental efficient kinetic morphed skins, to achieve different Kinetic origami-based shading screens categorized parametrically to provide suitable daylighting (El Ghazi et al. 2014).Kirimtat et.al, (2016) conducted a review of previous research work that utilized simulation modeling to analyze the impact of shading devices. More than a hundred paper were analyzed and organized by simulation type. Different types of simulation analyses were studied including the overall energy performance, daylighting, natural ventilation, indoor thermal and visual comfort among many others. However, it can be noted that only a few studies considered the view as one of the main objectives of shading devices design (Tzempelikos A.(2008), Kim & Kim (2010), Sherif et al. (2016)).

View to the outside is more than often left out during design, despite the undoubted importance of view and effects on users (Leather et al., 1998; Heschong Mahone Group, 2003), Hellinga and Hordijk (2014) attributes this to the reasons that research on daylighting and view quality belongs to different research discipline and secondly, there is usually very limited time and budget for architects and engineers to work on daylighting and view. Hellinga and Hordijk also found that users prefer distant and nature views and views that contain water. In design cases were view is an essential concern, such as spaces overlook-

| Shading type | Parameters | Range |
|---|---|---|
| Horizontal shading | Vertical Shading Angel (VSA) | 20° to 50° with a step of 5° |
| Vertical shading | Horizontal Shading Angel (HSA) | 20° to 50° with a step of 5° |
| Eggcrate | Vertical Shading Angel (VSA) | 20° to 50° with a step of 5° |
| | Thickness | 2.5 to 12.5 cm with a step of 2.5 cm |
| Diagrid structure | Vertical Shading Angel (VSA) | 20° to 50° with a step of 5° |
| | Number of Modules (Spacings) | 6, 12, 18, 24 and 30 Modules |
| Diagrid structure + overhang | Vertical Shading Angel (VSA) | 20° to 50° with a step of 5° |
| | Number of Modules (Spacings) | 6, 12, 18, 24 and 30 Modules |

Table 1
The studied shading devices and its parameters

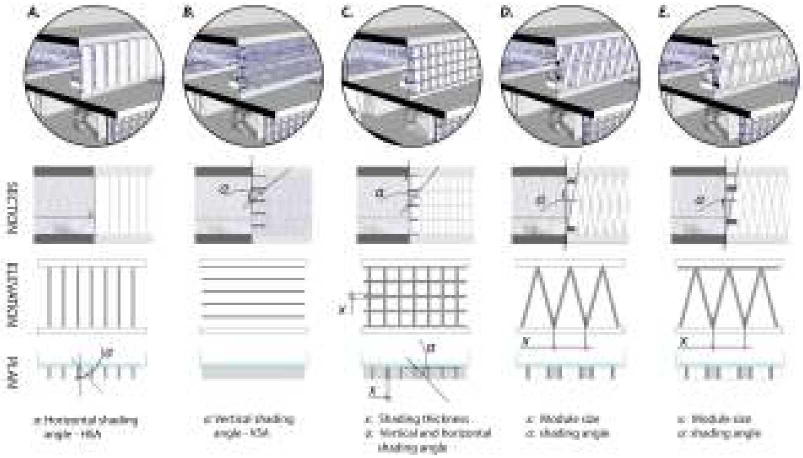



Figure 5
Main designed shading system selected. A.Vertical louvres. B.Horizontal louvres. C.Eggcrate. D.Diagird louvres. E.Diagrid with horizontal louvres. For each, the most effective variables were identified. represented in “modular size”, “shading angle” and “shading thickness”

ing important landmarks or natural features, such as the case presented in this paper, view to the outside cannot be neglected.This paper, therefore, tries to answer the question of How to design a shading system that ensures excellent daylight performance with minimum sacrifice of the view? In the design, utilizing computational and parametric tools to evaluate and optimize the shading systems for daylight and view quality.

## METHODOLOGY
### *PARAMETRIC MODELLING*

A parametric model for the multi-functional building was created using the Building Information Modeling software Revit. In order to have a greater control on the design parameters, the model was then exported to, and modified by, a visual programming language for parametric design Grasshopper. The investigated space, which is located on the top floor of the building, had the dimensions of 7.5 m x 20.0m with 3.3m ceiling height. Different types of shading devices were investigated for the daylighting performance, glare probability and view to outdoors. The performances of five shading devices were examined: horizontal shadings, vertical shadings, egg crate, an external diagrid structure, and an external diagrid structure with an overhang. For each of these shading devices, the impact of changing the vertical (or horizontal) shading angle was studied. The impact of changing the eggcrate thickness and spacing for the dia-

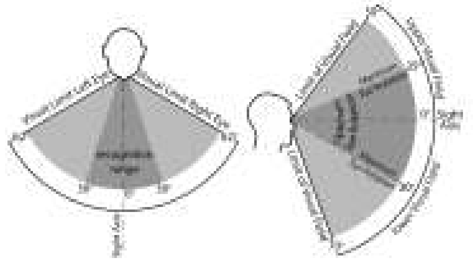
Figure 6
Diagram of the human cone of vision. showing the limit of the visual field and the area of recognition, in two directions, horizontally and vertically.

grid was also considered. Figure 1 shows an illustration of the five shading devices and their design parameters. 7 different cases for each of the horizontal and vertical shadings were studied and 35 cases for each of the other three shading devices. Overall 119 shading designs were examined. The ranges of the shading devices parameters that were examined are shown in Table 1. (see Figure 4)

## *SIMULATION METHODOLOGY*

Daylighting analysis was carried out using DIVA for Rhino, which is used as an interface to Radiance and Daysim simulation engines. The criteria used for evaluating the daylighting performance was the daylight availability which was found more suitable to the studied case. The DAv divides the measuring nodes according to three criteria daylit for points that receives illuminance between 300-3000 lux for 50% of the time, over lit for points that receives >3000 lux for at least 10% of the time and partially daylit for points that has illuminance values<300 lux for more than 50% of the time. The aim is, therefore, is to increase the daylit area of the space. The analysis grid had a desk-level height of 0.80 m and spacing of 0.60 m. (see Figure 5)

Glare and view analysis were conducted for a selective viewpoint that represents a seated person (height = 1.2m), 2.0 m from the facade and facing the window. For Glare analysis Evaglare was used to measure the discomfort using the Daylight Glare Probability (DGP) index. the GDP was analyzed at 9:00, 12:00 and 15:00 on the solstice and equinox dates to cover the different sun positions. In the DGP index, glare is divided into four categories: intolerable glare (DGP > 45%), disturbing glare (45% > DGPP 40%), perceptible glare (40% > DGPP 35%), and imperceptible glare (DGP < 35%). In this study, each category was given a score number with imperceptible glare having the highest score (3 pts) and intolerable glare the least (0 pts). the Accumulative Glare Percentage (AGP) is then calculated to compare the performance of different shading designs, where the highest possible value (100%) means that only imperceptible glare occurs at all times and the least (0%) indicates that an intolerable glare can be witnessed at all times.



For the view analysis, a view factor was calculated using 3D isovist. An isovist field is defined as ".. the set of all points visible from a given vantage point in space and with respect to an environment." (Benedikt, M. L.1979) . In this study, the vantage point is the same one defined for the glare analysis. A 3D isovist was created for the focal area of the viewer's field of view (see Figure 6). The ratio between the number points seen from the vantage point in each case to that without a shading device is calculated to compare between the different shading devices.

The results from the three analysis criteria, daylighting performance (DAv), Glare (AGP), and View Factor are compared to arrive at shading devices with a satisfactory performance. Acceptable values for the three criteria were assumed to be 75%, 50% and 50% for the daylight availability, accumulated glare percentage, and view factor respectively.

## RESULTS

### *BASECASE*

The unshaded facade was assumed as the basecase in this study in order to evaluate the effect of each shading device on the daylighting, glare and view performance. The basecase had a significantly low daylighting and glare performance due to the vast area of unshaded glazing in all its four facades. Due to the penetration of direct sunlight the daylit area reached only 36%, while the overlit area occupied almost two-thirds of the space. The accumulative glare score was found to be very low with a value of 13% as an intolerable glare was witnessed in most of the cases with the exception of the morning hours. however, even at this times, a perceptible or disturbing glare was witnessed. Although the basecase has a panoramic view with only the internal structure as a physical obstacle, such a high probability of glare occurrence and sun penetration would surely affect the possibility of enjoying the view.

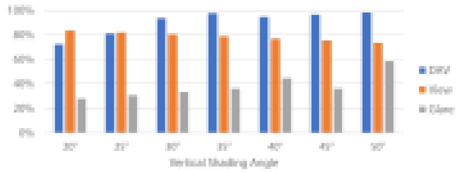


Figure 7
Daylighting, glare, and view performances for the horizontal shadings

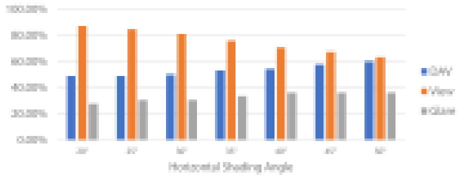


Figure 8
Daylighting, glare, and view performances for the vertical shadings

## *HORIZONTAL AND VERTICAL SHADINGS*

The horizontal shading devices enhanced the daylighting performance greatly were most of the cases had over 90% daylit area percentage, in comparison to just 36% in the basecase. The glare analysis, however, showed a high probability of glare occurrence and only one case achieved an AGP higher than 50%. The impact on the view was, however, better than anticipated with only between 17% to 27% of the view obstructed. Cases with larger extrusions (higher shading angles) had a better daylighting and glare performance while cases with smaller extrusions had a better view factor.

In contrary, vertical shadings provided a poor but mostly acceptable daylighting performance. The daylit area percentages ranged between 49% with a Horizontal shading angle = 20°, and 60% with HAS= 50°. Glare analysis also showed a high probability of glare occurrence all year round with a maximum accumulative score percentage of 36%. Nevertheless, the view factor was also found acceptable in all the cases with a maximum view factor of 87% and a minimum of 64%. Figures 7 and 8 show the daylighting, glare and view performances of the horizontal and vertical shadings.

## *EGGCRATE*

Thirty-five cases of eggcrate shadings were analyzed. Almost all the cases achieved over 80% daylit area and half of the cases reached 100% daylit area. Nevertheless, unlike the horizontal and vertical shading, the eggcrate reduced the chance of glare occurrence significantly. Most of the cases had an acceptable accumulative glare percentage and in few cases the AGP reached more than 80%. This, however, came in the expanse of the view performance. With the eggcrate cells causing a significant obstruction to the view, the view factor was found to be unacceptable in most of the cases. Only cases with very small thickness (high perforation ratio) and small extrusion achieved acceptable view factor. However, in these cases, the glare performance was at its lowest values and was below the acceptance threshold. Only one case achieved an acceptable performance in all the three criteria which had a thickness of 2.5 cm and 35° shading angle.

## *DIAGRID STRUCTURE*

All the 35 cases of the external diagrid structure had a good impact on the daylight performance with a minimum daylit area percentage of 76% and nearly half of the cases with 100% daylit area. Similar to the egg crate, the diagrid structure also enhanced the visual comfort significantly as the glare probability decreased and the AGP reached 100% in several cases. The external view also showed satisfactory performance with a maximum of 85.54% and most of the cases with view factor higher than 50%. Nine different cases achieved a satisfactory performance in all three areas of analysis. Figure 10 shows the performance of the diagrid cases. Cases with acceptable performance in all of the three criteria are highlighted)

## *DIAGRID WITH OVERHANG*

This unique shading solution aimed at combining the positive impact of both horizontal and diagonal shading devices. Once more, 35 different configurations were tested. It succeeded in achieving notable improvements in all of the three criteria. Daylighting performance achieved more than 90% daylit area in all cases with most cases having a 100% daylit area percentage. Glare probability also improved as almost all of the cases had an acceptable performance and AGP reaching 100% in few cases. While not all the cases had a satisfactory view performance, in many cases the view factor had an acceptable value and reached a maximum of 86%. In many cases the daylighting, glare and view were found to have acceptable and significantly improved performances. One notable case was with 45° shading angles and 6 modules of diagrid external structure, where daylit area percentage reached 100%, AGP of 75% and view factor of 71%. Overall 14 different configurations achieved an acceptable performance in all the three criteria.

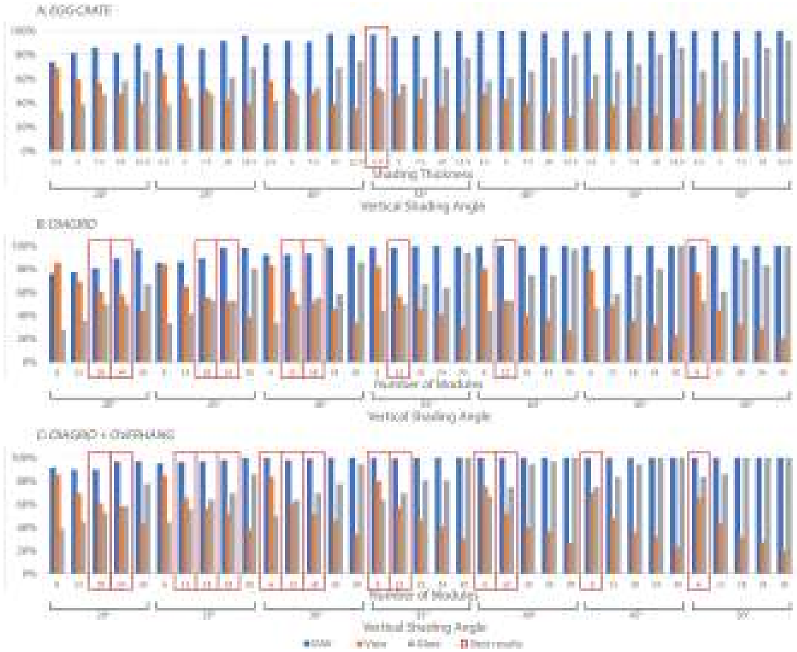



Figure 9
Daylighting, glare, and view performances for the Eggcrate, Diagrid, and diagrid with overhang shadings. The cases with satisfactory performances are highlighted.

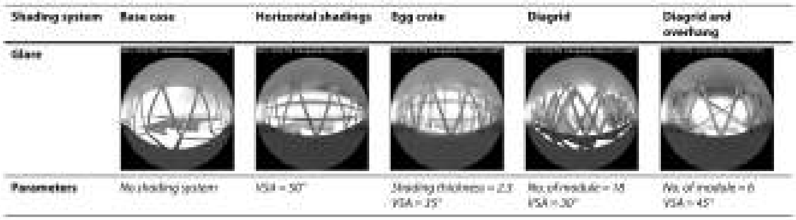



Figure 10
Glare performance at 12:00 on 21 June for the base case and four different shading configurations

Figure 9 shows the daylighting, glare and view performances for the eggcrate, diagrid and diagrid with overhang. The cases that achieved an acceptable performance in the three criteria are highlighted. Figure 10 shows the impact of the different shading devices in comparison to the basecase on the glare performance.

## DISCUSSION AND CONCLUSION

This paper presented and discussed a design approach for designing building facades that overlook exceptional scenery and views, which requires special care not to obstruct the view to the outdoors. Nevertheless, poor shading design can usually result in high solar penetration and glare probability affecting the ability of the users to enjoy the outdoor view. In this study, 119 different configurations of five shading types were investigated. Overall, 25 different configurations from 4 types of the shading devices achieved a satisfactory performance for daylighting, view and glare. The combined shading of an external diagrid structure and a horizontal overhang offered the best performance with 14 cases, followed by the diagrid shading and eggcrate and horizontal shadings. For future work, and depending on the case study other aspects such as energy consumption, Life Cycle Analysis, and Life Cycle Cost could be included in the framework.

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# Sun Shades

## *About Designing Adaptable Solar Facades*

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*External shading structures are a well-established typology for reducing solar heat loads. A major disadvantage is their inflexible nature, blocking views from inside and desired solar radiation for seasons with less sunshine hours. An adaptive approach on the other end can accommodate dynamic environmental exchange and user control. Furthermore, kinetic movement has great potential to create expressive spatial structures. However, such typologies are inherently complex. This paper presents the design process for two novel adaptive façade typologies, conducted on an experimental level in an educational context. Moreover, we will discuss the conception of a suitable methodological framework, which we applied to engage the complexity of this design task. Thereby we will highlight the importance of employing various methods, combining analogue and computational models not in a linear sequence, but rather in an overlapping, iterative way to create an innovation friendly design setting. The Sun Shades project offers insight into the relationships between design potentials inherent in adaptable structures and the advantages and limitation of computational methods employed to tackle them.*

**Keywords:** *computational design methodology, performance-based design, associative geometry modelling, solar simulation, physical form-finding, design theory*

## INTRODUCTION

*Sun Shades* is a project-grounded research studio (Findeli et al., 2008) exploring design possibilities for two novel adaptive solar façades typology on a prototypical, experimental level. It combines passive shading with energy harvesting through a kinetic concept; strong emphasis is placed on exploiting the expressive and spatial potential of such structures. Key design drivers include lightweight construction, spatially extending structures, low maintenance soft actuation, the capacity to adapt to environmental change through movement and a certain geometrical 'fuzziness', which allows the structure to adjust to different urban situations. (see Figure 1) The chosen technological basis are organic photovoltaic cells (OPV).

Computational design practice offers many advantages to tackle the complexity of such a task.

Figure 1
Design Concept Solar Swarm. Spatially extending structures as scenario for the integration into different urban situations - ´Solar Swarm´

However, they can also present a serious limitation concerning design innovation and creativity, because creative approaches require complex, ill-defined problems offering enough freedom to develop novel solutions (Sakatani 2005). Consequently, we employed a design methodology which included various analogue and computational models to create an open, innovation friendly design setting.

This paper offers both, insight into the conception of two functional adaptive, lightweight solar façades, on a prototypical scale, named *Miuso* and *Sola Swarm*, realized by a multi-disciplinary team of future architects, designers and engineers as well as a discussion about designing an adequate design methodology. We (a) identify key issues and design drivers relevant for the development of responsive kinetic solar façades. Furthermore, (b) we discuss potential advantages and limitations of digital design methods. Based on this discussion, we (c) present an open methodological framework, capable of representing interdependencies of analogue and computational tools, which informed design decisions across different design stages and scales. Finally, we demonstrate (d) how this framework was implemented in the actual design process and summarize our conclusions.

## KEY ISSUES OF CONTEMPORARY FAÇADES

The project starts with the simple assumption, that a large number of heritage buildings can be retrofitted with external solar shading structures, like Volker Staab´s *C10 High-Rise* Building, to reduce power consumption. In contrast to hermetically sealed, single-layer envelopes, external sun shading systems allow for environmental exchange and spatial expression. Such *second-degree auxiliary structures* (Hensel 2013), behave more like a membrane and less as barrier.

The major drawback of external sun protection, such as Le Corbusier´s seminal *Brise Soleil*, is their immovable nature potentially blocking views to the outside or desired solar radiation at winter times. The latter can be especially problematic for locations in central Europe, where only 35% of all daylight hours show actual sunshine (Achstetter 1995). Adaptable structures are a potential solution.

## FROM DESIGN POTENTIALS TO DESIGN DRIVERS

Based on this analysis, we identified the expressive and spatial potentials of kinetic structures in combination with solar shading and photovoltaic energy performance as key aspects for our *Sun Shades* façade typology. Four initial design drivers were selected to define the scope of our design framework: *spatial movement, adaptability, lightweight and organic photovoltaics*.

Existing examples of kinetic facades include the *Al-Bahr* Tower in Dubai or Jean Novell's *Institute du Monde Arabe* in Paris. However, they are either limited to passive solar shading, require massive substructure, or are comprised of highly mechanistic and complex components. Neither of those projects combines adaptive solar shading with photovoltaic energy production. A recent research project, *SoRo-Track* (Svetozarevic 2016) highlights the importance of designing appropriate actuation and movement control systems.

Figure 2
Example
Adaptability
´Miuso´

The driver **spatial movement** addresses a twofold aspect of kinetic structures: the aesthetics of the actual movements and the potential to exploit the three-dimensionality inherent in this movement. Both aspects require a rethinking of immobile façade solutions. Patrick Schumacher argues for a "differentiation of façades with respect to environmental parameters" (Schumacher 2009). However, our approach should not result in a parametric patterns without the possibility for actual dynamic responsive behavior. (e.g. as in Zaha Hadid´s *Madrid Civil Courts Proposal*)

**Adaptability** describes the capacity to respond to changing environmental parameters through movement. A good example is the bi-metal installation *Bloom* by Doris Sung, as it varies the permeability of its skin according to surface temperature. However, Adaptability refers in this paper also to the topology of a structure, which allows for the adjustment in relation to different architectural geometries. (e.g. sun screen for double curved facades). (see Figure 2)

The design driver **lightweight** refers to structures, which are physically and aesthetically light and which control their movement easily and logically with as little components as possible.

The implementation of organic photovoltaics forms the technological basis. We have chosen cells, sponsored by Opvius GmbH®, with an electric efficiency converting approx. 5 % of total sun power to energy. Although, overall efficiency is lower compared to high performance silicon based photovoltaic cells with approx. 20%. However, OPV cells do not suffer from substantial efficiency loss in case of partial coverage or imperfect solar angles. The cells are light, flexible, and partially transparent. The amount of grey energy required for their production is regained within days. Summing up, their properties are ideal to speculate on novel architectural applications and spatial potentials.

## DIGITAL DESIGN METHODS - THEORETICAL BASIS FOR DECISION-MAKING

Rittel and Webber observation that for wicked problems, "the choice of explanation determines the nature of the problem's resolution" (Rittel at al. 1973), was the starting point of our considerations about method design. We conclude, that how and by what means a design subject is approached already implies its potential solution - assuming, that a set of methods, at least implicitly, represents the explanation of a problem. For the *Sun Shades* project, we implemented several distinct methods to create a framework that is innovation friendly, generating solutions to address differing requirements in various fields. Methods design is a challenging task prone for misconceptions. Nevertheless, it offers abundant possibilities for new opportunities.

The multidisciplinary nature of our project, with its manifold areas of exploration, representation and realization, resulted in a high "effective complexity". Gell-Mann and Loyd defined complexity "as the length of a highly compressed description of [an entities] regularities" (Gell-Mann et al.. 2004). In the case of the *Sun Shades* project, a substantial amount of these regularities consists of relationships between geometrical elements and physical properties, within a kinetic, spatially expanding structure. From this perspective, digital design tools and strategies, potentially combined into a single process chain (see Figure 3), seem at first to be a self-evident choice, offering obvious advantages for exploring and maneuvering this complexity.

### *Potential advantages*

Geometrical, mechanical and kinetic qualities situate perfectly well within the realm of direct digital representation, because of their mathematical nature. Methods of "associative geometry modelling" (Burry 2003), geometry modelling in combination with physical analysis, allow to use resulting simulation data immediate for geometry formulation, or for iterative strategies like topological optimization. This facilitates a seamless extension of the digital, associative design model, which can include production data and assembly information. Furthermore, it can prevent, for example, fabrication and communication mistakes. If the final design consists of a high number of individualized members, or if its geometry adapts in detail to physical parameters, associative design modelling even becomes imperative. By altering design parameters, many variant solutions can be generated and easily evaluated. Next, the entire data model can be used as sole, central structure, as interface, which provides, for example all necessary data for model-making, prototyping, and for producing representations. In case of design thinking, the need to transform design intensions into formalized descriptions of relationship helps to reveal and structure a projects complexity. The digital design process can be understood "primarily as a disclosure of constantly reappearing patterns of thinking that govern the design process" (Kotnik 2011). Thus, a digital design process clarifies these thinking patterns and helps to develop the underlying methods concisely. However, this clarification process requires the interchange of project information, to use digital models as a medium for knowledge interchange.

The algorithmic representation of some design maps like the *Analysis-Synthesis-Evaluation Model* (Gero 1999) is similar to the representation used to depict algorithmic structures (i.e. flow diagrams of parametric models) - design as logical process, nicely organized in clear causal structures.

However, from a more practical, designerly point of view a design process can also be represented as "negotiation between problem and solution through the three activities of analysis, synthesis and evaluation" (Lawson 2006). This negotiation involves human communication and therefore inevitably a certain degree of vagueness. Negotiation refers, according to Lawson, to problem definitions, constraints and solutions, which are comparable to moving targets, adding a touch of unpredictability. Consequently, it seems natural to understand design as a fuzzy, potentially even messy activity, a far cry from well-organized structures. (see Figure 4)

For such a concept, effective complexity unfolds by imagining increasingly precise future designs in their different, dynamic forms of manifestation. This is not only true for clear, pre-rationalized cause-result-structure (read planning), but also for a post-rationalization approach, where the arguments may follow the solution. Moreover, the arguments may not necessarily align with any formal connection in this growing design mycelium of different positions, definitions and solutions, generated through a broad variety of tools and techniques.

Resuming Rittel´s argument, that our "´world view´ is the strongest determining factor in explaining [...] and therefore resolving a wicked problem" (Rittel at al. 1973), signifies that this is also true for the meta-task of designing a framework of design methods. A diversity of opinions, tools and methods favors different perspectives on a given design subject, and therefore expands the potential solution space.

### *Potential limitations*

However, a mindset appropriate for developing algorithmic design models is not necessarily suitable for an open, innovation friendly design setting. Thus, the just described advantages of a digital design perspective can also present potential limitations. These limitations may narrow the designers view on the problem at hand and constrain design possibilities to the solution space of his or her digital box.

It is rather doubtful, whether decision patterns, expressed in a digital design model, originate from considerations relating to desired design qualities or whether they are superimposed by instrumental needs related to the implementation of digital strategies. Therefore, the argument is relevant, that digital design has a tendency to favor cognitive patterns related to organization and hierarchy (read quantity) rather than patterns related to topology (read quality) (Kotnik 2011). Furthermore, representing design ideas within associative models implies an *´Ockham's Razor´*, which permits only information to pass, that can be explicitly expressed through formal language, favoring convergence over divergence and syntactic strength (read rules) over semantic (read meaning). Finally, activities associated with creativity have their own, non-linear temporal rhythms and rational-

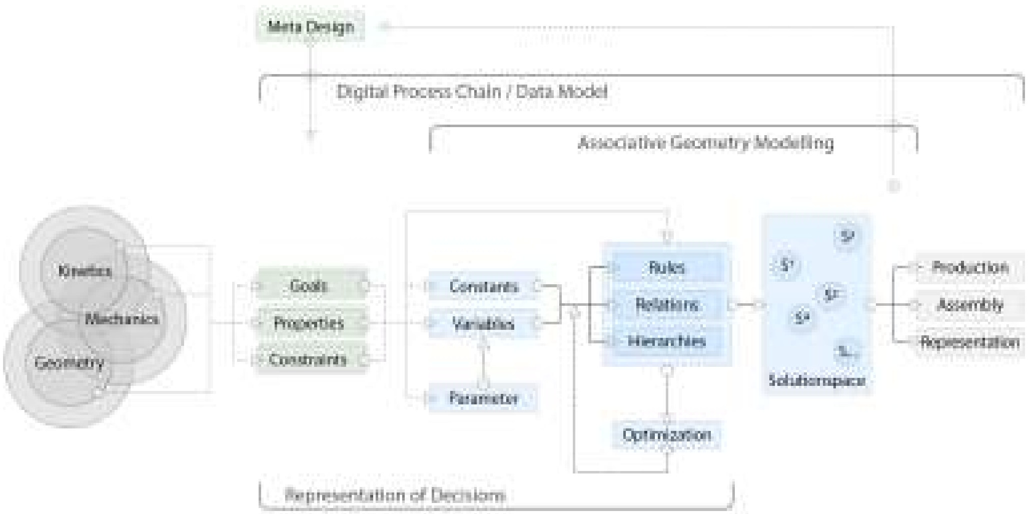


Figure 3
Generalized structure of a potential digital design process for the Sun Shades project, based on an associative geometry modelling (blue). The development of such a data model is a (meta-) design task on its own and superimposes the design intentions.

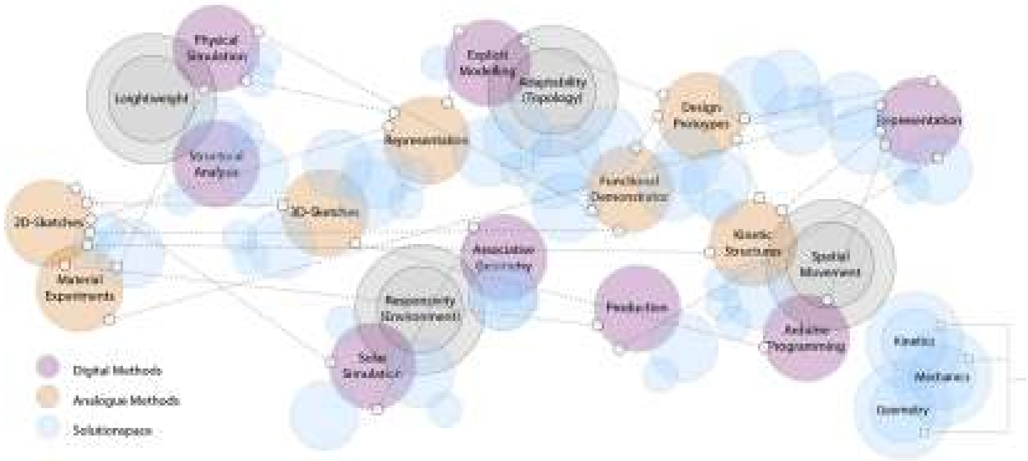


Figure 4
Network Design Model incoporating multiple methods and tools

ization strategies. These are different from the ones in digital modelling, characterized by the slow accumulation of a multitude of building blocks in a strictly causal, linear way.

## APPLIED DESIGN METHODOLOGY

Seeking for heterogeneous and experimental solutions, our foundation was not based on a single consistent digital design model. Instead, we used explicit geometry modelling, physical simulation, radiation analysis and some ´on-the-fly´ made grasshopper snippets as separate elements. A broad range of analogue modelling techniques accompanied the computational ones: two- and three-dimensional sketching, physical form-finding, and experimentation of material properties, kinetic models, mock-ups and prototypes, among others.

This diversity of modelling strategies facilitated explorations into different fields, mutually informing each other, without the need to connect them formally. Different patches of an associative computational model formed integrated but not limiting elements of this weave (read tools and methods).

Clearly formulated design tasks encouraged the use and interplay of those methodical patches along almost all stages of the design process, allowing for recapitulation of design choices from different perspectives. The result was a dynamic, accumulating network of models, representing a multitude of aspects of design knowledge and decisions.

## PRACTICAL IMPLEMENTATIONS

This paragraph exemplifies the practical implementation of our methodological setting, with the aid of our design drivers, reflecting on the design process from conception to completion of two fully functional demonstrators.

The design driver **spatial movement** implies a strong interest in the expressive potentials of kinetic structures. (see Figure 5)
In reference to Manuel de Landa´s interest in materials that "compute" form, we started with material properties and physical forces that "compute" movement (Landa 2010). This shows that analogue

Figure 5
Kinetic structures – Examples of video stills from the initial workshop. Wet paper stripes animated by a hair dryer, party balloons expanding in a tangle of threads, gravity induced swinging and tension induced folding.

form-finding procedures facilitate not only structural formation and expedite design decisions regarding shape but also regarding movement. The results confirm that analogue form-finding facilitates structural formation and expedites design decisions regarding shape and movement.

From this pool of ideas, some kinetic strategies advanced further. Refinement included cross pollination with information from solar, structural or fluid physics simulations, as well as with constraints inherent to different forms of movement actuation (i.e. pneumatic vs. mechanic). Other tools, besides physical models, were used to investigate movement scenarios. For example generated the use of *Blender*, a fluid physics simulation insight into the differing behavior of pneumatically inflated geometries.

An alternative approach analyzed the interdependencies between geometry and movement of traditional origami pattern through simple paper models. The results were diagrammed graphically, transferred into a three-dimensional digital model from which the unrolled geometry served as production data for a cnc-cutting center.

The qualities of a movement cannot be characterized solely through static forms of representation. Therefore, investigations refining speed, sound and movement choreography included prototypes, physically inflated by lungpower, bicycle pumps or a compressor, as well as the programming of physical computing components to test *muscle wire* actuation (e.g. shape memory alloys) or the behavior of pneumatic valves. This all shows that advancements evolved not in a linear fashion, but rather in a fractal way, leaping for example form physical model to computational simulation and physical computing.

The design driver **adaptability** is one of the key aspects of the Sun Shades project, referring to both kinetic and topological adjustment. Kinetic adaptability reflects the complex relationship of environmental exchange over time. Topological adaptability addresses the adjustment to different architectural geometries. The latter was mostly tested through a series of visualizations for different scenarios.

Kinetic adaptability designates, in our project, a specific focus on combining photovoltaic energy production and shading, which requires the functional adjustment of movements in time and space. The team used solar simulations (in this case off-the-shelf available Ladybug plug-in for Rhino Grasshopper) as a "[...] tool [...] to develop intuitions and analysis of performance" (Marsh et al. 2011). In our case, it supported a better understanding of the complex relationship between sun vectors and geometrical organization over time. (see Figure 6)

Digital solar analysis tools were applied in two ways, in a concise associative geometry model and

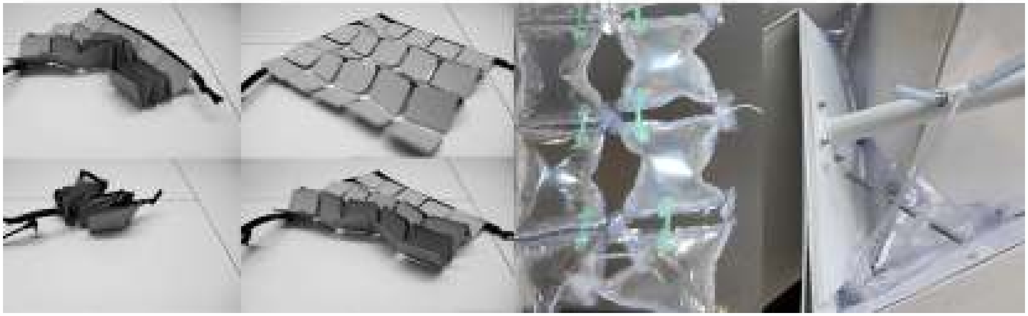

Figure 6
Physical samples from different stages showing movement's development process - ´Miuso´

at the end of various short digital process chains. The latter proved especially useful to inform design decisions by testing widely different geometric typologies (i.e. rotating logic vs. folding logic), and to test variations of macro-geometry orientation together with different opening states of photovoltaic cell assemblies. The former was used in a more general, educational sense, to provide an example how solar simulation data can directly inform geometry (e.g. size and inclination of elements) to understand and modify shading effects for summer or winter scenarios. Moreover, estimating overall photovoltaic energy performance, based on total sky radiation, proofed crucial for the communication with the engineering part of the team to determine the basis for self-sufficient actuation options. This knowledge sharing resulted for example in a kinetic scenario, which induced reactive movement. Light sensors triggered pneumatic actuators, controlled by physical computing components. (see Figure 7)

Lastly, a **lightweight** approach, matching the ephemeral aesthetics of OPV solar cells, requires material optimization and the actuation of movement with as little components as possible.

The *Miuso* team tested a topological optimization approach, which resulted in the increased structural stability of solar panels. The form of the panels evolved through a series of structural simula-

Figure 7
Setting for Arduino controlled pneumatic valves. Simulation of virtually inflated pillows - ´Solar Swarm´

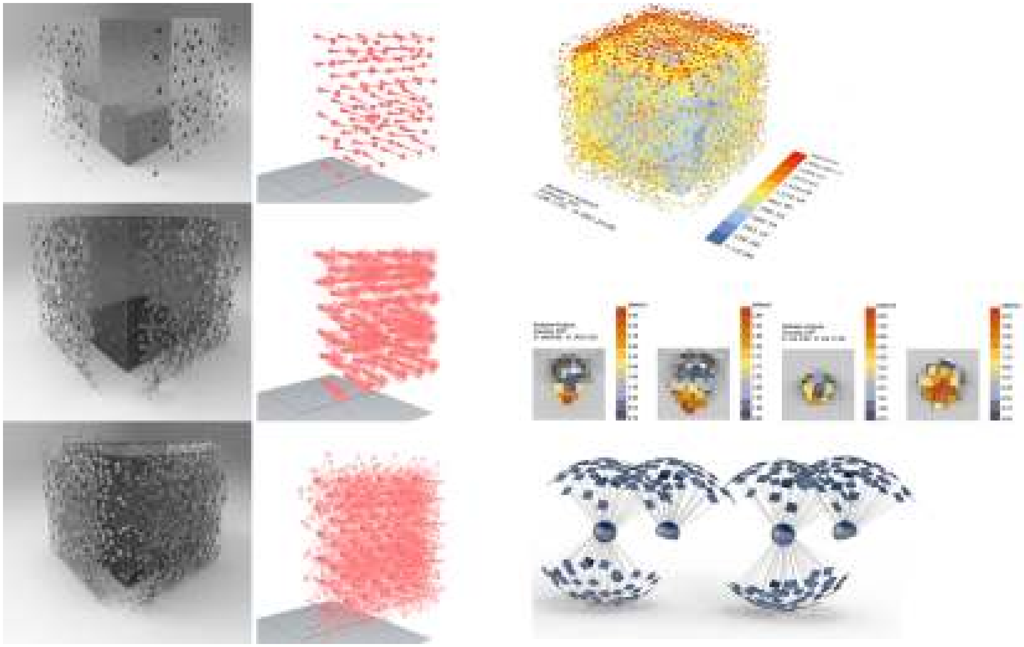

Figure 8
Exploring and representing adaptability with different digital models, derived from a single grasshopper description - ´Solar Swarm´

tions, conducted with Karamba plug-in for Rhino Grasshopper, to inform the topology of the supporting structure. These structures where then crosschecked through physical porotypes, realized by vacuum forming polyethylene-foil over a three-dimensional, cnc-milled mold.

The *Solar Swarm* team on the other end based their approach on the material properties of the available OPV-cells. They used the orientation of tree leafs and their growth patterns as functional metaphor to generate an assembly logic, based on soft, flexible and dynamic properties. In contrast to the Miuso team, this solution was mainly developed by a systematic series of physical models and prototypes, until the successfully implementation in form of a 1:1 prototype. However, a more rigorous computational analysis would have been necessary to develop this notion further. (see Figure 8)

## CONCLUSION AND FUTURE RESEARCH

To summarize, we can recommend our strategy of loosely connected ´method-patches´ as an innovation friendly way to combine digital and analogue models. It uses the advantage offered by digital design methods without implementing its biases. Although the specificity of our task does not allow for an overall generalization of this framework, it illustrates however, that a creative design practice can profit from combining computational methods with other raw materials for the advancement of ideas.

The methodical framework resulted in various novel design approaches. Within seven weeks, we had nine different, concepts for new types of solar facades, showing innovative, and at the same time realistic designs. From there, it took another seven weeks two develop two concepts further, *Miuso* and *Solar Swarm*, which are represented in this paper.

Quite often educational projects with such a broad, ambitious agenda show tendencies to diffuse their efforts and end up following design tasks of minor importance. This was not the case in the Sun Shades project, portraying a good balance between divergence and convergence. We assume, that our framework not only ´softly´ urged students to use multiple methods in an interrelated way, but also to evaluate and discuss their progress with each other. Consequently, knowledge in one area of expertise (e.g. analogue models) informed other areas (e.g. physical simulation or other computational techniques) in this network. Particularly the digital physical simulation reconnected our design investigations always with the properties of the real world; thus this tools formed a perfect connection to our early, vivid experiments.

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# Thermal and Daylighting Optimization of Complex 3D Faceted Façade for Office Building

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*Conventional façade design and its impact on building energy as well as indoor comfort is a well-researched topic in the architecture field. This paper examines the potential of a complex 3D shaped building envelope, elaborating on previous work by implementing energy simulation within the building façade optimization process. The multi-objective optimizations are conducted considering total thermal energy, electricity generation through BIPV, and daylighting in generic single person office rooms under meteorological data of Korea and Singapore. The performance of the non-dominants is analyzed and the results show an improvement in all objectives comparing with the preliminary study.*

**Keywords:** *Parametric facade design, muli-objective optimization, energy optimization, daylighting, form finding*

## INTRODUCTION

Designing façades is a crucial task for architects and engineers considering its high impact on energy performance, thermal and visual indoor comfort, and aesthetic appearance of buildings. The total energy consumption of a building mostly depends on energy need for heating, cooling and dehumidification, as well as artificial lightning along with other factors. Solar heat gain can be achieved and used effectively in a cold climate as the Window-to-Wall Ratio (WWR) increases, however, it leads to the increase of cooling loads as well as visual discomfort in the building. Conversely, when WWR decreases, the amount of light coming through building fenestration reduces, thus leading to the rise of energy need for artificial lighting in the building. Therefore, in order to attain successful designs with the consideration of proper thermal and daylighting performance, building façades should be optimized taking into account the composition of its most common elements that influence them most. Such elements are: opaque walls and semi or full-transparent windows with the combination of external shading devices and building integrated photovoltaics (BIPV).

In literature, a vast number of studies have been carried out to adjust the relationship of physical and thermal properties of these elements. In Echenagucia et al.'s study, the position, number, and shape of the fenestration, as well as the wall thickness were investigated with the multi-objective optimization method (Echenagucia et al. 2015). The single corridor office building's façade has been optimized in terms of thermal and visual comfort (Goia et al. 2013). As a result, a WWR in the range of 35-45% is found optimal considering an oceanic climate zone. External shading devices were investigated by different authors with a variety of parameters. Ho et al. optimized the linear horizontal external shading de-

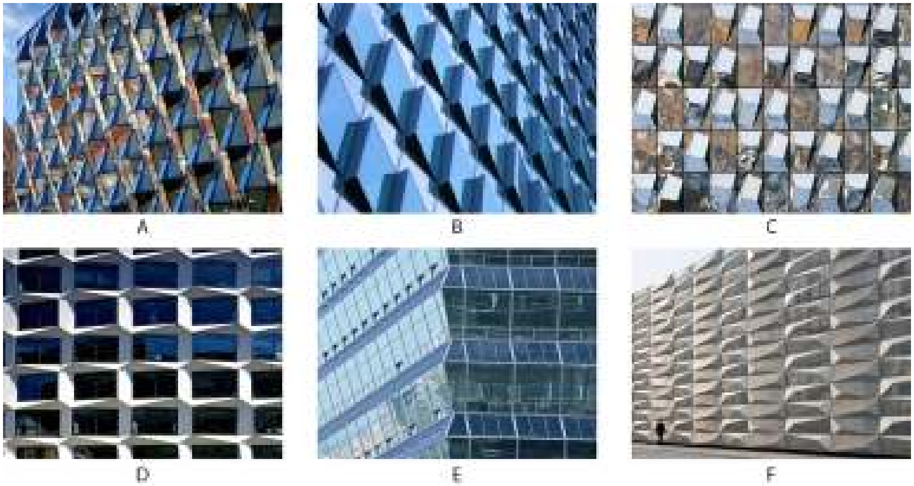


Figure 1
Non-planer facade building examples

vice for a classroom façade in subtropical climate (Ho et al. 2008). As a result, 70% of energy saving had been achieved along with indoor illuminance improvements. The inclination angle, the width, and the distance from façade (Manzan 2014), and also the number, width, and limited inclination of angle (González and Fiorito 2015) of external shading devices have been optimized with multi-objective optimization.

Although above-mentioned studies successfully explore optimal solutions, the majority of the research considered the performance of a homogenous flat shaped façade, and almost no studies were found of a 3D or complex façade replicating the conventional method. In spite of the relatively less academic research, the interest of more complex shapes and patterns applied to the building façade is growing significantly in contemporary architecture due to technological and fabrication advancements (Rahimzadeh et al. 2013). Moreover, the non-planar complex shaped buildings are becoming familiar in urban areas; some examples of such buildings (Figure 1) are the 367 Oxford Street by Future Systems (A), Ropemaker Place in London by Arup Associates (B), Trutec Building in Seoul by Barkow Leibinger architects (C), One Coleman Street by David Walker Architects (D), FKI tower in Seoul by Adrian Smith + Gordon Gill Architecture (E), S2OSB Headquarters Conference Hall by BINAA (F).

This paper emphasizes and elaborates on the multi-objective optimization of a complex 3D façade, specifically including the energy simulation modelling and its often contradictory objective to natural daylighting. While this work builds upon previous work, the main differences are the integration of energy simulation in the optimization process and the number of testing units as well as a different location of the building within a different climatic zone.

This paper starts with the literature review of building façade design, performance, as well as façade optimization followed by the façade generation method. Furthermore, the simulation environment and base case simulation (the preliminary study) as well as two types of pattern optimizations are presented in both locations.
The results of multi-objective optimizations are explicitly presented after the base case study followed by the analysis of the results. Finally, the findings are discussed and research limitations and future works are identified.

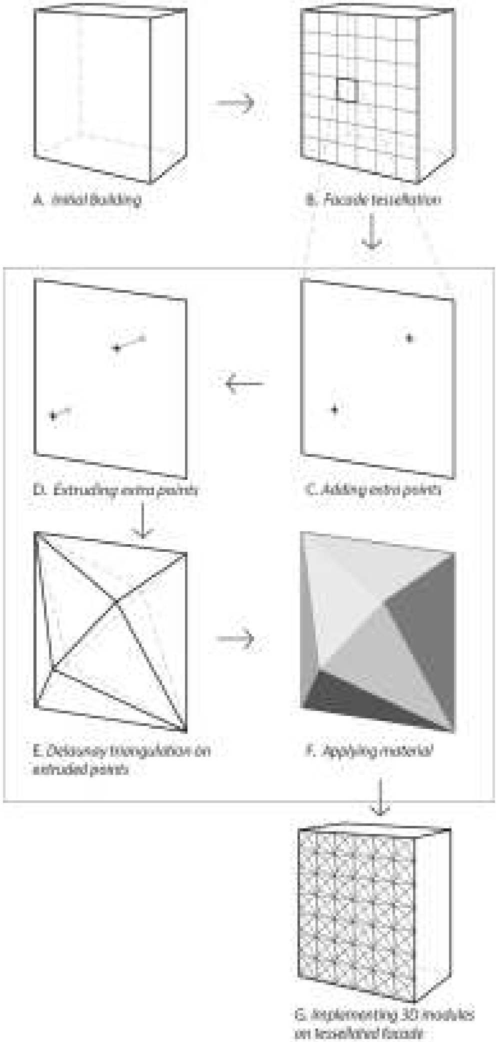


Figure 2
Facade generation method

## LITERATURE REVIEW

Conventionally, rectangular fenestration on a flat vertical surface is the most common practice in façade design. A variety of research and experiments have taken place to find the most ideal method to meet their needs.

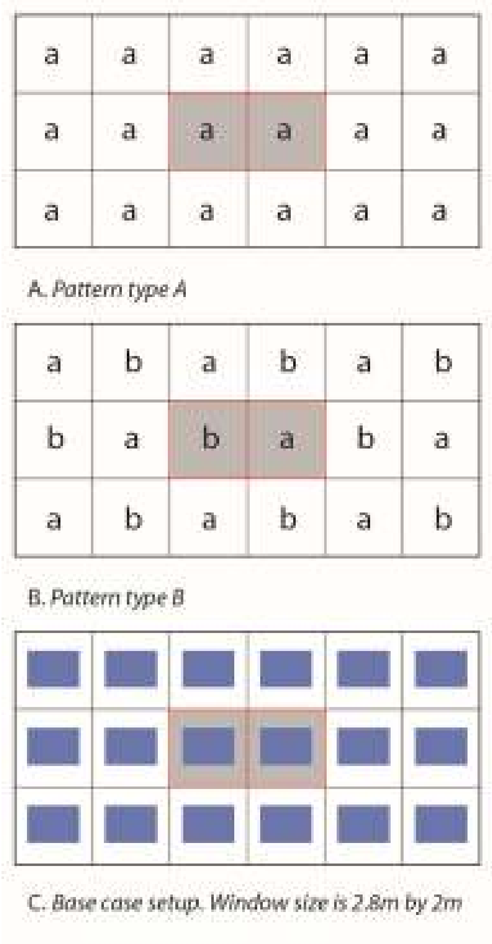


Figure 3
Pattern tessellation and base case setup at the bottom. Test rooms are two adjacent rooms in the middle in the facade

Among them, parametric design is a highly prioritized method that effectively generates large number of instances (Turrin et al. 2011) which could be easily altered by parametric value manipulation by decision makers for further design progress (Dino 2012).

The consideration of photo-voltaic panels in façade design is a prominent factor to improve the building performance, transforming the bland building façade into an active collective platform. Accordingly, this trend makes BIPV part of the building envelope as an independent material rather than an additional feature (Bonomo et al. 2015). Consequently, almost half of the energy used in the building could be covered by a properly installed BIPV (Berkel et al. 2014).

| | | |
|---|---|---|
| Lighting setup | Wall reflectiveness | 0.7 |
| | Ceiling reflectiveness | 0.8 |
| | Floor reflectiveness | 0.2 |
| | Window Transmittance | 0.76 |
| Test points | Base surface distance | 0.75 m |
| | Grid size | 0.5 m |
| Thermal setup | Wall U-Value | 0.46 W/m2.K |
| | Window U-Value | 2.37 W/m2.K |
| PV setup | Module material | Crystal Silicon |
| | Module type | Close (flush) |
| | Module efficiency | 15% |
| Optimization setup | Population size | 10 |
| | Generation number | 50 |
| | Elitism | 0.5 |
| | Mutation probability | 0.1 |
| | Crossover rate | 0.8 |

Table 1
Simulation environment setup

Furthermore, the amount of natural light introduced into a building also has a critical impact on energy performance, thus it should be considered in the early design phase. Useful daylight illuminance (UDI) is one of the simulation based predictive methods that determines how many hours of per year is achieved in pre-defined illuminance range of 100-2000 lux at the workplane in a given space (Nabil and Mardaljevic 2005). This method is used in this study as one of the design objectives in the optimization process.

A multi-objective optimization is very suitable in dealing with problems in architecture design, since the output provides a global pareto-front set of solutions, which trade-off two or more objectives in a given problem such that decision-makers make their own choice from the pareto-front solutions (Stevanović 2013) based on their judgement for later design stages. A number of studies focus on façade design exploration in the early design stage (Gagne and Andersen 2012). Gagne and Andersen suggested a micro-genetic algorithm based façade optimization method, in terms of indoor illuminance and glare modifying façade elements, such as external shading device, fenestration geometry, and envelope material. The base case (testing room) was defined by the user's input in Google Sketch-up and three case studies have been tested in single and multi-objective optimizations. Although the outputs were satisfactory, the search seemed to be stuck in local-optima solutions (Gagne and Andersen 2012).

Wortmann et al. (Wortmann & Nannicini 2016) compared different methods used in architecture design optimization; metaheuristics, direct search, and model based methods with selected "Galapagos" (Rutten 2013), "DIRECT", and "Opossum" (Wortmann 2017) plug-in respectively. The methods were tested for four different problem cases which were two structural and two daylighting problems. The direct search and model-based approaches performed better than metaheuristics method (genetic algorithm), and the model based approach, especially showed the most promising method when tackling a daylighting optimization (Wortmann & Nannicini 2016).

## SUGGESTED METHODOLOGY

We proposed a method for generating a 3D faceted façade that consists of two main parts: the geometry generation and the optimization (Narangerel et al. 2016). In the façade geometry generation part, the building façade surface is divided for a base unit as can be seen in Figure 2 B. A regular tessellation is selected since concave shapes can be generated by the summation of convex shapes. Then, extra points are added on the tessellated unit. The additional points' locations are limited by the perimeter of the base tessellation without overlapping each other in order to avoid self-intersecting shapes that are not ideal for simulation as well as construction. The extra points are extruded outside of the building.

The vertices of the base unit and extruded points are connected by means of the Delaunay triangulation method. The Delaunay triangulation is a commonly used method in the computational design domain to maximize all the angles in the generated triangles. This method is selected to reduce the very thin and sharp fractured surfaces that are not ideal for the fabrication and manufacturing process in the façade design. It is followed by the materialization of the surfaces which are generated upon the Delaunay spaceframe with 3 different properties, e.g., window, wall and wall with building integrated photovoltaics which is shown Figure 2 F. The rest of the units will have the same properties in terms of geometry and material thus the façade surface becomes a collection of 3D faceted units.

In order to improve the sustainability factor of the 3D faceted façade generated through the suggested method, building energy, BIPV as well as daylighting simulations form part of the optimization. The optimization objectives are determined as to increase the UDI 100 - 2000 in the single room office, and decrease the thermal load while maximizing the generated electricity through BIPV on the external wall. These three objectives conflict with each other thus we implemented a multi-objective optimization method for optimization. In the optimization, the parametric inputs that feed the optimization algorithm are categorized into two main classes. The first inputs indicate the location of the external points, i.e. the coordination information (x, y) with extrusion length (z). The second category inputs are the binary material selection of the triangular faces that are generated from the Delaunay triangulation.

The generation process of the façade is parametrically designed in Grasshopper 3D's environment and Ladybug and Honeybee plug-ins for Grasshopper are used for connecting the Radiance and EnergyPlus simulations to the optimization process. For the optimization, the multi-objective optimization Octopus plug-in is used. In order to reduce the evaluation time in the optimization process, hypervolume-based search algorithm HypE is selected due to its effectiveness comparing to other evolutionary algorithms (Bader and Zitzler 2011) in multi-objective problem solving.

## IMPLEMENTATION AND RESULTS

In the present work, the south façade of a generic high-rise office building is optimized for two different locations, Korea and Singapore, which are in different latitude and climate zone. The initial testing facades are flat and they are divided by equal square tessellations. The dimension of each square is 4.2m in width and height and squares are aligned vertically and horizontally.

Two types of patterns of façade, which refer to the location of the additional points on the base tessellation unit, are investigated in both locations, in total four optimizations have been taken place. The first type is "Pattern A" - illustrated in Figure 3 A- where all the additional points are the same in every square unit in terms of number and location. Consequently, it generates a repetitive pattern throughout the whole façade. On the other hand, a chess type of pattern - "Pattern B" - is generated with two different sets of additional points - same numbers but different location - added on the square grid (Figure 3 B).

One-person rooms are attached to the backside of the square units and they are identical in terms of size and material properties. Accordingly, the width and height of the room are the same as the square tessellation dimensions, while the depth is specified at 6m. A corridor with 1.5m width is attached at

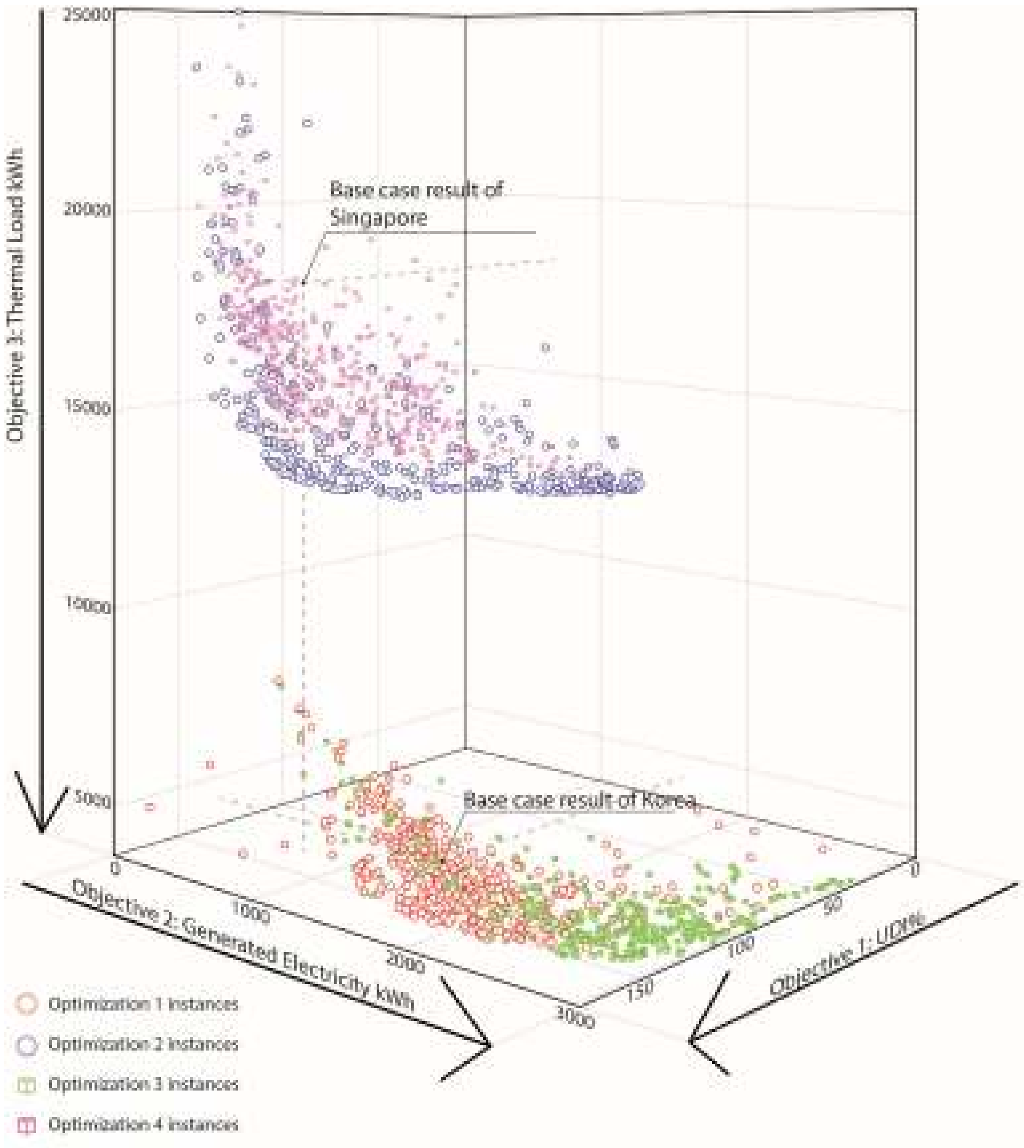


Figure 4
Result of four
Multi-Objective
optimizations and
Base case
simulation results

Table 2
Optimization description and result

| | Name | Optimization 1 | Optimization 2 | Optimization 3 | Optimization 4 |
|---|---|---|---|---|---|
| Setup | Pattern type | A (Single face) | A (Single face) | B (Double face) | B (Double face) |
| | Location | South Korea | Singapore | South Korea | Singapore |
| | Number of extra points | 4 | 4 | 4 | 4 |
| | Number of parameters | 18 | 36 | 18 | 36 |
| | Number of Objectives | 3 | 3 | 3 | 3 |
| Results | Number of Non-dominants | 47 | 89 | 45 | 57 |
| | Average UDI (non-dominants) % | 76.3 | 44.06 | 66.7 | 56.1 |
| | Average Electricity generation (non-dominants) kWh | 1169.6 | 596.4 | 1397.8 | 523.4 |
| | Average Thermal load (non-dominants) kWh | 2094.3 | 6495.3 | 1961 | 7120 |

the back side of the units in all levels. In order to obtain realistic data regarding the 3D façade, testing units are situated at an intermediate floor, surrounded by identical single person office spaces, in total a 3-by-6-unit testbed is generated and used for both the base case simulation and the optimizations (Figure 3). More specifically, the summation of the thermal load, energy harvesting and UDI of two adjacent rooms in the middle at the second level is targeted as the optimization goal. Heating and cooling loads are considered as total thermal load in this study. A more detailed simulation setup is presented in Table 1.

## RESULT ANALYSIS

A generic rectangular window in the horizontal center of each façade unit with the dimension of 2.8 meters by 2 meters, and 1.2 meters above the testing floor (Figure 2 C) is set as base case and simulated in both locations. The simulation results of "Base Case 1" which is located in Korea are as follows, 64.8% in UDI (100-2000) and 789.7 kWh energy generation with 2207.8 kWh total thermal load. On the other hand, "Base case 2" with the same model but under the Singaporean weather data performed 66.4%, 333.2 kWh, and 9103.9 kWh in UDI, generated electricity and total thermal load respectively.

Pattern A and pattern B optimizations and optimization settings and results are shown in Table 2 explicitly. In this section, optimization non-dominants are exclusively analyzed against respective base case results. The best average UDI from non-dominants is found in optimization 1, while optimization 2 was least performing. In terms of electricity generation, optimization 3 performed the highest in average among the optimizations. The average thermal load of pareto-front of optimization 3 also shows the lowest average by 1961 kWh.

Its shows that the thermal load is significantly higher in Singaporean weather featuring the 3D façade design, shown in Figure 4. However; the thermal load decreases 25.9% and 8.1% in Singapore and Korea, respectively, when comparing the average thermal load value of non-dominant against the respective base case results. The lowest thermal load of a single room was found with 6013.2 kWh and 1862.8

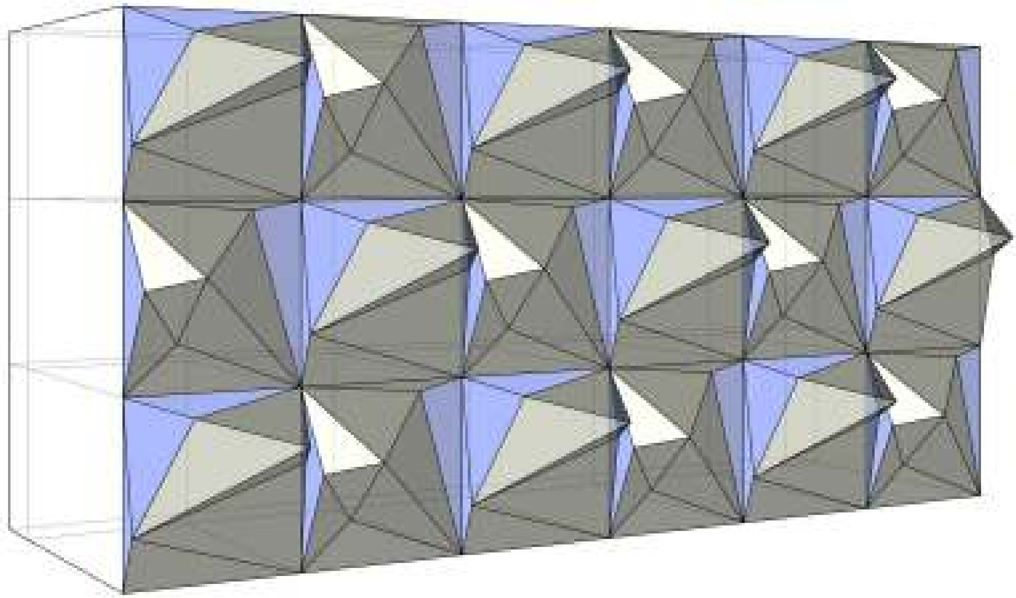

Figure 5
Highest UDI facade of non-dominants of Optimization 3

kWh in Singapore and Korea respectively. In terms of energy harvesting through the BIPV panel, the best design instances were 1817.5 kWh and 1681.kWh potential in both locations, more specifically the optimization shows a 70.4% and 62.2% increase for average non-dominated results in Singapore and Korea, compared with the respective base case results. Despite a 26.5% decrease in average value of non-dominants compared with the base case in Singapore, the best individual value among all solutions is found in Singapore with 89.3% UDI through optimization. On the other hand, the best performing non-dominant considering UDI in optimization 3 (Pattern B adjacent two rooms optimized simultaneously) is found with 81.5% and 81.3% in room 1 and room 2 respectively. This non-dominant solution is illustrated in Figure 5.

In spite of differences in base cases' window to wall ratio compared with the previous study, the suggested method successfully achieves the same amount of improvement in terms of electricity generation that is 113% which was 117.2% in (Narangerel et al. 2016). Both studies obtained improvements, 10% in the previous work, 31.1% in this study comparing the best design alternative regarding UDI to a base case result under Korean meteorological data. There was no remarkable difference in terms of façade geometry in pareto-fronts, no completely planar non-dominant solution was found in either study. Overall, this method was able to improve the UDI and electricity generation while providing a unique geometrical façade.

## CONCLUSION

The energy efficiency of a 3D complex façade along with BIPV energy harvesting and daylighting potential have been investigated in this study using Narangerel et al.'s (2016) method. Based on the optimization results, the suggested method successfully enhances building performance, while providing a visually and topologically interesting façade shapes. Generally, non-dominants feature a combination of concave and convex parts (Narangerel et al. 2016). This unique topology makes the window positioning completely different than the traditional rectangular window in terms of shape and positioning. Consequently, the UDI distribution becomes more proportional in the given space than the traditional façade which usually generates visual discomfort to the area near the window. On the other hand, generated façades are not flat thus conventional window blinds such as venetian, roller blind etc., are not suitable. Therefore, a more innovative blind system controlled by cutting edge AI home technology will provide better lighting conditions in peak hours.

The optimization value differences between pattern A and B were not remarkable in both locations. Therefore, pattern B could be suggested to avoid single unit repetitive pattern, if undesirable. Nonetheless, the choice should be made from the non-dominants considering the trade-offs from the solution space. Not only the increase in performance of the façade generation, but also the method shows great potential generating any type of typology that could be useful in other form finding applications considering the important parameters in the optimization process.

The view from the office through the generated building fenestration was out of the scope of this study, thus part of the non-dominants are blocking the occupants' view to the outside. The occupant's view will be considered in the optimization for future work. Furthermore, alternative strategies for boosting optimization time will be investigated since the computational time was significantly long.

## ACKNOWLEDGEMENTS

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# Daylight Optimization

## *A Parametric Study of Urban Façades Design within Hybrid Settlements in Hot-Desert Climate*

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*Unprecedented growth of hybrid settlements causes deterioration to the indoor environmental quality. Due to their narrow street-networks and fully packed urban fabric, lower floors are subjected to severe overshadow condition, which has adverse effects on the health of the inhabitants. This paper aims to investigate techniques to mitigate the under-lit indoor environment for a group of buildings with variable heights and orientations, with regard to the urban façades parameters. It reflects an intervention in an existing hybrid settlements, within hot-desert climate, to alter façades configurations for daylight optimization, and ultimately recover the lost indoor quality of users in such contexts.*

**Keywords:** *Daylight Optimization, Urban Façade, Simulation, Hybrid Settlements , Parametric Design*

### INTRODUCTION

Informal settlements are unplanned urban areas where buildings and housing units do not comply with local planning regulations. They are common phenomena in Middle East and North Africa regions, especially in large cities such as Cairo and Alexandria in Egypt. This unauthorized housing development causes undesired impacts on both local inhabitants and the whole society. Unlike residential units in informal areas, the 'Hybrid' or 'Ex-Formal' settlements (Figure 1) are housing units in formal areas, which have already been built illegally, or have acquired degrees of informality overtime, such as increasing floors and buildings heights illegally (Soliman 2007). The Egyptian Unified Code for Construction, Law 119 of year 2008, term 15 states that the minimum street width for urbanized areas is 10 m, and the height of the buildings should not exceed 1.5 times the street width. However, it is clear that illegitimate physical features are evident through illegal heights exceeding two to three times the street width, which led to a catastrophic high-density situation for inhabitants. One of the biggest problems that characterizes hybrid settlements is the fully packed urban fabric. Due to attached buildings and narrow street-networks, lower floors are subjected to severe overshadowing condition. The absence of natural daylight led to the deterioration of indoor environmental quality, which has adverse effects on the physical and psychological health of the inhabitants. This demands the use of non-traditional solutions to allow adequate daylight to enter lower floors of such contexts.

Figure 1
An Example of Hybrid Context in Al Mandarah Qebli, Qism Thani El-Montaza, Alexandria, Egypt (from Google Maps)

Actually, using a daylight controller technique can increase indoor daylight quality and decreases lighting energy consumption significantly (Gadelhak 2013; Moazzeni and Ghiabaklou 2016). Applying light shelfs is ones of the most effective passive techniques for controlling indoor daylight. Light shelves are horizontal plates that reflect daylight into the internal spaces, and are placed above human eye level in the upper half of the window. They can increase the light penetration by distributes daylight more appropriately in internal spaces, and reduce direct sunlight by reflecting it to the ceiling and reflecting it into the space (Hegazy et al. 2013; Wagdy and Fathy 2015). On the other hand, one of the ideas to enhance the natural daylighting is to repaint the exterior surfaces of the buildings in those areas. Newly applied reflective paints can increase the daylighting significantly by reflecting more daylight to reach the internal spaces (Aly and Nassar 2013). Many researchers have considered the impact of urban fabric configuration on natural daylighting, while others have studied the implementation of different techniques to enhance the daylight autonomy (Table 1). However, those previous studies have almost been done for predetermined experimental models rather than existing real-life situations. Furthermore, only very limited numerical researches on these techniques actually have been conducted for Alexandria, Egypt. This paper hypothesizes that implementing a combination of light shelves and reflective paints on the exterior surfaces of the buildings can enhance the natural daylight that enters the internal spaces in Alexandria hybrid contexts.

Table 1
Sample of Reviewed Studies on the Urban Fabric Configurations and the Implementation of Different Techniques to Enhance the Daylight Autonomy

| Author(s) | Investigation and Contribution | Focus |
|---|---|---|
| (Aly and Nassar 2013) | Formulates a combinatorial optimization problem to investigate how can painting the buildings' surfaces can increase the availability of daylight. | Applying Reflective Paints |
| (DeKay 2010) | Identification of a relationship between street widths and daylighting for interior zones, to find out the effects of daylighting for urban patterns. | Urban Fabric Configurations |
| (Dogan et al. 2012) | Introduction of a new tool for urban façades to compute the interior daylighting distribution faster than the standard Daysim Radiance approach. | Urban Fabric Configurations |
| (Gadelhak 2013) | Optimizing the daylighting performance of a typical office room in hot-desert climate by a redirecting system. | Addition of Light Shelves |
| (Hegazy et al. 2013) | Enhancing the daylighting in the informal settlements. Changing window parameters on external façade can improve daylighting significantly. | Techniques for Façades Configuration |
| (Lim et al. 2012) | Assessing daylight performance of three methods for typical office buildings in highly luminous climates. | Techniques for Façades Configuration |
| (Mashaly et al. 2017) | Developing a design process of a light harvesting system for southern façades, simulating and manufacturing it as a prototype to validate the results. | Techniques for Façades Configuration |
| (Meresi 2016) | Evaluating daylight performance of light shelves parameters of width, heights, and rotation, with external blinds in south-facing classrooms in Athens. | Addition of Light Shelves |
| (Moazzeni and Ghiabaklou 2016) | Studying the influence of light shelfs parameters, such as rotational angle, position and orientation on enhancing the internal distribution of daylight. | Addition of Light Shelves |
| (Wagdy and Fathy 2015) | Exploring all possible screen configurations to investigate the effect of each parameter and their interaction on daylighting performance. | Techniques for Façades Configuration |

## METHODOLOGICAL PROCEDURE

This paper seeks to mitigate the under-lit indoor environment for a group of buildings with variable heights and orientations within a common hybrid context in Alexandria, Egypt, which represents hot-desert climate. It aims to maximize the amount of daylight that reaches indoor spaces at the first floor levels by studying and optimizing the configurations of urban façades, with regard to façades orientations, building heights, and narrow-street widths. Herein, the problem of optimizing urban façades can be explored regarding a number of primary parameters: (1) Window-Wall-Ratio (WWR), (2) Street Width to Building Height Ratio (Urban Scale), and (3) Façades Orientation. This research also investigates other secondary parameters that can optimize suitable daylighting: addition of (4) Light Shelves (LS) and (5) Reflective External Facades (REF). This study is realized through two main phases. The first phase of the investigations aimed at exploring and assessing the quantitative effects of variable WWR on daylighting performance over variable streets widths and opposing buildings heights (Urban Scales), and with different orientations. This will conclude the near optimal façade configurations that can achieve adequate daylight autonomy in an obstructed context. The second phase seeks to investigate the effects of coupling LS with REF to urban façades in order to optimize the daylight of the selected hybrid context in Alexandria, with regard to the WWR optimal parameters taken from the first phase. A set of computational investigations is performed on a selected existing hybrid context in Alexandria, Egypt.

Sustainable building rating systems, such as the Green Building Council Leadership in Energy and Environmental Design (LEED), require some level of quantifying daylighting designs (USGBC 2013). The Daylight Dynamic Performance Metrics (DDPMs) are used for simulations and evaluations throughout this research, which are in compliance with the LEED v4 Dynamic Daylight Performance Metrics of Spatial Daylight Autonomy (sDA300/50%) and Annual Sunlight Exposure (ASE1000/250h). These metrics are based on the IES (LM) 83-12 approved method for daylight metrics (IESNA 2013). The desirable daylighting conditions set by IES Committee are as follows: the thresholds for the Spatial Daylight Autonomy (sDA) are set as 55-74%, and Annual Sunlight Exposure (ASE) should be less than 3%, which are considered as 'nominally acceptable' ones. These conditions will help assessing iterations for the computational investigations of first and second phases. The suggested Radiance daylight annual simulation parameters are listed in (Table 2). These values are calibrated so that the simulations will be accurately conducted throughout this research.

Table 2
Radiance Simulation Parameters

| | |
|---|---|
| Ambient Accuracy (aa) | 0.15 |
| Ambient Bounce (ab) | 6 |
| Ambient Division (ad) | 1024 |
| Ambient Resolution (ar) | 256 |
| Ambient Sampling (as) | 128 |
| Analysis Grid Spacing | 0.45 |

The investigations in this research utilize Grasshopper, which is an algorithm editor of Rhinoceros, for urban façades parameterization by modeling and designing with geometrical sets of geometries that hold fixed and variable attributes (Ayoub, M., 2012, p. 86). The annual simulations are conducted using Diva-for-Rhino, a plug-in for Rhinoceros that interfaces Radiance and Daysim engines for environmental performance evaluations (Jakubiec and Reinhart 2011; Lagios et al. 2010). The DIVA-for-Rhino simulations are conducted in compliance with the LEED v4 DDPMs.

### *The First Phase: Computational Investigations*

The first phase encompasses developing a variations-oriented algorithm in Grasshopper by the authors to generate a parametric Reference Residential Unit (RRU), which represents a domestic residential space created to reflect different orientations, with the regard to the Urban Scale as external obstructions (Figure 2). The RRU layout is daylight-illuminated from one side, located on the first floor (common residential level at +3.20 m above the ground level to represent a zone with the least amount of daylight), with internal room dimensions of 3.60 m x 8.20 m x 2.80 m. The RRU parameters, configurations, and internal materials reflectivity percentages (Table 3) are meant to act as a baseline for the first phase computational investigations, and assumed to coincide with the Egyptian Code for Energy Efficiency in Residential Buildings, ECP 306-2005, First Section (306/1), and the guidelines set by Reinhart el al. (2013).

This phase utilizes a parametric approach to investigate and conclude the quantitative effects of the urban façades to identify their most acceptable configurations, in relatively narrow street widths, based on the amount of light reaches the first floor levels that can achieve adequate daylight autonomy. Through this phase, investigations are performed for the effects of WWRs configurations with regard to variable surrounding factors by the previously mentioned variations-oriented algorithm. This algorithm is used to link Grasshopper with Diva-for-Rhino that interfaces Radiance engine for simulating daylighting performance. A set of computational investigations is carried out on the above mentioned RRU. They are realized by identifying the geographical location of Alexandria (31.21 °N, 29.92 °E), and the conditions of the chosen site's climate. Location, Area, Volume, RRU Function (residential space), Glazing Properties, and Materials are all constraints that hold fixed attributes. While WWR, Urban Scale, and Façades Orientation are all variables (Table 3) so that the effect of selecting a certain WWR over urban façades can be quantified. To promote the architectural reasonableness, various RRU façades are explored through (N, S, E, and W) orientations, considering variable Urban Scale heights from 9 to 30 m, which corresponds to levels from third to tenth floor, and narrow-street widths of 4, 6 and 8 m against their corresponding variable WWR configurations of 0%, 10%, 20%, 27%, 34%, 41%, 45%, 54%, and 64%. Wherever possible, window dimensions are multiples of 0.50 m. WWRs are expressed with respect to the outside gross façade area (Reinhart et al. 2013). The annual simulations are based on a variations-oriented algorithm inside Grasshopper, where the combinations for all variables contain 864 iterations,

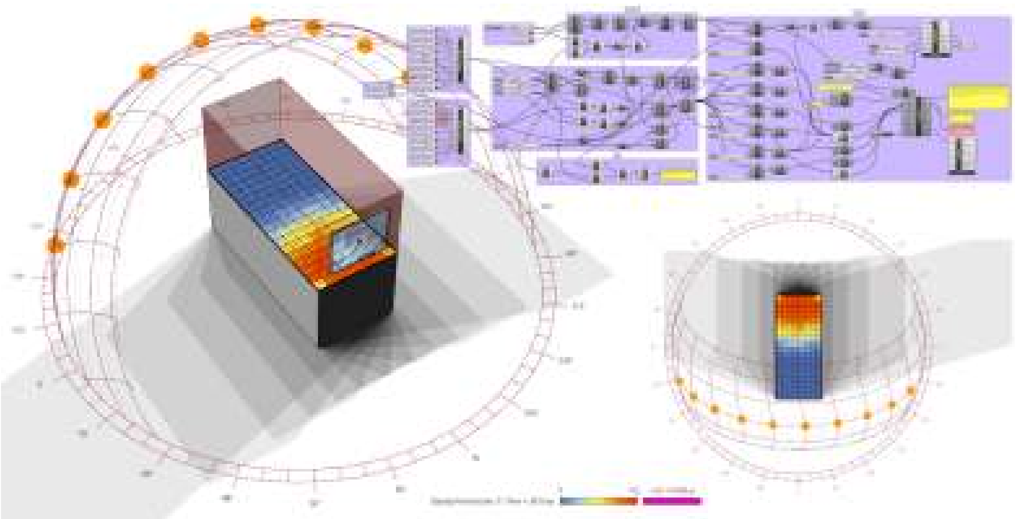

Figure 2
Phase (1): The Developed Variations-Oriented Algorithm in Grasshopper to Generate a Parametric RRU and Simulate Daylight Autonomy

which are divided into 4 sets each having 216 simulations based on the of the RRU N, S, E, and W orientations.

Table 3
Phase (1): RRU Configurations and Computational Investigations Parameters

| | |
|---|---|
| **RRU Internal Materials Reflectivity %** | |
| Walls | 50% reflectance |
| Roof | 80% reflectance |
| Floor | 20% reflectance |
| **RRU Window Parameters** | |
| Glazing | Single Pane Clear Glazing, 88% reflectance |
| Window Frame | Wooden Frame of 5 cm without any Dividers |
| **Variables** | |
| Orientation | N, S, E, and W |
| Street Widths | 4 m, 6 m, and 8 m |
| Building Heights | 09 m, 12 m, 15 m, 18 m, 21 m, 24 m, 27 m, and 30 m |
| WWR | 0%, 10%, 20%, 27%, 34%, 41%, 45%, 54%, and 64% |

## *The Second Phase: Daylight Optimization*

The second phase establishes a mediation for the existing indoor daylight quality for a group of buildings with variable heights and orientations. It starts with surveying and modeling a small housing area of 18 buildings in Al Mandarah Qebli, Qism Thani El-Montaza with street average width of 5.90 m, and total area of 2376 m2 as a case study, which is associated with common hybrid context in the city of Alexandria (Figure 3). The physical and spatial configurations of the selected case study, windows parameters, and other collective data are illustrated in (Table 4), which correspond with the existing conditions extracted from a field survey carried out by the authors. However, it was hard to acquire the internal materials reflectivity percentages, and therefore, they were selected to correspond with the Egyptian Code for Energy Efficiency in Residential Buildings, and the first phase parameters (Table 3).

The second phase encompasses the addition of LS on the Southern façades openings only, as applying LS on Northern Orientations can decrease the inner spaces daylight. This occurs because LS obstructs indirect sunlight entry. The windows condition is assumed without any operable blinds or shading systems. The LS is located at +2.40 m above the residential second floor level (+5.70 m above ground level), and the material reflectance is set to 90%. While there are limitations in designing LS because of their high dimensionality variations, this phase used only one size for the case study. The selected LS is 1.20 m wide, where it is centered exactly at the window plane, in (0) angle degree (horizontal LS) (Moazzeni and Ghiabaklou 2016). A slight variation in the size and rotation of the LS can result in a change in the daylight amount, however, this research will not address that issue, due to its scope limitations. On the other hand, the second phase also involves applying REF on opposing buildings façades. Actually, there are usually three types of paint finishes that most manufacturers offer in exterior products: Matte, Satin and Gloss/Semi-Gloss paint. The Matte paint finish is the most porous of the three and doesn't reflect light too much, as its reflectance percentage is only 1-10%. The Satin paint finish is more popular because it is neither dull nor shiny and has a subtle shine that is ideal for painting exterior walls, as it reflects a minor amount of daylight from 10-40%. The Gloss/Semi-Gloss paint finish has a reflectance ranges from 40-70% of total light (Ji et al. 2006; Li et al. 2011). For the simulation purposes, a Gloss paint will be applied to upper floors (5th floor and above) only to collect and reflect the natural daylight and reflect it to inner spaces, and a Satin paint will be applied on exterior walls of lower floors (from ground to 4th floor) to avoid any visual discomfort.

A set of computational investigations is carried out on the above mentioned 18 buildings. As was the case in phase one, they are realized by identifying the chosen site's geographical location and climate conditions, in addition to other variables and constraints (Table 4). A dedicated generative algorithm is developed by the authors for the parameterization of urban facades that allows running calculations rapidly for large number of iterations. Given the predefined parameters, the second phase involves four-step annual simulations and optimizations: First, a preliminary annual simulation of the existing situation without any optimization is conducted, to acquire urban façades DDPMs of sDA and ASE as a base case for comparison. The location of the existing openings overlooking the street and WWR are taken from collective data extracted from earlier field survey (Figure 3). Second, another simulation is conducted, only this time by altering the existing WWR values with the enhanced ones, considering the WWR optimal parameters taken from the first phase. It is worth mentioning that, due to compact urban fabric and narrow street-widths, the WWRs cannot be maximized to the ultimate extent, as this as this increase jeopardizes the privacy aspect, which is subjected to common acceptable habits of the Egyptian society. Third, optimized urban façades are introduced by adding LS to the existing Southern façades windows only. Fourth and last, even more optimized urban façades are introduced by maintain adding LS to the Southern façades windows only, and applying REF to all Opposing Buildings façades. The simulation will investigate the effects of these optimization techniques on the selected housing area.

## RESULTS AND DISCUSSION

### *Simulation Results of the First Phase*

**Northern Orientation.** According to the results graphs (Figure 4), significant increase in sDA can be detected with the increase of both WWR and Street Widths, while a decrease can be observed by increasing Buildings Heights. Through the entire Northern Orientation simulations, sDA obtained the highest values of 42.40%, 47.20%, and 51.40% per higher WWR 64%, and lower Opposing Building Height of 9 m, with Street Widths of 4 m, 6 m, and 8 m respectively. Over the same higher WWR 64%, sDA acquired significantly lower values of 4.20%, 20.80%, and 27.10% with higher Opposing Building Height

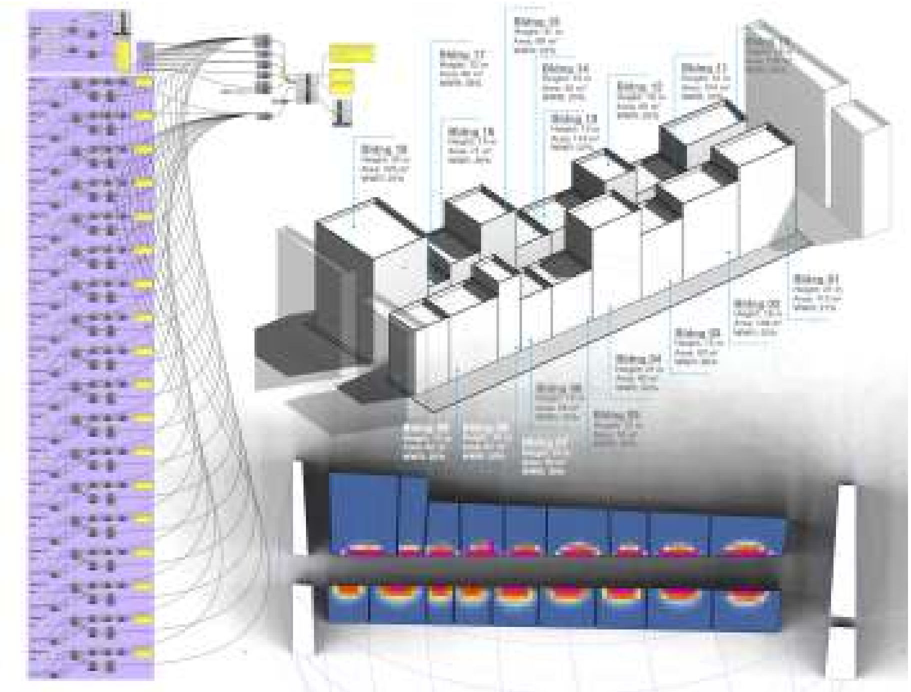

Figure 3
Phase (2): Case Study of 18 Buildings in Al Mandarah Qebli, Qism Thani El-Montaza That Represents a Common Hybrid Settlement in the City of Alexandria, Egypt

of 30 m, with the same respective Street Widths. It is clear that sDA obtained the highest values with higher WWRs and widest Streets, and vice versa. However, there are no detected ASE values over this orientation, as WWR and Urban Scale do not influence on the annual results due to the lack of direct sunlight entering the inner spaces from the North.

Table 4
Phase (2): The Selected Common Hybrid Settlement Configurations and Daylight Optimization Parameters

| | |
|---|---|
| **Study Existing Parameters** | |
| Windows Type | Without any Operable Blinds or Shading Systems |
| Orientations | N and S |
| Street Widths | 5.90 m (6 m) |
| Building Heights | 12-24 m |
| WWR | 21-36% |
| **Variables** | |
| WWR | From First Phase Annual Simulation Results |
| LS | 1.20 m wide, +2.40 m above the residential second floor level (+5.70 m above ground floor level) |
| LS Reflectivity % | 90% reflectance |
| REF | The upper floors (5th floor and above): Gloss paint<br>The lower floors (ground to 4th floor): Satin paint |
| REF Reflectivity % | Gloss paint: 70% reflectance<br>Satin paint: 40% reflectance |

Table 5
Phase (2): The Selected Common Hybrid Settlement Existing and Optimized WWRs (showing here the Southern Façades) to Achieve a Trade-Off in Terms of Daylight and Sunlight Allowed into Indoor Spaces

| Building no. | Building Height (m) | Opposing Building Height (m) | Existing WWRs | Optimized WWRs |
|---|---|---|---|---|
| 10 (S) | 18 | 21 | 26% | 54% |
| 11 (S) | 12 | 18 | 23% | 54% |
| 12 (S) | 18 | 15 | 25% | 54% |
| 13 (S) | 12 | 21 | 22% | 64% |
| 14 (S) | 12 | 12 | 23% | 41% |
| 15 (S) | 21 | 12 | 22% | 41% |
| 16 (S) | 15 | 18 | 26% | 54% |
| 17 (S) | 12 | 15 | 36% | 54% |
| 18 (S) | 24 | 15 | 22% | 54% |

**Southern Orientation.** Same as the Northern Orientation, an increase in sDA can be detected with the increase of both WWR and Street Widths, while a noticeable decrease occurred by increasing Buildings Heights. It can be observed that that sDA obtained the highest values of 31.90%, 34.00%, and 38.90% with higher WWR 64%, and same lower Opposing Building Height of 9 m, with Street Widths of 4 m, 6 m, and 8 m respectively, which are lower than the corresponding Northern Orientation parameters by 24.76%, 27.97%, and 24.32%. Over the same higher WWR 64%, sDA acquired significantly lower values of 2.80%, 16.70%, and 22.90% per higher Opposing Building Height of 30 m, with all Street Widths. Generally, sDA obtained the highest values with widest Streets, Same as the Northern Orientation. In contrast, there is a notifiable increase ASE values over the Southern Orientation (Figure 4), due to larger amounts of direct sunlight. However, this effect is only evident over the higher WWR, combined with Street Widths of 6 m and 8 m, and Opposing Buildings Heights of 9 m and 12 m.

**Eastern and Western Orientations.** Since the sun path is symmetrical for East and West in this climate zone, results are approximately the same. Higher sDA is associated with larger WWR and Street Widths, while it decreases by increasing Buildings Heights (Figure 4), as the buildings heights prevent indirect sunlight entrance. The Western Orientation results show a slight increase in the ASE values over the Eastern one, especially with Opposing Buildings Heights of 9 m and 12 m. Like the Southern Orientation, this only occurs with higher WWR, combined with Street Widths of 6 m and 8 m, and Opposing Buildings Heights of 9 m and 12 m. Whereas ASE of 4 m street remained at lower values for these orientations.

## *Simulation Results of the Second Phase*

**First: Preliminary Annual Simulation of the Existing Situation (Base Case).** The results of daylight performance for 18 buildings overlooking a 6 m narrow street, without any optimization technique, are shown below (Figure 5). With higher WWR 30-36%, sDA results reached higher values of 21.40-24.10% only with buildings Northern Orientation cases facing lower Opposing Buildings Heights of 12-15 m. This happened because more daylight is allowed to reach the indoor spaces without obstacles. The ASE values increased over buildings facing Southern Orientation as expected, especially for cases facing lower Opposing Buildings Heights. In general, higher Opposing Buildings in narrow streets block daylight and sunlight from entering indoor spaces. This situation changed for lower Opposing Buildings of 4-5 levels that face Northern Orientation allowing more daylight. However, for lower Opposing Buildings that face Southern Orientation, uncomfortable amount of sunlight is perceived.

**Second: Optimized WWR Annual Simulation.** With regard to the existing condition, another simulation was conducted, only this time the existing Northern façades WWRs were substituted with optimized ones of 64%, while the Southern façades WWRs were altered with variable optimized ones (Table 5), considering the parameters taken from the first phase to achieve a daylight/sunlight trade-off, as any increase in sDA was accompanied by a rise in ASE. All the cases obtained a much better sDA values from 9.10-39.60%, which improved the results compared to the base case by 16.00-165.25%.

In general, sDA showed larger values with lower Opposing Buildings Heights, allowing more daylight to reach the indoor spaces (Figure 5). On the contrary, the ASE values increased slightly over buildings facing the Northern Orientation, but did not exceed the desirable ASE conditions of less than 3% except for Building 08 by 3.30%. However, ASE values increased over buildings facing the Southern Orientation by the value of 7.30-14.50%, which are 52.08-90.79% more than the base case.

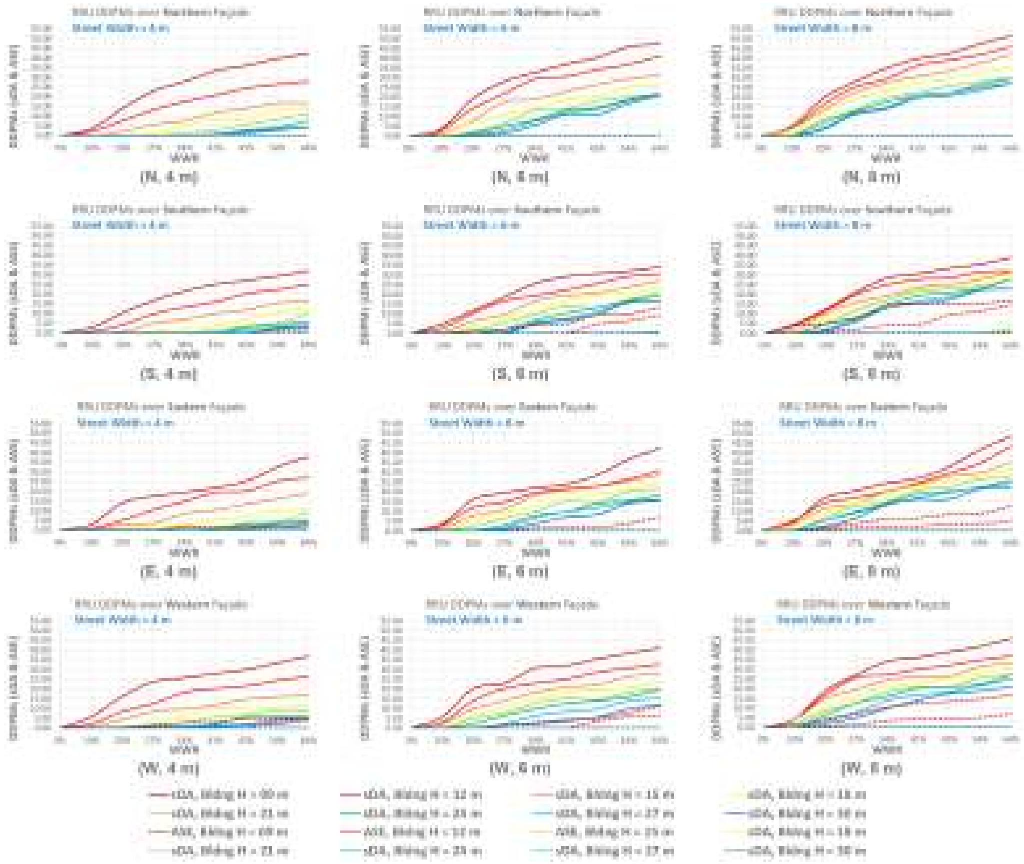


Figure 4
Phase (1): RRU Annual Simulation Results Showing DDPMs of sDA and ASE for Different 864 Iterations

**Third: Optimized Urban Façades Annual Simulation (LS Only).** The optimized urban façades were introduced in this step. They dealt with the issue of increased ASE values over the Southern façades, which was caused by optimizing WWRs earlier in the second step. This increase in ASE could be mitigated by introducing LS to windows of these façades only with regard to the specific parameters shown in (Table 4). The results (Figure 5) show a minor decrease in sDA of values 6.00-15.20%, which are lower than the corresponding second step cases by 9.89-31.03%. In contrast, the results of ASE decreased substantially to the values of 2.40-7.70%, which are lower than the corresponding second step cases by 44.44-69.23%. The addition of LS effects on ASE are best noticed with cases having lower Northern Opposing Buildings Heights of 12-15 m, which already gained higher ASE values earlier. This happens because LS blocks a major amount of direct sunlight, while allows daylight to enter the inner spaces.

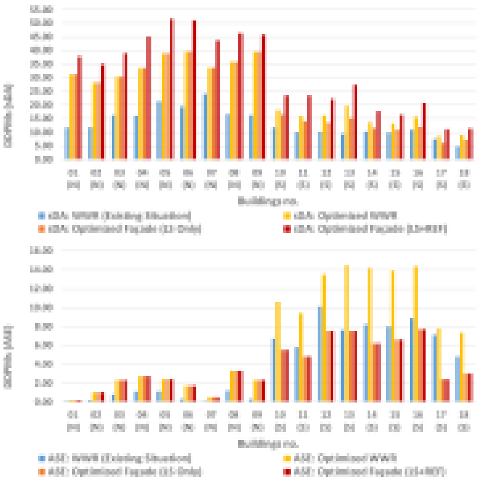

Figure 5
Phase (2): Four-Step Annual Simulation Results Showing DDPMs of sDA and ASE for the Selected Case Study of the 18 Buildings in Al Mandarah Qebli, Qism Thani El-Montaza

**Fourth: Optimized Urban Façades Annual Simulation (LS+REF).** This final step maintained the LS to the existing Southern façades, and applied REF to all buildings façades, with regard to the specific REF Reflectivity percentages shown in (Table 4). All the cases obtained a much better sDA values of 11.10-51.60%, which promoted the results compared to the third-step by 15.95-85.00%. Although the Southern façades obtained a lower sDA values of 11.10-27.50%, they are 43.29-85.00% higher than the corresponding third-step results. The application of REF indicated a proper upgrade to the results of sDA, generally for the Southern façades, especially for cases with higher Opposing Buildings, which allowed more daylight for internal spaces. On the other hand, Applying REF showed no influence on ASE results, neither on Northern nor Southern façades.

## CONCLUSION

While, the city of Alexandria benefits from a substantial amount of daylight throughout the year, the lack of natural daylight entering internal spaces within its hybrid settlements is considered a serious problem in residential buildings. This paper represents an attempt to explore the effects of applying cost-effective optimization techniques to urban façades that can maximize the amount of daylight for indoor spaces. The parametric approach was utilized for the two-phased experimental study to mitigate the under-lit indoor environment for a group of buildings with variable heights and orientations, and narrow-street widths, which reflects an intervention in an existing situation for optimizing urban façades. One of the most significant findings of this study is that the daylight simulation results of the first phase do not comply with the corresponding existing situation results of the second phase, as hybrid contexts are associated with highly inconsistent variables that alter the uniformity of natural light-rays. Actually, utilizing 'shoebox' experimental models for studying each parameter on its own apart from the variable surrounding conditions cannot produce realistic results for existing situations. Taking all parameters interactions into consideration, it was found that major increase in daylight occurred by increasing both WWR and Street Widths, while a noticeable decrease could be observed by increasing Buildings Heights, regardless of façade orientation. Despite an acceptable sDA threshold is a far-sighted target to reach for this degree of contextual informality, applying LS and REF was found to have a remarkable influence on daylight optimization. However, the simulations covered only a selected range of optimization techniques, and a future investigation of their interactive effects is needed. Future research should also consider the thermal effect of different external and internal materials, which leads to a necessity to conduct a prospective study for coupling daylight autonomy with energy consumption, especially in hot-desert climates.

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# CAAD EDUCATION - HISTORY

# Reinventing Design-Build projects with the use of digital media for design and construction

## *A survey of 120 educational pavilions*

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*During the last decade the hype for digitally fabricated educational pavilions has become very popular among architecture schools. A survey with the aim to catalogue and classify educational pavilions revealed more than 120 cases of digitally fabricated pavilions within the last decade. The analysis of the sample of 120 Design-Build projects built during the period 2006-2016 revealed, apart from obvious similarities and differences, the prevailing trends relating to the materials and the technology used for the design, manufacturing and assembly. From the processing of the gathered data a set of typologies emerge, which relate both to morphological characteristics as well as to the design process. The paper concludes by discussing the advantages and critical points of this educational practice and the learning outcomes for both students and educators.*

**Keywords:** *Design-Build, Digital fabrication, architectural education, CAD / CAM, pavilions*

## INTRODUCTION AND PRECEDENTS

Throughout the history or architecture, architectural education had always been one step ahead of the actual praxis with regards to innovation. This is common in several disciplines, as education often deals with experimental methods and innovative practices in order to "create" new knowledge that will later on be adopted by the industry. It is not easy to trace the developments in architectural education, it has always followed several different paths, relating to a range of pedagogical methods, the technological developments, political conditions, the philosophical background and the avant-garde design explorations of the time.

Many researchers agree that introducing new forms of pedagogy in architecture have become a necessity and that architectural education needs to change (Buchanan, 2012; Colomina et al., 2012; Nicol and Pilling, 2000; Salama, 2013). Among them Buchanan considers apprenticeship as an effective way to teach design, referring to the observation of the master to learn the skills of the discipline (Buchanan, 2012). At the same time, digital technologies have changed the nature of architecture and this was inevitably reflected in architectural education. "Educators in engineering schools are experiencing a new pressure to change the way they teach design-related courses in order to equip their students to interact with CAD/-

CAM/CAE systems and have a knowledge of their fundamental principles" (Lee, 1999). In this realm, reinventing the well-established tradition of Design-Build projects with the use of digital media for design and construction, appears to be an effective way to blend new technologies with traditional apprenticeship and craftsmanship.

One of the problems that have been identified is that the current generation of architecture students, which are digital natives are taught by digital immigrants. The rush to engage with digital media was further accelerated by the market needs and the digital culture in general. Within this transition phase several educational experiments have taken place, we would however need to discuss those from a pedagogical point of view and relate to learning theories, to evaluate them as source of knowledge. Focusing on digital media in particular, schools across europe have already gone through several years of experimentation with digitally fabricated Design-Build projects, some of which have proven to be particularly useful for the advancement of education and architecture in general (Figure 1).

Figure 1
Architecture Schools in Europe were Design-Build experiments have taken place

Since the early years of architectural education, the design studio has always been the space where the creative work takes place. This is common in the professional and the educational world and it is usually a flexible place for production, model making, drawings, and technology hub, currently enriched with both analogue and digital media. A design studio has its own culture of research by making, experimentation and testing of ideas. "Historically the link between a drawing and the execution of that drawing on site, were much closer and time and place than they are today. A mason might mark out the design on a piece of stone immediately prior to cutting it directly on site. The design studio has evolved as a place that enables design to be developed both far away and far in advance of its actual implementation" (Anderson, 2010). This separation has both advantages and disadvantages. On one hand it gives the opportunity to consider the coherence of the whole scheme prior to construction (Anderson, 2010), on the other hand it broadens the gap between what is designed and what is constructed due to a variety of reasons that relates to the transfer of information, the feasibility and technical competences among others. Current developments, particularly the use of CAD-CAM in a so-called file-to-factory continuum (Oosterhuis et al., 2004) tend to minimize this gap, offering the possibility for a seamless transfer of information and a better overview of the entire process. This is better understood through Design-Build projects, as the student has the opportunity to actively participate in the entire workflow, from design to construction. The practice of design-Build projects is not a new concept in architectural education, it dates back to the previous centuries, emerging from the holistic approach introduced by the Ecole De Beaux Arts in mid-1600, moving on to the BAUHAUS model as an iconic example of practice based education, further evolving through Buckminster Fuller's domes and the radical experiments of the 60s and 70s (Colomina et al., 2012).

During the last two decades, with the emergence of digital tools, the hype for digitally fabricated student pavilions has been further boosted by Avant-garde architecture schools, such as the Architectural Association in London, the ETH in Zurich and the ICD in Stuttgart and it has been propagated at light speed across the globe. This new trend has been boosted by the introduction of new media in the architectural practice (CAD/CAM) and the culture of open source code across disciplines. In addition to that, there are numerous reasons that facilitated this surprisingly fast diffusion of ideas and practices, among which we can undoubtedly identify the sharing of information through the web, the social media and the internet of things. Within the scope if this paper, educational pavilions are considered as vehicles of innovation, they are at the same time artefacts as well as experiments that test out new ideas in both education and praxis.

## DESIGNING AND CONSTRUCTING PAVILIONS

As two of protagonists of this trend and authors of the book "Making Pavilions" explain, the premise of a temporary, sponsored, architecturally experimental London summer event pavilion was inspired by the Serpentine Gallery (Self and Walker, 2010). The main concept is to test architectural ideas through making. One of the reasons that led to the survey on Design-Build projects is the necessity to identify current trends in contemporary architectural education, understand the modus operandi of contemporary Design-Build projects, compare their morphological characteristics and reflect on the technology used to design and construct them.

More specifically, and within the particular realm of architectural education, Brett Steele, director of the Architectural Association in London, alludes to the common belief that "architecture is only ever learned by getting your hands dirty" (Self and Walker, 2010). He explains that this is done through the construction of physical prototypes, 1:1 models, whose "working difficulties and eventual results offer the designers vital insight and understanding into how they take a next tentative step forward".

The hype for digitally fabricated pavilions, coincides with the broad use of internet, the emergence of open source tools and ideas and is in line with the global rise of the MAKER movement which in turn touches upon well established educational concepts. The MAKER movement praises the virtues of constructionism propagating the idea of learning by making. This is in line with the ideas of Montessori about acquiring knowledge, "He does it with his hands, by experience, first in play and then through work. The hands are the instruments of man's intelligence" (Montessori and Chattin-McNichols, 1995). Beatriz Colomina. Professor of Architecture at Princeton, affirms that it is pedagogically useful to take people outside the design studio, and to actually "produce media" in the form of a prototype, a publication, and exhibition. The actual production is a pedagogical approach, the model of the isolated scholar within the boundaries of the university lab is deemed inadequate in our times, architectural research calls for a collaborative and interdisciplinary environment.

Design-Build educational experiments aspire to offer multiple learning opportunities, they encourage the shift from passive listening to active learning, with the aim to produce new knowledge through active engagement in a broad spectrum of mental and physical activities. The design and building of a pavilion is a participatory exercise rejecting the role of an architect as solitary genius, and encouraging the contemporary idea of collaborator. In his book Learning by Building (Carpenter, 1997) the author William Carpenter highlights the importance of craft in architectural education. He claims that this type of experiences inspire architects and artists to see construction as a creative act, drawing upon examples from the work of renowned artists such as Richard Serra and Donald Judd and presents case studies of Design-Build experiments at Universities of Oregon, Washington, Michigan, Cranbrook and Yale.

This research has catalogued and classified Design-Build projects of the last decade with the aim to understand the modus operandi of both the design and production process as well as the educational aspect of teaching architectural technology through full scale constructions. The survey reports on the type of pavilion, the school were the design and construction took place, the location where it was built, the duration of the construction, the year it was built, the materials used, the technology that has been used for the design, manufacturing and assembly (Figure 2).

Figure 2
Student pavilions from the Architectural Association London, ETH Zurich, Detmold University, University of St. Joseph, University of Southern California, Lodz University, Porto University, Washington University, Tonji University, ICD and ITKE Stuttgart – Compilation of images from various sources

## COLLECTION AND ANALYSIS OF THE DATA

The date was gathered through different sources and media, including bibliography, conference papers, websites and blogs, complemented with site visits, interviews and documentations. The pavilions are grouped according to geographic location, chronology, materials used, CAD/CAE/CAM tools employed. The classification and analysis of the 120 samples offers an overview on main trends. The taxonomies of Design-Build pavilions mainly relate to the construction method or governing formal principle. It is clearly seen that both the design as well as the construction highly relate to the digital media that has been used for the design, engineering and manufacturing.

According to the obtained data, the school that produced the biggest quantity of pavilions during the last decade is the Architectural Association, counting more than 20 full scale pavilions in the last decade. This is easily understood by the entire school's tradition, the machinery and equipment at Hooke Park as well as the experimental nature of the school's curriculum. Following the AA, ETH Zurich, ICD/ITKE in Stuttgart are pioneering in the construction of pavilion. Among the runners-up are the University of Tokyo, Columbia University, MIT and TU Darmstadt. According to the data gathered, most of the pavilions were built as temporary installations, some of them were relocated and very few of them were designed to be permanent structures.

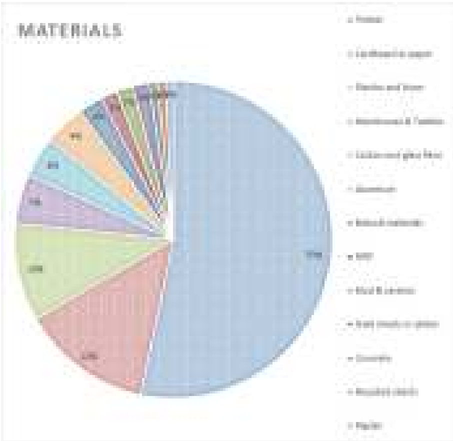


Table 1
Materials used in the construction of Design-Build projects

The materials used for the construction of pavilions are displayed in the following chart (Table 1). It is seen, that the most usually encountered material is timber and this may be explained by a variety of reasons. Timber is an ecological material that is easily available in most countries and relatively cheap in comparison to other materials. There is a huge body of knowledge on wood processing, therefore, there are great resourses, equipments and processes that the students may use for the fabrication of pavilions. On top of that, timber is a soft material that can easily be processed by CNC milling machines as well as by manual mills and routers. Timber is relatively light and easy to carry and assemble and there is a huge variety of different qualities, ranging from raw material, to plywood, laminates and composites. The material properties of wood with regards to deformation, stiffness and tolerances renders it as a great material for design experimentation.

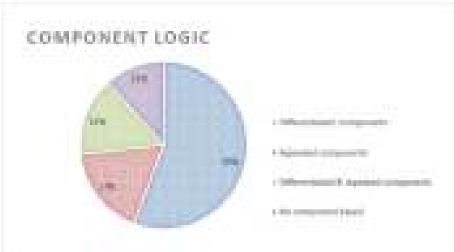


Table 2
Component logic

The great majority of these constructions are designed as an assembly of components (Table 2). This may be explained by the fact that the fabrication laboratories (fab labs) in the universities have a capacity of a determined, relatively small cutting and printing area, and the sizes are constrained by the available equipment. The modular elements are usually differentiated to respond to design requirements, while being in line with the global fashion in architecture, the parametric variation and differentiation of component based systems. The component logic also relates to the assembly process, which in the majority of cases is done manually by the students without making us of industrial equipment such as cranes.

There is a certain level of prefabrication before the final assembly. “In these non-standard constructions we can easily identify two main trends (Figure 3): a) Differentiated components, displaying mass customization at component level, which have a standard method of assembly, b) Standardised components that explore new assembly methods, ie non standard placement of the material with the use of robots. Both approaches obviously relate to the parametric processes of initial form generation and the possible differentiation induced in different scales, at component or assembly level” (Symeonidou, 2014).

The Design Media used are primordially parametric CAD systems providing an easy link from design to construction, a seamless connection of media from design to production in a “File To Factory Continuum” (f2f). The materials used for the construction of pavilions show a clear preference for timber (more than 50% of the examine cases). Being a relatively cheap, environmentally friendly material that is easily available in most countries together with the abundance of knowledge on wood processing, makes timber an ideal material for the fabrication of pavilions. On top of that, timber is a soft material that can easily be processed by CNC milling machines as well as by manual mills and routers. It is relatively light and easy to carry and assemble and there is a huge variety of different qualities, ranging from raw material, to plywood, laminates and composites. The material properties of wood with regards to deformation, stiffness and tolerances renders it as a great material for design experimentation.

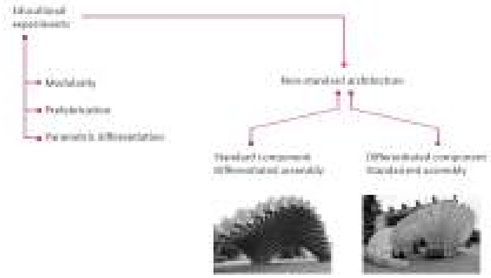

Figure 3
Main trends in educational construction experiments

The manufacturing technologies used for the construction of components are displayed in charts (Table 3). We can observe that more than half of the pavilions were constructed using CNC milling machines for cutting, and these are usually combined to several processes such as bending, folding, forming, sectioning, interlocking, several of which are also identified by Iwamoto in the book “Digital Fabrications” (Iwamoto, 2009). The type of processing relates to the morphology of the pavilion. Based on that the survey revealed 18 distinct taxonomies: Folding, Bending, Shell, Cellular, Reciprocal, Sectioning, Stacking, Cladding, Tensile & Tensegrities, Layered, Intersecting, Weaving, Aggregate, Suspended, Pneumatic, Branching, Lattice (Table 4).

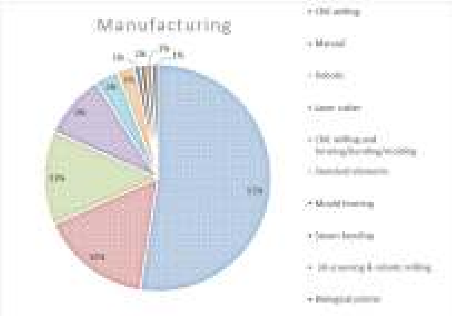


Table 3
Manufacturing technologies

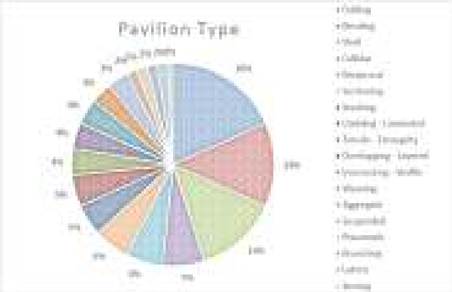


Table 4
Types of pavilions

The connectors used to assemble components are also seen as an important design feature, and usually very indicative of the innovative character of the design, the hierarchical levels of sophistication as well as the materials used for the pavilion. It has been observed that the majority of pavilions employ conventional connection strategies, such as steel bolts or cable ties. However in few occasions there is a great level of inventiveness and innovative design thinking with regards to the way each component is connected to one another.

## CONCLUDING REMARKS ON MAKING PAVILIONS AND LEARNING OUTCOMES

The scaling up of a model is a very complex exercise. Even if a model seems to function in a 1:10 scale, the full-scale model would require a thousand times the material volume, considering x y z dimensions (10 x 10 x 10). This is also one of the reasons why 3D printed models would not easily scale up without changing fabrication strategy, as it would require 1000 times the amount of material and fabrication time of a 1:10 prototype. Scheurer, one of the founders of the Swiss firm Design to Production explains that “methods that create complex form from homogenous materials are very convenient and simple to use on a model scale, but when naively applied at full architectural scale, they inevitably and very quickly reach a point where they lead to both very inefficient production processes and overly massive structures” (Kolarevic and Klinger, 2008). Therefore component based structures are in the majority of cases the way to go, for designing and fabricating a 1:1 structure within an educational context. Architecture has been traditionally built from components and diverse building elements standardized in the course of the years to particular shapes and sizes that emerged from the market demand in the building industry. The established standardized elements have in a sense been optimized for a particular use and construction strategy. However non-standard architecture evidently requires non-standard components, and it is within this new emerging field of innovative architecture where most educational experiments take place.

In the majority of the projects, emphasis is given on the surface, both with regards to design as well as to fabrication. How a surface is manipulated, controlled, divided, connected to other surfaces, machined and assembled is a key concept. As Brett Steel remarks, this “is not a coincidence, nor some kind of imaginary, epistemological imperative. We must remember that nearly every aspect of projects like these is being driven by software that is entirely surface-oriented in its underlying mathematics, the very same surface mathematics that are, of course, now also being utilized in the machines, making possible new output technologies, such as 3D printing, milling or laser-cutting" (Kolarevic and Klinger, 2008). Therefore the form and fabrication strategy is closely related to the technology employed for the design and construction.

Though there are several publications, videos and online material that explain the design and construction process, very little has been said or written about the difficulties faced and the mistakes that occurred during the process from design to construction. The survey, was complemented by discussions and interviews that focused on the design process, the educational strategy and most importantly the difficulties and mistakes that occurred which are not usually documented in publications or other media. In such processes, mistakes are seen as a vehicle for further exploration, trial and error is a common routine in an experimental set-up, therefore they are not to be seen as a negative result in an exploratory design process, rather as an indication for further investigation of one particular aspect. From an educational point of view, it is important to reflect upon the process; the aim is not simply to construct an artefact, but to learn from the limitations and mistakes, seek alternatives and evaluate every decision in relation to feasibility, time and cost. Only experience that is reflected upon can yield new knowledge, according to Kolb, "Learning is the process whereby knowledge is created through the transformation of experience" (Kolb, 1984).

In the majority of projects practical issues of fabrication and assembly, reconfirmed the educational aspect of mistakes and the importance of teamwork in problem solving among others. As it was also confirmed through the interviews, decisions taken at each stage highly depend on the available time and resources. From the examples discussed here, it has been seen that not all difficulties can be anticipated and several problems have to be solved on the spot. However the difficulties that are faced in certain circumstances, always serve as prior experience for future projects, and this is where the role of the educator becomes crucial. The effectiveness of learning through mistakes, lies in the fact that one has to realize the reasons in order to provide a solution. This is an amazing opportunity for students to reflect-in-action (Schön, 1990, 1985) and learn through making. This realization is in line with Kolb's experiential learning model, where critical reflection leads to new decisions (Kolb, 1984).

Evaluating the Design-Build projects, it is understood that construction experiments are of incredibly high educational value as the "explicit knowledge that is only achievable through physical making is made communicable and reproducible through a process of reflection" (Geissbühler, 2014). The software used and the digital fabrication strategies have a direct repercussion on the constructed object. However, after the initial fascination with the medium, students tend to seek methods to twist and tweak the established methods, thus producing new knowledge. In turn, the additive or subtractive methods of manufacturing play a crucial role in the design process, defining the necessary steps for a file to factory continuum.

By trying things out physically, an architectural idea can be easily classified according to the engineering expression "it works" or "it doesn't work". This no matter how acid it sounds, it does indicate whether something can be constructed and be functional. According to Charles Walker, the physical act of "making things" has two important aspects, that relate to the pedagogical approach of learning by doing (Self and Walker, 2010).

- The actual construction offers a "profound sense of accomplishment when finished" which is a very central part of most educational processes. There is a direct feedback on the work produced, it involves critical thinking, self-assessment and self-motivation and reward.

- The possibility of "craft", meaning the refinement and modifications that are made through "physical and repetitive engagement with the specific material itself"

Since the introduction of computers and CAD software for drafting, the actual interaction with materials, has been practically lost, or limited to exclusive detailing when an architectural object falls outside the range of standardized detailing. Walker explains that "true craft in construction can only be achieved through physical labor that leads to a deeper and more sophisticated understanding of what it means to build, as opposed to what it means to draw or to speculate" (Self and Walker, 2010).

Within the collaborative design processes that are employed for the design and fabrication of Design-Build projects, models and prototypes are both design tools as well as presentation tools. They are media for presenting an idea, but also experiments for material performance or assembly sequence. They investigate tangible and qualitative characteristics that cannot be evaluated on the computer screen. While digital models prove effective with handling numbers, forces, physical simulations and other quantitative data, built prototypes offer themselves as means for evaluating qualitative data. Materiality and tactility can only be experienced by constructing an artifact. Thus the combination and convergence of analogue and digital media supports the school of thought of Learning by making.

Design-Build projects provide a very fertile ground for teaching construction, innovation and inventiveness. The immediacy of gaining feedback from fabricated prototypes through assembly and testing of both components and nodes, is a great asset. In agreement with the doctrines of problem-based learning, students are able to assess the structural performance of the artefact locally and globally, and thus pinpoint optimized node solutions, both with regards to functionality and material resistance, as well as considering construction logics and assembly sequence.

Jason Griffiths in his paper for the EAAE-ARCC Conference in 2008 suggests that "digital fabrication in architecture can be roughly categorized in two ways: Those that we can use today and those that we cannot" (Griffiths, 2008). Educational construction experiments prove to aliment both categories, as they are driven by the desire to innovate and educate. With Design-Build projects students gain an experiential understanding of architectural structures, they train their intuition to understand material limits, as for example the breaking limit of a wooden component. This knowledge implicitly or explicitly is fed into their future designs.

An important aspect among the learning outcomes is the collaboration among student groups as well as between students and external consultants or industrial partners. This requires a clear distribution of tasks in the form of construction-management which emerges naturally within the group. At the same time, as these activities are rather intensive within a small amount of time, it has been very often highlighted by the educators, that construction experiments have been a good team building exercise and have helped students to develop the capacity to work under stress in a team environment. Moreover, these projects are characterized by high motivation in students, as there is tangible feedback of their work and satisfaction with the constructed result. The teaching briefs presented in this dissertation were developed based on the research on learning theories and the results were evaluated and presented.

Having studied numerous cases of educational pavilions placed within the urban context, it is evident that in their great majority they represent contemporary architectural culture, they comprise of structures that employ new design and construction methods. By placing such artifacts in public spaces, they disseminate the findings of a broader design research agenda to the local community and engage users to appropriate them, change them, use them and involve them in their everyday life. The aforementioned pavilions are punctual events, and off course they cannot be said to change the physiognomy of a city, however they do change the way the academic world interacts with the city; merging cutting edge knowledge and urban culture, establishing a dialogue between the university and the city. Due to their scale and style, the pavilions oscillate somewhere between art and architecture, between the size of urban furniture and building, this leads to a very unique form of creative freedom (Baker, 2014) and they can serve as a potential source of inspiration for the rest of architecture (Jodidio, 2011). This growing trend of pop-up spaces and pavilions leads to the inoculation with fresh ideas and motivates the community to practically engage in similar design-build projects, generating small changes within the city, which however lead to greater changes in the way knowledge is experienced and communicated.

In more than one cases, the combination of tools and methodologies of design and construction can propel the emergence of new ideas that combine traditional craftsmanship and digital techniques. According to Burry "today's students are far more aware of other disciplines and their respective ways of working, combined with intimate association through sharing the same digital tools, points to a new era of design collaboration regardless of how 'digital' as individuals we are inclined to be. It is for this reason that I believe the academy should resist both any tendency for conservatism or a total rush into technology. Rather, it seems best that they seek to consolidate both traditional and digital design processes within teaching programmes lest we lose the skill to pass on skill - the malaise currently besetting some schools of fine art" (Burry, 2005)

The study of pavilions may offer an insight of the direction where contemporary experimental architecture is moving. There is obviously some convergence of trends in the majority of projects. However, those that do not fit into the established categories are those indicating fertile field for future investigations. While component based wooden elements is an undoubtable trend and an easy starting point for design explorations in 1:1 scale (in the sense that both materials and fabrication methods are long known and tested), however it is non modular projects such as ICD fiber pavilions that constitute a real breakthrough in construction methods, utilizing and synthetizing known processes into brand new construction methods. This is not to say that all future architecture and research will move towards that particular direction; nevertheless it is an example of synthesizing known processes (such as weaving) in un-known / un-tested scales (such as building scale). Innovation is achieved by relating phenomenologically unrelated research fields and processes. Therefore, interdisciplinarity lies in the core of innovative thinking.

The educational impact of Design-Build projects is manifold. Apart from being a highly motivational activity, it integrates several aspects or architectural knowledge, and therefore proves to be a fertile ground where a student can combine different skills and competences ranging from composition, to computation, logistics, construction technology, detailing among others. Instead of focusing on isolated and often disconnected courses, like learning software tools, or theory, or technology, Design-Build projects offer themselves as a platform for capitalizing the knowledge gained in other courses, see how different bits and pieces fall together aiming at a cohesive architectural praxis. Chad Schwartz in his article Debating the Merits of Design/Build: Assessing Pedagogical Strategies in an Architectural Technology Course, highlights the benefits of this practice for learning about architectural technology, "Design/build in a technology course has the potential to grow directly from the lessons of construction and assembly. Design, guided by real constraints, offers a significant platform for learning, especially for novice students still in their first years in the program" (Schwartz, 2016).

It has been seen throughout the research that hands-on learning experiences are very efficient with regards to learning. A hands-on approach is timeless, it has always formed part of architectural education, earlier in the form of scale models, nowadays also in 1:1 scale. The learning process does not depend on the medium (be that analogue or digital), Design-Build projects is a highly adaptive teaching approach that can perfectly fit the teaching of digital media, enriching the virtual world with the necessary notion of materiality. A 1:1 prototype helps to highlight errors, pose future questions in quest for new knowledge. Mock-ups are both educative and experimental, they "link tool and process in the course of learning how to build"(Hailey, 2014). It has been proven that traditional learning theories are perfectly compatible with digital media. Therefore combining the established knowledge in learning methods with new media we devise research and teaching methodologies that push the limits of design experimentation, offer students the opportunity to take risks reflecting in action and promote innovation. Students acquire a working knowledge and practical experience with tools, techniques and methodologies of design and construction. The knowledge gained is not the result of direct instruction from teacher to student, but the result of a natural self-organized skill sharing that occurs within the group. This educational approach has numerous benefits and is seen as a great learning opportunity for the generation of digital natives, as it possesses the unique ability to blend analogue and digital media, with craftsmanship and design thinking.

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# Optical Integrity of Diminished Reality Using Deep Learning

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*A new method is proposed to improve diminished reality (DR) simulations to allow the demolition and removal of entire buildings in large-scale spaces. Our research goal was to obtain optical integrity by using a scientific and reliable simulation approach. Further, we tackled presumption of the texture of the background sky by applying deep learning. Our approach extracted the background sky using information from the actual sky obtained from a photographed image. This method comprised two steps: (1) detection of the sky area from the image through image segmentation and (2) creation of an image of the sky through image inpainting. The deep convolutional neural networks developed by us to train and predict images were evaluated to be feasible and effective.*

**Keywords:** *Diminished Reality, Optical Integrity, Deep Learning, Augmented Reality, Landscape assessment*

## INTRODUCTION

Augmented reality (AR), which gives extended information to a real scene, has received a lot of attention in on-site architectural design study and landscape assessment. In urban design or construction projects, AR can help build consensus on urban or architectural design in the early design stages because it can simulate full-scale future view after construction and show new structures realistically in terms of their scale and surroundings (Schubert et al., 2015). Another advantage of AR is that it eliminates the need to create three-dimensional (3D) models of the surrounding environment, leading to a reduction in 3D modeling time and cost (Fukuda et al., 2012).

However, the existing AR approaches cannot correctly simulate views after the demolition and removal of exterior structures. This is because a 3D virtual model of a new structure will overlap the existing structure, which should be removed in the webcam image. As a result, part, if not all, of the structure will still be visible and displayed. In such cases, the problem can be solved by adopting diminished reality (DR). DR is a technique that visually deletes the existing object and superimposes the background image of the removal target area. Generally, however, when using DR, it becomes difficult to obtain the background image for a large-scale urban or architectural space where the entire building is to be removed because the background is wide and the shape is complicated.

Yabuki et al. (2014) suggested developing a DR system for a large-scale space using point cloud data.

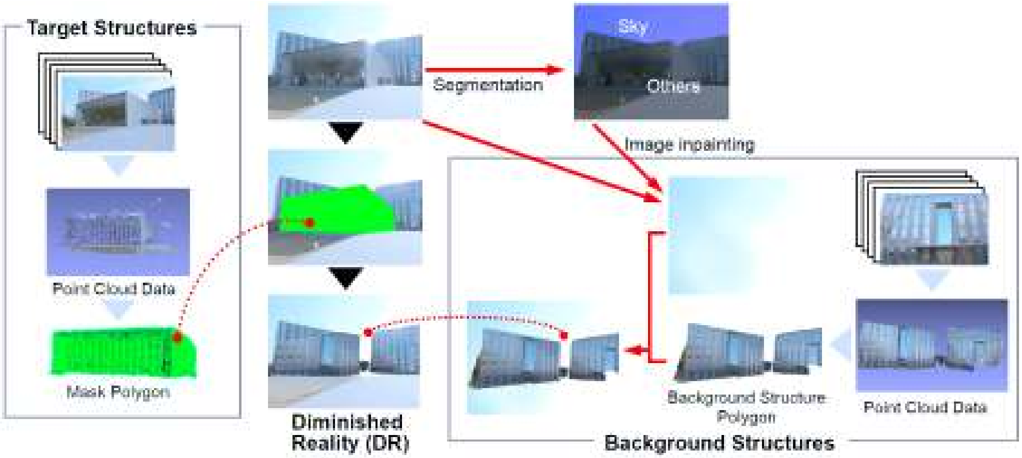


Figure 1
Overview of the proposed DR system

In this system, the 3D virtual model of the background would be created using a 3D laser scanner. Inoue et al. (2016) proposed a method for creating a 3D model of the background by photogrammetry in advance and realizing DR for a large-scale space at less time and cost. However, three issues with this technique stand in the way of realizing optical integrity. First, this system cannot create the background sky in advance because the sky varies from moment to moment. Second, it is impossible to remove the cast shadows of the demolished target objects. Third, when the background image is superimposed, the pasted area in DR was perceived by users due to an obvious edge.

This research proposes methods to improve DR simulation for a large-scale space where an entire building is to be removed. Our research goal is to realize a scientific and reliable simulation approach with achievement of optical integrity. Thus, we focus on presumption of the texture of the background sky in this study (Figure 1).

## PRESUMPTION OF BACKGROUND SKY TEXTURE USING DEEP LEARNING

For presuming the background sky, this research focuses on image inpainting technology (Telea 2004). Image inpainting involves filling in the missing pixels of an image automatically by presuming them from the surrounding pixels. For image inpainting, it is necessary to specify the area to be used for presuming. In this case, the sky area should be detected from the image captured by the webcam for DR. There are three kinds of approaches to detecting a particular area from the image: using an average and standard deviation of pixel values (Fijita 2006), using a depth map (Zhang et al. 2010), and using machine learning (Badrinarayanan et al. 2017). Of these, machine learning methods known as semantic segmentation enable robust object recognition by using various training images, without any special equipment. Therefore, this research selected a machine learning method for image segmentation.

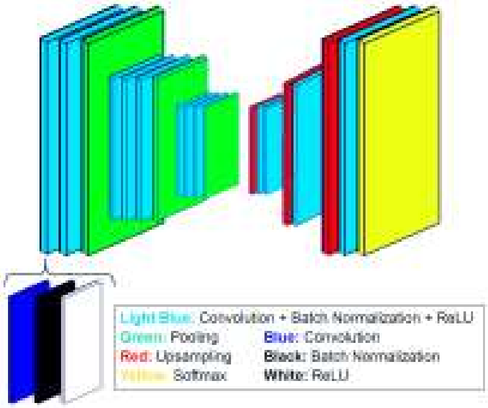


Figure 2
Structure of Sky-DetectNet

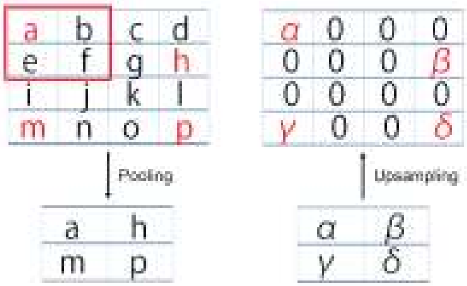


Figure 3
Correspondence between pooling and upsampling

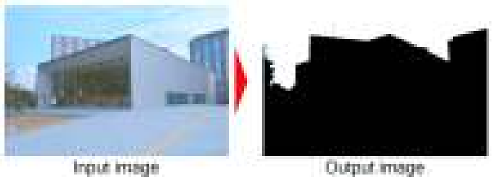


Figure 4
Ideal output example by Sky-DetectNet (created by Adobe Photoshop CS4)

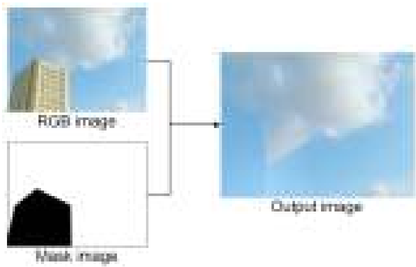


Figure 5
Image inpainting example

Our approach presumes the background sky from the sky that appears in the photographed image. This method comprises two steps: (1) detecting the sky area from the image using image segmentation and (2) creating the sky image using image inpainting.

### *Detecting the sky area from the image using image segmentation*

A machine learning method is adopted for image segmentation. Our deep convolutional neural networks (hereinafter referred to as Sky-DetectNet) that train and predict images are developed based on SegNet (Badrinarayanan et al. 2017). Sky-DetectNet is structured in layers; each layer is composed of an encoder network and a corresponding decoder network (Figure 2). The input data for Sky-DetectNet are images defined in the RGB color space. Batch normalization is applied to normalize outputs from all convolution layers (Ioffe and Szegedy, 2015). Rectified Linear Unit (ReLU) is used for the activation function. The space size of the final output result is decided according to the number of classes to be classified. In the learning process, the output result is normalized by the SoftMax function. Sky-DetectNet takes an image defined in the RGB color space as input data.

The first half-layer of Sky-DetectNet is an encoder network, and it comprises eight convolution and three pooling layers. Using VGG (Visual Geometry Group) results as a reference, we developed this structure such that the size of the processed data array is reduced two-fold by the pooling layer after two or three superposed convolution layers (Simonyan and Zisserman 2015). All convolution layers have a $3 \times 3$ filter and a fold in stride 1 and padding 1 to ensure the space size remains unchanged in these layers. However, the number of channels increases in accordance with the depth, 16, 16, 32, 32, 32, 64, 64, 64, in order, starting from the front layer. The pooling layer has $2 \times 2$ spatial windows, and stride 2 is performed such that space size is reduced two-fold by max-pooling without overlap. The index used for max-pooling is recorded and then used in the decoder network.

The position information may be lost because of the decrease in the space size during pooling. In FCN (Fully Convolutional Network) and other similar methods, position information is held prior to pooling and sub-sampling is performed (Long et al., 2015). However, in the Sky-DetectNet, pooling occurs only thrice and since the possibility of losing position information is low, sub-sampling in the pooling layer is not performed.


Figure 6
Plan for verification experiments

The second half-layer is a decoder network that comprises four convolution and three upsampling layers. The role of the upsampling layer was to restore the previously reduced space size by pooling. The reduced space size exiting the encoder network is expanded in the upsampling layer to return to its original space size before it is passed through one or two convolution layers. The convolution layers of the decoder network are in the reverse order compared with the convolution layers of the encoder network. Therefore, the number of channels decreases to 64, 64, 32, 16, in order, from the previous layer and followed by folding of stride 1 and padding 1, which was performed by $3 \times 3$ filters. The upsampling layer increased the space size two-fold using the index recorded in the corresponding pooling layer (Figure 3). During pooling, elements other than index were set to zero. The pooling and upsampling layers correspond to the space size, i.e., the indices used in the first three pooling layers from the front layer are used in the last three upsampling layers.

The output by Sky-DetectNet is an image in which the sky area and the non-sky area of the input image are divided. Figure 4 is an ideal output example. One drawback is that false detection may occur if pixels other than those of the sky are erroneously detected (i.e., pixels determined to be part of the sky even when they are not). In this case, the accuracy of the resultant image by image inpainting method, which will be described later, significantly deteriorates, making it necessary to exclude erroneously detected sky pixels. Therefore, the outputs from Sky-DetectNet are corrected by assuming that while the output of Sky-DetectNet includes false detection, most of the pixels are the result of correctly detected sky. Thus, it can be said that the average of these pixel values is representative of the pixel value for the sky area. The average value and the standard deviation of the hue, brightness, and saturation in the HLS color space of specific pixels that are judged to be the sky are used as reference. Therefore, it is possible to determine erroneously detected pixels by comparing their hue, lightness, and saturation values to that of the known sky pixels.

### *Creating the sky image using image inpainting*

Image inpainting is a technique that uses mask images to estimate noise and missing parts of an image from surrounding pixels (Figure 5). The output by Sky-DetectNet is used as mask image. Image inpainting was performed using an algorithm previously described in the literature through implementation in OpenCV (Telea, 2004). Afterward, blur processing is applied to the output image to create a natural sky image.

## VERIFICATION EXPERIMENT

In this chapter, we describe the results of on-site verification on outdoor structures using the DR system by applying the method described in the previous chapters.

This system was developed using C# programing language through the game engine Unity 5.4.2f2 with OpenCV for Unity. Unity was not used to implement the deep-layer neural network for detecting the sky area. Instead, the deep-layer neural network was constructed, learned, and estimated using Python 3.5.2 with NumPy, Matplotlib, and Pillow libraries. We used a standard laptop, SONY VAIO SVS13A1AJ with Intel Core i7-4500U @ 1.80 GHz of CPU, 4.0 GB of RAM, with the operating system Microsoft Windows 7 Professional 64-bit. A Logicool HD Pro Stream Webcam C922 with resolution of HD 1080p was also used.

We implemented a DR system that applied an optical integrity method with the existing structure as the verification target. The two-story dining hall at Osaka University (Poplar Street Welfare Center) was selected as the object for removal, and the nearby Buildings A and B of the Information Science Department were selected as the hidden backgrounds (Figure 6). The reason for choosing these buildings is that photographs used for SfM can be taken from multiple viewpoints. Moreover, facades of structures with hidden backgrounds are distinctive and, therefore, are easy to recognize when superimposed as the hidden background image. Furthermore, the sky is included in the hidden background, and there is a time zone during which the shadow of the removal target building falls to the front. All verification experiments from the next section were performed at this selected location (Figure 7).

### *Detecting the sky area from the image using image segmentation*

Sky-DetectNet was performed using Python 3 without the use of an existing machine learning framework. The initial data set used for the learning network was 450 pairs of images created using Adobe Photoshop CS 4 and then increased to 2700 pairs by inversion, smoothening, the addition of Gaussian noise, contrast adjustment, and application of grayscale. The increased data set was further classified into 2160 sets of training data and 540 sets of test data. The example data given by a "teacher" comprised an image showing the sky (Figure 8). The corrected image has the sky part of the image in white and all other parts are painted black.

Figure 7
Experimental photograph


Figure 8
Teacher data example

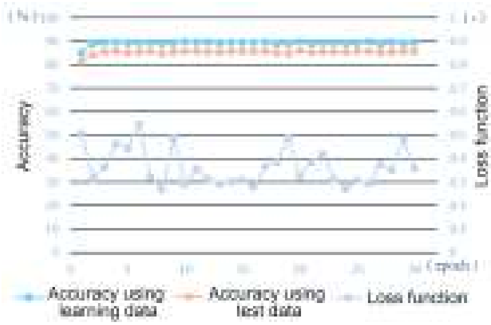


Figure 9
Sky-DetectNet learning result

All images are RGB images resized to 224 × 224 pixel resolution prior to input to Sky-DetectNet. The challenge is to segment them into two classes: sky and others. The parameters of the convolutional layers are initialized using the method proposed by He et al. (2015). As for the optimizer to update parameters,

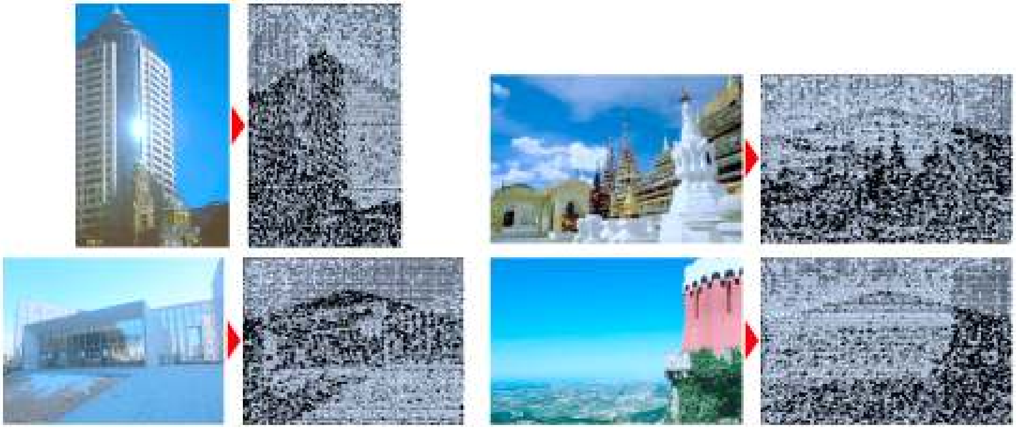

Figure 10
Input images (left) and the identification result images (right)

we use Adam (Kingma and Ba 2015), not stochastic gradient descent (SGD), and a learning rate of 0.01. We used cross-entropy error for the loss function and learned the mini batch size to be 8. The results of learning 30 epochs are shown in Figure 9.

For all test data, the identification accuracy for two-class classification was 85%. This accuracy rate was calculated by taking the average of the ratio of correct pixels to each image. Estimated processing of one 360 × 480 image took 422.50 ms by SegNet (Badrinarayanan et al. 2017) and 317.09 ms by FCN and using GPU (Long et al., 2015); in comparison, Sky-DetectNet can achieve a similar processing speed of 426.02 ms with only one CPU operation. Therefore, Sky-DetectNet can be implemented in DR operating environments without GPUs, such as laptop computers or tablets. Figure 10 shows a part of the identification result image; Sky-DetectNet determined that the pixels filled with white were part of the sky and the pixels filled with black were not part of the sky.

We observed that, although there were many white pixels in the sky area, erroneous detection was present throughout the image. We used dilation and erosion processing to exclude the areas where

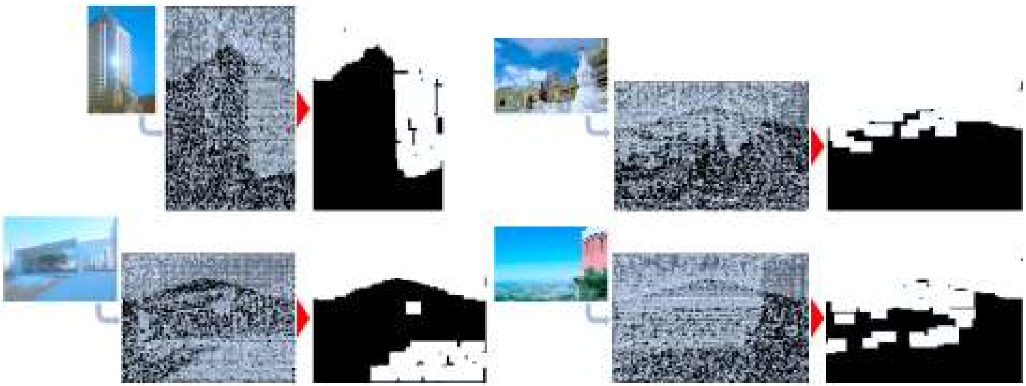

Figure 11
Erroneous detection correction by dilation and erosion processing

erroneous detection occurred, which was generally where the density of the white pixels was low. The dilation process replaced the target pixel with a white one if there is a white pixel around the pixel of interest, and the erosion process did the same for black pixels.

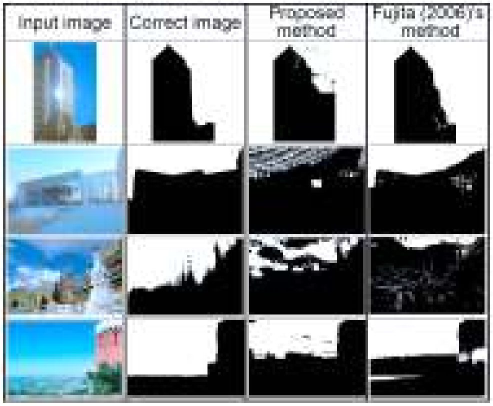


Figure 12
Sky detection results

It was necessary to specify kernel size, which is the number of pixels surrounding the pixel of interest. The output by Sky-DetectNet was dilated with kernel size 3. After that, it was eroded with kernel size 20 and finally dilated with kernel size 17 (Figure 11).

Erroneous detection was excluded by several processing methods performed sequentially. Also, if the sky area exists above the image, the white pixels that were present in the lower half of the image were regarded as erroneous detection and excluded. Figure 12 shows part of the detection result obtained by this method and the result of detecting the sky by the method of Fujita (2006) using only the average value and standard deviation of pixel values.

Detection error was measured by applying the proposed method and the method of Fujita (2006) to 10 images with randomly selected photos of the sky. The sky image was restored using image inpainting; pixels determined to be the sky even when they were clearly not part of the sky was a larger problem compared with pixels determined to not be a part of the sky even when it was part of the sky. Therefore, the detection error was calculated as the ratio of pixels judged to be the sky when it was not the sky for all pixels. Since the lower half of the image was judged not to be the sky, the detection error was measured using only the upper half of each image. Detection errors are shown in Figure 13.

The detection error of the proposed method decreased in 7 out of 10 images. Also, there were cases where there are many erroneous detections (Figure 13; image F), and there are cases where pixels detected as sky do not exist (Figure 13; image J); depending on the image, the detection result was not stabilized (Fujita 2006). Conversely, in the proposed method, stable detection could be achieved by narrowing down the sky candidate region by Sky-DetectNet.

Figure 13
Sky detection error (%)

| ID | Image | Proposed method | Fujita (2006)'s method |
|---|---|---|---|
| A | | 1.01 | 0.34 |
| B | | 3.21 | 1.27 |
| C | | 0.09 | 0.71 |
| D | | 0.03 | 3.79 |
| E | | 0.00 | 0.05 |
| F | | 0.00 | 10.2 |
| G | | 0.00 | 0.02 |
| H | | 0.02 | 0.00 |
| I | | 0.06 | 0.03 |
| J | | 2.18 | N.D |

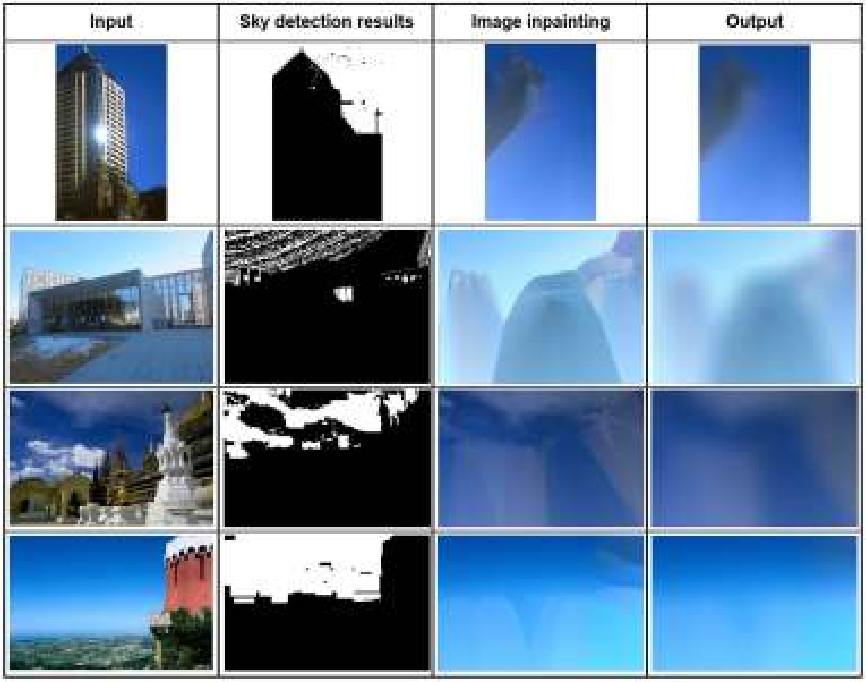


Figure 14
Sky image creation results

### *Creating the sky image using image inpainting*

Image inpainting processing was performed using both the image input to Sky-DetectNet and the result image divided into regions in the previous section. Blur processing was applied to the output image after image inpainting process to create a sky image. Some of the output results are shown in Figure 14.

In addition, we compared the sky area of the input image to the created sky image by the following method:

1. Obtain a sky range for hue (HLS color space: H value) using pixels in the sky area of the input image.
2. Regard pixels from the output image with hue values outside the sky range of the input image as mismatched pixels and calculate the ratio of occupying the entire image.
3. Create a scatter plot from the lightness (HLS color space: L value) and saturation (HLS color space: S value) of pixels with values within the sky hue range of the input image among all the pixels of the output image. Compare pixels in the sky area of the input image with those in the output image.

For the four images shown in Figure 14, the results of scanning pixels after resizing to 112 × 112 respectively are shown in Figure 15.

The t-test with a significance level of 5% was applied to plots for lightness and saturation, a significant difference was observed for saturation (Figure 15 (c)). Statistical matching was difficult because it involved erroneous detection at the time of sky area division. In Figure 15 (a), there was a large variation in saturation, and in Figure 15 (b), the brightness of the output image was low. As can be seen from Figure 14,

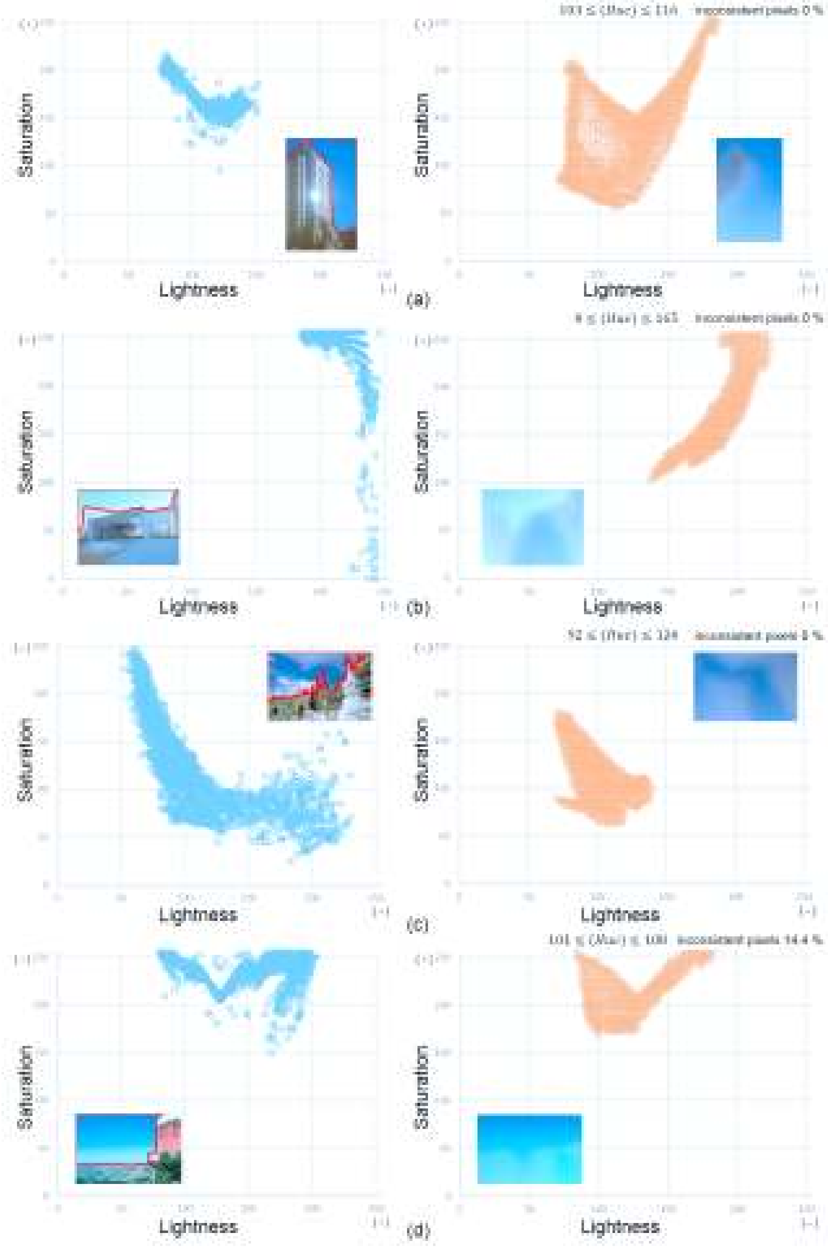


Figure 15
Comparison of pixel values of input image sky area (left) and output image (right)

it was thought that information on pixels other than the sky was also used when creating a sky image because there was false detection present. Conversely, the pixel value distribution of the output image is biased to a narrow range via the sky area of the input image (Figure 15 (c)). This may be because only a few pixels were detected as sky and a small sky area of the input image was used for image inpainting processing.

## CONCLUSION

This research proposes a method to minimize optical inconsistencies that occur when simulating landscape after the targeted structure is dismantled and removed in a landscape examination by DR. A system was developed to obtain optical consistency by applying deep neural network to estimate the sky area of photographed images and hidden backgrounds. In an architectural design study with landscape simulation by DR, the proposed system allowed the background sky to be accurately estimated and extrapolated.

Future work will examine the removal of the cast shadows of demolished objects and edge blending for the pasted area.

## ACKNOWLEDGEMENT

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# New digital trends in current architecture

## *A comprehensive critical examination*

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*The research presented is about digital revolution in architecture, which has contributed to the birth of new figurative trends. The work was conducted through the definition of a framework to identify and classify architectural design elements that should be attributed to the methods and techniques of design computing, then applied to sixty prominent recent architectures which are acknowledged products of digital means. The early results suggest that a new era is coming, where the conceptual starting point of designers is often born in the digital space, taking advantage of the augmented representation skills to control and manipulate form. We will also do an overview of these new architectural trends, discussing both causes and cultural roots and identifying eventual criticisms and further developments.*

**Keywords:** *digital design thinking, contemporary architecture, design process, digital trends*

## INTRODUCTION

At the beginning of digital revolution, the computer was only an exclusive toy for an academic and technological elite of researchers and developers jealously guarding an expensive technology and its applications, and restricting it to their internal preoccupations. However, since the commercialization of the first CAAD (Computer Architectural Aided Design) programs in the '80s, initially born to *aid* the production of *drawings*, software has progressively begun part of designer's tools. Despite at first an undoubted advantage was the extensive exploration of the architectural space and the direct control of its transformations in all phases of the project, after some years of experimentation it was clear that software aided the expression of designer's creativity too.

Through current modelling software, you can get even more complex forms of representation: they add up to traditional graphics media and an additional system of information is directly available. It becomes a stimulus to our conceptual skills, using new media to govern the complexity and to give free rash to design creativity. Definitely, this has led the architect to a radical change of its relationship with the design. The classical conceptualizations, previous to the final form configuring and expressing architecture, go now almost in parallel with the representation of the form itself. Nowadays everyone agrees that digital tools are currently used in architectural professions and that the effect of their use is rather evident on the formal and aesthetic configuration of some buildings. On the other hand, it is actually unclear how much CAAD software influenced this new figurative dimension.

Therefore, the first goal of the research is identifying the extent and scope of digital influences on real architectural expressions. It is unclear what these influences entail and what evidence we have for their existence and significance. It seems that we all generally agree to the existence but are not able to recognize their influences and effects. After a closer inspection, it becomes evident that the main reason for recognizing digital elements is what the designers themselves or some critics said. Indeed, after the objective identification of digital influences in a new architecture, we should be able to identify their origin, too: do they derive from a research or are they products of general computer literacy? In this scenario, what is the role of composition and why is architectural expressivity changing? This question is central to the role of design computing in architectural education but also points out research goals and directions that may be absent in current research (Riccobono et al. 2013).

Figure 1
NOX Lars Spuybroek, Son-O-House, Son-en-Breugel, The Netherlands 2000-2004, © NOX.

To achieve this goal, we need first of all a coherent and comprehensive overview of elements derived from design computing, so that we can unambiguously identify them in some recent architectures. Then we have to apply it to real cases in order to verify its adequacy and, when this is done, to examine how these elements appear and are used in practice and what is the linkage with geometry and spatial composition. Finally we must consider how digital influences contribute to a new way to intend architectural design and its formal expressions, to understand what is the state of architecture nowadays: which are the most common trends? Which are the positive and negative aspects of the digital revolution? Which could it be the future of our work?

## RESEARCH METHODOLOGY: A BOTTOM-UP APPROACH

Everybody can state that digital influences in a building are often easy to perceive in the overall shape [Fig. 1], as well as in some critical parts such as the architectural envelope, but it is rather difficult to understand when and how extensively the designers actually used the digital media in the design process (Pellitteri 2010). They might use digital means to solve specific problems, e.g. to represent complex geometries, or for design actions constrained by the use of digital tools (frequent use of particular geometric primitives or operations, for example). In many cases, the computer is used to facilitate representational and design actions, e.g. model complex surfaces that tend to be hard to specify by hand and may require more information than what is available in conventional orthographic projections. But in many others the digital media software were used for specific and technical aspects, like the optimization of performance features or for the facilitation of construction phases.

The identification of digital influences in a single project is quite useful for the refinement of the framework, i.e. the definition of the repertories and the clarification of the specific forms their members may assume. This problem could be approached in two opposite ways: with a top-down or a bottom-up approach. The first means the production of an extensive, possibly exhaustive series of examples for each digital element and use the results, properly classified and clustered, as templates for identification. Such a series can be produced by observing designs, collecting relevant occurrences and probably augmenting the results with plausible, possible and probable variations. Instead, we have opted for the bottom-up approach: identifying instances of digital elements directly on the existing projects, without attempting to complete the spectrum with additional instances. This agrees with the critique moved by Dorst (2008), who have denounced a certain absence of consistency and logic in researches on digital design, a lack of scientific methodology, and at the same time he has suggested to apply the scheme observation-description-explanation also to our field of knowledge.

For a real bottom-up analysis, in order to clarify how much CAAD software have contributed on the emergence of Digital Design with precision and overview, we have avoided opinions (either from academia or from practice) and focused instead on the actual products, analysing sixty recent buildings clearly related to digital methods or techniques.

The analyses were conducted in a uniform objective manner and collected in a database, which allows a wide variety of queries on the identified features and where the collection of data, the classification of projects on the basis of predefined objective parameters and, above all, the interrelations between two or more parameters. They permit us to understand the role of digital means in contemporary architecture with clarity and consistency, so that we can not only describe but also explain the state of the art.

## *Inclusion criteria*

The case-studies were chosen from the high end of contemporary architecture. They are:

- architectures where the influences of digital tools and culture are strongly evident;
- high-quality buildings, testified by the publication on international journals. We have chosen not to include projects that exist only on paper, because this does not permit analysis and evaluation of many aspects, e.g. the real relationship with the environment or tectonic issues;
- buildings from all over the world, since the effects of digitization on current architecture have been not dependent on local culture;
- projects realized in the last twenty years;no specific typology. As in the case of global scale, digital influences on current architecture are not dependent on the specific functions accommodated in the building.

## *Database Structure*

To make easier our analysis, it was chosen to collect all the information related to these buildings in a database so as to ensure consistency: each building is analysed in the same manner and the results are described in the same terms, thanks to some predefined parameters [Fig. 2]. The use of a database has several positive aspects: firstly it gives us the possibility to apply a combinatorial approach, which allows us to figure out relationships among several elements in a building's description, to visualize them and to interpret the results; secondly, organizing information in a database forces us to think in a concrete way, less vague than textual discourses, according to a rigorous logical scheme, where several aspects and their interrelationships can be made explicit.

The first part of data collection concerns the description of each building through fields such as *Building Name* and *Designer(s)*, identified as primary keys, *Location (city), Country, Date from* and *to, Client, Type* and *Context*. The description is completed with photographs, drawings and dimensional data. After this first descriptive part, we deal with the real analysis and close examination of the cases.

To develop the analytical framework, in order to search for digital influences in a building, we have based our investigation on formal and representational repertories offered by digital means, grouped under two main categories, *general features*, that do not refer strictly to the use of computer, but put attention on other important points, and *local features.*

Figure 2
The main interface of the database.

*General features* regard the taxonomical analysis of each project, through the recognition of its *Geometry* and *Morphology*. *Local features* have a wider purpose, especially as new digital methods and techniques continuously add to them. They comprise three complementary groups, the first of which contains the *geometric primitives* and *models* used in a project: cones, cubes, cylinders, freeform solids, *NURBS* surfaces etc. In this group, the dual role of digital means becomes quite evident: at least some of these primitives are not bounded by computational environments; it is simply their definition and manipulation that becomes significantly easier and more reliable with digital means. Other geometrical models are inconceivable outside computational environments either because they emerged in relation to computation or because they are mathematically or geometrically hard to implement and control.

About *primitives*, we have also distinguished two different levels. In the *first* level, it is possible to choose among the several parameters with a forced selection, so that the primitive detected is one and unequivocal; you cannot pick both parallelepiped and sphere, because always one is prevalent on the other. For this reason, we have admitted a *second* level where to identify the other elements which participate to composition, with the possibility to choose more parameters [Tab. 1].

Following this taxonomic exploration, the analysis continues with the other two groups of local features, regarding the role of composition in the design process. Firstly, we focus on the recognition of the *formal concepts*, which cover local, general, bilateral and multilateral relationships such as *alignment, axiality, horizontality, symmetry, verticality* etc. These underlie the conceptual arrangement of primitives but

| **Category** | **Parameters** (underlined words indicate the parameters related to the digital domain) |
|---|---|
| Geometry | Rectilinear, Curvilinear, Hybrid |
| Morphology | Anthropomorphic, Biomorphic, Geometrical, Zoomorphic |
| Geometrical primitives and models (1st and 2nd order) | Cone, Cube, Cylinder, Ellipsoid, Free-form solid, Helix, NURBS Surfaces, Parallelepiped, Prism, Pyramid, Solid of extrusion, Solid of revolution, Sphere, Tetrahedra, Torus, Wedge, None |

Table 1
The classification of case-studies, with respect to geometrical features. (Riccobono, Koutamanis, and Pellitteri 2013).

are not limited by themselves: they are discernible as patterns and coordinating devices that may be quite indifferent as to the elements they apply to (Arredi 2006). In digital representations, such formal concepts are often expressed as constraints.

Then we focus on the *compositional operations* (Di Mari and Yoo 2012), which serve two related purposes: the implementation of formal concepts, e.g. as in the use of reflections and translations to create symmetric forms, and the transformation of primitives to produce generally more complex forms. The effects of these operations arguably determine most of the cues that allow us to recognize digital influences in a design, e.g. a Boolean combination or the adaptation of a mesh [Tab. 2]. Even in this case, it was previously defined which operations were born in the computational domain and which not.

While these repertories were initially compiled in a bottom-up manner by observing the several cases and correlating their features to the capabilities of digital design environments, there is also substantial support from literature, especially in some studies about the theoretical conception in architectural design, conducted through the observation and analysis of morphological features related to digital tools (Evans 1995, Liu and Lim 2006, Oxman 2008, Wong 2010). The choice of the parameters used in each category was based on the Getty Art & Architecture Thesaurus [1], in an attempt to add lexical consistency to the description of digital designs.

The analysis concerning these repertories can be done in two complementary ways, *syntagmatically* and *paradigmatically* (Van Sommers 1984). *Syntagmatic* analysis refers to the sequence of actions by which different primitives, concepts and operations entering in the design. *Syntagmatic* aspects can be of great value in computational and algorithmic studies (e.g. in shape grammars) but they are also difficult to detect in the final design and in many cases only loosely related to design thinking, as there can be various sequences of actions by which we arrive at the same results. Consequently, *syntagmatic* analyses tend to reveal more about contextual factors, including a designer's understanding of digital means.

*Paradigmatic* analysis focuses on the elements of the design, in our case primitives, concepts and operations, their existence and interrelationships without reference to temporal precedence or such mental hierarchy. This allows us to identify traces and effects of digital means in design representations, with the obvious exception of prescriptive algorithmic techniques like shape grammars. The economy and effectiveness of *paradigmatic* aspects made this analysis a safe starting point for this research.

## QUERIES, RESULTS AND INTERPRETATION

After collecting all data and settling all parameters for each case study, we have used the database to obtain results through its combinatorial possibilities. The main operation was setting out of several queries and questioning the software to visualize quickly the results and combinations in form of graphs, tables, reports, etc.

We have queried the database to show the related prevalence per each category. Referring to *Geometry*, we noted the high prevalence of the curvilinear one (67%), which confirms our first impression and cases selection. In turn, the strong tendency to-

Table 2
The classification of case-studies, with respect to compositional issues. (Riccobono, Koutamanis, and Pellitteri 2013).

| Category | Parameters (underlined words indicate the parameters related to the digital domain) |
|---|---|
| Form and compositional concepts | Alignment, Articulation, Asymmetry, Axiality, Balance, Complexity, Contrast, Disproportion, Frontality, Gesture, Harmony, Horizontality, Linearity, Monumentality, Obliquity, Plasticity, Proportion, Rythm, Scale, Simmetry, Simplicity, Unity, Verticality |
| Compositional Operations | Align, <u>Boolean</u>, Break, <u>Bulging</u>, Copy, Divide, <u>Extrusion</u>, <u>Folding</u>, Interrupt, <u>Loft</u>, <u>Mesh</u>, Move, <u>Offset</u>, Overturning, Repeat, Retract, Revolution, Rotation, Scale, Slicing, Sliding, <u>Smooth</u>, <u>Stretch</u>, <u>Sweep</u>, Taper, Tilt, Translation |

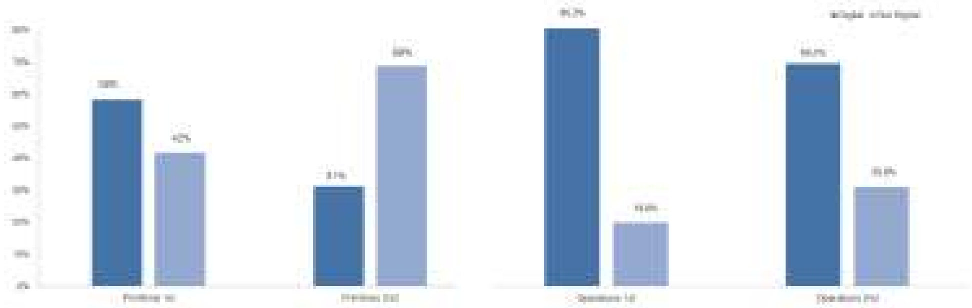


Figure 3
Prevalent primitives and operations in both levels and digital attitude (Riccobono 2014).

wards designs with curvilinear configurations is accompanied by a rigid geometrical control, testified by the high percentage (70%) of geometrical parameter in the category *Morphology*.

At level of *Primitives*, where we have identified two orders the most represented is *NURBS* Surfaces (25%); it is also significant that, filtering our results through the variable Digital-not Digital, there is an high prevalence of digital primitives (60%) in the first level, but not in the second level (only 24%). This suggests that the conceptual phase begins in the computational space with a primitive, rather than with e. g. a sketch (Dorta et al, 2008), but subsequent primitives used in the composition are conventional and not digital [Fig. 3].

If we look at *compositional* level, it is evident that a high percentage of designs used operations totally digital (81%), where *folding* (33,8%) dominates both as an expression of the ability to reliably control complex surfaces by computer and of certain tendency to abandon straight and regular geometries [Fig. 3]. Preferring curved lines, sloping planes and organic spatial configurations is one of the fundamental evidence of Digital Expressionism.

This attitude is arguably also confirmed by the relevant presence of operations like *loft* and *bulging*. As regards formal concepts, most of them cannot be called strictly *digital*. However, the popularity of concepts like *plasticity* (12%), *complexity* (10,1%) and *unity* (9,7%) confirms the feeling that architectural products of this trend are often intended as artistic expressions.

Figure 4
Zaha Hadid Architects, Heydar Alyev Centre in Baku, 2007-2012. © Zaha Hadid Architects, Iwan Baan.

Looking at the Figures 3 and 4, we can assert that the digital attitude is pretty evident in both morphology and composition. Design thinking and conception are becoming more and more identified by a pervasive use of digital technology and by geometrical and mathematical operations offered by commercial software. Proliferation of curvilinear geometries and plastic spatial configurations appears related to the main change allowed by digitization of architecture that is linked to representation, but not just to it.

Table 3
The main features of Digital Expressionism (Riccobono and Pellitteri, 2014) .

| *Geometry* | *Operations* | *Concepts* | *Design Strategies* |
|---|---|---|---|
| Curvilinear | Digital Domain | Plasticity, Complexity, Unity | Artistic Fact, Blob, Flows, Fluidity, Folded Surfaces |

## EMERGING TRENDS IN THE DIGITAL AGE

The last part of analysis is devoted to map the conceptual criteria based on each case. Despite some projects could seem affine looking at their formal configuration, materials and overall style, their concepts could often start from very different point of view. We can recognize these conceptual strategies only by tightly studying what designers say in projects description and identifying, e.g. which software were used to conceive design. Hence, we have defined a vocabulary of the recurrent conceptual strategies derived by the use of digital technologies, describing and explaining each category in all specific aspects. Each architecture was classified according these several categories and we have considered that some buildings might have more than one classification. Among the categories identified, we find *blob*, term coined by Greg Lynn (1998), which refers to digitally designed buildings that have an organic and bulged shape, as an *amoeba*, and *grid*, traditionally a Cartesian structure that generates static and rational shapes, but that computationally deformed becomes instrument for designing forms and spaces unpredictable and changeable. Other used identifying terms, which here we limit to list, are: *fluidity, flows, diagram, pattern, artistic fact, deconstruction, folded surfaces, mathematical derivation, natural derivation, performance* (Pellitteri and Riccobono, 2012).

Comparing those results with what already obtained by the analysis of digital operations and primitives, it is possible to identify some transverse movements in which we could subdivide the digital-influenced architectures.

### *Digital Expressionism*

This trend gathers architectures with a strong morphological approach, where building envelope, often with curvilinear configuration, is treated as an art work, refining, folding and shaping surfaces [Tab. 3]. This appears linked to the main change caused by digitization of architecture, related to advances in representation field and its consequences. Indeed the easy three-dimensional control guaranteed by software has meant a change in the ways of exploration and conception of architectural space. Since the origins, prerogative of architectural design have always been the extensive use of visual methods and techniques in composition and each radical discovery in representation field had always constituted a revolution in the architectural design thinking.

Nowadays it seems that morphological approach to architectural design takes over and this starts often from the curvilinear manipulation of shape, pushing to the limit the potential of software to search for often unusual spatial configurations. It does not mean that curvilinear geometries and complex surfaces were not used and not experimented in the past; rather this trend seems the right continuation of the expressive tendencies born in the Post War, with personalities as Eero Saarinen, Hans Scharoun, Felix Candela. The main difference with respect to the '60s is the extreme facility to conceive free forms, without minding about their geometry in the first stage, and to progressively refine the configuration according to aesthetical, structural, functional needs. This is undoubtedly a pro, but it is a contra at the same time: facility and speed can make designers loose the way, not considering aesthetical, contextual and tectonic and other relevant factors.

### *Hi-Tech Evolution*

This category includes buildings in which the generation of the shape is digitally derived by optimizing one or several parameters, e.g. environmental, procedural, structural, and so on [Tab. 4]. When digital media appeared in the practice, some architects with a strong technological approach had adapted their design methodology to new software. Starting from the optimization of one or more parameters to

| Geometry | Operations | Concepts | Design Strategies |
|---|---|---|---|
| Curvilinear | Digital Domain | Complexity, Articulation, Plasticity | Performance optimization, Mathematical Derivation |

Table 4
The main features of Hi-Tech Evolution (Riccobono and Pellitteri 2014).

increase building *performances*, the new software allows the creation of autonomous architectural forms, arising directly from the optimization of different parameters. Another approach to build performance is to obtain the final shape through the modification of a primitive (e.g. from a sphere, a cube, a parallelepiped), which will further deformed by following approximations, until it reaches the best possible configuration. This trend was called by some critics *Performative Architecture* (Kolarevic and Malkawi 2005), even if it not properly a new attitude. In fact, looking at the protagonists of this kind of methodology, we find Norman Foster [Fig. 5], Nicholas Grimshaw, Renzo Piano, who are the same protagonist of the so-called *Hi-tech* trend in the '80s. It seems we are looking at a natural evolution of a trend, that through the possibilities of digital design has pushed until the limit the building technology, creating an old expressivity in terms of material - almost always steel structure with glass walls - but new regarding to the envelope's shapes.

Figure 5
Foster & Partners, The Sage Gateshead, Gateshead, UK 1997 – 2004. © Foster & Partners.

### *Diagram Architecture*

This trend was not born with digital technologies, but with their huge diffusion the sense and use of architectural diagrams was modified [Tab. 5]. Let's start from the term: *diagram* in architecture it is usually thought of as graphic tool (Bijlsma, 1998), that is the translation of a series of possible relationships between the parties in a drawing, but it can't be attributed either to the type, nor even to a sketch. The term derives from Greek *dià* (through) and *grámma* (something written). Although it is usually made up of points, lines and surfaces organized in two-dimensional or three-dimensional patterns, it may include data, legends, text, and then relate different aspects at the same time, crossing data, connecting functions and needs. Digital diagrams, often integrated in some software or add-on, have become an operational concept tools.

It is often happened that what was initially mapped as diagram, e.g. for function or users movement, in the final phase of project become the base of formal configuration. This way to proceed is very common in designers like UN Studio [Fig. 6] and Rem Koolhaas, but we have not to forget that the first to use digital *diagrams*, conceived as deformed grids, was Peter Eisenman, one of the most important architects of avant-garde and Deconstructivism.

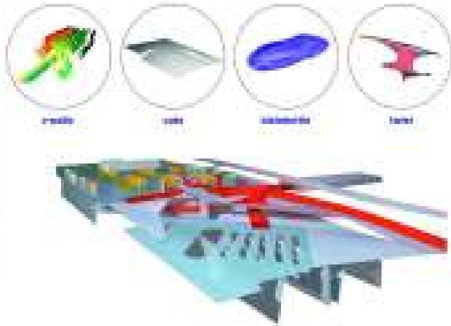
## CONCLUSIONS

The first thing evident in our multi-case analysis is that there is no easily discernible the digital approach concerning methods and techniques used. In con-

| Geometry | Operations | Concepts | Design Strategies |
|---|---|---|---|
| Curvilinear (50%) Rectilinear (50%) | Digital Domain | Complexity, Articulation, | Diagram, Grid |

Table 5
The main features of Diagram Architecture (Riccobono and Pellitteri, 2014).

Figure 6
UNStudio, Masterplan of Arnhem Central Station, Arnhem, The Netherlands, 1996-2015 . © UNStudio.



trast to the assumptions underlying design computing research and teaching, there is no predefined process or even clear strategies for each particular problem. The application of digital means seems opportunistic and generally dictated by contextual or cultural reasons - as many decisions are in architectural design (Till, 2009). Such reasons may result in-to effective, innovative solutions that serve well goals relating to function, performance and, more often, visual impact. Computational media produces the novel forms of *Digital Architecture* that attract the attention of a wide public and presents opportunities for combining different aspects and elements in ways that interest the architectural public. From our sample, it is evident that digital means are used for differentiation: just like modernists avoided decoration, digitally influenced designs seem to prefer *curvilinear* forms, even if tactics and concepts may have very different foundations. This seems to be done to indicate their opposition to earlier architecture and show clearly that the design is (partly) motivated by design computing ideas as expression of the future.

Prominent designs shows these digital influences in critical, high-risk situations where designers tend to pay more attention to project success, client requirements and overall appeal than to any computational principles and approaches. Our sample verifies the claim that digital means have become a ubiquitous part of architectural design tools and have irremediably changed the architects' way-to-design. Despite the existence of many algorithms and programs currently used, their architecture is not able to leave the visual approach out of consideration. Indeed, the main advantage given by the computer is the possibility to work visually in real time on 3D-shapes, by seeing what effects are produced by their actions. On one hand this fact has speeded up the design operations, but on the other hand the risk to "run into a loop", endlessly modifying the geometrical configuration, appears quite real (Riccobono, 2015). Increasing the number of younger architects who have had the benefit of early exposure to the computer and formal education in design computing (even if it is restricted to practical skills), it is unavoidable that digital influences at the morphological level will keep increasing. From our research it is still unclear whether this will be accompanied by increased compositional awareness and more intensive use of digital methods in synthesis (as opposed to representation).

This new style of *digital-influenced architecture* is formally based on free expressions, without a *canon* or a *style*. We think that this recognized digital trends, driven by international firms, introduces new degrees of complexity in the profession. Indeed, during the development of a project, it could happen that some architects will tend to keep merely the style or the formal configuration of some fashion designs, forgetting and not considering other aspects, such as cultural references and contextual choices (Pellitteri 2010). In many projects as those reported in this research, where the taxonomic values are strong we can see that designers tend to develop their own style, conducting to a simple reproduction of *beautiful forms*. Up to now, just by giving a superficial look at architectural websites like Archdaily.com [2], where anyone can upload their own projects, we can note strong similarities in some professional projects with international firms' ones.

Academic research and teaching may be rich in compositional studies and approaches, but if digital means enter practice primarily as design representations, it is inevitable that emphasis will be on *what* can be done with software rather than on *how* and *why*. In the war between conceptualization and morphology, actually the second seems to have the best. Consequently, each design project serves as a testbed firstly for morphological development (which tends to produce similar results to other designs) and secondly for experimentation with primitives, concepts and operations.

At the end of the game, despite of a general *expressionist* tendency, we cannot anymore talk in terms of language, style or aesthetic values. What the digital revolution has effectively produced is a free way to intend the project, with endless geometries, materials, building systems present at the same time and in the same places, without any consideration about a shared Architecture's Identity.

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[1] http://www.getty.edu/research/tools/vocabularies/aat/

[2] http://www.archdaily.com/

# Learning Space

## *Incorporating spatial simulations in design history coursework*

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*Art and architectural history education has long relied on photographic imagery. The geography of architectural history often demands an analog representation for the built form and photographic recordings have long been the widely adopted standard. In many cases, specific buildings have been taught for generations based on a handful of historical exposures. The impact of this precedent is an imperfect and highly privileged conception of architectural forms. Students learn only of a particular viewpoint of any given building, rather than understanding the building as a whole. Augmenting the tradition of select and static imagery in the classroom with new technologies can create a more comprehensive understanding of architectural precedents. This paper discusses an experiment conducted in Spring 2017 in presenting an architectural case study to a history class using a Virtual Reality 3D experience in comparison to a set of canonical photographs.*

**Keywords:** *Unreal Engine, Virtual Reality, Photography, 3D, Education*

## INTRODUCTION

Art historian Irwin Panofsky proposed that meaning can be derived initially in two ways when one seeks to understand the subject of a work of art/architecture: first, perception is what he called "natural subject matter" by recognizing forms and situations that one knows from his/her own experience. Then one identifies the conventional meanings associated with forms and figures as bearers of narrative or symbolic content, often specific to a particular time and place. Panofsky called this process iconography. The third step is what he termed as iconology. In this step, the goal is to interpret the art/architectural work as an embodiment of its cultural situation within broader social, political, religious, and intellectual contexts. This approach requires an understanding of the beliefs and principles or goals and values that underlie art/architecture's cultural situation as well as the position of an artist/architects and patron within it rather than identifying subject matter or conventional symbols.

While first two steps could easily be achieved in architectural survey courses, due to the inherent limitation of images and architectural representation techniques, educators come across difficulties to explain the cultural aspect of the architectural work or its iconology.

Besides architectural representation tools such as drawings, sketches, models, architectural history has been taught with the utilization of images, often photographs. This creates two main issues:

1: Architectural representation tools have more sophisticated inner dynamics than simply signifying the architecture that they represent. With reference to McLuhan's famous motto which suggests that "medium is the message," architectural drawings and models have been building their own "virtual" realities that refer to themselves before the architectural product. (McLuhan 1967)

2: Architectural documentation, mostly photography since its invention in the 19th century, that claims some sort of objectivity is purely illusion. Photography had never been used to document reality with pure objectivity, but this had almost always been the claim. The will of the photographer, his/her gaze shaped by that will, purpose of the photograph have served as the illusionistic tools. Showing photographs of a building, thus, embodies a more sophisticated network of representations rather than simply revealing facts about that building. Interestingly enough, this potential of photography has been deliberately used by the patrons, photographers and the architects from early times of the photography on. A good example would be the integration of the automobile to the images of Le Corbusier's buildings, for instance, to the iconic Weißenhofsiedlung project he contributed, Villa Savoye and many other "modernist" projects.

Julius Shulman's iconic photographs of Case Study Houses designed by different architects would be another example. They are arguably more valuable to explain how those photographs were utilized to socially construct the "image" of modernist architecture and how they reinforced that image by propagating the points that modernist architects aimed to disseminate such as emphasis of transparency (of both architecture and the society), hygiene, standardization, modularity. Among these, the Case Study House No. 22 by Julius Shulman (Figure 1) is a resonant example of staged photography creating an iconic image of modernist design ideals. The women seen occupying the house are youthful models recruited for the photo shot and the furniture within the residence was specifically staged for the shoot.

Neither the self-referential nature of architectural representation nor the constructed message of architectural photography, indeed, should create a problematic situation in architectural history education unless they are defined and promoted as tools of objective documentation.

Figure 1
Case Study House #22, 1960 Los Angeles, CA / Pierre Koenig, architect © Julius Shulman

The project we developed in Spring 2017 at New Jersey Institute of Technology adopted new tools such as VR technologies and aimed to overcome these pedagogical issues, to introduce photographs as sophisticated mediums rather than simply representational tools.

We are using VR technologies not to represent a particular building with all its details and its architectural paradigm, but to help students understand dysfunctional attempts to represent an architectural space through 2D representations that were not produced to document an architectural situation objectively in the first place. On the contrary, as explained, they were produced to be the very tools of architectural and discursive fiction.

The building selected was the Barcelona Pavilion by Ludwig Mies van der Rohe, which was the German Pavilion for the 1929 International Exposition in Barcelona. The Barcelona pavilion survived less than a year. When the International Exposition was over it was torn down in early 1930. Despite its short lifespan, visual representations such as photographs and architectural drawings kept the structure's memory alive. For decades the Barcelona Pavilion was praised as one of the masterpieces of Modernist architecture and design.

Figure 2
Berliner Bild-Bericht, Barcelona Pavilion, 1929

Figure 3
Student using HTC Vive Headset in the VR Simulation

The Barcelona Pavilion was eventually reconstructed permanently in Barcelona between 1983 and 1986 by a group of architects with the help of the visual representations of the building which already did an important job by reconstructing the image of the building in people's minds.

The Barcelona Pavilion (Figure 2) was a well situated foil for this study: a long history of existence only in historic photographs, a role in architectural education as a waypoint in modernist design, and a clear set of modern design principles students could be tested for the cognition of.

Our project aims to take advantage of complex nature of architectural representation and documentation tools by appreciating their invaluable potential to explain the historical context that the buildings were located into. How these tools besides the actual space play a crucial role in terms of "building" their -virtual- reality i.e. concepts of monumentality, nationalist/romantic architecture and so on.

By giving students a chance to experience virtual space, we emphasize, that space is not the space that it claims to represent. At this point one should remember René Magritte's "Ceci n'est pas une pipe." Similarly students in our project were well aware that what they experienced was not the Barcelona Pavilion, but, with its limited and problematic resemblance, tools that they can adopt to rebuild that specific building with the references to its reality: its fragments, parameters, compositional and discursive elements. In short, they were taught how they could build their own version(s) of Barcelona Pavillon.

## VIRTUAL REALITY

Recent advances in Virtual Reality (VR) have made immersive viewing hardware highly accessible. The HTC Vive and Oculus Rift are relatively affordable and available at the consumer level. These technologies have the capacity to playback highly immersive spatial simulations. On a more ubiquitous level, the Gear VR and Google Cardboard framework make VR available to most members of our College student body.

VR technology was adopted early on for architectural design studios (Achten 1999) but has been relatively underutilized in architectural history. While visual simulations have recently been implemented in some historical studies (Favro 2010), especially in the realm of Digital Humanities (Wendell et al 2016), the adoption of VR has yet to become common. The potential for VR in expanding architectural knowledge through experience over imagery has been acknowledged but largely understudied (Alvarado 1999).

Figure 4
Screen Capture of Barcelona Pavilion VR Simulation, NJIT, 2017

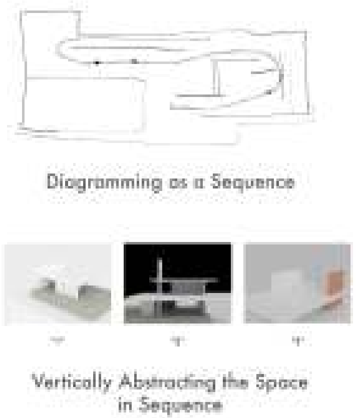


Figure 5
Vertical Reorientation. Andrew Carter, NJIT

## SIMULATION

Based upon the convergence of our discussions, the presence in our school of ubiquitous VR technology, and an eager cohort of undergraduate design students we decided to undertake a study. We designed an experiment to gauge the effectiveness of augmenting traditional photographic history with an immersive VR simulation. We posed the question of whether an architectural virtual reality simulation could create a demonstrable understanding in students beyond that of historic photographs.

An existing 3D model of the Barcelona Pavilion was used as the foundation of our VR simulation (Figure 3 and 4). A project in Unreal Engine 4.0 collected the 3D model assets and the controls for the HTC Vive Head Mounted Display into a real time 3D simulation. The HTC Vive hand controllers were used for a step based interactive navigation. With the head mounted display calibrated at floor height any participant could experience the simulated space according to their natural height. Participants could crouch, lie down, jump or otherwise manifest height and viewpoint differences in a natural manner.

## STUDENT ASSIGNMENT

The project leveraged 50 undergraduate design students in Spring 2017 semester. Students were required to complete an assignment exploring these topics in the final weeks of the semester. Students had the capability to navigate throughout the entire Barcelona Pavilion and view it from any location or direction they chose.
During the simulation, each student was given the opportunity to save images of their first person experience. The framing and composition of these image became an empowering act of virtualized photography through the lens of unique experience.

Students were expected to produce a visual narrative of what they learn during their VR experience. In doing this, they were asked to use formal parameters given by the instructor. Although students were allowed to add different elements, textures or colors, they had to use all the given shapes which are essentially produced from actual Euclidean geometries of the structure. Students were mandated to instrumentalize their recorded images from within the VR experience to produce the visual narrative.

Students had two options: they could either transform given shapes into a 3D assemblage by using software or they could craft those forms by hand and integrate them into a collage.

The final student deliverable was a PDF file including the images they captured during their VR experience, their visual narrative (i.e. collage or assemblage), and one-page written report that explained their project.

In addition to the visual narrative assignment, all students executed a questionnaire prior to the start of the VR experience and upon completion of

Figure 8
Student work.
Daniel Han, NJIT
2017

the VR experience. The project team used this questionnaire to assess the familiarity of students with VR HMD technology and to measure simple associative cognitive measurements of spatial perception. The questionnaire made clear that; 66% of participants had previous experience with VR HMD, and that after the VR experience 78% of participants perceived the Barcelona Pavilion as primarily horizontal.

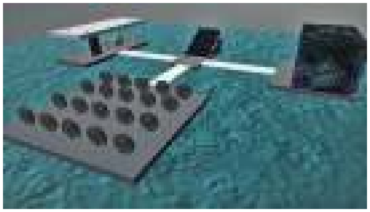

Figure 6
Horizontal panel
reconfigurations.
Andrew Carter, NJIT

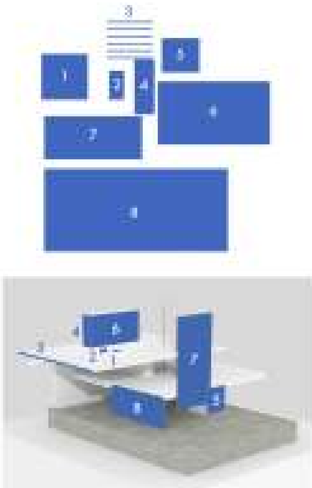

Figure 7
Student work.
Jenna Stuiso, NJIT
2017

## STUDENT OUTCOMES

Andrew Carter (Figures 5,6) developed an investigative approach. Rohe's De Stijl connections defined a starting point for him to test whether the architectural tools of the Pavilion could be reduced to its elements. These elemental forms were then employed to re-construct the "dynamic equilibrium" that Piet Mondrian investigated in his works. He simultaneously explored this opportunity to experiment with the fluidity of space as an architectural idea. Translating his fluid virtual visit to pavilion he reversed Pavilion dynamics and re-arranged the architectural tools and elements vertically.

Jenna Stuiso identified large fields of physical materials in the pavilion. Figure 7 shows the extraction of these materials into a two dimensional collage reflecting the collapsed and collected planes. The proportion of each band in the image reflects the gross horizontal proportion of the pavilion. The translation from three dimensional to two dimensional presents a critical analysis of material use cast into the organizing principles of the architectural form.

Daniel Han created an interactive game environment. Daniel developed a platform based game (Figure 8), inspired both from the architecture and from his VR experience. The large scale horizontal canopy reflects the horizontal bias of the Barcelona Pavilion. He investigated the terrace and architectural flooring as platforms carefully aligned and arranged. He suggested re-purposing those platforms as interaction devices where the player encounters historical events and paradigms in Europe such as WWI, colonialism, Industrial Revolution which he believes informed the creation of the pavilion.

## MAKING AND LEARNING

In order to evaluate the students' understanding of this building, it was important that the project aimed beyond simply a virtualized recreation of space. While a thoughtful and attentive recreation was authored, it was in service to larger idea. We conceptualized the project as creating an opportunity for the students to experience an outcome of the tools (color, material, volume, proportion, etc) of modernism in an effort to have them then use those tools. The adoption and use of these same tools is a way to measure knowledge.

The Barcelona Pavilion, and modernism in general, are fitting topics for this approach. Within the confines of this project early modernism can be approached as a parametric design process. Roofs become wide horizontal planes, windows become dissolved barriers, floors become planes of material. Modernism was positioned as a demonstration of parametricism. Students could demonstrate a cognition of this systemization through a new parametric design implementing these ideas.

## CONCLUSION

The use of photographs in teaching architectural history presents a skewed reality. From a pedagogical standpoint, it is important to acknowledge and embrace this condition. The complex conditions surrounding the use of photography, agency and influence create an informed teaching opportunity. Through the adoption of new technologies, we are simultaneously becoming capable of augmenting students' perceptions of historic spaces. These new teaching tools hold a promise to make present aspects of architecture previously masked through the lack of photographic evidence.

Virtual Reality is an important technology to facilitate a tangential experiential study of historic spaces. The ability to occupy, explore and record these experiences places students in a powerful role as explorer and witness to history. However, occupation of space is not enough to overcome our current pedagogical challenges. We must acknowledge the role students' agency and making plays in learning. The active engagement of the student in exploration, recording and synthesizing experience is critical learning. The application of principles, systems and concepts into creative outcomes solidifies learning and aids in assessment.

The study we undertook was an informative first step in developing a pedagogical dialog and approach

## ACKNOWLEDGMENTS

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# Tradition and Innovation in Digital Architecture

## *Reviewing the Serpentine Gallery Pavilion 2005*

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*Please write your aToday, in a moment when digital technologies are taking command of many architectural design and construction processes, it is important to examine the place and role of traditional ones. Designed by Álvaro Siza and Eduardo Souto de Moura in collaboration with Cecil Balmond, the Serpentine Gallery Pavilion 2005 reflects the potential of combining those two different approaches in the production of innovative buildings. For inquiring this argument, this paper investigates the development of this project from its conception to construction with a double goal: to uncover the relationship between analogical and digital processes, and to understand the architects' role in a geographically distributed workflow, which involved the use of computational design and robotic fabrication technologies. To support this examination, the authors designed and fabricated a 1:3 scale prototype of part of the Pavilion, which also served to check and reflect on the technological evolution since then, which is setting different conditions for design development and collaboration.bstract here by clicking this paragraph.*

**Keywords:** *Serpentine Gallery Pavilion, Computational Design, Digital Fabrication, Wooden Construction, Architectural Representation,*

### INTRODUCTION

As Vieira observes (1995), manual processes imply the mental and physical activities that allow us to easier reach our intuition. The production of drawings by hand was - and still is today - at the foundation of many architectural projects. The tradition of such manual representations can be traced back to the XV century, when Alberti claimed that the architect's role was to draw and not to construct their buildings (Carpo 2013). Lasting from the Renaissance, his notational system based on plan and section drawings have remained today as the most used normalized process to translate design into construction. Aside with these technical representations, sketching also has kept its importance as a privileged mean to bridge mind and hand, supporting the imagination and agile communication of architectural ideas.This is the main body of your paper. You can either add one paragraph at a time using the "(+)>" menu on the left side or fill it using "import paper".

With the introduction of digital technologies in architecture during the 1960's and 1970's, computers didn't offer much more than the emulation and automation of manual techniques to assist the development of conventional technical drawings. It was in the early 1990's, when architects started to explore the conception of architectural design ideas with the help of computers. For instance, the paperless studios at Columbia University were a declared move on using the digital as an alternative media to analogical ones (e.g sketching) to engage intuition and imagination. Since then, the evolution of the computational power and applications did not stop to grow. Today, digital technologies can assist at any stage of the architectural design process, from conception, to engineering, fabrication and construction.

The way architects are managing those possibilities is very diverse. In one extreme, there are those trying to resist them by insisting on the traditions of analogical representational tools and techniques. In the other, there are those expressing a universal faith in the digital and looking for exploring its full and exclusive potential of innovation in the design process. Between these poles, the majority of architectural practices set their own combination of analogical and digital tools aligned with the traditions of analogical-based design processes. Nonetheless, some practices like Frank Gehry, have innovated without denying neither traditional processes (e.g. sketching and physical modeling) nor digital ones (e.g. digitalization, parametric design or digital fabrication) (Lindsey 2002).

## *Research Topic*

In this context, the present article summarizes the investigation and findings of a Master thesis developed by first author (Almeida 2015) on the Serpentine Gallery Pavilion 2005, which was designed by Álvaro Siza and Eduardo Souto de Moura, with the collaboration of Cecil Balmond (Figure 1). While the architects are known from their design processes rooted in traditions and analogical representations [1] [2], the engineer is known by his disruptive and digital integrated design methods (Balmond 2007). Thus, this paper seeks to disclose the way such different approaches came together in such project. By investigating that question, both through literature review, contact with direct sources and practical experimentation with digital technologies, the authors argue that the Serpentine Pavilion 2005 is an exceptional project to demonstrate that innovation can emerge out of the combination of traditional and digital pro-

Figure 1
Serpentine Gallery Pavilion 2005 designed by Álvaro Siza, and Eduardo Souto de Moura with Cecil Balmond - Arup, Photograph © 2005 Sylvain Deleu

cesses in architecture. At this age of accelerated technological evolution it is important to highlight that the "old" and the "new" do not have necessary to be in constant opposition. Indeed, the use of digital technologies in architecture can actually include traditional processes and still produce innovative results.

## THE SERPENTINE GALLERY PAVILION 2005

Since 2000, the Serpentine Gallery in London has invited international architects every year to design a temporary pavilion in the gardens of the main gallery. The project is usually commissioned in January and has to be built and ready for opening in June, which thus gives six months to develop its design and achieve its construction. In 2005, the pavilion was conceived by the Portuguese architects Álvaro Siza and Eduardo Souto de Moura in collaboration with Cecil Balmond, a structural engineer at Arup by then. Besides the official book by Larner (2005), there is little bibliography available describing such singular collaboration and its resulting project. To investigate it, the authors contacted direct sources, like architect Tiago Figueiredo from Eduardo Souto de Moura's office, who was the project architect in charge of the Pavilion, and Michael Keller, a former Vice-President of Merk Timber, which was the company responsible for the digital fabrication of the wooden parts of the pavilion.

### *Design Development*

In Solà-Morales opinion (1997), contemporary architecture is characterized by its capacity to take advantage of scientifically and technological innovations. Thus, by looking at its formal and structural result, it seems possible to argue that the Serpentine Gallery Pavilion 2005 can illustrate that statement. However, a more in-depth review of its design process shows that it was not neither linear nor usual.

Known by their respect with the context and attention to building details, the architects desired this building to dialog with the big centennial tree that exists in the gallery gardens. With that in mind, the architects didn't want the building to look high-tech, in opposition to the previous Serpentine Gallery Pavilions (Figueiredo 2015). From a simple rectangular grid, the design sketches evolved to a more organic twisted version, with the intention to create a more fluid look (Figure 2). Nevertheless, as stated by Álvaro Siza (Larner 2005), those twists weren't made just for aesthetic reasons, but rather as a response to the natural slopes, directions and constrains of the site. The organic form of the building, resembling a crouching animal (Figueiredo 2015), made the architects decide to create a wooden building only with mortise and tenon joints (Figure 3). This kind of generative design process unfolded analogically through many sketches and conversations.

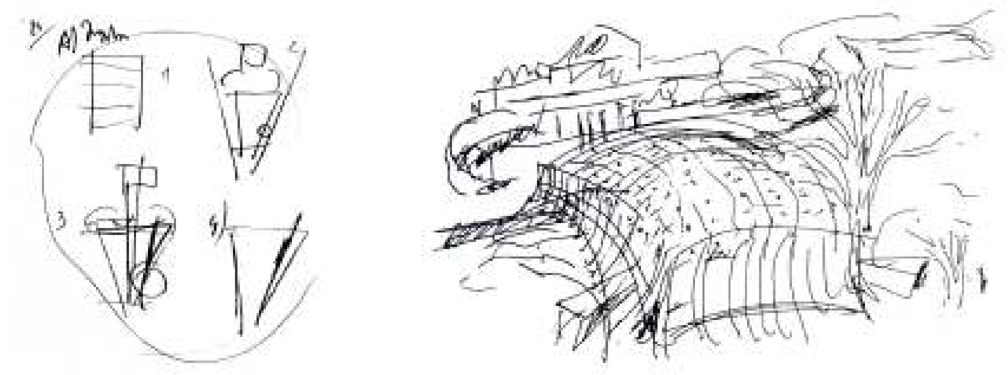


Figure 2
Conceptual sketches by Álvaro Siza for the Serpentine Gallery Pavilion.

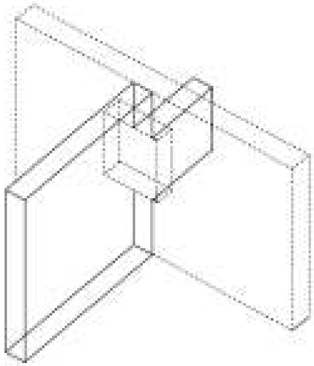


Figure 3
The mortise and tenon joint detail, which is very common in the wood industry.

Reacting to the architect's proposal, Cecil Balmond suggested a more intricate and sophisticated lamella system, by offsetting every wooden piece, to create a more random look. Conscious of their lack of computational design capabilities and the limitations of two-dimensional drawings to capture such design intention, the architects turned into LT Studio, a 3D visualization company based in Porto, in order to study and evolve the overall form of the pavilion. The first digital model of the pavilion was done with Rhinoceros but, given that it was not a parametric representation, every minor change made to the design implied the re-modeling of every piece. To overcome that limitation, Cecil Balmond and its Advanced Geometry Unit (AGU) at Arup took the responsibility to develop a computational model of the final design of the pavilion in Arup. Knowing that wouldn't be able to precisely model each one of the different wooden members, the architects defined a list of constraints and parameters. This allowed them to have some degree of control through the final modeling, even though they didn't took part on it. Regarding this, Tiago Figueiredo (2015) says "our concern was to look to the pavilion as a whole and not to the specification of each piece".

### *Construtive Development*

Coming from the interactions between the architects and the engineer, the structural concept behind the Serpentine Gallery Pavilion 2005 relied on the reciprocity principle (Sakamoto and Ferré 2008). As explained by Pugnale and Sassone (2014), "the principle of reciprocity is based on the use of load-bearing elements which, supporting one another along their spans and never at the extremities, compose a spatial configuration with no clear structural hierarchy". Led by Cecil Balmond in London, the AGU team applied that principle to the lamella system to achieve the necessary structural stability of the complex form of the pavilion (Figure 4). This endeavor originated a new model of the pavilion, based on a mathematical relationship between the constraints given by the architects and the position of each part on the three-dimensional grid. A script was then applied to create 36 coordinate points for each piece and thus automatically generate each of the 427 differentiated wooden components (Sakamoto and Ferré 2008).

Figure 4
View of the lamella configuration of the Pavilion structure.

Figure 5
The robotic cutting of the pieces (left) and a close view of the precision achieved in the connection.

### *Fabrication and Construction*

The digital fabrication of the pavilion was made in Germany by the Finnforest Company, which was later divided in two different companies, MetsaWood and Merk Gmhb. To handle with their variable size and slanted edge thickness, the pieces were milled using 5-axis KUKA robotic arms, running directly from digital data. Avoiding the production of printed drawings, the workflow was totally digital, and required a straight collaboration between the engineers from Arup and the Finnforest manufacturers to integrate fabrication parameters in the design model. As Michael Keller told the authors (2015), the entirely digital process allowed getting all pieces done in a small amount of time and with a great degree of precision (Figure 5). The robotic arms were programmed to detect the laminated veneer lumber boards (LVL), which was the material used to make the pavilion due to its lightweight, and automatically change its end-effector for the different operations (Menges 2006). Curiously, Martin Self, a member of the AGU team by then, acknowledges the Serpentine Gallery Pavilion 2005 as the first robotically fabricated building [3]. All the structural parts were then transported from Germany to London and assembled at the project site. Due to the irregular nature of the structure, the building had to be assembled in a strict order to avoid collapsing during that process. Once it was finished, the structure could hold itself just by the mortise and tenon joints. However, for extra safety reasons, the pieces were also fastened with bolts and nuts.

### *Remarks*

The built pavilion emerged from the successful articulation between two different approaches to architectural design. Indeed, the contextual and material interests of the architects unfolded through sketching and, without any digital influence, resulted in the imagination of an architectural solution featuring a complex form and structure. To make it real, the use of computational design was then essential to think and evolve such design intention towards a particular solution of a wooden lamela system with a unique expressive effect. Finally, digital fabrication was the only solution capable of solving on time and with precision, the materialization of all the different pieces. Besides assisting those stages in the design process, the digital also provided the media


Figure 6
Map of the geographically distributed collaboration behind the production of the Serpentine Gallery Pavilion 2005. Legend of cities / countries: 1.Porto, Portugal; 2.London, UK; 3.Esmoo, Finland; 4.Aichach, Germany

Figure 7
The 3 parts selected from the Serpentine Gallery Pavilion to develop a more in-depth geometric study.

Figure 8
3D printed model of the Serpentine Gallery Pavilion 2005 produced by SLS.

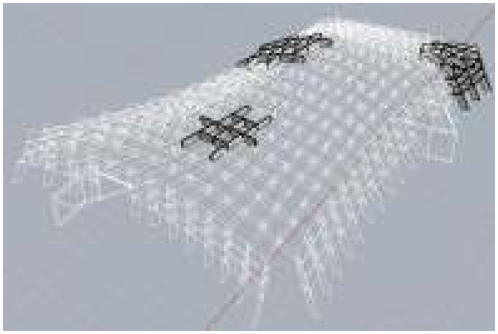
to support a geographically distributed collaboration through different European countries (i.e. Portugal, UK, Finland and Germany) (Figure 6). Indeed, ten years ago, the different expertise required for this project could not be found in a single place. The tectonics of the Serpentine Gallery Pavilion thus clearly prove how traditional interests and processes can be expanded by means of digital technologies, driving towards innovative built results.

## EXPERIMENTAL WORK

For a better examination of the Serpentine Gallery Pavilion 2005, the authors conducted an experimental work on digital design and fabrication. The goal was to understand the geometric challenges and the contribution of digital technologies in the process, while investigating the possibility of, ten years later, doing all the tasks in a single geographic location.

### *Design*

In this experiment, the authors identified three parts of the building - a corner, a flat part of the roof, and a curved one - and developed the corresponding digital models (Figure 7). This task revealed all the geometric complexity behind such a clear and apparently simple structural concept. Due to the virtual double curved form of the Pavilion, its direct conversion into a structural lamella configuration gave origin to a myriad of differentiated wooden pieces, many of which, featuring a complex surface on their contour depth. Just like in the real pavilion, the first step was to create a three-dimensional shell from a two-dimensional grid plan in Rhinoceros, with every interception on it corresponding to a different elevation. Then, each structural piece was created through offset, intersect, loft and extrusion commands. For modeling all the mortise and tenon joints, the authors used the constraints given by the architects, such as the maximum and minimum heights, and the length and the natural inclination of each piece.



### *Prototyping*

As stated by Tiago Figueiredo (2015), during the search for the ideal formal and constructive solution for the Serpentine Gallery Pavilion, it was extremely hard to make physical models, due to the intricate nature of the structure. The high number of different pieces and the impossibility to get the true shape of each one of the parts from bi-dimensional drawings determined that almost no physical model was developed during that process. In order to overcome the limitations of traditional representation methods, the authors took now advantage of 3D printing technologies and produced a 1:50 scale physical model of the whole Pavilion, using SLS (Selective Laser Sintering) process (Figure 8).

### *Fabrication*

From the three detailed digital models produced to study in depth the geometry and connection system of the structure, the authors decided that the double curved part of the roof would be the most challenging one to test the use of digital fabrication technologies and, more specifically, the capabilities of the robotic arm. Thus, the materialization of the structure at 1:3 scale unfolded through 3 stages: digital planning of the pieces, robotic fabrication and manual finishing.

In this experiment, the authors used a 6-axis Kuka KR120 r2700 belonging to the Digital Fabrication Lab (DFL) at the Faculty of Architecture of the University of Porto (FAUP), which has a 120kg payload and 2.7 meters of work range. Although also a Kuka robot was used to fabricate the original pavilion, back in 2005, the programming of the robot was more complex and would have involved the articulation between three different softwares (Braumann and Brell-Cokcan 2011). Now, in this experiment, the authors could take advantage of a single digital environment for designing and fabricating by using Grasshopper and the Kuka|prc plugin, running in Rhinoceros. By including a kinematic motion simulator and the automatic generation of the KRL code, the robotic fabrication could be executed by the robot without the need of using any other software.

Prior to the fabrication, all the pieces were scaled to 1:3 in Rhino, which allowed to be milled all at once from one MDF board with 22mm thickness. Using Grasshopper to define the geometries and KUKA|prc to program the motion of the robotic arm, the wooden parts were digitally fabricated within a couple of hours (Figure 9). The robotic arm was equipped with a milling tool mounted in the spindle, very similar to the one used in the fabrication of the original pavilion. It should be noticed that besides the irregular geometry of their contours, the lateral surfaces of the edges are variable ruled surfaces. For that reason, the 6-axis movements were a requirement for cutting out the pieces. Since the pavilion works as a reciprocal structure and the prototype was just a part of it, the pieces had to be fastened with bolts and nuts to stabilize their position. For covering the Pavilion, the architects used an acrylic panel attached to the wooden structure with a neoprene band below. For cutting those differentiated panels, this experiment took advantage of robotic hotwire process.

Figure 9
The robotic cutting of the wooden pieces at the DFL, with 6-axis movements.

### *Assembly*

The assembly process of the prototype was easy and the morten and bolten connections fit all together (Figure 10). It was interesting to observe the continuity of the ruled surfaces across the edge surfaces of the different pieces. Thus, one can affirm that the prototype captured the different aspects of the design and fabrication process of Serpentine Gallery Pavilion 2005.

Figure 10
The assembly at the DFL of the prototype of part of the Serpentine Gallery Pavilion 2005 at 1:3 scale.

## CONCLUSION

The research work presented in this paper investigated the role of traditional design processes in the digital era. To do so, the authors studied the design and construction processes behind the Serpentine Gallery Pavilion 2005, where traditional ways of understanding and representing architecture converged with advanced technologies to materialize an innovative building in wood.

The first lesson to retain from this project is the possibility to establish a symbiotic relation between analogical and digital technologies with a clear benefit for the architects. While sketching proved its validity to assist the architect's mind in the imagination of a complex solution, the digital design and fabrication means were decisive to evolve and materialize it. Without such integration, the architects' ideal vision could have been lost, or, most probably, several design simplifications would have to occur to make the project -for sure different- happen through conventional means. Methodologically, despite the switch of the process into the digital media and the geographically dispersed collaboration, Álvaro Siza and Eduardo Souto de Moura found a way to continue controlling the design development towards its materialization. As Tiago Figueiredo mentioned, even not directly controlling the computational design and digital fabrication tools, the architects had a key role through every stage of the process.

The experimental work developed by the authors confirmed the considerations made throughout this paper. On the one hand, it allowed realizing the difficult geometric challenges of the project, and experiencing the power of computational design to handle such complexity. On the other hand, reminding that it took only a couple of hours to robotically fabricate the 15 pieces for the 1:3 scale prototype, one can image the impossible task, in terms of time and craftsmanship, of fabricating the 427 different pieces of the structure through traditional methods. Also, it was interesting to verify that ten years after the Serpentine Gallery Pavilion, the technological evolution has created the conditions to produce drawings, digital models, prototypes and mockups in the same location. Given that architects tend to think through representations (i.e. graphic and physical), the possibility to collapse into a single place what was by then a geographically spread collaboration, draws new conditions to develop architectural projects.

To conclude, one can affirm that in an age of continuously technological evolution, it doesn't make sense to perceive the concept of innovation as an opposition force to that of tradition. Contemporary architecture, as a multidisciplinary area that requires the integration of different fields of work, certainly benefits from the synergetic process between traditional and digital tools. As stated by Tiago Figueiredo (2015) "it is for the best of architecture that we learn how to master the emerging digital technologies, nevertheless we may not let ourselves be dominated by them." Thus, in the Serpentine Gallery Pavilion 2005, advanced digital technologies clearly helped to expand and materialize the creative vision of Álvaro Siza and Eduardo Souto de Moura. The story of this building is exemplar in the way it can serve to encourage academic and professionals to find natural ways of integrating advanced digital technologies in the curriculums and practices. At the end of the line, it is the architect's judge that shall prevail, taking advantage of existing traditional and digital tools to fulfill his ideal vision for the built environment.

## ACKNOWLEDGMENTS

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# CAAD EDUCATION - PHILOSOPHY

# Computation As Design Logic Indicator

## *The Expo Project Experiment*

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*The city of Lodz is bidding for hosting International EXPO in 2022. The proposed theme is ``City Re:Invented''. The paper presents the EXPO project experiment conducted at Lodz University of Technology in cooperation with Lodz City Council. The idea was to prepare design proposals for promotional purposes, first in the form of computer visualisations, then as physical scale mock-ups produced in a digital fabrication laboratory. It is planned that the best solutions would be adopted and built in 1:1 scale if Lodz received a nomination. The results of the project are illustrated in the paper by selected examples. The main aim of this study is to examine computational thinking as a design medium. The paper presents background studies in this regard. It also looks into the approach to articulate digital fabrication and robotics as not merely the methods of delivery of a final product but their role in a design process. It deliberates pros and cons of computational design and its influence on creativity. It concludes with a statement that computation may help to construct, reveal, enhance and develop logic in a creation process.*

**Keywords:** *computational design, parametric modelling, digital fabrication, creativity, EXPO*

## INTRODUCTION

The city of Lodz is bidding for hosting International EXPO in 2022. It has been already involving intensive planning and promotional activities at the local, national and international levels. The proposed theme for EXPO is "City Re:Invented". The main idea is to revitalise the city downtowns and bring the event to the city centre which is opposite to the recent tendencies to organise such events in the city outskirts. What is more, since expos are expected to act as showrooms for new trends and technological solutions, hosting EXPO becomes even more challenging in numerous aspects. Therefore, Lodz University of Technology, Department of Digital Technologies in Architecture and Urban Planning undertook cooperation with the City Council and the EXPO Team. The idea was to prepare design proposals for promotional purposes, first in the form of computer visualisations, then as physical scale mock-ups produced in a digital fabrication laboratory. It was planned that the best solutions would be adopted and built in 1:1 scale if Lodz received a nomination.

The EXPO project experiment had much more complex role to play since it was expected that the process of developing ideas would gain strength and logic through the application of parametric design tools. Acquiring skills in advanced computer techniques was a crucial element of fulfilling the course learning outcomes. Thus, the approach to articulate computational thinking in a design process was formulated as the main assumption. In consequence, a discussion on the outcomes of the design task addresses the topic of computational design in education. The paper also looks into computational workflow from form-finding at the early stage of design, through modelling and optimising to digital fabrication processes.

## BACKGROUND

For the purpose of this study two background topics need to be elaborated on. The first one is connected with the shift in the paradigm of Computer Aided Design, while the second issue brings more details about the plans for EXPO 2022 in Lodz.

### *Computational design*

Dynamically developing advancements in information technologies which influence architectural domain have been observed for decades now. Although not all of them have been implemented or adopted in everyday practice, they are a stimulus for further innovations. The pace of change may be well illustrated by the following statement: "The current transition from Computer Aided Design (CAD) to Computational Design in architecture represents a profound shift in design thinking and methods. Representation is being replaced by simulation, and the crafting of objects is moving towards the generation of integrated systems through designer-authored computational processes" (Menges and Ahlquist 2011). Complementary, research and experiments in digital fabrication techniques bring novel opportunities for IT driven design process. However, it is still observed that "with the developments in digital fabrication, the production and assembly of complex forms has been compromised by the constraints of selected fabrication techniques" (Erdine, Elif and Kallegias 2016). Another constrain which may aid the background study is that "at this moment in history (...) technical challenges restrict design thinking, the creative process, and also visions of 3D printing possibilities" (Turunen 2016).

Referring to Sousa, Varela and Martins (2015), the last decade assisted to emergence of robotic applications in architecture, and popularity of robots in this domain is growing. Braumann and Brell-Cokcan (2011) presented a user-centred research where the objective was to enable a wide range of architects in the use of robots with a similar ease of use compared to conventional CNC-machines and an intuitive approach towards mass customization.

Actually, the world's first architectural robotic laboratory for non-standard assembly processes was erected at ETH Zurich. The pioneering work of Gramazio and Kohler (2008) should be mentioned here. Robotic technologies were used to bridge design and construction in architecture. The technology was tested on bricks as the basic modules. As the authors revealed, "bricks, being the primary module for construction (...) allowed us to concentrate on the design of completely programmed walls (...) In using an additive digital fabrication process, a novel architectural product of the kind "brick wall" emerged, which could not have been conceived or fabricated manually" (Bonswetch et al. 2006).

However, after more than decade and despite the continuity of further development of applications robots still remain "an expensive and uncommon technology in building construction, which, furthermore, require several other automation devices to assure a flexible and autonomous functioning (e.g., a system for feeding the bricks to the robot, a tool for laying the mortar or glue on the bricks, or sensors to monitor the correct geometric evolution of the built structure)" (Sousa, Varela and Martins 2015). It might be concluded that "while digital technologies have freed architectural innovation for star-architects while producing several layers of intricate morphological complexities, small and medium architectural firms deal with other levels of day-to-day challenges, dependent of the architect's level of expertise and size of firm" (Stals, Jancart and Elsen 2016).

The state of the art in computational design domain would not be complete without mentioning coding as a new medium for architects. According to Davis and Peeters (2013), coding has become increasingly accessible as a design medium in architecture and design. Furthermore, design software is more and more extended and customised through the development of scripting interfaces, add-ons, plugins, libraries, integrated development environments and programming languages. On the one hand, it is believed that designing "through writing custom code has shifted from being practiced by a handful of academics and pioneers to a broad emerging culture of coding in architecture and design" (Burry 2011). On the other hand, the tendency is not so obvious when it comes to small and medium firms since they actually constitute the majority of architectural practices (Stals, Jancart and Elsen 2016). Another author argues that coding is not a mere tool for designing but a particular design medium, with its own affordances and resistances. "Using code as a design medium provides a specific form of feedback, it influences the design process and its outcomes. Code is a technological and conceptual support for design thinking" (Cannaerts 2016). Lorenz and Wurzer (2016) go further and point out problem thinking is still underrepresented in architectural practice. Recently they conducted a didactic experiment which purpose was to emphasize problem thinking over solution generation. So, students were expected to express their designs in terms of code. However, Lawson experiment proved that while scientists have a problem-focused strategy architects perform a solution-focused strategy (Lawson 2005). There is no doubt, while considering computational methods in architecture, visual results depend mainly on cognition of algorithmic design and programming skills. (Kepczynska-Walczak 2008).

## *Bid for the EXPO in Lodz*

The World's fairs have long-standing tradition since the very first event organised in London in 1851. The exhibitions promoted progress in science and technology. In the 19th century this meant industrialisation while themes of recently organised fairs shifted towards social and environmental issues. The next International EXPO is expected to be organised either in 2022 or 2023. Three cities are bidding for hosting this event. One of them is Lodz, the third largest city in Poland.

The proposed topic of the exhibition is "City Re:Invented". This idea is based on a local experience. Lodz was once major textile production centre. Since the early 1990s local authorities have had to deal with issues related to industrial decline. This requires - apart from solving numerous problems of versatile nature - to answer a question: what should be the city about, now and in the future? This is a universal challenge, since - as recent studies indicate - more than a half of the world population lives in urban areas, and virtually all countries of the world are becoming increasingly urbanized [1]. The current figure (54.5 per cent) will increase to 66 per cent by 2050, which means that one third of people will live in urban areas then [United Nations, 2014]. What is more, it is expected that by 2030 some 60 per cent of people will live in cities with at least half a million inhabitants [United Nations, 2016]. In the light of the above, there is an urgent need for the improvement of the quality of life in the cities. Therefore, urban regeneration becomes a global challenge and a prerequisite for further development of agglomerations around the world (Monclus 2006).

Unprecedented revitalisation process has been already launched in Lodz. The program will cover a large part of the inner city. The figures are impressive: the designated urban regeneration zone embraces some 4500 acres with 21.000 buildings inhabited by more than 150.000 citizens. The development strategy of the city of Lodz aims at higher quality of life, inclusive and varied public spaces, social cohesion, creative atmosphere, well-kept heritage, living culture and more inhabitants in a city centre.

All recently organised World's fairs were situated at the city outskirts. Such location would be in contradiction to the proposed topic of the EXPO in Lodz. Therefore, local authorities designated an area next to the city centre, where the exhibition could be organised. In other words, the EXPO would return to the city, as it was in the 19th century. On the one hand, the location is a great asset of Lodz application, while on the other hand, this is a great challenge not only in terms of managing a successful integration of the EXPO with the city, but also of achieving a synergistic and sustained city-creative effect. Therefore, the bidding for Expo involves not only intensive planning but also promotional activities.

## PROJECTS FOR THE EXPO

The EXPO project was conducted at the Department of Digital Technologies in Architecture and Urban Planning. It was done within the frameworks of Computer Methods In Architecture course at the undergraduate studies. The aim of the course is to introduce the latest tendencies and technologies of computer aided design (e.g.: parametrisation, generative architecture, generative methods of design, computer aided architectural survey tools, 3D scanning, point clouds, photogrammetry, rapid prototyping, reverse engineering, VR, AR). Tutorials are in English since they are addressed not only to Polish but also to foreign students. This is one-semester course, which means that students had some 15 weeks to develop their ideas, transform them into projects and finally prepared scaled models with the use of digital fabrication tools. It is necessary to add that there are 30h and 3ECTS assigned to the course altogether.

It was expected design proposals would reflect computational thinking and selected projects would be fabricated digitally. Since gaining skills in advanced computer techniques was a crucial element of fulfilling the course learning outcomes, students were asked to use computer methods from the very beginning, in particular algorithmic and parametric tools to find and follow logic in design process. In all cases the design geometry was modelled in McNeel Rhinoceros and then Grasshopper plugin played a key role in parametric explorations. It is necessary to stress here, participants were not familiar either with parametric tools or computational problem thinking.

There were thirty six students enrolled to the course working out their individual design ideas in the first phase. Then, eleven most promising concepts were chosen for further development. The evaluation was made after students' midterm presentations with the participation of the City Council representative. Thus, the second phase of the project based on working in groups. The motives of eleven final design proposals were as follows: "Lodz Genius Loci", "Re:Connection", "Urban Tap", "Spool Pavilion", "Folk Interactive Bench", "Back To Childhood", "Brick Reinvented", "Public Toilet Unit", "Bright Boat", "Gift Box Brick", "Bike Bell". The final presentation of project results took place in January 2017.

Figure 1
Brick Reinvented - a design proposal for EXPO 2022 in Lodz

The Faculty authorities as well as City authorities were invited to evaluate the outcomes. It developed into a fruitful discussion and plans for further co-operation.

To demonstrate outcomes and illustrate computational design processes selected projects will be described and discussed.

### *Brick Reinvented*

An inspiration for this project was twofold: the softness of fabric, reflecting Lodz industrial past power in textile production, and brick - a building material typical for Lodz factories, chimneys and workers' houses. Thus, heritage values played a prominent role from the first phase of the design. Since the project was expected to be technologically driven, students searched for the best solutions to turn their first ideas into physical model. They started from modelling a brick module in 3D digital environment - a basic component, allowing for testing complex compositions. Then, the actual purpose for a composition was defined. So, it was decided to propose a unique bench which could be constructed ideally with the help of a robot. As students were asked to make some studies on technology, they found the idea of "programmed wall" (described in the "Background" section) which inspired their vision. There is no doubt, building such an object up for EXPO would attract visitors and citizens since such event is not a commonplace (yet). However, for the purpose of the final presentation a 3D printed mock-up was prepared what required different processing of the digital model, and affected its final appearance. It is well illustrated in figure 1.

The author of the initial concept of this project was Maria Kierzkowska-Kłys. She was supported by Piotr Mrówczyński, Alicja Zbrojewska and Xuejiao Xu at the stage of its development and fabrication.

### *Folk Interactive Bench*

Music became the main motive for this project reflecting the fact that Alexander Tansman and Arthur Rubinstein were connected with Lodz. The concept was to educate citizens and visitors by allowing them to interact with music. A design (geometry and colour concept) itself took inspiration from a special paper-cut flower pattern, characteristic for traditional folk culture from the Lowicz region in the province of Lodz. Such interactive bench would attract people and improve the quality of revitalised downtown. The crucial aspect in this project was the question how to transform two-dimensional floral forms into urban furniture. Looking for computational logic students decided on triangulation of initial geometrical form to build a 3D structure from that (figure 2).

The author of the initial design idea was Karolina Dróżdż. At the second phase of the project a team was formed by three more students: Katarzyna Jackiewicz, Martyna Jankowska, Yiming Gui.

Figure 2
Folk Interactive Bench - a design proposal for EXPO 2022 in Lodz

### *Spool Pavilion*

The title of the project refers to the city industrial past. Moreover, it is embedded in the shape of designed pavilion. A wooden spool with the thread wrapped around makes a light structure which can be used as a pavilion to sit and rest inside or walk through. In the first model threads were composed in a way to resemble real spool, but finally, due to modifications required by construction and transparency of the top part, the object seems to be rather inspired by a spool than a copy of it (figure 3).

Figure 3
Spool Pavillion - a design proposal for EXPO 2022 in Lodz

There were four students involved in this project, namely: Joanna Sobczak, Paulina Dobroszek, Sylwia Pietrzak and Paula Popczak.

### *Lodz Genius Loci*

Students proposed an installation for a public space that would tell a story of the city on specially designed panels. A unique history of Lodz, its dynamic growth, prosperity, then collapse, and finally the rise towards revitalisation and EXPO 2022, has become the main motive for the project. A colour code was taken from the Lodz EXPO logo. This light semi-transparent structure can serve as a meeting point, offering not only a historical path to follow or a journey through time but also a shadow in a sunny day and creative space for children. What is more, students made proposals for other cities in Poland to place this installation in a position it would point geographically towards Lodz and EXPO 2022. In the case of this project the transformation from intangible to tangible, from historical facts into geometrical form, was the principal challenge. As the first panel is a metaphor of small weaver houses, and the last one is a symbol of EXPO, whereas middle panels show the growth of Lodz in 19th century and collapse of textile industry in the 1990s, the crucial task was to elaborate on the geometry of metaphorical transformation (figure 4).

The author of the initial concept of this project was Lucia Barancokova, supported by Alvaro Soriano Lazaro, Ongan Caglar at the stage of its development and fabrication.

### *Re:Connection*

A task undertaken in this project was to make a connection between Piotrkowska Street, a principal axis of historical area in Lodz, and New Centre of Lodz where the new main railway station has been opened recently and where the EXPO 2022 is planned. Therefore, a neglected empty plot at the corner of Sienkiewicza Street and Traugutta Street, being half-way of the pedestrian route between the

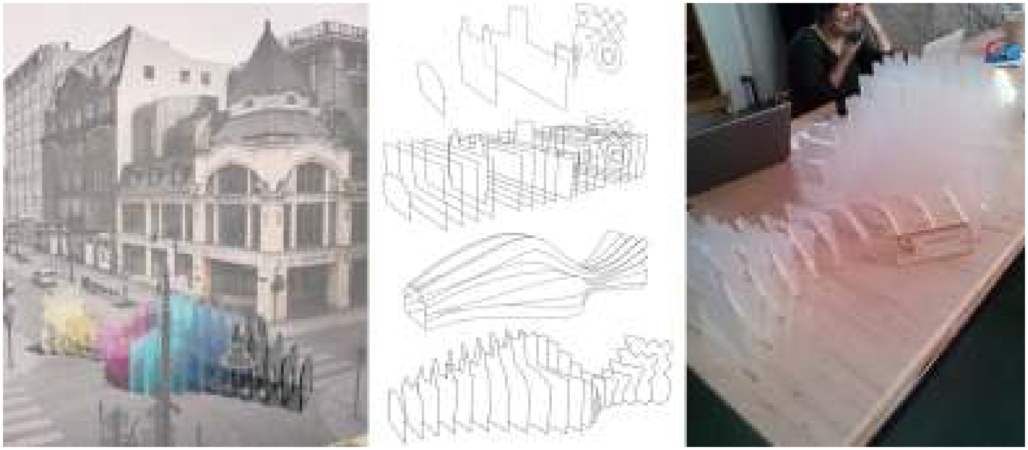

Figure 4
Lodz Genius Loci - a design proposal for EXPO 2022 in Lodz

railway station and Piotrkowska Street, was chosen for the project. The proposal focused on revitalisation of the area to make it attractive for all ages. The individual arrangement of modular elements, enhanced by the city of Lodz logo colour code was proposed. The cubical forms might also resemble Avant-garde Modern design of the 1920s which was important for sculptures and paintings of local artists, being themselves icons of Polish art of the period. Designed modules allow to arrange the area in various ways. Simulations and different scenarios were tested. Due to this flexibility the system of elements may be adopted in many places in the city (figure 5).

The idea of this project was proposed by Miriama Butkova. She was supported by Baris Kavraroglu at the stage of its development and fabrication.

## DISCUSSION AND CONCLUSIONS

The cooperation between Lodz University of Technology and Lodz City Council strongly supported the promotion of hosting Expo in 2022. The project results revealed the complexity of the topic on the one hand, and the creativity of students on the other hand. The span of the first set of ideas was immense: from small scale products to urban space improvements. Eleven projects chosen for the second phase development were also manifold.

The key value for students was to open minds to creativity, yet reflecting genius loci, local heritage and revitalisation aspects, and, on the top of that - due to the nature of the course - employing parametric design and digital fabrication as a compulsory toolset for the task. It is worth noting here, participants did not have a prior experience either in parametric design tools or digital fabrication, so this part of the course was a challenge itself. There is no doubt, the course was experimental in nature. For the purpose of fulfilling the course construct, graphic coding and visual parametric modelling in Grasshopper was introduced and became a design medium for elaboration on EXPO projects.

The experimental nature of the task involving a variety of digital technologies allowed to test students abilities in IT driven design logic. It must be stressed that neither robots nor 3D printers are the common place in architectural offices in Poland. Both, the infrastructure and software, are too expensive and by that not affordable for small and medium architectural practices. What is more, since it would require specialised staff and time investment to learn and keep up with the latest technology, it seems smaller firms are not interested in such development. Though, it does not mean they do not use digital tools, they just choose the most necessary ones to deal with design process. This situation is not local, viz. Polish, and it was well described by Stals, Jancart and Elsen (see "Background" section for more details).

Another problem is attitude polarization and resistance to paradigm shift. Architects, especially those with more than twenty years of practice, are the main opponents of technological innovations assumed as disruptive innovations. Thus the EXPO project gave participants the unprecedented possibility to experiment, research, learn and open minds to computational design as an alternative at least if not the future design methods. However, the problematics of computational design requires more attention.

It is observed that predefined working environment has an evident impact on a creative process. What is more, the creative process is limited or even blocked when necessary computational skills are missing. That is why such phenomena as dichotomy, dualism or hybridisation are associated with an early phase of design (Kepczynska-Walczak 2014). It is worth noting that students who start a design task by opening a certain program need much more time to come up with an idea, since they are limited not only by their imagination but also by chosen software capabilities.

Despite the EXPO project was predefined in terms of digital tools to be used from the early design phase towards fabrication process, the methodology adopted was to learn by experience. (cf Kepczynska-Walczak 2013). In this regard, the author would agree with Lorenz and Wurzer (2016) who observed that from the very beginning of the design process students tend to have an almost finished picture - or at least a sketch - of their design ready in mind. Even this picture may change during the process of analysis and/or design, an interim result is present. Furthermore, when concerning problem thinking over solution generation it turns out that in most cases students still have certain results in mind. Sometimes the algorithm is even developed to fit this idea.

To sum up, computation may help to construct, reveal, enhance and develop logic in a creation process, but first technical competences are essential to be acquired.


Figure 5
Re:Connection - a design proposal for EXPO 2022 in Lodz

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# Competences for Digital Leadership in Architecture

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*The use of ``digital technology'' - computer software, new material application, rapid prototyping, Computer Aided Manufacturing, Virtual Reality, collaborative design - is no longer a novel and innovative aspect of architectural design. In fact, many offices and architects use a varied mix of these technologies in their daily practice. We can observe that digital technology has become a mature part of architectural practice. In this paper, we want to outline an outstanding level of excellence in the use of digital technologies that enable certain widely acknowledged offices (for example Foster and Partners, UN Studio, BIG, and so on) to take their design work to high degree of quality and performance. We call this level and phenomenon ``digital leadership.'' Digital leadership goes beyond technical digital skills. It is an integrated and holistic approach that makes no distinction between ``architectural design'' and ``digital technology'' and in fact creates a new blend of both. We propose that digital leadership has six key areas: Technological Ecologies; Creativity, Knowledge Processes, and Experimentation; Design and Research; Human Resources and Leadership; Collaborative and Explorative Environments and Impact of Digital Leadership. These are discussed in more detail in this paper.*

**Keywords:** *architecture, digital leadership competences, research by design, creative practice, design research, impact*

## INTRODUCTION

Digital technology has reached a level of maturity and is embedded in architectural practice, accompanied with well-developed research, but lacking the aspect of leadership and knowledge integration within the discipline of architecture, but also beyond to the affiliated disciplines to avoid the effects of fragmented knowledge. Digital leadership is a novel concept that will dramatically improve the performance of creative industries to produce sustainable, effective, and meaningful solutions. This paper aims to develop the initial digital leadership competence areas and challenges the discussing about their potential within the eCAADe community. It builds on two eCAADe workshops organized by the authors of this paper (Verbeke et al. 2015, Zupancic et al. 2016) in which the concepts were introduced.

Digital technologies have become commonplace in architectural practice. Most of the regular design and production work is currently to some extent supported by digital tools at most of the architect's offices in Europe. Schools of architecture offer regular (but mostly technical) training in digital tools and media.

## THE ROLE OF DIGITAL TECHNOLOGIES IN CONTEMPORARY ARCHITECTURAL PRACTICE

In March 2016, the Strategic Policy Forum on Digital Entrepreneurship delivered its final policy recommendations [1]. This recommendation asks for actions to re-skill our workforce, and building up innovative ecosystems to take advantage of the digital revolution. Architecture is one of the largest industrial sectors and is substantially behind when it comes to digital technology. Therefore, the interrelation of digital leadership and architecture need to be explored and developed.

Although there is a general acceptance of digital tools and media in the field of architecture, the state of the application in architecture concerns the support of traditional and conventional production processes of architecture. The application of digital tools and media does not yield any further competitive advantage since it is generically applied to almost all offices. Additionally, we see a saturation of computer skills in graduates of architecture, but this is not accompanied by a clear understanding of the how, why, and who. The innovative power of digital tools to advance the business of architectural design seems far underdeveloped. Knowledge is scattered and fragmented. The built environment requires integration, especially the integrated processes and methods for designing, building and maintaining the build environment in the sustainable framework. In the future the major challenge is to avoid the current tendency of fragmentation and separation of these processes as different areas of expertise. Graduates need to develop interests beyond architecture (Achten 2008); architects always work in teams, teams need leaders; architecture is a business, architects can learn business skills; architects must sell and negotiate, focus on people and process, not only on product, and keep up to date with new technology. (Dobson 2014)

It is safe to say that application of and education about digital tools and media have reached a base level of competent application. At the same time, however, we can observe that beyond this base level, there are research institutions and architectural practices that are pushing the boundaries how digital tools and media can be used and developed. This is extremely important and relevant because the built environment is facing pressures that it cannot solve with the current state of knowledge, digital tools and media, and work processes:

- Sustainability; the need to reduce the carbon footprint of buildings, and preferably make them 0% [2], [3].
- Business process; management of increased complexity in client requirements, design team, stakeholder balance, time for design, quality guarantees in construction, FM, POE, and so on (Robinson et al. 2010).
- New materials and products: the main dependence of building industry on concrete, steel, and glass is expanding to especially low-carbon materials, such as wood and/or moisture resistant biodegradable composites and other new materials, not to forget include plastics, nano-materials, composites, and new production and manipulation techniques like Rapid Prototyping, robotics, and 3D printing of components and buildings (see e.g. the eCAADe Conference Proceedings of the last decade (CUMINCAD [4])).
- Well-being and quality of life in the context of the built environment, especially of the user-friendly adaptive solutions for technology-rich built environments.

These challenges ask for radical changes in processes and approaches. Artificial Intelligence (AI) and digital tools and media provide possibilities to change the workflow and impact of the profession. In order to develop this further, architectural and design offices are in need of people who can take a leadership role in innovating and enhancing the current working processes.

## DIGITAL LEADERSHIP: GOING BEYOND CURRENT PRACTICE

As we have argued above, there are pressing needs on the Building and Construction Industry to address questions of sustainability and improve performance of the built environment. Several sources and authors indicate that these pressures cannot be solved with regular technologies and processes used today. We can see several architecture and engineering offices (for example Foster + partners, UN Studio, MVRDV, HOK, Ove Arup, and so on), as well as research centres (e.g. ETH Zurich), and educational institutions (e.g. The University of Stuttgart, CITA at the KADK) that are actively engaging these problems. All these organisations demonstrate leadership in the investigation and application of new technologies in research and practice. They inspire and push the boundaries of the field.

Apart from tackling the problems identified above, we see also that graduates of architecture are technically skilled to a certain extent, but do not have the knowledge and skill set to act as digital leaders neither in an academic setting nor in practice. We notice that the complexity of today's world and architectural design problems require approaches that are inclusive of as many factors as possible. The complexity and skills required to manage and innovate such processes well and to create good design solutions exceed the capabilities of traditional competencies for work processes and technologies. The most comprehensive technological platform and process models incorporated in the so-called Building Information Model (BIM) are not that well developed yet to support such approaches.

## THE CONCEPT OF LEADERSHIP

Leadership is a term that originates mainly from organizational sciences. There is a great amount of research on the aspect how leadership is compounded of interpersonal skills and managerial skills (Vries et al. 2010), but the amount of research on leadership in a design context is almost non-existent. Pahl et al.'s (1999) review of 12 years' interdisciplinary empirical studies of engineering design in Germany shows that leadership in design is not well understood. In design, where often results are achieved through teamwork, leadership attitudes have an important effect on the quality. Lee and Cassidy (2007) discuss leadership in industrial design. They identify among others "the leader as a catalyst of organization change," which seems to be the closest to a "digital leader." Their list of good leadership traits includes interpersonal skills such as personal characteristics, maintain friendship, attitudes and values, leading styles, and proper roles. Adams et al. (2011) stress strategic leadership in cross-disciplinary teams. More specifically, among others, they identify the ability to "making or enabling conceptual connections," and "facilitating systems-oriented strategies or frameworks that leverage diverse perspectives" as important factors for leadership success. This view is supported by Buhse (2012), who stresses agile management as an important building block for successful Enterprise 2.0 business model, including aspects like the team-based formulation of agenda, goals, and strategies. He sees the digital leader as moderator, bridge builder, and network organizer rather than a classical top-down manager (Adams et al. 2011). Furthermore, active and passive leadership behaviours are crucial (Dóci et al. 2015). The authors of this paper take all these definitions of leadership and digital leadership into account while dealing with the digital leadership in architecture. This is due to the multidimensional definitions of architecture as a profession in general, that requires the widest possible variety of approaches to and from the digital aspects and leadership.

## ARCHITECTURE AND DIGITAL LEADERSHIP

It has often been mentioned that developments in digital technologies are fast, and require constant updating of programs, hardware, and skills in the office, and the content of curriculum in architectural education. Often this is contrasted with a "traditional view" of architectural practice and education that is depicted as "slower," "less innovative," and "traditional." This depiction has become so commonplace that it is hardly challenged. We feel that this picture does not reflect reality, and in fact does both fields of architecture and computing a disservice. Instead we propose that digital technologies are part and parcel of contemporary architectural practice, and we would do well to promote and support the synthesis of both. "Digital leadership" in this sense, means for us taking the lead in the constantly evolving practice and theory of architecture.

To summarize, based on discussions and workshops, we believe the following competences are critical for the contemporary architectural practice:

- Comprehensive knowledge to manage and innovate the use and development of advanced digital tools and media in architecture and closely related fields.
- Management and process knowledge of businesses to become effective leaders.
- Skill set to use analytical and research skills for leadership in design processes.

All of the above are of course set in the context of designing.

## THE DIMENSIONS OF DIGITAL LEADERSHIP

To clarify the concept of digital leadership, we have distinguished six dimensions or key areas that are critical to this concept. We take these key areas as a practical working set for the time being. Only through engaging with these six key areas, will we be able to develop the descriptive and prescriptive values of the areas. Although these six areas emerged from our activities and research, we see do not see them as fixed and exhaustive. Hence, it may be that in future versions we will need to adjust them. For now, we propose that the digital leadership concept thus integrates the following key areas: Technological Ecologies; Creativity, Knowledge Processes, and Experimentation; Design and Research; Human Resources and Leadership; Collaborative and Explorative Environments and Impact of Digital Leadership. This paper aims to discuss how the knowledge of digital competences, business management, innovation, creative leadership, design entrepreneurship and design strategy can be exploited to develop a deeper understanding of digital leadership competences. Additionally, each dimension provides us with an informal metric along which we can assess the degree or profile of the digital leadership of a person.

## TECHNOLOGICAL ECOLOGIES

Technological ecologies impact the way design solutions can and are created. To create adequate and innovative design solutions, many aspects need to be balanced; these are often contradictory or unclear at the start. Design is both about exploration and stepwise learning about the design problem, and needs to incorporate knowledge from many people. Parametric design allows the systematic investigation of many more options than is usually possible in a traditional design process. Coupled with the architect's knowledge and experience, parametric design has the potential to lead to better design solutions. It would be a mistake however, to view the design process as an isolated phenomenon from all the other aspects that are related to architecture, such as new materials, the construction process, collaborative design aspects, and so on. Many of these aspects are technological by nature. The "digitalisation" process potentially brings these various fields of knowledge and expertise closer together. For example, rapid prototyping technology lessens the gap between design model and materialization; laser scanners lessen the gap between surveying and the environment model; virtual reality lessens the gap between the design and client; BIM/IFC lessens the gap between expert models in the design team; and so on. Obviously, in the mind of the architect such technologies are never seen in isolation, but now we can also witness greater coupling of these phenomena in the digital realm. Therefore, the possibility to synthesize many areas and aspects together is increasing with increasing digitalization of these technologies. What it results in, is not a collection of distinct technologies, but rather fields of connecting technologies; in other words, an ecology of technologies. The term "ecology" is used on purpose here to describe the interrelatedness of the technologies. In our view, an architect or firm that understands this "technological ecology" viewpoint, will better use such technologies, and create and realise potentially better designs.

We propose that a digital leader is capable to set up and maintain a technological ecology at his/her workplace. The digital leader understands how various technologies can be brought together in a fluent process. The level of competence can be mapped on a scale; at the lowest level this means steering or appointing a system manager to establish a technological ecology, moving towards increasing levels of personal commitment and contribution to innovation of such systems. At the highest level, a digital leader is responsible for most part of such an ecology.

## CREATIVITY, KNOWLEDGE PROCESSES, AND EXPERIMENTATION

Creative processes are sources of knowledge and digital leaders can improve these processes. Creative processes have well been studied, in academic settings or based on the testimonies of practitioners and designers (Verbeke (ed.) 2017). Furthermore, already since Donald Schön (1983), reflection on activities has been stimulated to generate valuable knowledge. It is crucial for digital leaders to understand the underlying knowledge processes and they should be able to stimulate these knowledge creation processes amongst their collaborators. It is a way of life-long learning and building on experience. It is also why most MBA degrees include a course on knowledge management. Consolidating on experiences and sharing and deepening insights is a crucial element for any organization to develop. Within a university context this is custom, but in architectural and design offices, these knowledge processes are currently less developed. Hence, we propose that any digital leader in the contact of architecture and design need to understand and be able to further develop such knowledge processes. At the lowest level, the digital leader should be able to recognize the value of developing and sharing of insights and knowledge, on the highest level, a digital leader needs to be able to initiate valuable knowledge processes amongst collaborators and help them to explicate and share their understanding.

## DESIGN AND RESEARCH

Architecture comes into being through a long and usually chaotic design process. The aim of architecture is to contribute to and improve the built environment and hence, to provide a suitable context for the well-being of citizens. This implies that digital developments should preferably contribute to better processes in practice. Huge possibilities and opportunities have become available, but they are not yet fully exploited in architectural profession. Consequently, digital leaders need to be able to understand the fundamental aims and developments of architecture and its consequences for digital tools and media. On the other hand, digital leaders need to be able to incorporate possibilities and opportunities offered by digital tools and media to enhance the underlying design and research processes.

Hence, digital leaders need to be able to master design and research methods in such a way that they can point collaborators to opportunities and potentialities. Furthermore, they need to master research skills as developed in the ADAPT-r project (Architecture, Design and Arts Practice training - research, see www. adapt-r.eu) which allow practitioners to better understand what really concerns them, where their architectural practice is aiming to, how they position themselves within the field and how they can explicate crucial elements and share that with colleagues (inside and outside the office).

Consequently, it became clear, that digital leaders need to master important research and development processes on the line between architecture and the digital. On the lowest level, a digital leader should understand and recognise such processes, on the highest level, he or she should be able to undertake research and develop a deep understanding of the processes and how they can be innovated.

## HUMAN RESOURCES AND LEADERSHIP

From a management perspective, the interrelation between human resources, leadership modes and creative design processes is crucial. In order to further our understanding we need to explore the interrelation between human resources ("social and cultural capital") / innovative and transformative leadership and design/research methods; establish a theoretical framework of the interrelations discussed: supporting and guiding research and facilitating transitions to new research arrangements, for instance, to accomplish multidisciplinary approaches. This is how we can develop, for instance, leadership success strategies about design/research approaches and methods. We also need to understand the inclusive role of gender in digital leadership in/of architectural offices. Thus we can develop gender and also lifestyle sensitive leadership models. Furthermore, we need to investigate the drivers and triggers of knowledge creation deriving from interactions within communities of practice: dialectics of integration and individuation. This can lead to dynamic leadership models based on facilitating skills of group integration and individual autonomies.

We propose that a digital leader can identify the leadership modes appropriate for the specific working situation and take that role effectively. At the lowest level, he/she is able to arrange a group of collaborators, identify what motivates his/her collaborators and motivate them in using and applying relevant digital tools and media. At the highest level, he/she is able to shift the leadership role depending on the specific situation, scale of group and/or institution as well as stimulate the development and use of contextual opportunities.

## COLLABORATIVE AND EXPLORATIVE ENVIRONMENTS

The challenges of studying collaborative and explorative environments are manifold since they simulate, if not being, the real life world environments. The confidence and know-how of the built environment has a clear practice-based approach, wherein research, theory and practice are in genuine interaction with each other. Accordingly, the shared interest when building up innovative ecosystems to take advantage of the digital revolution in architecture is to study and elaborate integrated processes and methods for designing, building and maintaining of the built environment in order create a new theoretic base for sustainable architecture. Furthermore the aim is to contribute to the digitally oriented theoretical and methodological development of the research of interaction between human beings and the built environment. Hence, special emphasis is on a built environment that creates well-being and quality of life, as well as is based on user-friendly adaptive solutions for technology-rich built environments, such as the process of digital and structural design for fabrication and manufacturing. Although the themes of the studies vary, the interest is on present and future solutions in the scale of buildings and the urban environment in real life world context.

When aiming to take control of digital leadership of collaborative and explorative environments it requires strategic leadership of cross-disciplinary teams as Adams et al. (2010) suggests. Considering architectural practice the cross-disciplinary teams are formed project based and are therefore temporary organizations. Hence, there are great similarities with research project managing of temporary organizations (Herneoja et al. 2015), where according to Ernø-Kjølhede (2000) and Lundin et al. (1994)

team building is one of the most important aspects of managing the research project. In order to attend to the teambuilding digital leaders should have not only broad understanding of the possibilities of digitality within architectural design, but also knowledge of the digital interfaces between architecture and affiliated disciplines effecting to material and immaterial solutions of the final outcome (Herneoja et al. 2015). Thereby, digital leader should also have knowledge of the digital solutions beyond daily base maintenance to the entire life span of the building as well as of the digital solutions creating well-being and quality of life in built environment. As it is, digital leaders should have instead or in addition of narrow expertise of digitality in architecture quite broad understanding of possibilities of digital solutions in the long run, and have the skills and network of finding the experts also beyond the discipline boarders of the field of architecture.

## IMPACT OF DIGITAL LEADERSHIP

How does digital leadership help to contribute to change and innovation at different impact levels? At the lowest level this change means the incremental everyday impact. However, our vision is the need for a fundamental shift from digital support of architectural design to architectural directions of digital support.

We propose that a digital leader in architecture is able to identify the target relevance communities in scales and is also able to communicate with these target groups effectively. He/she is aware of the interrelationship of architecture and digital and leadership. At the lowest level the digital leader understands the extreme impact contexts of what he/she and his/her group is dealing with. At the highest level, he/she sees and relates to the colourful societal situation and to the in-between-ness of the impact potentials.

Hence, we believe that focus on digital leadership can push the field to its next level: a level where the digital and architecture are in full synergy and guide each other. Architecture guides the needs for the digital and the digital helps to push architecture forward. Digital leadership brings a fundamentally new approach to the field which is so far mainly developed through technological possibilities while not itself impacting on the energy spent by software developers.

## DISCUSSION

From the above elaborations, we hope it has become clear to the reader that a digital leader is not just someone who has a high level of digital competence. We see such a person as someone who manages to combine such competences with a high level of understanding of what is developing in architectural or design practice. It is someone who is able to manage digital ecologies to the benefit of the practice and the disciplines; someone who is able to induce learning and knowledge processes amongst collaborators, especially in relation to creative processes; who is able to learn from creating and implementing architectural projects, and to instigate critical reflection from his/her working environment. Furthermore, it is someone who is able to understand the required human resources for such developments and who is able to recognise and bring together the competencies to innovate and push the organisation forward to a new and unexplored innovative level. It will be clear that such all-encompassing endeavours can only be developed by establishing collaborative and inspiring creative working environments. Only then, we will be able to impact on the discipline as to consolidate the work and research in the digital in architecture and to give an answer to the challenges mentioned in the beginning of this paper.

We believe this requires a new mind-set where the technological developments are not the ones pushing the field, but where the added value is generated by experts who complement their design skills with research and management competences. We believe that such position could become part of a potential vision for the future of the discipline.

The competences of digital leader seem to be widespread and manifold, in short demanding. Thereby, it is most likely that variation of competence in content and level of knowledge will differ between the digital leaders to confront the cross-disciplinary needs within field of architecture and beyond, with the affiliated disciplines. The purpose of this article is in addition of drafting the target profile of the digital leader, to stress the importance that specifically architects take the responsibility of digital leadership in architecture and not alienate it to the representatives of other disciplines or professions.

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# Unfolding the design of architecture as a strategy to assess intellectual property

## *Bridle pirating architecture*

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*Modeling tools are evolving the process of architectural design from the use ordinary digital tool into a role of creator of complex shapes, through coding configurations. These procedures are becoming the structural ground of the architectural shape, going beyond their sole tools role. The increasing in importance of such codes implies a major level of awareness for their use, which is worth of a deeper analysis. The system of relations among parts in an architectural design picks a single configuration among infinite others, because it is produced by a design process which find its fulfillment in the final portray. Through the spreading of digital design tools, such final configuration becomes a step in a clearly reproducible process. The project is achieved through a series of starting conditions, which undergo a parametric process, that produces the final result. An identical parametric process can be applied under slightly different starting conditions and produce completely different results. These results are connected with the code which produced them, but is the authorship still property of the original author?*

**Keywords:** *Morphogenesis, Parametric, Authorship*

## INTRODUCTION

Reading from Dezeen website, 2/1/2013: "Satoshi Ohashi, project director at Zaha Hadid Architects, told the German website: "It is possible that the Chongqing pirates got hold of some digital files or renderings of the project." He was speaking about the Chongquing project, which was a copy of Hadid's Galaxy Soho Complex in Beijing. From this brief comment, it is clear how the deep integration of digital tools into the generation process of architectural shape has transformed its role from pure support digital tool into a complex shape creator through computerized codes and procedures. The increased importance of such codes implies a profound awareness in their use, which is worth to be analyzed in a more detailed way. The code exists as a connection between the idea of the architecture and its representation. The study of such relationship is fundamental to understand the origin itself of architecture as a totality of geometries and constraints. The way in which these geometries interacts each other has changed deeply through time, enduring an abrupt acceleration with the dissemination of generative design modelers. Through the studies of (Moussavi 2009) and (Pottman 2007), it was already clear the dependency of the components which build up the architecture system, starting from geometry which is connected with a system of analysis and discretization of the infographic knowledge model (Empler 2007) . In this system the software tool intervenes in defining the bidirectional relationship between model and idea, aiming to representation. With the spreading of advanced digital tools the representation diminishes its role as aiming point in the process of architecture definition. The centrality of architectural process is shifted from representation to the process itself. In this design path the singularity of the final result is counterposed to a multiplicity of results linked together by the original code. The concept itself of architectural originality is absorbed in this way by the code itself, subtracting importance from architectural manufacture. Starting from the single digital code it is possible to create an envelope of multiple architectures, which share common generative features. It rises therefore the problem of defining the affinity of different architectural manufactures within a certain degree of originality and recognizability. Is it possible to scientifically differentiate different architectures if they are generated by a single code? Is it possible to speak of finalization of architectural process of a single building or it would be more adequate to speak about an arrested development in the progressive refining path ? This process of systemic evolution is not limited to modify the whole building but it spreads its influence on the single part of the architectural manufacture.

The relationships among the parts, once they have been drawn through traditional representation tools acquire a unique spatial configuration, which derives from a design process which finds its fulfillment into final definition. With digital design tools this final configuration is a single step in a reproducible and modifiable process, available to anybody who owns the original code. The architectural project is fulfilled through starting conditions, which undergo a parametric process that provide a (final?) result. Therefore starting from initial condition ( the problem invariants) it is possible to define an envelope of results. This process can be outlined through a coordinate Cartesian system, where it is possible to point out the single generator character of the architecture on the abscissa, and the application intensity of the previous characters on the vertical axis. This scheme can be updated for any step of the shape generation process. The results envelope can be combined in an animation which represents the variation of the influence of single components in function of different steps in time. A function of this scheme, obtainable by changing values of variables, is the identification and differentiation of the result belonging to the same envelope, which houses interconnected architectures. Among all the possible generative features of a building, a small part among them build up the shape of architecture, so a question arise, how it is possible to distinguish one from another? Some designers describe in detail the morphogenetic process that brings to the shape of the buildings; many others instead leave unexplained details.

## METHODOLOGY

Starting from aforementioned thinking it is possible to grasp the need to describe the generative process in the most detailed possible way. The main reason for this necessity is the extension of the right of intellectual property, up to the possible iterations with adequate software tools. It is impossible to fill with these methodologies the whole spectrum of cases falling into the architectural envelope, because it would prevent the use of known architectures as a base for new buildings. It is paramount to identify a separation between the group of buildings falling into this envelope and the rest of architectures. An hypothesis of the process of building a class of architectures that can be considered linked to the initial one is the purpose of this work. Once an architecture has spread out the knowledge of its shape features, it is a common habit to describe the process of form generation through the means of media as Internet *conference* hardcopies. This process is accomplished through isolated spots on the design process, which focuses on main features only. It is metaphorically as a seeing a movie where the projection lamp works for brief lapses of time, leaving long obscure timespans. The process of rebuilding all the steps of morphogenesis is a work which has been started in Politecnico di Milano from the mentoring of prof. Andrea Rolando. Students of the courses of School of Architecture, as 3d Parametric Cad drawing (Disegno Cad Parametrico 3d) have built a share of studied buildings from contemporary architecture. These architectures has been studied starting from representation point of view, producing all the missing steps from the "metaphoric movie". These studies have been deepened into the parametric approach, analyzing the morphogenetic process using a generative design tool as Grasshopper. This process has built a limited sample of buildings which has been the base for the present analysis. Each case study has a unique path which end with the final shape, passing through a series of steps. Each step is a set of basic geometric transformations, clearly identifiable. Two kind of directions arrive to the final result. First one is a simple consequential series of transformations which, taken one after the other, lead to result. The other is an application of the same series of transformation within a certain number of iterations. Editings can be understood by applying methods explained by the text explained above, both of which follows the general rule to show only a step in the whole process of transformation. Pottman's studies groups transformations into chapters, so the explanation is limited to one figure; Moussavi's text is made of data sheets with small drawings where comprehension of the full morphogenetic process is very limited. Although endowed with incomplete descriptions, for the purpose of this work, the aforementioned book have a value as a mark for categories of transformations; acquiring categories from both books it is possible to cover a wider range of the possible building operations. Some examples of categories will be explained to clarify this issue, more specific details are worth to be analyzed in further following studies.

A first group of transformation valuable to be analyzed is the standard volume modifications, specifically, rotation and scaling. Furthermore rotation is itself a group of sub operations, because it includes more specific alteration, as revolution and roto-translation. Starting to focus on rotation only, it is easily recognizable the possibility to choose a given form and apply the transformation. The choice of the architecture for the transformation to be applied is important, because the parameter to be adjusted must be present in the morphogenetic process. In fact, for the present transformation, it is important that the process of building-shaping would possesses the rotational parameter. A practical example is described in Figure 1, it is the Turning Torso, a skyscraper located in Malmo, Sweden, designed by Santiago Calatrava, where the process of rotation is evident.

Figure 1
Turning Torso, Malmo, Sweden, by Santiago Calatrava, photo of the author

A Grasshopper algorithm has been worked out for the aim of rebuilding a shape as similar as possible to the original Calatrava's building. The step of form generation evolves by the rotation of a single layer around an axis that run perpendicular to the ground up to the top floor of the building. The building is composed of nine blocks, each of which rotates a fixed angle, creating a whole arc of rotation of 90 degrees. Each block is divided in five floors, each of which rotates of a submultiple of the rotation of the single block. Furthermore the void between two modules gets involved into the rotation; the result is a continuous wave of rotation that starts at the first floor and goes up to the top of the building. The parametric approach to this building has choses a set of shape-drivers that remains constant, as it is the axis of rotation and the base perimeter, which is generated by a parametric procedure itself (D'Uva 2014). Six parameters are instead flexible, the floor height, the floor distance, the number of stories per module, the number of modules, the panel width (in which module windows are built) and the number of modules. The sixth parameter is evidently the rotation, which is 90 degree in the built architecture, but it is possible to increase the rotation, to a higher value, as 180 or decrease to zero. Both extreme values, as 180 degrees or zero give possibilities to build a real building where structural, HVAC considerations are similar to the original one. Other possible variations based on rotation only is the inclination of rotational axis from the ground. It is clear that an infinite number of results can be obtained, whose intellectual property is worth to be preserved. In this case the envelope of preserved building can be obtained by the extension of rotational property which group all of possible alternatives to the original.

Scaling an architectural building is commonly an operation which commits in several issues, because of the quantity of components involved and the non-scalability of ordinary components. Therefore a scaling operation is not a simple changing in dimensions of an architecture, but it involves a changing in number of components. If an enlarging is needed, the result is not a modification in dimensions of single components, but an operation of multiple instances of the single elements, which fills up the increased volume. This operation is one of the sparkles that has been giving propulsion to the spread of Building Information Modeling, because of the modeling structure, that eases the copy of similar elements which are endowed with constrained one each other. It is more difficult although to control the shape, starting from the design of single elements. A proper strategy is to point out shape drivers (Rolando 2008) that give geometrical constraints to groups of elements. The case of scaling is applied the London Serpentine Gallery Pavilion (see Figure 2) by Cecil Balmond and Toyo Ito, built in London in 2002 and demolished the same year.

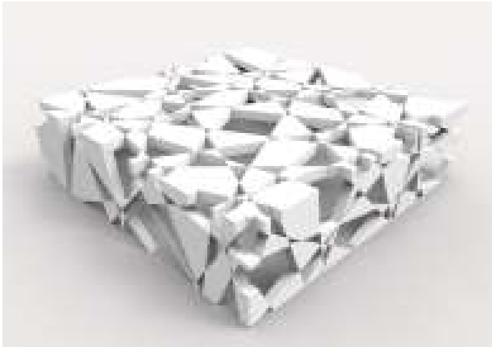

Figure 2
Serpentine Pavilion, London 2002, by Toyo Ito and Cecil Balmond, rendering by Paolo Tomelleri

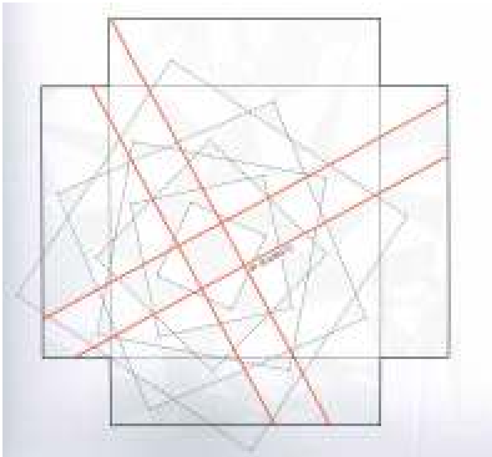

Figure 3
Serpentine Pavilion, London 2002, Toyo Ito, by Toyo Ito and Cecil Balmond, drawing by Paolo Tomelleri

The starting conditions are a box which contains the main shape, which dimensions are 5 modules of 4 meters, which is 20 meters, extruded by a module of 4 meters. The shape of this pavilion is based on geometric adaptation applied to a parametric system.

The geometric adaptation is the application of the same rule in plan and elevations.

The same procedure is applied on all the sides by the rotation of façade around a revolution axis which lies on the eaves (see Figure 3). With this premises all the rules applied to the base square are linearly extended to the façade. The parametric system that underlies beneath this architecture is the square, whose sides are respectively divided with the following scheme: two counterposed sides are splitted in two halves, the other two are splitted in thirds; the resulting points are connected by adjacent sides by forming a smaller square into the bigger one. The newly formed square is splitted in the same way, and process is repeated recursively for seven iterations. The eight iteration is impossible because the splitting would result in a degenerate square because of the side dimensions. The edges of all the created square are extended up to the boundary of the figure, together with the rotated façades. The edge of the second iteration are limited to the base only without extending to the outer border of the figure. The geometry generated with this parametric system creates a square based grid which makes the main structure of the building. The final step is the filling of part of the gaps created by the grid with an opaque white cladding. The substantial overlapping between form, geometry and structure is an envelope, where openings are defined by material subtraction. These subtractions are made starting from a model of the building as a result of the generative process. The resulting mode, indeed, is different from pavilion real consistency because it has been necessary to create variations for functional purposes. A paradigmatic example of this process is the cladding subtraction which has allowed the positioning of building entrance.

Once the pavilion algorithm has been worked out it is effortless to apply a straighforward scaling transformation to get a different building. In this very case it is the architect himself, who applies the scaling in upward direction to get the results. It is TOD's Omotesando Building in Tokyo (see Figure 4), whether in completely different context. It is pointed out, in this way, the problem of identifying the intellectual property of a potential new architectural manufacture generated by a parametric process already used by another building.

Figure 4
Omotesando Tod's flagship store, Tokyo by Toyo Ito, photo of the author

The plan has a base ruled by a similar 4 meters module with a perimeter L shaped instead of square. The structural system is strictly connected with the external skin façade, like in London pavilion. The façade has been thought using the same algorithm as London Pavilion, in a way to have a realistic comparison of similar mass volume structures. The algorithm flexibility has given the chance to modify the pavilion height to be similar to Tokyo building. Within these hypotheses, the degree of similarity is pretty high. In this very case, the buildings chosen as case studies have no intellectual issues, because author is the same. It would have been an issue, although, if two different architects had produced building whose codes were common. It seems evident, given the two case studies, to point out some of the elements discovered.

## CONCLUSION

The first and most important commitment in design an architecture is the spreading of design path. Most of the architectural works are explained and published in limited printing, where a part of the design process is unveiled. Most of the times only the inspiring sparkles are explained in detail, together with deep sensations and genius loci which have driven the architect into creating a masterpiece. No explanation at all is given on how different parts of the building cope each other and how geometry is parameterized to create the final shape. A paramount example of this hypothesis is Calatrava's works which originates from natural forms, as human body, for instance the torso that rotates which is the base for the first aformentioned case study , or the eye, which is the base of Valencia's Ciutat de les Arts i les Ciències. Therefore it seems clear that once code has been completely worked out, it is possible to generate an infinite array of buildings linked to the original one by the code only, completely different in dimension, aim and location. In this way it is clearly recognizable the problem about intellectual property of an architectural product, which is generated by a second-hand algorithm. A need for rules to protect intellectual property is arising, with new tasks to accomplish. A possible field of research is the creation of an algorithm database where base designs are recorded and computer generated softwares forecast the possible variations needful to be preserved.

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# Digital Design Hermeneutics

## *Proposing a Metacode for Architectural Pedagogy in the Information Age*

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*This paper forms part of a broader inquiry regarding possible theoretical models for interpreting and understanding digital architectural design. Such models include hermeneutics, activity theory and design protocols. Starting by highlighting the limits of computational methods in an architectural context, it will be attempted to explore certain implications of the introduction of digital media in the design process. Certain elements from the field of hermeneutics will be introduced in order to understand the impact computational logic has on architectural culture especially in a pedagogical setting. It is argued that such an understanding is crucial in order to design effective strategies for architectural design education in the Information Age.*

**Keywords:** *Computational Design, Architectural Pedagogy, Digital Design Education, Architectural Hermeneutics*

## INTRODUCTION

In order to support the need for a holistic theoretical framework for digital architecture pedagogy, we will approach the issue of digital design media in architectural praxis from two different perspectives.

On the one hand, we will focus on identifying and describing certain characteristics that are inherent in digital design discourse. It can be hypothesized that these characteristics are an element the majority of contemporary computational design methodologies share in common, notwithstanding individual differentiations on the tools and logic utilized in each individual approach. Furthermore, we will attempt examine the effects these common characteristics have on the design discipline, especially in the context of architectural education. It will be argued that the questions posed by computational design logic to architectural pedagogical strategies cannot be answered through a narrow focus on information technologies.

On the other hand, an attempt will be made to utilize concepts drawn from the field of hermeneutics in order to address the broader challenges computational design poses for architectural pedagogy. It is posited that approaching digital design education as a process of understanding in the interpretive sense will aid in the comprehension of the broader architectural context in which it is situated. Although a comprehensive theoretical model for architectural pedagogy in the information age cannot be determined, it is hoped that the insights provided by a hermeneutic approach to the digital design process, some points of reference may be established.

## NATURE AND LIMITS OF DIGITAL DESIGN

The introduction of information technologies in the form of digital design media in architecture has led to the emergence of autonomous field, that of computational design. In its context, computational tools and methods are not used as a glorified pen limited to the digital reproduction of preconceived projects (Pongratz & Perbellini 2000). On the contrary the digital is conceived as a collaborating partner in the architectural process, able to autonomously influence the design project (Negreponte 1973).

The far reaching implications of this conception of digital design in architectural praxis cannot be adequately examined in the context of this paper. Nevertheless, it is important to note the common assumption shared by these approaches, namely that how we design (i.e. "computationally"), ultimately affects what we design (i.e. "digital") (Kolarevic 2000).

In any event, these approaches are usually described as constituting a "paradigm shift" in the field of architecture (Terzidis 2006). Most of them revolve around the implementation of computational models in design via digital media and are therefore described as "algorithmic", "parametric", "emerging" etc. A detailed presentation of the "project" presented (Schumacher 2008) in each individual approach is beyond the scope of this paper. Suffice to say that it can be argued, that all "digital architectures" beyond the obvious influence on the "why" and "how" of design are affecting the "why", that is the purpose of the design process (Zellner 1999).

This unique "digital architecture project" (Leach 2002) revolves around the underlying principle that it is possible to computationally express at least some part of the design process and in doing so allow for a radically different approach to the architectural project. These computational expressions define digital methodologies (Kolarevic 2000) and borrow models from fields such a mathematics and geometry, biology and physics, computer science etc. In other words, digital design methods are based on concepts and structures transferred from the realm of the natural sciences.

In any case it can be argued that the important and usually overlooked aspect of digital design is the relation of these natural science frameworks vis a vis those parts of the architectural process that cannot be expressed in a computational manner. Furthermore it can be suggested that a disproportionate focus on digital methods in design could lead to the reduction of the broader field of architecture solely to those aspects that can be quantified (Vesely 2004).

Setting aside the broader philosophical questions regarding the conception of architectural design as a formal logic process of formal logic (Snodgrass & Coyne 1997) two individual issues of this paradigm shift will be briefly explored.

On the one hand it is highly doubtful that technology in and of itself can be the generator of meaning for the architectural project (Vesely 2004). Computational models are incapable of answering the question of "why we design" save in that case where the architectural project has been reduced to its basic and quantifiable elements. Therefore, methodologies revolving solely around such models of digital architectural design are limited in scope.

On the other hand, the fascination with advances in the field of information technologies often link architectural praxis to certain digital media or concepts. The rapid evolution of the field of computer science means that these tools and methods will be outdated in a matter of years. Since architectural thinking cannot adapt to the pace by which computational methods evolve, it risks either being rendered obsolete by technological advances either relegated to following the latest digital trend. Therefore, it is highly doubtful that it is possible to establish a meaningful theory for architecture based solely on digital media. On the contrary, linking design discourse exclusively to them affords architectural thinking neither the time nor the space to articulate a conceptual framework of its own. Instead it is relegated to describing fragmented personal visions (Vesely 2004) or isolated design methodologies (Goulthorpe 2003) without coalescing into a cohesive framework for architectural design in the Information Age.

The issues briefly outlined above constitute but some of the challenges facing architecture and design education in an increasingly digital world. One could list a vast number of issues that stem from the broader changes brought upon by the Information Age. Furthermore, it can be argued that it is a futile exercise to ignore these changes or even more try to resist them, since this new age is a fact whether architecture as a discipline agrees with it or not. What is at stake, is the position that architecture occupies within this new world, and how it can avoid either disappearing into the processes of production or retreating into a hypnotic solitude (Taffuri 1969). It is useful to cite Mies van der Rohe's description regarding the stance architecture should adopt when faced with another New Age, that of the Industrial Revolution. Mies suggested that what was important was not the mode of building, on the contrary, what was at stake according to him was a matter of spiritual nature. Architecture should focus not so much on the how and what, rather on how it can reassert itself vis a vis these new givens (Neumeyer 1991). This it can be argued remains true, whether we are discussing the Industrial or the Information Revolution.

Any such effort is essentially ontological in nature. As a result, it cannot be tackled through a strictly technological approach, since such an approach, as has been demonstrated will be limited to discussing the technical and quantifiable aspects rather than the spiritual ones. Therefore, it seems necessary to transcend a narrow computational logic that by definition limits the scope of architectural discourse. In order to achieve this, it is proposed that design thinking must turn to other fields to obtain the conceptual tools necessary for articulating a broader theoretical framework. This framework it is argued is vital if architecture is to address the issues that the Information Age raises and by extension if design thinking can escape a narrow computational interpretation and reassert itself in a digital environment.

## TEACHING COMPUTATIONAL DESIGN AND ARCHITECTURAL EDUCATION

Before we turn to the description of the theoretical tools that will be used to underpin the proposed theoretical framework it is useful to briefly mention the educational aspect of the introduction of digital media to the design process.

The discussion regarding the optimal methods of introducing computational design to architectural education is almost as old as the concept of computational design itself (Asanowicz 1989) (Akin 1990) (Gero 1990). Again, it is not possible in the context of this paper to examine the nuances and particularities of each approach.

There is an ongoing discussion that covers various aspects, such as if digital design be taught in isolation or integrated in the design studio (Kvan 2003), if the curriculum should be changed to incorporate the new media or if the new media should be integrated in existing frameworks (Mark et al 2001), whether a process centric or project centric approach to digital design training should be adopted (Oxman 2008) and so forth.

It must be noted that any attempt to articulate a holistic conceptual model for design education is hampered by fact that it requires the backdrop of a broader architectural culture that can act as a point of reference. Unfortunately, contemporary architectural culture has been subsumed by architectural theory, which in turn is considered an autonomous entity, completely separated from what is considered architectural praxis (Hays 1998).

This fragmentation is especially pronounced in the field of digital design, due to the apparent autonomy of computational design methods from established architectural thinking. In other words it is even more difficult to reconcile digital media with architecture theory in order to establish and ultimately teach a cohesive architectural culture. As a result, it can be said that in contemporary architectural education the practical aspects of digital design methodologies receive far more attention than theoretical architectural elements. This phenomenon can also be viewed in the context of two broader issues.

On the one hand it is the logical result of a broader trend against theory in the field of architecture (Martin 2005). This trend can be described as a preference to approach design projects in isolation as opposed to situating them in the broader social, cultural and political context of which they are ultimately a part. One can easily see how digital design methodologies, already somewhat distanced from physical reality due to their very nature are especially suspect of such a stance.

On the other hand, it is an unavoidable fact that elements subject to rapid change command far more attention than those that remain relatively unchanged (Gadamer 1975). In this sense, when considering computational design, it comes as no surprise that new digital tools and the capabilities they offer will inevitably be the focus of architectural discourse, as opposed to other aspects of the architectural field that it can be argued remain more or less the same.

Bearing in mind the factors mentioned above, namely the criteria of a pedagogical system and the fragmentation of contemporary architectural culture the theoretical models presented in the following paragraphs will attempt to outline the possible form of a conceptual framework to address said issues. It must be noted that it is not the goal of this paper to provide a detailed description of a mode of thinking, rather it aims to suggest certain elements that can aid in the articulation of a strategy regarding digital media and their introduction in architectural education. In other words, this paper aims to briefly explore certain "codes" that can be combined to form a "meta-code" of digital design. The term "meta-code", as elaborated by Frederic Jameson refers to the process of setting into active equivalence two preexisting codes that result in a new one that is more than a synthesis of the two previous ones (Jameson 1981).

Therefore it is hoped that the concepts described here will aid in the expression and interpretation of digital design and its impact on architectural education.

## COMPUTATIONAL DESIGN WORLDS

It has been argued that digital design discourse shares a common theme. This can be defined as the implicit or explicit belief that at least a part of the architectural design process can be described, codified and explained in terms of a conceptual model based on computational logic (Snodgrass & Coyne 1997).

We can juxtapose this belief with the understanding of architectural process as series of "design worlds" (Mitchell 1990). In this context, design activity can be conceptualized as a series of operations involving primary elements (such as graphical tokens) according to a certain set of rules (for example a computational logic). This is termed a design world. Furthermore, within each design world, the operations undertaken should produce a result that satisfies both the internal logic of the design world as well as the original design intent.

Now it is important to note that nature of both the primary tokens manipulated as well as the rules that govern their manipulation depend on the nature of the design world selected. Therefore, a design process utilizing clay models will operate in a different framework than one utilizing freehand sketching, digital fabrication methods or parametric design software. In other words, what is designed depends on the chosen design world's interpretation of the architectural project.

It can be theorized that during the course of the design process, the architect utilizes multiple design worlds, depending on the aspect of the project he wishes to focus on. One can further assume that the ensemble of the utilized design worlds is in some way connected and influence the final design product to varying degrees. Taking into account the previously mentioned limitations inherent in computational logic models derived from the natural sciences, one can question

- the impact of digital design worlds on the whole of the architectural process and product (Salman 2016)

- the issue of integrating the teaching of these digital design issues in contemporary architectural pedagogy (Kvan 2003)

It must be noted that the utilization of digital means is not necessary for the implementation of a computational logic in design (Antonio Gaudi, Pier Luigi Nervi, Frei Otto are examples of a digital-less computational approach to architecture design). Nevertheless, this paper's argument will focus mainly on those methods / design world that utilize both digital media and digital logic.

## THE LOGIC OF DIGITAL DESIGN

As has been established above, digital design methodologies can be conceptualized a category of design world, where both the elementary tokens and the rules according to which they are manipulated are dictated by the computational logic behind the digital media utilized. This leads to the description of the architectural process - that is to say the sequence of manipulations within the design world - as a formal grammar. (Mitchell 1990). As a result, at least part of the architectural process is codified in a language based on such models as syntactic structures and mathematical logic. In other words it constitutes positivist approach to architectural design (Snodgrass & Coyne 1997).

In the following it will be attempted to describe the limitations of such an approach and more specifically the problems it creates in an educational context. It is argued that the proliferation of digital media in the architectural field (Kolarevic 2003) has led to an increase in the possible design worlds that are structured around some type of mathematical - computational logic (Lynn 1999) (Spuybroek 2004).

As a result, it can be hypothesized that these "digital design worlds" form the majority of design worlds that constitute the entire design process. Therefore, computational and digital logical systems play an increasingly dominant role in architectural process and the resulting architectural product (Terzidis 2006) (Schumacher 2008).

It has already been discussed that these systems, being positivist in nature are unable to encompass all aspects of the architectural praxis, and are confined to those aspects that are in some sense quantifiable. Thus, the increase of digital design worlds in the process of architectural synthesis leads to those elements of architecture that are quantifiable to assume precedence over those cannot be codified and manipulated in the framework of a mathematical logic.

Therefore, how can the teaching of digital design methods incorporate the influence of digital media in order to restore the balance between quantifiable and non quantifiable elements in architectural pedagogy?

## THE LIMITS OF COMPUTATIONAL DESIGN LANGUAGES

At this point, it is useful to briefly describe some characteristics and limitations of such computational logic structures and as a consequence, the characteristics of the models of architectural design they frame.

At its essence, computational thinking is conceived as a positivist model of language (Snodgrass & Coyne 1997).One can therefore infer that the design worlds structured by such logic will share the same characteristics. As such they claim, as Wittgenstein noted, to escape contextual preconceptions, subjective opinions and critical judgements and remove such notions from the domain of concrete experience.

"The limits of my language are the limits of my world. Logic fills the world: the limits of the world are also its limits" (Wittgenstein 1921)

This positivist conceptual model has several severe limitations, namely that understanding actually occurs in a context, as a "form of life" not through a logically described system of rules imposed on a situation. Wittgenstein utilizes an architectural metaphor to describe the relation of everyday language to the formal languages of logic.

"Our language can be seen as an ancient city - a maze of little streets and squares, of old and new houses with additions from various periods and surrounded by a multitude of new boroughs with straight rectangular streets and uniform houses"(Wittgenstein 1921)

It could be argued that digital design methods are the new boroughs around the old city of non quantifiable aspects of the design process. In this context, how can a holistic framework for digital architectural language be understood in conjunction with the introduction of computation in design education (Kvan 2003)?

In describing the mechanism by which children learn languages, Wittgenstein states that they are engaged in a form of life, in which they share goals and interest with the teachers and parents who in turn do not so much define words and set rules, rather share a context with the child through which understanding is attained (Snodgrass & Coyne 1997)

"What one acquires here is not a technique, one learns judgments. There are also rules but they do not form a system and only experienced people can apply them right. Unlike calculation rules"(Wittgenstein 1921)

It is interesting at this point to compare this with strategies proposed to introduce shape grammars to architectural education (Stiny 1980) (Dokonal & Knight 2007). In both we can find a method of gradually introducing elements in conjunction with problems to solve as an educational tool. Therefore, we can hypothesize that in order to avoid the limitations of mathematical logic inherent in "digital design worlds" computational education in the context of an architectural pedagogy can be approached as a language game (Cheng 1996), in which computational tools are introduced as an element of the broader design process rather than an autonomous design world (Kvan 2003).

Thus, what can be claimed to be missing is an architectural language able to incorporate computational thinking into the broader architectural culture in order to teach design for the digital age.

## ARCHITECTURAL DESIGN AS A HUMAN SCIENCE

In order to better understand the nature of this missing architectural language, the distinction between natural and human sciences must briefly be described. It has been proposed that digital design methods constitute models of thinking drawn from the field of the natural sciences (Kolarevic 2000).One can further argue that computational design logic, despite being based on an inherently positivist concept of language, as described above, has proved useful in architectural discourse and has indeed provided new paradigms and insights regarding the design process and product (Yessios 2006).In this context, whether these models are actually suited to represent the totality of architectural design seems beside the point (Snodgrass & Coyne 1997).

The counter argument to this thesis hinges on the differentiation between human and natural sciences. A general trend has been observed in the field of human sciences, regarding the adoption of precise and formal languages derived from the natural sciences. This is seen as the only method for the human sciences to be able to lay claim to the concept of truth and knowledge (Gadamer 1975).In other words, a field of human knowledge is seen to be in a way less truthful if it cannot be expressed in a mathematical - logical model.

It can be hypothesized that the current trend towards computational logic and digital media in the architectural design process represent such a phenomenon. Nevertheless, it is valid to claim that architecture as a field of knowledge cannot be conceived outside the context of human activity, and as such requires elements and modes of thinking from the human sciences.

The scientist of humanities cannot break free from human society - context and therefore cannot step outside it to examine it as an external object. By contrast, the domain of the natural sciences ignores facts and theories that do not conform to the strict logic of formal languages (e.g. mathematics). Focusing on the domain of architectural design, this means that computational logic, when used to externalize at least part of the design process (Spuybroek 2004) ignores those parts of the architectural project that cannot be expressed in a digital design language.

One can remark that no pattern of human behavior can be understood unless the context (i.e. the non quantifiable aspects) can be taken into account. On the same note, no -digital- design methodology can be understood outside a holistic framework of architectural context that also takes into account the non quantifiable aspects of architecture.

A more elaborate examination on how human sciences and their methodologies differ from the field of natural sciences cannot be made here. Suffice to say that the natural sciences examine and explain phenomena which do not ascribe meaning to themselves. Human sciences by contrast attempt to understand phenomena which have a self-reflexive quality. As a consequence, they differ radically from the natural sciences in their goals, relation to practice and type of knowledge they disclose (Snodgrass & Coyne 1997).

When approaching design, especially in an educational setting, how can architectural thinking address and the limitations of computational logic in describing the architectural project? In order to examine this we will utilize the model of the hermeneutics circle

## A HERMENEUTIC CIRCLE OF COMPUTATIONAL ARCHITECTURE

As has been described above, hermeneutics examine why understanding arises. In this sense, hermeneutics can contribute to the articulation of an architectural education framework regarding computational design by helping understand

- the impact of digital media on architectural education (on part of the educators)
- the purpose of teaching computational design methods (on part of the educated)

In order to achieve this it is proposed to approach the -digital- design process and education in the context of the hermeneutic circle. It is not possible in the context of this paper to fully elaborate on the structure and workings of the hermeneutic circle. Suffice to say that it is a model of understanding based on the dialogical relationship between part and whole.

To illustrate this consider the example of a text . It is obvious that the words that comprise it only make sense in the context of the particular sentence. But how does one reach understanding if in order to comprehend the sentence (the whole) one must be able to interpret the individual words (parts).(Snodgrass & Coyne 1997)

According to the hermeneutic circle one neither first ascertains the meaning of individual words (which is impossible considering the need for context to give meaning) nor reads the whole sentence and retroactively understands what is being said. Rather, we approach the sentence and project certain expectations regarding the meaning as soon as some sense can be established. This projection is based on the prejudgments we bring to each situation, which Gadamer termed prejudices. As the process of interpretation proceeds, our preconceptions are redefined based on new information acquired and the projected meaning is revised. This is a cyclical process in which one cannot isolate either the part or the whole.

“A person who is trying to understand a text is always preforming an act of projection. He projects himself a meaning for the text as soon as some initial meaning emerges in the text. Again, the latter only emerges because he is reading the text with particular expectations in regarding to a certain meaning. The working of this fore project, which is constantly revised in terms of what emerges ... is understanding what is there” (Gadamer 1975).

In broader terms, in any interpretive event, (which we can argue includes the design process) before we begin to consciously interpret, we have already placed the matter to be interpreted in a certain context, viewed it from a given perspective, conceived of it in a certain way.

“The process that Heidegger describes is that every revision of the fore project is capable of projecting before itself a new project of meaning, the rival projects can emerge side by side until it becomes clear what the unity of meaning is, that interpretation begins with fore conceptions that are replaced with more suitable ones. This constant process of new projection is the movement of understanding and interpretation" (Gadamer 1975)

It is these preunderstandings, or prejudices that form the core of Heidegger and Gadamer's critique of the Enlightenment's (and by extension natural science's) logic. The crucial role of these preconceptions, cannot be adequately explored in the context of this paper. Suffice to note that without preconceptions, i.e. based on a formal rule model, no understanding - as defined by human sciences can emerge.

Returning to the domain of architecture, we can question how computational design can be conceived in this context and how the hermeneutic circle can be applied to the -digital- design process.

## A DIALOGICAL MODEL FOR DIGITAL DESIGN EDUCATION

We will now examine in some detail the potential of applying the hermeneutic framework described above in understanding computational design methods and teaching digital design. It has been demonstrated that architectural design can be approached as a dialectical process. The protocol studies conducted by Donald Schon describe design and design education in terms very similar to those of the hermeneutic circle presented above.

According to Schon, design can be defined as a reflective action, that is to say a process of dialogue between the architect and the design project. Briefly, this means that design progresses through a constant interplay between the designer and the design as well as between the part (i.e. the design element being examined) and the whole (the entire architectural project). What is important to highlight is that the process commences with the projection of the designer's expectation regarding the possible form of the architectural project (it can be noted that this is the literal interpretation of the word "project"). This projection is mainly based on the preconceptions the designer brings to the process.The design project then "talks back" to the designer, who in turn responds by adjusting his approach to the problem and by extensions revising his preconceptions.

This constitutes a circular model. Each design move (or question) is informed by the previous ones, while also affecting the expected projection of the whole. Therefore the designer creates a "web of moves, consequences, implications, appreciations of further moves"(Schon 1987)

This has several implications regarding the way we approach design activity.

- In the context of a hermeneutic approach design is not approached as a "problem", that is to say a situation that has a single correct solution. On the contrary the design process is conceived as a dialogue that aims at understanding the design situation.
- The relation between parts and whole, i.e. the relation of particular design actions to the total architectural projection. In other words, "local" design elements (such as those to which computational logic can be applied) cannot be viewed in isolation from the "global" architectural project the two elements define each other.
- Viewing architectural design as a hermeneutic act underlines the importance preconceptions play in the process. These "prejudices" frame the design situation by defining the expected outcome. Contrariwise, by providing answers to the questions posed by the architect, the design situation leads to the revision of those prejudgments. Thus the project is continuously modified and refined in tandem with the evolution of our preconceptions regarding it.

In light of this, it can be argued that designers can either allow this questioning to reframe his preconceptions or proceed in a one sided manner and ignore the inputs of the design process. It is obvious that in a pedagogical process, it is crucial to be able to reconsider and evolve these preconceptions. Thus an hermeneutic approach is of use in an educational context, since it demonstrates that the design process, digital or otherwise is a process of understanding in two senses

- Understanding the design project
- Understanding the architectural preconceptions that led to it

"If the design educator acknowledges the ineradicable existence of presuppositions, recognizing them as stemming from experience that underpins all understanding and as the base from which the design image is projected, then the educator, rather than attempting to eradicate all prejudice in the students, will introduce them to a design dialectic, in which those presuppositions and preunderstandings are constantly under question and are revised, expanded or rejected as responses to those questions.We believe (sic) that this, rather than any model based on logical sequences of operation is fitting and appropriate foundation for a digital design pedagogy."(Snodgrass & Coyne 1997)

## EPILOGUE

Further implications of the hermeneutic model to digital design cannot be adequately explored here.

It has been briefly demonstrated that computational logic is incompatible to certain architectural elements and that even those that are quantifiable and therefore able to be manipulated according to such a logic must refer to the architectural project as a whole iin order to be meaningful.

Also, the role of prejudgments and the ability to revise them according to the progress of the architectural process is something that is problematic in methods of computational design, since such models have no way of contextualizing them and therefore rendering them open to question.

It is hoped that a hermeneutic context may help in provide some insight to these issues especially in juxtaposition with other theoretical frameworks. It is further hoped that such a process will aid in the emergence "metacode" of architectural pedagogy for the digital age.

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# Why Immersive?

## *Using an Immersive Virtual Environment in Architectural Education*

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*Teaching the process of design is a primary objective of the architectural studio. Due to the complexity of the process, the studio encourages active learning and peer participation during crit sessions. This paper explores the potential of immersive virtual environments (IVEs) for enhancing architectural learning, and proposes a framework for evaluating its educational potential.We have developed a model for coding the three main activities of the architectural design process (analysis, synthesis and evaluation), along with their physical and social settings. The model comprises of units we call Knowledge Construction Activities (KCAs). We suggest that this model presents a detailed description of the environmental implications of each activity. Applying the KCA model to a studio course that used both a traditional classroom and an IVE revealed that the IVE increased the number of synthesis KCAs, and supported effective criticism. Though limited in scope, the results clearly indicate IVEs potential contribution to architecture pedagogy.*

**Keywords:** *Architectural education, Design process, Immersion, Virtual environments, Place*

## INTRODUCTION

### *The Pedagogical Aims of the Architectural Studio*

Teaching "design knowledge" to architecture students has always been the greatest challenge of the architectural profession, because it has no determined definition (Rittel & Webber 1973). Rather, students must independently construct their knowledge by personally experiencing the design process as it is applied to solving a design problem. They are asked to apply acquired knowledge, concepts, and skills to their design project, guided by a professional tutor and by peer support.

Architectural design encompasses multiple problems, ranging in complexity from the conceptualization of desired goals to the point of attaining a satisfactory solution (Kalay, 2004a) (Figure 1). Goldschmidt highlighted this complexity, revealing the numerous repetitions of different design steps (Goldschmidt et al., 2010; Goldschmidt, 2014). Since learning is based on the learner's progress, each step must provide stimuli for the production of progressive design decisions, creating learning opportunities that can be discussed in class. Students are often required to use representational objects, such as models and scaled drawings, to communicate their ideas. However, these means only partially convey the complexity and richness involved in the reality they represent, thereby limiting the ability of students to develop their knowledge.

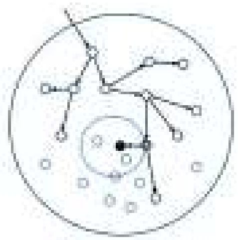

Figure 1
Design search process. Source: Kalay, 2004, pp.18

Furthermore, architects learn by sharing knowledge with colleagues and consultants, and through evaluating their own decisions post construction. Students' projects, on the other hand, are never realized. Hence, learning is highly dependent on precedents and the teacher's experience.

In order to overcome this obstacle, the studio pedagogy strongly promotes peer participation during design crits. In this respect, architectural knowledge acquisition follows the principles of the constructivist theory of learning, contending that learning is individually and actively constructed by the learner, and strongly bound with its community of practice (Kurt, 2011; Lave, 1991; Lave & Wenger, 1991). Research indicates that peer participation is beneficial, because it enriches the learner's understanding with multiple opinions and possible solutions, and encourages self-assessment (Farivarsadri, 2001; Oh et al., 2013; Ochsner, 2000; Schön, 1987). Peer support, however, should be viewed in a critical manner, given that it can sometimes be unconstructive or misleading, due to lack of knowledge or competitiveness (Dutton, 1984). However, the fact that exposure to peer projects promotes self-assessment highly emphasizes the advantage of presenting design decisions in group crits.

### *Changes in the Architectural Learning Environment*

Technological developments have affected pedagogy in many fields, including architecture. Since the 1990s, Virtual Environments (VEs) have captured the attention of researchers and educators, prompting them to explore the potential of this technology (Bailenson et al., 2008; Bowman & Hodges 1997; Dede et al., 2005; De Freitas, 2008; De Freitas et al., 2010; Kim, et al., 2013). Survey studies outlining the varied applications of VEs to education (Mikropoulos & Natsis, 2011), emphasize the support that this technology lends to constructivist learning principles and learner engagement (Bronack et al., 2008; Lorenzo et al., 2012; Vosinakis & Koutsabasis, 2013).

Similarly, due to developments in computer aided architectural design (CAAD) tools and information delivery technologies, the studio has rapidly evolved both in terms of its setting and its curricula. New learning environments have emerged, affording virtual, immersive and mixed reality settings (Andia, 2002). Studio courses utilizing VEs have been found to enhance learning behaviors and design thinking processes, indicating the significant role that settings play in the learning process (Clark & Maher 2005; Hollander & Thomas, 2009; Kalay 2004b; Mallan & Foth, 2010).

Immersive Virtual Environments (IVEs) are of particular interest to the current paper. They facilitate overcoming the "barrier" between the user and the visual display by creating a sense of "presence" for participants (Slater et al., 1995). Originally designed as a "Virtual Reality theater", CAVE (Cave Automatic Virtual Environment) type of IVEs were developed with the intention of supporting the discovery process (Cruz-Neira, et al., 1993). Special attention was given to architects' need for a "walk-through" experience of a proposed design (Cruz-Neira et al., 1993). IVEs provide a shared visual display for all the attendees; thereby support the architectural learning need for peer participation.

The advantages of IVEs have been proven in fields that demand the analysis of complex information, such as spatial cognition (Natapov & Fisher-Gewirtzman, 2016; Billen et al., 2008), geosciences (Magali et al., 2008), chemistry (Limniou et al., 2008) and engineering (Messner et al., 2003). In the field of architectural and urban design, research has highlighted the benefits of IVEs in supporting the design process (Okeil, 2010), collaborative design between remote users (Dorta et al., 2011; Dorta et al.,2016), spatial comprehension (Maftei & Harty, 2012; Sopher, 2015; Sopher & Kalay, 2015) and providing a tangible display (Kalisperis et al., 2002; Portman, et al., 2015; Otto et al., 2009; Zikic, 2007). Although IVEs are still very expensive compared to other available VEs, these studies show their potential for achieving the objectives outlined earlier. Through the collective, dynamic experience created by an IVE, students can share knowledge and experience a richer learning process. This is especially important when aiming for an in-depth appreciation of the design's different levels of complexity, a process that would warrant extensive design decisions.

In light of these recent developments, architectural education is now at a critical junction: how may one discern which learning environment is more beneficial, or what degree of fit it has for different students? Historically, the studio space has served as the sole learning environment. Therefore, most existing research has neglected to consider this component. While this omission may not have made a significant difference when assessing other design tools, it now bears substantial impact, given the transformation of educational environments. Addressing these shortcomings, this paper proposes a framework with which to evaluate the educational potential of IVEs, assuming that they can indeed enhance the architectural learning process.

## CONSTRUCTING A SITUATED LEARNING MODEL

We propose addressing the questions listed above by using place theory as a methodological tool for examining the relationship between the environment and its users. "Place" is defined as an emergent phenomenon, constantly shaped according to situated surroundings through time. It is derived from the activities whose performance is enabled by both physical and social settings (Alexander, 1979; Canter, 1977; Lefevbre, 1991; Malpas, 2006; Norberg-Schulz, 1988; Tuan, 1978). This theory is also used in other disciplines, such as in computer science, promoting human computer interaction (Harrison & Dourish, 1996; Dourish, 2004); and in environmental psychology, investigating personal attitudes towards settings such as place-identity (Proshansky et al., 1983) or place-attachment (Lewicka, 2011). In recent years the design field has experienced a revival of "place" theory as a setting for inquiry (Aravot, 2002; Clark & Maher 2005; El Antably, 2011; Rieuf & Bouchard, 2017; Schneekloth & Shibley, 2000).

Examining learning through the lens of place proposes considering learning behaviors as situated acts, bound and constructed upon their environmental components. Hence, a learning space would be the physical and virtual settings that afford learning, while a learning place would refer to the act of learning performed in particular settings. In accordance with this approach, each design decision that is presented and discussed during the crit is considered a "Knowledge Construction Activity" (KCA) unit. Each KCA consists of a situated pattern derived from three domains (Figure 2): the spatial setting, which includes all physical and virtual components utilized during the crit; the social setting, which includes all crit attendees (e.g. tutor, peer, learner); and the design activities, which consist of the learning behaviors involved in developing the design product, such as verbal and visual communication.

### *Forms of Design Knowledge*

Linking the construction of design knowledge with its social and spatial settings suggests evaluating the environment through the learners' performances. Learners' assessment in the studio frequently involves, however, additional components, such as the quality of outcomes, or creativity (de la Harpe et al., 2009). These aspects may obscure the objective of investigating how the environment affects the learning process: a high-quality project may be produced by a few design activities, as much as a low-quality project.

Focusing on the process of design creates a premise with which to overcome this ambiguity. The design process is considered to comprise of the activities of analysis, synthesis and evaluation (Cross, 2006; Goel & Pirolli 1992; Jones, 1980; Kalay, 2004; Lawson, 1990; Rowe, 1998). Framing it as a set of well-defined skills creates an opportunity to assess learners' expertise and to develop instructional design strategies (Christenson, 2016; Öztürk & Türkkan, 2006).

We propose applying the KCA model to design activities, assuming that the number of activities produced in a certain environment may indicate its capacity to enhance learning. The KCA model affords a detailed description of the environmental implications of each activity, as well as of the design process as a whole. Each design decision is analyzed according to its pattern of activity. Analysis, in this context, consists of recognizing and defining existing problems and their conditions. These include site description, identifying commonalities or anomalies, and formalizing design goals and principles. Synthesis consists of changes to the design regarding its form, function and use. Evaluation consists of various queries made by the learner regarding the artifact's ability to achieve desired goals. These goals include acoustics, energy or structural tests; comparison between design alternatives; and verifying limitations, such as height, ergonomics or density, to fit the desired performance.

### *Coding KCA Settings Through Time*

Seeking to identify how settings affect particular KCA patterns, we now consider their contribution to knowledge construction through time. Although students are expected to make progress from one crit to the next, learning does not necessarily ensue. A learner may receive comments regarding a design issue during one crit, yet only respond to them a few crits later. In addition, reflecting on an artifact can induce comments on various design issues (e.g. size, scale, or concept) that cannot be encoded in a particular KCA. Thus, comments are recorded at crit time, including their subject of interest, commenter and learning environment. Subsequent KCAs, carry the information of the social settings, and where they were conceived (Figure 3).

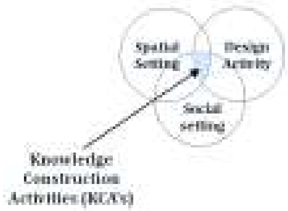


Figure 2
A Situated Learning Model constructed by KCAs units.

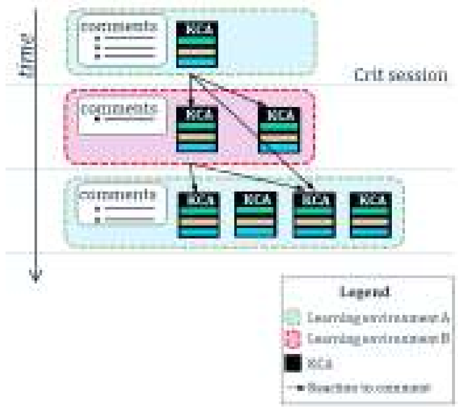


Figure 3
KCA social implications through time. Present comments are encoded at each crit. KCA units contain relevant past comments and their environment.

Table 1 demonstrates KCA encoding methodology. Each design decision presented at the crit is encoded, along with its environmental setting and related comments.

| Student | Social Setting | | Spatial Setting | | Design Activities | Decision |
|---|---|---|---|---|---|---|
| [illegible] | Past comments | | Environment | Display | Analysis | Description of the design decision |
| | Environment | Commenter | Studio | 2D | Synthesis | |
| | Studio | Learner | F/F | 3D with [illegible] | Evaluation | |
| | F/F | Teacher | Other | | | |
| | Other | Peers | | | | |

Table 1
Data encoded in student's KCAs

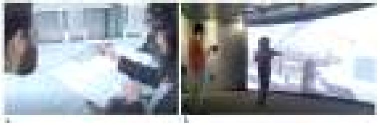

Figure 4
Course's spatial setting: a. The studio classroom; b. The IVE

Figure 5
Students O&L final digital model, presented at the IVE.

Figure 6
Evaluating the width of a designed ramp

Figure 7
A peer student is commenting during an immersive walk-through

## CASE STUDY

We followed a novel studio course, taught in the Fall of 2013 by Prof. Dafna Fisher-Gewirtzman at the Faculty of Architecture and Town Planning, Technion. The course alternated between a traditional studio classroom (Figure 4a) and an IVE (Figure 4b) as its educational setting. Our IVE has an advanced computer graphics system, compatible with most 3D modeling software programs. The room is equipped with a 2.4 x 7.0 meter screen with a 75° field of view, and three high-definition, synchronized projectors that can project a uniform and continuous display. The IVE can host up to twenty people for a simultaneous shared immersive experience (through the use of 3D glasses): one participant leads the tour through the model in a variety of scales, while the audience follows and actively shares this dynamic virtual walk-through.

The research sample consisted of four design projects, produced by six undergraduate students (two pairs and two individuals) in their third and fourth year of studies. The expected learning outcomes were similar to those of a traditional studio course at this level, requiring the design of a small-scale public building. In order to perform a virtual walk-through, the students were all obliged to develop detailed digital models.

The students were followed by means of observations, crit recordings, and design product documentation, over the course of one semester. Design analysis was used to determine KCA patterns. Protocol analysis was used to encode the participants' comments. Figures 5-7 demonstrate the students' work in the IVE, showing the detailed models achieved during the course (Figure 5), and critiquing activities during a virtual walk-through by the teacher (Figure 6) and a peer student (Figure 7).

## KCA ANALYSIS

Students' KCAs were coded through the analysis of four projects. Figure 8 exemplifies this process. The analyses, shown in this section, demonstrate the environmental implications on the emergence of KCA with each project.

### *Design Process KCAs*

Analysis of the design process KCA pattern revealed that most KCAs, especially synthesis activities, emerged in IVE crits (Figure 9); allowing further communication and project development. Synthesis activity encompasses the learner's knowledge, applied and expressed in the proposed form; thereby it is highly significant for further progress. Figure 10 shows the number of synthesis KCAs that were prepared for IVE crits, in accordance to their mode of display. As opposed to other representation for-

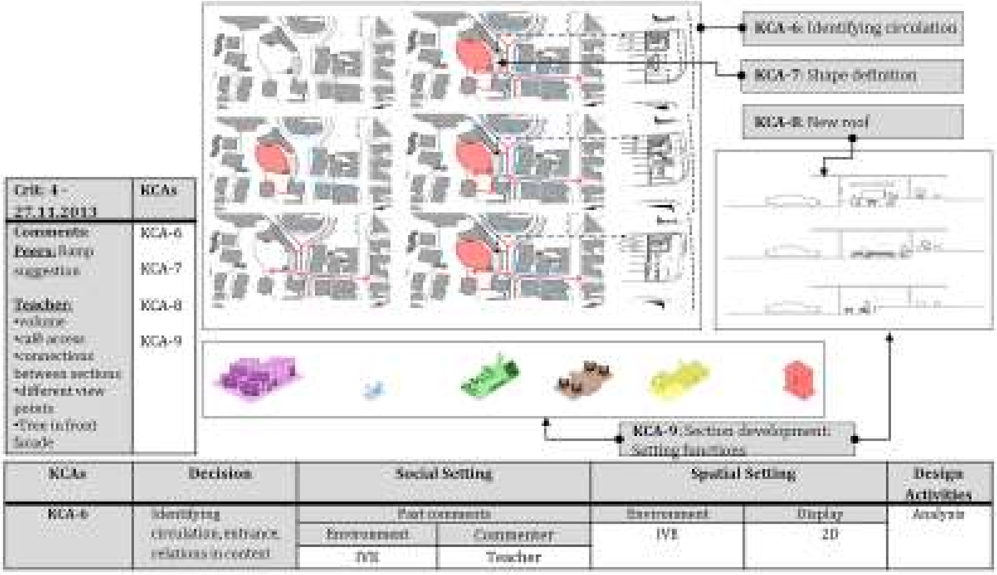


Figure 8
Coding KCAs from the data

mats such as sections or animation, the walk-through mode is not preplanned. This factor encouraged students to thoroughly develop and detail their models, thus creating the opportunity for them to enrich their design knowledge and to improve their modeling skills. The results that are shown in figures 9 and 10 indicate, hence, the IVE's support in experiencing a richer learning process.

Figures 10, 11a and 11b reveal the manner in which different learners used the educational settings. Students O&L and A rapidly 3D-modeled their design, producing synthesis KCAs to be reflected upon during a virtual walk-through. Students N&D, however, presented design alternatives for shared evaluation. The Evaluation pattern was rarely used independently by the students. The analysis of this activity, hence, does not depict significant results. Observations depicted different Evaluation patterns performed at the IVE. These ranged from the comparison of design alternatives to a prolonged evaluation of one design alternative, conducted through multiple viewpoints during walk-through mode.

### *Social Setting Analysis*

The analyses in this section show KCAs that emerged in response to comments made in previous crits, demonstrating the comments' effectiveness.

| Student | IVE | Studio | IVE & Studio | Other [illegible] |
|---|---|---|---|---|
| O&L | [illegible] | [illegible] | [illegible] | [illegible] |
| N&D | [illegible] | [illegible] | [illegible] | [illegible] |
| A | [illegible] | [illegible] | [illegible] | [illegible] |
| B | [illegible] | [illegible] | [illegible] | [illegible] |

Table 2
Student KCAs frequency (%) of comments' learning environment

Table 2 quantifies the comments that were followed by KCAs according to their setting, and indicates that the IVE significantly contributed to the emergence of further KCAs. Students N&D an A used the IVE as their main stimulator, reacting with subsequent KCAs. Although students N&D had difficulty using the immersive technology, being too embarrassed to walk-through their project, their learning pattern reflects extensive stimuli by the IVE. Students O&L were assessed as highly skilled students. As such, they produced many new decisions (shown in "Other" category, table 2), reflecting self-assessment abilities and an independent learning profile. Student B, who rarely used the IVE, used the studio as his main learning source and hence mostly relied on the teacher as a learning resource.

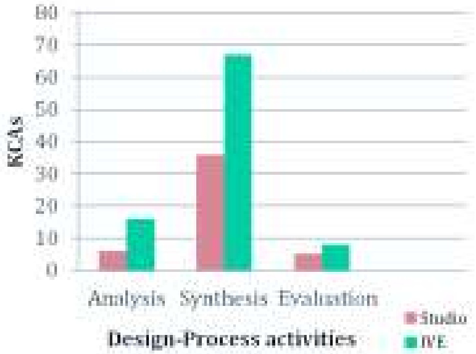


Figure 9
Distibution of Design-Process KCAs according to thelearning environment

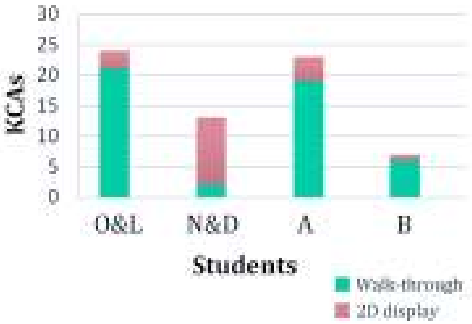


Figure 10
Synthesis KCA Patterns viewed in IVE crits

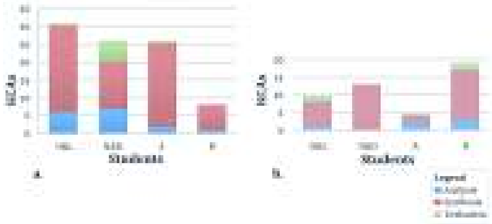


Figure 11
KCA design-process pattern distribution according to the learning environment. (a.) KCA distribution at the IVE; (b.) KCA distribution at the Studio

Figures 12a-12d show effective comments in accordance to different commenters. The "Teacher-Peer" comments category describes a discussion over a certain subject. The results indicate this activity was effective solely in the IVE, indicating the communicative qualities afforded by this environment. Consequently, the charts reflect the IVE's dominant efficacy in the "Peer" category. Peer participation occurred mostly in the IVE, leaving the studio environment to be used for personal crits. Students N&D and A made significant use of shared knowledge, presenting design alternatives that had been deliberately prepared for peer evaluation. The "Teacher" category shows that more KCAs emerged due to the teacher's comments in the IVE than due to comments in the studio. This indicates the environment's role in the interaction. The "Learner" category indicates some evidence of self-assessment activities. Despite their low frequency, they mostly occurred due to IVE crits, highlighting the need for further work on this topic.

Figures 12a-12d warrant close observation. Although they indicate social and environmental influences on the learning process, the students' own learning capacities need to be considered as well. Findings show that highly skilled students easily adapted to the technological challenges, and profited from independent learning. On the other hand, weaker students, with low modeling skills, or ones who were ashamed to use the technology, profited mostly from the IVE's social advantages, by utilizing group discussions and peer comments. Since students O&L were both in their fourth year of studies and had well-developed skills, they were able to participate and contribute to their peers' learning during crits. This led to the presence of more peer-related KCAs for students A and N&D, who were in their third year of studies.

Social setting analysis reveals that despite the teacher's dominance in emergence of subsequent KCA, group discussions and peer commentary facilitated by the IVE stimulated further KCA emergence, emphasizing this environment's capabilities of supporting a diverse learning model. However, the studio's social settings are highly dependent on the group's dynamics. Since this study was performed on a small scale, these results need further inquiry.

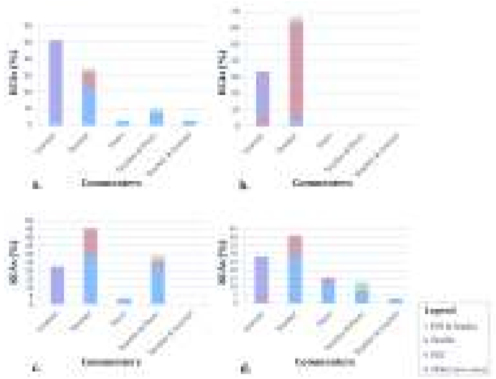

Figure 12
KCA emergence according to commenters and comments' learning environment. a. Students O&L; b. Student B; c. Student A; d. Students N&D

## CONCLUSIONS

This paper set out to describe the impact of the use of IVEs on architectural education. Although the case study was performed on a limited research sample, the results clearly demonstrate the pedagogical role played by IVEs in enhancing design activities and supporting peer participation.

The research results underscore this environment's substantial capacity for encouraging the emergence of synthesis learning activities. This is a highly significant factor, given that the crit's social interaction strongly relies on learning outcomes. The findings show that the IVE supports different use patterns according to personal skills and learning profiles. Future research should examine IVEs impact on learner expertise.

The research findings suggest that the studio space was dissolved from its original role as a shared learning environment, and mainly served as a setting for intimate, informal desk crits. Additional observations conducted with similar studio courses using both IVE and traditional space support this understanding, raising the question of studio design principles in view of current and future technological changes.

## ACKNOWLEDGEMENTS

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# CAAD EDUCATION - TEACHING

# The Use of Simulation for Creating Folding Structures

## *A Teaching Model*

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*In architectural education, the demand for creating forms with a non-Euclidean geometry, which can only be achieved by using the computer-aided design tools, is increasing. The teaching of this subject is a great challenge for both students and instructors, because of the intensive nature of architecture undergraduate programs. Therefore, for the creation of those forms with a non-Euclidean geometry, experimental work was carried out in an elective course based on the learning visual programming language. The creation of folding structures with form-finding by simulation was chosen as the subject of the design production which would be done as part of the content of the course. In this particular course, it was intended that all stages should be experienced, from the modeling in the virtual environment to the digital fabrication. Hence, in their early years of architectural education, the students were able to learn versatile thinking by experiencing, simultaneously, the use of simulation in the environment of visual programming language, the forming space by using folding structures, the material-based thinking and the creation of their designs suitable to the digital fabrication.*

**Keywords:** *Folding Structures, CAAD, Simulation, Form-finding, Architectural Education*

## INTRODUCTION

Simulations, which are the virtual models that reveal the behavior of a system according to specific time parameters, and map the behaviors of the system by changing the time parameter. In other words, simulations can be described as an experimental environment which, depending on the time, enable inferences to be drawn on the basis of exact or approximate information. As in the areas of science and engineering, in those cases where it is impossible to carry out the experiments, or where that systems are very complex, the use of simulation to observe the change of time can provide important data for inferences to be made. With the advent of computational design in the field of architecture, the acquisition of the impression related to the life cycle process of architectural products and in the design process, there has

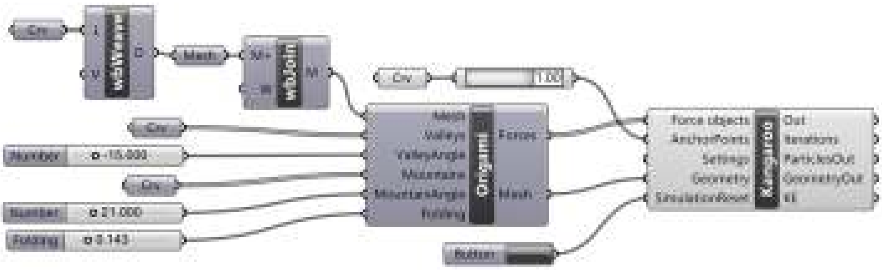


Figure 1
Origami script

been an increased use of simulation system, which allows these impressions to be added as information.

Thus, in the architectural design process under the title of sustainability, there are available; heat, wind flow (such as EnergyPlus, eQuest, Ecotect and Autodesk Vasari programs) and daylight simulations (such as Velux Daylight Visualizer, Daysim and Dialux programs) as well as acoustic simulations (such as Odeon and Aurora programs) that perform analyses so that the sound can be controlled, the user's movement simulations which can estimate the user's movement in the building, fire simulations (such as PyroSim program) and heat island simulations (such as Envi-met program) which are all beginning to find application. Furthermore, simulations which examine the behavior of the structures, are used by the structural engineers, while those related to building performance, which are attached to the computer-aided design programs, are presently widely used for such purposes as sustainability and energy performance, and more recently as a tool for form-finding (Agirbas and Ardaman, 2016).

First reaction to the traditional drawing methods developed with the form-finding perspective, which appeared from the result of the complex relationships between structure, form and material and from the aim of examining unusual optimized structures at the end of the 19th century. The pioneers of this perspective: Gaudi (1852-1926), Isler (1926-2009), Otto (1925-2015) and Musmeci (1926-1981) rejected the typology and looked toward the self-formation processes that occur in nature, which they attempted to apply in architecture. The traditional drawing method cannot be used as a tool to create a design product since form does not come from proven solutions, and therefore, the pioneers of the form-finding methods began to make physical models. Thus, instead of using the drawing as a tool in the search for forms, they preferred to use physical form production as a tool employing analog methods. This method was able to demonstrate self-optimizing dynamic forces in architectural forms (Tedeschi, 2014).

Figure 2
A student work on folding structure, which was made with the use of thin cardboard.

Form-finding in architecture (which has rapidly increased during the past 10 years) became an important strategy for the creation of complex forms.

According to Pugnale (2014), the reverse hanging method is likely to be the oldest method for form-finding of shells, vaults and arches.

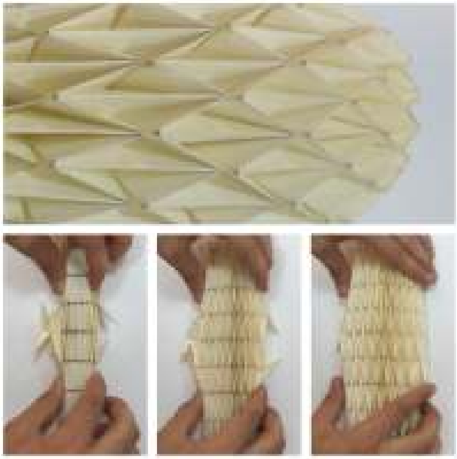

Figure 3
A student work on folding structure, which was made with the use of thin cardboard.

This physical model was made using elastic cords or membranes. Thus, the first effective force on the physical model was gravity, and structural pure tension could be identified, following which, the force of mechanical compression could be defined by reversing the model. Robert Hooke expressed this principle for the first time in 1675, and he suggested the reversal of the curve which is formed by a chain, supported only by the tip end points and hanging under its own weight for the definition of the structural optimization of the arch. This curve is called a catenary, and later, in 1697, David Gregory provided a mathematically definition of it (Pugnale 2014). In the present age, mathematical solutions for these systems can be found in the simulation environment.

Since architecture has been increasingly moving away from that based on the Euclidean geometry, architects are directed to computer-aided form-finding methods. The development of design environments with non-Euclidian geometries has enabled the creation of variations in the forms of buildings. Building forms in non-Euclidean geometry can be created with the new computer technology and these have appeared against building forms which came with the industrial revolution and can be produced easily and many in Euclidean geometry. This development of computer-aided architecture has also influenced the architectural education environment.

Today, courses that teach students about various computer programs are included in the curriculum of undergraduate architectural education. In some architectural schools, these are taught about in the form of separate courses, while in some other schools, the use of these programs is integrated in the architectural studio course. No matter which way they learn, students are expected to use these programs, to a greater or lesser degree, in the design process. Moreover, especially in the conceptual design stage, these programs can direct the form of the students' designs. In fact, rediscovery in the sketches of design (Schon, 1983; Schon and Wiggins, 1992; Garner, 1992; Goel, 1995; Suwa and Tversky, 1996; Agirbas, 2015) also arises with the use of these programs.

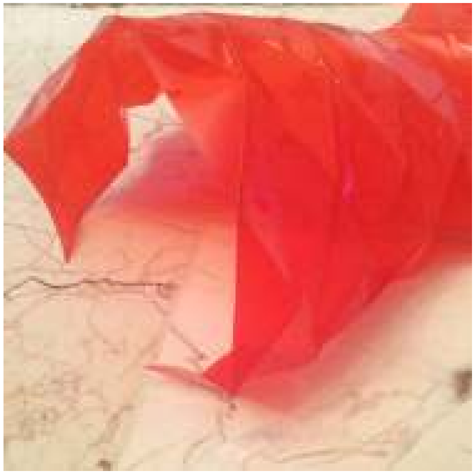

Figure 4
A student work on folding structure, which was made with the use of acetate material.

Especially, since the programs produce complex forms that are not present in Euclidean geometry, their development has increased their involvement in the concept design stage of design.

In the present study, folding structures with the origami concept, which is defined as the content of the elective course "Introduction to parametric design", which is given to the undergraduate architecture students, are considered.
With the use of simulation, form-finding studies were carried out for the folding structures which were departing from the Euclidean geometry in a holistic sense, and in the end of the course, it was attempted to obtain kinetic structures by digital fabrication.

Figure 5
A student work on folding structure, which was made with the use of thick cardboard.

## METHODOLOGY

In the "Introduction to parametric design" elective course of the architectural undergraduate education, basic 3D modeling is primarily intended to teach students by means of the Rhino program. Following the teaching of basic modeling techniques in Rhino, a focused was made on the basic logic of the Grasshopper visual programming language, which works as a plug-in of the Rhino program. Using Grasshopper, a few scripts were written and forms were produced and altering these forms parametrically was focused on. Next, the students were asked to install Kangaroo (add-on of Grasshopper) onto their laptops.

Figure 6
A student work with the multi-module.

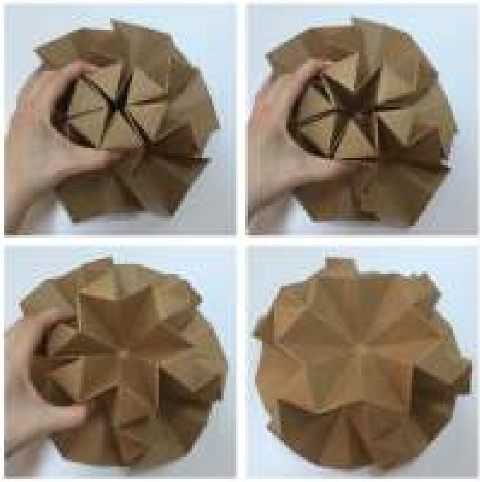

Figure 7
A student work with the fewer module.

The Origami component (Vergauwen et. Al., 2014) in Kangaroo, which was written by Daniel Piker (2013) and known as a form-finding physics engine program, was used as a basis for the production of folding structures during the course.

Figure 8
A student work which was produced by combining the modules.

A description was given to the students, simultaneously with the application process, static resistance and the characteristics of less volume spatial occupation of folding structures. Creating a stable form by folding structures was also focused on and examples implemented such as the following; the Folded-Plate Hut in Osaka by Ryuichi Ashizawa Architects, Yokohama International Port Terminal in Tokyo by Foreign Office Architects, United States Air Force Academy - Cadet Chapel by Leo A. Daly, Inc., Henningson and the Chapele St. Loup in Switzerland by Danilo Mondada (Stavric and Wiltsche, 2014) are shown. In addition, experimental examples on a regional scale using Miura-Ori pattern as folding structure were also focused on, as was suggested by Mattoccia and others (2016). Additionally, some examples of academic articles (Liapi, 2002; Hemmerling, 2010; Lee and Brian, 2011; Abdelmohsen et. al., 2016), which contain different drawings and models on the folding structures, were given to the students for their preliminary work. Subsequently, the students were asked to provide a proposal with the concept of shelter for the refugees or homeless for the folding structure. At this stage, the students had already examined various origami examples from the internet to use in their own folding structures, and were then asked to include their selections of origami tissues to the script (Figure 1) which was prepared by using Kangaroo (Piker, 2013) and to make the simulations of folding. Specifically, the students have to set the curves to the *mountains* and *valleys* components in this script, which are related to folding which they make. After all the students performed their simulations, they were asked to make a digital fabrication of their 2D patterns by using laser cutting.

Figure 9
A student work with the fewer module.

## RESULTS

Although the students benefited from 2D and 3D examples (found in the internet), they found it difficult

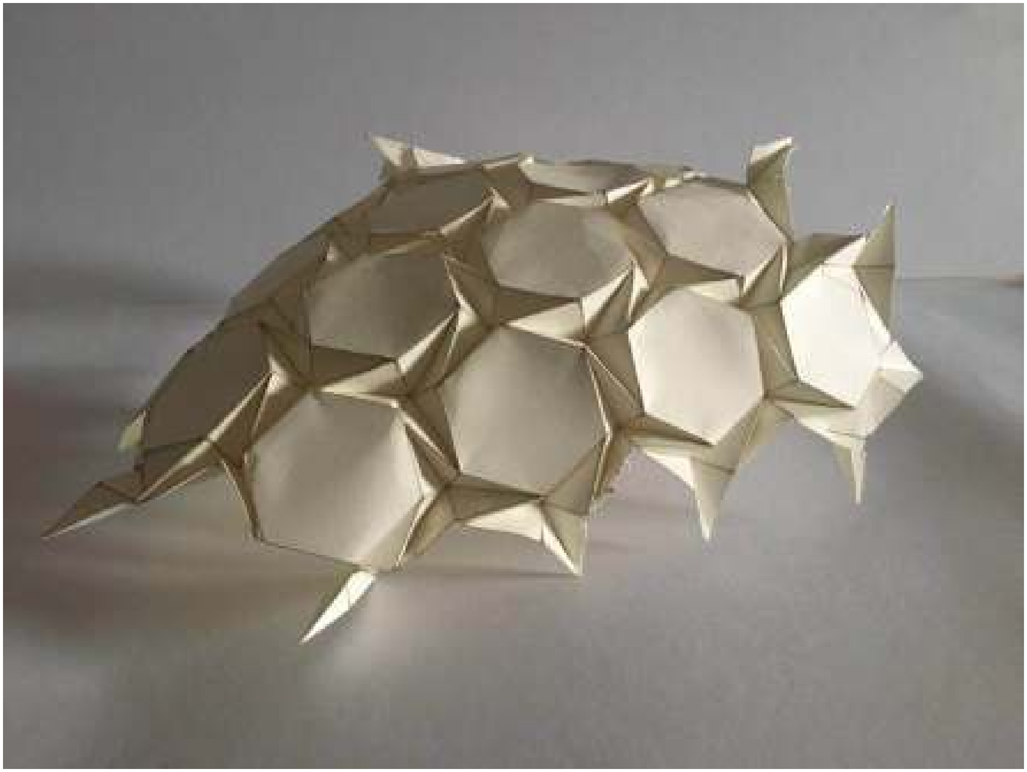

Figure 10
A student work which was produced by combining the modules.

to envisage the folding principles of these examples. At this stage, the use of simulation provided a useful means to help the students understand the principles of folding. Furthermore, if the simulation that they carry out does not work properly or if it fails to give the preferred form of folding, the students are directed to find the correct folding principle. This helps them to imagine the transition of folding from 2D to 3D (or vice versa) and also develops the student's ability to think in three-dimensions. Additionally, during this process, students can gain insight about how they can create a form with a folding type of their choice. Thus, at this stage, as the students were trying to solve the principles of folding, they have simultaneously already started the form-finding studies.

At the digital fabrication stage, the students held the 2-dimensional structure lines as different types (i.e. *mountains* with dashed lines and *valleys* with straight lines). Thus, after the laser cutting process as scoring, students easily understood which line was *valley* and which line was *mountain*.

Before carrying out the laser cutting, students decided upon the materials themselves to be used. Those who used cardboard-like materials, completed the folding process easily, according to the lines (Figure 2, Figure 3). However, the students who selected semi-transparent materials such as acetate (Figure 4), were unable to achieve a satisfactory result as desired in the folding process. Likewise, the students who used very thick cardboard (Figure 5), were unable to sufficiently feel the foldability of the material. These outcomes were useful in assisting the students to understand the great importance that the choice of material has on the final design. Thus, the students assimilated the necessity of an integrated consideration of design together with materials during their experience in their early years of architectural education. As Roudavski and Walsh (2011) noted, "early adaptation of material-based consideration by digital fabrication effects on design."

The number of modules which was used in the folding structures, was left to the student to choose. Some of them preferred to use more modules (Figure 6), while the others preferred to use fewer of them (Figure 7, Figure 9). The students, in fact, noticed that the design is highly influenced by the number of these modules. And some who used fewer modules to produce folding structures, were able to reproduce them with more modules, although this was not specifically stated (Figure 8, Figure 10).

## CONCLUSION

As a result of this study, architecture undergraduate students were able to comprehend the inclusion of simulation as a part of form-finding in the design process. It is important to introduce this new way of thinking to architecture students, since the design representation has been transformed to intelligent modeling and simulation from 2D and static 3D representation. Furthermore, they were able to define the space by using folding structures and in the early years of their architectural education, and had the experience of making complex forms of design with a concept, which was removed from the Euclidean geometry. This provides a basis for students who will make the design studio projects over the coming years.

Also, in the early years of architectural education, students were able to learn that, in practice, design is not an aspect of single thought but it is necessary to use many different tools together in combination. They were able to take advantage of simulation scripts as well as using a 3D modeling program, and they had contributions from both an analogue from the products of digital fabrication as well as their experience of digital fabrication. By considering the frequency of modules in folding structures, they discussed how these modules can affect the volume of the space that they create in their designs. Therefore, the students were able to experience the necessary versatile thinking in computer-aided design and to use multiple tools.

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# Digital Fabrication in Education

## *Strategies and Concepts for Large-Scale Projects*

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*The consequences of automation technology on industry are currently widely discussed in terms of future tasks, work organisation and working environments. Even though various novel education programmes specialise in digital fabrication, relatively little has been written on concepts for a deeper integration of digital technologies in the architectural curriculum. This paper gives an overview of interdisciplinary educational approaches and digital project development techniques and describes a teaching method featuring intensive collaboration with research and industry, an iterative teaching method employing digital production of large-scale prototypes and a moderated self-learning process. We describe two examples of teaching initiatives in particular that were undertaken at TU Munich and ETH Zurich and analyse their results in terms of physical outcomes, teaching accomplishments, resource efficiency and connection to research. We discuss the relationship between necessary teaching intensity, project size and complexity of digital fabrication equipment and conclude by giving an outlook for future initiatives.*

**Keywords:** *interdisciplinary collaboration, iterative process, self-learning*

## INTRODUCTION

While the age of *"personal fabrication"* - an analogy to the age of *personal computers* - was enthusiastically proclaimed (Gershenfield 2005), recent articles focus on analysing the jobs most likely to be replaced by algorithms and machines, calling for a new culture of lifelong learning to cope with constantly progressing technology [1] . Most architecture schools feature digital fabrication equipment (Hemsath 2010) and a number of them now offer one or two year programmes specialising in digital technologies, such as the EMTech at the AA [2], CITAstudio at the Danish Academy of Fine Arts [3], MAA at the IAAC [4], ITech at the ICD Stuttgart [5], MDIT at the RMIT Sydney [6] and the MS_DT at Taubman College [7]. Countless structures and pavilions using innovative technologies have been created through various fabrication labs and digital design institutes. Nevertheless, teaching initiatives often remain centred on important *singular* digital practitioners (Oxman 2008), and the strategies and concepts for a holistic incorporation of digital fabrication into the architectural curriculum are still rarely described in literature. This paper aims to give an overview on important historic interdisciplinary educational initiatives and current digital project development approaches and discusses an educational method featuring a highly collaborative environment of research and industry, an iterative teaching methodology of short, full-development cycles using digital fabrication (see figure 1) and an approach fostering self-organisation and self-learning of students. In the methods section, we present the general teaching method and describe two teaching initiatives regarding their organisation, concept, project tasks and interdisciplinary setting. In the results section, we analyse physical outcomes, teaching accomplishments, efficiency and integration into current research. In the conclusion section, we compare the two education programmes in terms of resources and resulting conceptual adaptions, discuss the study environment in relation to research and industry integration and conclude by showing possible future initiatives.

### *Interdisciplinary education, learning by making and digital project development*

Even before digital technology existed, teaching at Bauhaus (Moholy-Nagy 2012) gives valuable insights on how arts, crafts, materials and fabrication methods could be placed as a basis for architectural education. Later, Frei Otto created experimental laboratories in which students and researchers from different disciplines were able to study and analyse structures using physical models and prototypes (Otto 1984), allowing new forms of social interaction. Since software and machines are likely to change rapidly over time, researchers discuss the applicability of teaching digital methods in practice in the future (Garber and Jabi 2006), also in combination with a project-based approach to technology (Bechtold 2007). The *Maker* movement (Dougherty 2012) has extended tremendous influence in education (Halverson and Sheridan 2014) and even industry (Ramsauer and Freissnig 2016). This concept of *"Learning by Making"* or also *Constructionism* (Papert and Harel 1991) has been further developed through the combination with digital technology (Blikstein 2013).

Figure 1
Students working with robots during fabrication of case-study project of the MAS Digital Fabrication at ETH Zurich

Novel innovative teaching formats and work organisation strategies can also be found in related professions and research institutes: Students at the product development group at ETH Zurich are provided with standard mechatronics kits and access to rapid prototyping to allow complete product design cycles (Heinis et al. 2015). In software development firms, the traditional task of the "Software Architect", who draws up a detailed structure of programme classes and their functions, is being increasingly replaced by a method called "Scrum" which favours self-organized teamwork instead of rigid organisational structures (Beedle et al. 2000). Realizing that all requirements cannot be specified up-front and context and environment evolve during development time, this method employs short development cycles without predefined working processes. Studies highlight that digital technologies can be more efficiently taught using a *"conducting"* rather than *"instructing"* teaching method (Sawn et al. 2000). Recognizing the importance of interdisciplinary social interaction on innovation, technology firms make large investments in working environments that encourage new encounters and exchange of ideas [8].

## METHODS

In this section, we introduce our teaching methodology and describe two examples of teaching initiatives. Our strategy was to place digital development of large-scale prototypes with real construction materials at the centre of the educational programmes. This provided us with the means to rapidly evaluate not only the spatial and architectural qualities of projects, but also to analyse the functionality including material, fabrication and joining constraints. The digital development was undertaken in short-term iterative development cycles (see figure 2). During each cycle a full project development including 3d models, digitally fabricated prototypes, structural concept, renderings, analytical sections, plans and diagrams had to be delivered. After each cycle, problems were meticulously analysed and new solutions, constraints and more detailed requirements and analyses were integrated in following iteration cycles. Considering the vast variety of materials, their processing and joining possibilities and the limited amount of time available in our education programmes, we focussed on teaching a method of how to acquire basic knowledge of material properties and directly explore digital processing, joining and spatial possibilities. Instead of a traditional teacher-centred approach, we promoted a moderated self-learning process. Students worked in teams which provided the possibility to self-organise and adapt throughout the course of the programmes. For both programmes, which we conducted at TU Munich (academic year 2012/2013) and ETH Zurich (academic year 2015/2016), we created a study environment which allowed students to have multiple ways of interdisciplinary social interaction. This was enabled by a series of common events, lectures, meetings and discussion rounds with researchers, collaborating professors and industry partners.

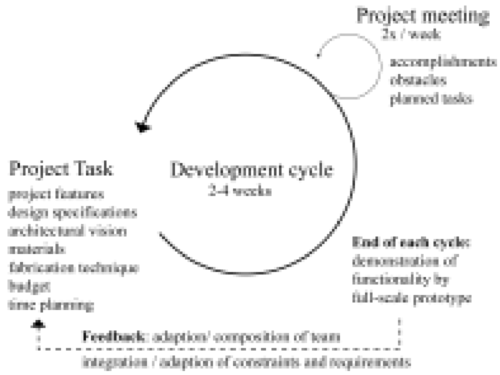


Figure 2
Iterative full development cycles of digital design and fabrication of large-scale prototypes, 3-4 cycles /semester

### *TUM studio einszueins*

**Organisation.** Studio einszueins was established through the guest professorship programme of the architecture faculty of TU Munich. The programme was organised by Philipp Eversmann in collaboration with Philipp Molter at the chair of Architectural Design and Building Envelopes of Prof. Tina Wolf. Studio einszueins was integrated in the Master of Science programme of TUM, and was attended by 26 architecture students. The programme was organised as a design studio in two consecutive semesters, which was necessary in order to fit in the Master's curriculum. Most of the students continued throughout the whole year, which helped to establish a continuous design process. We advised skills in 3d-modelling to enter the studio, but no prior knowledge in programming or digital fabrication was required.

**Concept.** We defined the development and realisation of large-scale prototypes as a central part of the programme. Through this fabrication-integrated design process, the students could deal with a variety of processes between design and execution. In the course of the studio, we investigated various project organisation and development methodologies through digital means questioning existing design, planning and realisation paradigms. The students had to bear the responsibility for a planning process that dealt not only with the architectural aspects of a building, but also included financial and scheduling constraints as well as feedback between multiple project partners. We focussed on investigating digital fabrication processes through the development of new material applications and manipulation of production facilities. Through the integration of various industry partners, collaborating chairs and a client into our teaching activities, we created a social network in which a variety of interdisciplinary encounters were enabled (see figure 3).

**Design Project Development.** The students' task was to create envelopes and structures for exhibition pavilions using digital fabrication processes. Even though the material choice was unrestricted, students had to verify feasibility with digital fabrication equipment. Through a competitive process, schemes for four different projects were developed in the first semester. Already at this stage, each team had produced multiple prototypes with the envisioned material, digital processing and assembly technology (see figure 4). The final realisation of the projects was made highly dependent on the students' initiative, which was further enhanced through their direct contact to clients and collaborating firms.

**Industry Collaborations.** In order to allow knowledge transfer and experimentation with advanced fabrication technology a number of collaborations with local facade and material production companies were directly integrated in the programme. This enabled a range of external teaching activities and even an outsourcing of parts of the manufacturing processes. This allowed students to gain insights into the latest facade and structural design and fabrication technology as well as to develop their designs directly with technical inputs from renowned experts in the field. We organised a series of meetings, presentations and project discussions corresponding to our development cycles throughout the year in order to foster a continuous interdisciplinary exchange.

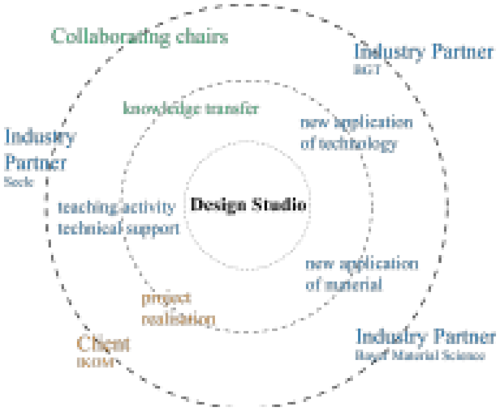


Figure 3
Teaching network of studio einszueins: a multitude of interaction possibilities with collaborating chairs, industry partners and clients

Figure 4
Prototype for the project "STITCH", a double-layer curved-folded aluminium structure

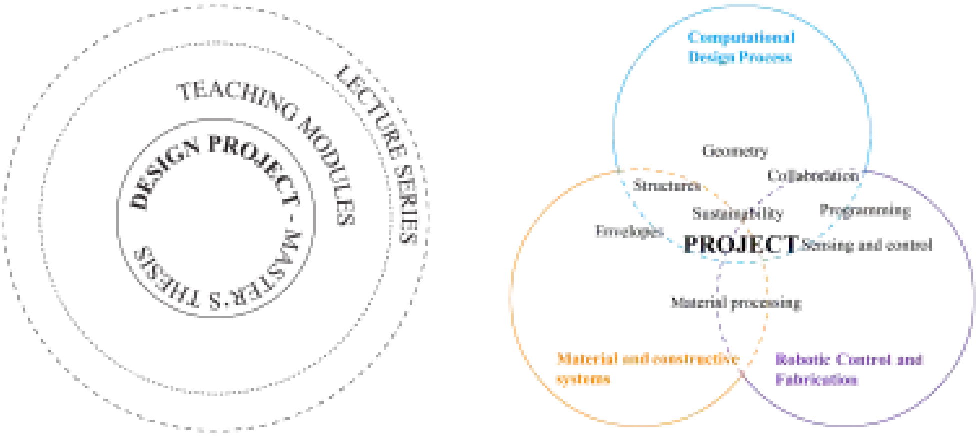


Figure 5
Left: Organisation of modules and design projects
Right: Study areas and teaching modules

### *MAS ETH Digital Fabrication*

**Organisation.** The Master of Advanced Studies MAS in Digital Fabrication programme was organised as the central part of the teaching platform of the National Center of Competence in Research NCCR Digital Fabrication at ETH Zurich. It was hosted by the chair Gramazio Kohler Research in collaboration with the BLOCK research Group, the chair for sustainable construction and the ADRL Robotics Lab. The programme was organised by Philipp Eversmann (NCCR Head of Education), and Luka Piskorec. We selected 17 students with Master's and/or Bachelor's degrees in Architecture, Design and Engineering for the first class. The programme was conceived as a postgraduate programme for students who want to specialise in the field of digital fabrication. Prior knowledge in programming and digital fabrication was required and evaluated to enter the course.

**Concept.** The MAS was structured as a central design studio which was surrounded by a series of teaching modules. Necessary interdisciplinary knowledge as informatic programming, geometry, automatic sensing, robotic control, digital collaboration techniques, material processing and structural analysis was provided by the teaching modules, while hands-on experience with design and fabrication was practiced in the studio. The teaching modules clustered around three main study areas: (1) Computational Design, (2) Material and Constructive Systems and (3) Robotic Control and Fabrication (see figure 5). Teaching modules would typically last between one to four weeks, with the exception of the programming module, which was conducted throughout the whole year. The modules were organised as pieces of knowledge inputs provided by collaborating chairs, PhD-students and external guests relating to current design work. These inputs were deliberately not conceived as complete entities of a topic, but as basic nodes allowing the students to reach out to a range of resources for further self-study. Furthermore, we used the interdisciplinary network of the NCCR Digital Fabrication to create a dense social environment for the MAS students, researchers and professors through the organisation of a series of common activities, lectures and meetings.

**Design Project Development.** The students' task was to design a double-story structure with a basic envelope as a minimal house using spatial robotic fabrication processes for timber construction. From the beginning, complete development cycles of computational design-work up to full-scale robotically fabricated prototypes were effectuated. This allowed us to iteratively evaluate architectural as well as functional, material and constructive features for each cycle (see figure 6). In order to find a better ratio of design development and time for fabrication with the robots, and allow multiple design investigations, teams chose to regroup and adapt multiple times. Even though students were initially provided with a set of exercises of analytical and design work, the subsequent development strategy was developed and implemented together with the student team according to the current state of development, problems and external constraints. Through a lecture series, international guests were invited to not only give a presentation to an open audience at ETH, but also spend a day working with the students on their projects. This allowed the students to hear about valuable external views and to receive feedback on their design-work in the process.

**Research Collaborations.** We established the design and fabrication task of the design studio in direct connection to ongoing and future research. Already in preparation of the MAS, we conducted a collaborative research project on topological optimization of robotically assembled timber structures together with guest researchers from Aarhus University and Israel Institute of Technology (Soondergard et al. 2016). The development of our robotic fabrication process directly built on research of the NRP66 project "Additive Robotic Fabrication of Complex Timber Structures" (Zock et al. 2014). Furthermore, the development of the topic of spatially fabricated housing units provided a conceptual basis for the ITA-PhD research project "Architecture of Bespoke Modular Prefabrication". Additionally, we encouraged NCCR PhD-students to provide mentorship to the students. This enabled MAS students to get in-depth understanding of research projects through helping doctoral students with demonstrator setups in exchange for technical counselling on their design projects. We also allowed students to pursue an independent research master's thesis as well as realising a large-scale fabrication project. Furthermore, we were able to establish multiple industry collaborations for the realisation of the robotic setup and the final case-study project.

Figure 6
Multiple geometric configurations for the robotic assembly of timber structures: a double-layer reciprocal structure, discrete triangulations, spatial truss (used in the final project)

## RESULTS
### *Physical Results*
At TU Munich, we realised four large-scale prototypes in structural glass, aluminium, timber and polycarbonate. The projects were funded by collaborating firms and the organizers of the IKOM industry fair [9], who commissioned a demountable exhibition stand (see figure 9). Additionally, the projects were featured in two separate exhibitions at the Vorhoelzer Forum and the Bavarian Chamber of Architects in Munich [10] (see figure 10). At ETH Zurich, we were able to realize a robotically assembled double-story timber structure (see figure 8), which was used for the opening reception of the AAG conference in 2016 [11]. We are currently planning to present the structure again at the Zurich Design Biennale 2017 [12].

Figure 7
Left: Exterior view of the final case-study project, MAS Digital Fabrication, ETH Zurich Right: Interior view of the upper floor, image courtesy of Kasia Jackowska

### *Teaching accomplishments*

In both teaching initiatives, participants successfully developed their projects through multiple design cycles incorporating material studies, design development, digital fabrication processes and design validation through full-scale prototypes. Classes did not focus on specific software, but instead employed general digital design methods through visual programming or object-oriented programming in Python. Through the task of building large-scale projects, the students were confronted with a range of other topics such as material and structural analysis, management and organization, kinematics, simulation, digital sensing and robotic control. Each student was able to independently solve complex design tasks, and program digital fabrication tools as well as robotic arms accordingly. Furthermore, at TU Munich, diverse project development methodologies could be investigated in relation to digitization and automation. Students had the chance to act and perform as a “digital general contractor” (stand for the IKOM fair, see figure 8) to cooperate with external companies (“TWIST” - Lampart, Hundegger , “VITRINE” - Seele, BGT, see figure 9) and to conduct independent research projects (“STITCH”, see figure 4). Both teaching activities were showcased in documentary films [13, 14].

### *Teaching Efficency*

While a similar teaching methodology was used in both education programmes, the project size and complexity of digital fabrication equipment was different. At TUM, teams of 2-4 students worked on multiple projects with CNC-equipment, such as laser cut-

Figure 8
exhibition stand, commissioned by the IKOM fair, Munich, image courtesy of Philipp Molter

Figure 9
Left: View of projects “Stitch”, “Twist” and “Vitrine”, exhibition at Vorhoelzer Forum
Right: View of Project: “Twist”, exhibition at Bavarian Chamber of Architects, Munich, image courtesy of Philipp Molter

ters, 5-axis mills and cutting plotters; at ETH, a team of 8 students worked on a single project using robotic technology. This difference in team size and digital tools had a large impact on team organization, collaboration techniques, teaching focus, student evaluation, and intensity of teacher interaction. Digital workflows in larger projects and therefore large teams require a precise definition of responsibilities and protocols for each student. In comparison to a smaller team size, this can demand a greater intensity of participation of instructors until resulting work becomes efficient. More complex digital fabrication tools like robots also demand much more work in their initial setup in comparison to CNC-machines whose processes are already defined. The iterative self-learning process of defining tasks, protocols and also fabrication processes proved to be a valuable part of education for the students. The social interaction and learning with and from multiple team members can be an extremely efficient study method.

### *Research Integration*

We established multiple collaborations with ongoing scientific research in both teaching initiatives. At TUM, the authors’ research of on curved-folding techniques for multi-panel shells could be continued through the development of a double-layer curved-folded structure (see figure 4) (Eversmann et al. in press). Similarly, research on the application of structural glass in computational architectural designs (Eversmann et al. 2015) was further progressed through a glass structure with joints that, too, were made out of glass. At ETH, results were published in online magazines [15] and multiple research papers are currently awaiting publication in peer-reviewed journals and conferences. The robotic setup, which was developed by the authors, featuring a fully integrated CNC-Saw, could be further integrated in a CTI-research project undertaken under cooperation with Swiss construction company ERNE.

## CONCLUSION

Moderated self- learning can provide students with a method allowing continuous learning of digital fabrication technologies in architecture even beyond the educational programme. The realisation of large-scale prototypes through interdisciplinary networks with research and industry allow students and researchers to benefit through a variety of social encounters, enable interdisciplinary exchange and foster collaborative working. These interdisciplinary networks can be created on multiple levels, depending on the local opportunity to integrate the schools’ chairs and infrastructure, research and industry partnerships. The two examples of teaching initiatives show that a local difference in available fabrication equipment, material budget and integration in the school’s curriculum can be actively integrated in the teaching strategy: While integration with research and interdisciplinary exchange was highly encouraged by the nature of the NCCR Digital Fabrication and its funding principles and state of the art robotic fabrication equipment was made available, at TU Munich the studio profited immensely by collaborating with a cluster of local high-tech facade and material processing companies. Therefore, instructors need to carefully evaluate and weigh available infrastructure and the possibility for external partnerships.

### *Integration of Research and Industry*

The integration of research and education can have a very positive impact on both sides. Researchers can realise demonstrators together with students at a much larger scale and higher level of detail. Students respectively profit from gaining insights in latest technology and can prepare for future doctoral studies. Furthermore, through the open and investigative approach and resulting work, new ideas can be generated for future research. The realisation of prototypes in educational programmes also allows partners to collaborate on a short-term project before engaging in longer-term research relationships. Teaching collaborations with industry and practice necessitate long-term planning coupled with short-term availability, which can make them very challenging to integrate in educational programmes. Once established, they can create a potent interchange for both the educational institution as well as the industrial partner. In return for their technical and material support, companies can profit from the high visibility that large-scale case-study projects can attract. In addition, novel applications of company-specific materials and fabrication equipment can be realised.

### *Future Initatives*

Current teaching programmes in digital fabrication still remain far from being conceptually completely integrated in the architectural curriculum. New initiatives could focus on integrating computational design and fabrication techniques already in the very beginning of architectural studies. Instead of pursuing an educational concept of specialisation on digital technologies, a novel and holistic approach to architectural education could allow a new generation of architects to conceive and develop computation and fabrication at the core of architectural production. Even though the teaching of higher level digital design concepts and advanced robotics might not yet be directly applicable in architectural construction, it provides students with a method and broad basis from which they can easily learn and apply specific digital tools and software in a future of rapidly progressing technology. New experimental education approaches similar to those used in product development and informatic programming can provide a framework and experimental breeding ground for new ideas and studies. Instead of passively reacting to upcoming industrial changes, a holistic approach to digital fabrication in education can provide architects with the means to shape and create ways in which these technologies can be used in the future of construction.

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# Adaptive Lighting for Knowledge Work Environments

## *A Pilot Design*

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*Adaptive lighting technologies and control of lighting by users provide new possibilities for lighting design in the context of knowledge work environments. In our research project, we study innovation supporting knowledge work environments and their features, such as lighting. In this paper, we present and reflect the design of a pilot intervention, where the use of adaptive lighting was tested. We discuss how different forms of data and knowledge can be applied as a rationale for adaptive lighting behaviour which as an ambient feature in office environment supports knowledge workers` well-being and supports different working situations. In addition, we present the data-based evaluation methods with which we could gain feedback from users' experiences and their way of using the lighting and the pilot office environment. The potential of this kind of real-world data for future design processes is discussed.*

**Keywords:** *knowledge work environment, adaptive lighting, dynamic lighting, user-controlled lighting, lighting design*

## INTRODUCTION

Adaptive lighting is defined as a wide concept referring to lighting, which adapts to information about environment and its users or to other information relevant to intended lighting behaviour. This information can be, for example, sensor-based data, or the information can be obtained from different databases, such as meteorological data. On the other hand, the control of lighting behaviour can be based on some idealized natural process, such as the model of daylight's temporal changes of intensity and spectral characteristics, which support human biological rhythms and is, thus, employed in biodynamic lighting. Additionally, one approach to adaptive lighting is direct or indirect control of lighting by users of environments. The essential common features in all the cases described above are, firstly, that lighting is not static but an altering element of environments, and, secondly, the designer has defined the light's behaviour to follow some reference information, knowledge or logic. (Pihlajaniemi 2016) In this paper, we present a case study concerning the use of adaptive lighting in knowledge work environments. We describe a temporary pilot intervention in a real world office environment and reflect the design, which applies different forms of information and knowledge as a base for adaptive lighting behaviour.

Contemporary knowledge work environments are designed to support multiple work situations, which range from individual concentration intense work to collaborative knowledge creation situations (Wohlers and Hertel 2017). Knowledge work occurs through mental processes and varies from mundane tasks, such as storing and retrieving information, to high-level cognitive tasks, for example, designing, developing and creating new products (Heerwagen et al. 2004). In today's knowledge work organizations, collaboration is highly valued. Therefore, new offices are often designed as multi-space offices (Boutellier et al. 2008) or activity-based offices (Appel-Meulenbroek et al. 2011). Both of these office types aim to provide spaces that support both individual, concentration intense working and spaces that support collaboration and teamwork. Shared workstations and work areas enable more efficient use of space, but may also increase distraction and decrease the sense of comfort (Wohlers and Hertel 2017).

Knowledge work environments have several ambient features, such as lighting, temperature and noise. In combination with office layout, ergonomics and organizational factors, the ambient features have remarkable influence on knowledge workers' work performance and satisfaction of their environment, and importantly, on occupants' well-being and health. Functional and comfortable workspaces support users' task performance, whereas uncomfortable design leads to users' stress when they need to expend their energy on overcoming environmental impediments to perform their tasks, for example, when lighting is insufficient or too bright. (De Korte et al. 2015, Vischer and Wifi 2017). Numerous studies have assessed the influence of lighting on knowledge workers. One of the published studies of user-controlled lighting in real office environment (Moore et al. 2003) revealed nearly tenfold differences in individual preferences for lighting when individual work plane illuminance was measured during a long-term study. The preferred work plane illuminance levels ranged from 91 lx to 770 lx, with average of 288 lx (Moore et al. 2003). Results from mock-office studies and laboratory experiments have revealed even larger scale of individual preferences (Newsham et al. 2004). These results implicate that fixed illuminance levels do not optimally support all individuals' preferences and needs in shared spaces.

Subsequent studies, such as Veitch et al. (2013), have linked lighting appraisal to increased workplace satisfaction and work engagement. Daylight is typically perceived as a positive factor in the knowledge work environments. It is dynamic by its nature, it changes intensity, color temperature and direction throughout the day. (Leslie 2003). The positive effects of dynamic changes in color temperature and intensity (Van Bommel and Van den Beld 2004) can be applied into knowledge work environments with luminaires and lighting control systems. This is particularly important in knowledge work environments where amount of daylight is insufficient. Furthermore, the color temperature of polychromatic white light has been shown to affect alertness levels. Higher correlated color temperature (CCT) levels, such as 4000 K and above, promote alertness by affecting the circadian rhythm (Kraneburg 2017). Also, shorter periods of brighter and cooler light positively affect alertness, work memory and performance (Smolders et al. 2012, Huiberts et al. 2016). The level of satisfaction can be elevated through user-controlled personal lighting (Veitch et al. 2013). Although technology is unlikely ever to be able to simulate natural daylight and its properties completely, today's lighting technology is, however, able to display dynamic lighting changes in terms of illuminance levels and color temperature of white light. Dynamic changes can be applied to knowledge work environments by pre-programming dynamic light scenes or, alternatively, by giving users a choice to adjust their personal lighting through different control methods, such as lighting control applications that are installed in their personal smartphones.

The aim of our research project InnoStaVa is to study and develop knowledge work environments in startup-companies in the Oulu region in order to support their innovation. Our object is to gain deeper understanding of the connection between space, innovation and collaborative knowledge creation processes. The aim of this specific paper is to present and reflect the design of one pilot intervention, where the use of adaptive lighting was tested. We discuss how different forms of data and knowledge can be applied as a rationale for adaptive lighting behaviour which as an ambient feature in office environment supports knowledge workers' well-being and supports different working situations. In addition, we present the data-based evaluation methods with which we could gain feedback from users' experiences and their way of using the lighting and the pilot office environment. The potential of this kind of real-world data for future design processes is discussed.

## METHODS OF RESEARCH

This research was carried out in a real world environment as part of our ongoing case study. The complete setup of this case study was to study innovation supporting knowledge work environment in a local startup company. In addition to lighting, other central elements of knowledge work environment were researched. These included spatial layout of office, acoustic elements and collaboration supporting elements. The research followed a four-phase process: *observation - design - intervention - evaluation*. The outline of the study has been described in more detail elsewhere (Markkanen 2017). The pilot study was divided to two phases: First, dynamic lighting was programmed and users had no control over lighting control. Second, dynamic lighting was programmed and users were able to control illuminance level, color temperature of light and dynamic changes of lighting using an application in smartphones.

### *Pilot environment and context of research*

During the intervention phase, a complete redesign and implementation was constructed in the premises of the participating startup company. The research area comprises of a two-room office of 65 m2. The office was occupied by 10 participants, including the co-founders of the company and employees, during the study. As an outcome of observation and design phases, the two-room office was redesigned into two teamwork areas and a brainstorming area during the intervention phase of the study. It should be noted that participants of the study preferred assigned workstations and that they also perform their individual tasks in the teamwork areas. The workstations were organized into groups to support short communication events and a brainstorming area was separated from another office room to support longer collaborative knowledge creation events.

The office space is in an attic of a wooden building constructed in 1900, thus the windows in the research area were very small and in comparison to contemporary office buildings, this severely limits the levels of natural daylight in the research area. Furthermore, the startup company is in Northern Finland, thus the length of day varies greatly throughout the year, from less than 4 hours to over 22 hours. The research was completed during the calendar weeks of 7 to 18, during which time the daylight increased from 8 hours to nearly 18 hours.

### *Lighting design and lighting control*

Lighting in the research area was studied and designed with 3D modelling and rendering software 3ds Max. LED luminaires with digital addressable lighting interface (DALI) control and colour temperature control were used used in this study (Fagerhult). The dynamic lighting was programmed using programmable DALI lighting system DIGIDIM (Helvar). The control of lighting was constructed using two different methods. Due to the temporary nature of the pilot intervention, no physical lighting control was installed to the research area. First, the lighting was turned on using passive infrared (PIR) motion detectors, which were installed to ceiling-mounted acoustic boards. Lighting was programmed to turn off after 30 mins of inactivity of motion detectors. Second, the individual luminaires or groups of luminaires were controlled using SceneSet smartphone application (Helvar). During the first phase of the pilot (pilot weeks 1 to 5) users had no control over lighting. During the second phase of the pilot (pilot weeks 6 to 12) users were able to control the lighting with SceneSet smartphone application (Helvar).

### *Data gathering methods for user-generated knowledge of work environments lighting*

Understanding the individuals' and organizations' daily routines provides designers important information when and where different light-generated atmospheres should be used with dynamic changes of light intensity and color temperature. During observation phase we gathered knowledge on users' daily situation through interviews and a participatory design workshop. We will outline different ways to collect data on user experiences of dynamic lighting and personal lighting control in this paper. Results of evaluation will be discussed elsewhere (Markkanen and Pihlajaniemi, unpublished results). We used following methods in our research to evaluate participants' experiences of piloted dynamic lighting and the use of personal control of lighting: evaluation probes (Luusua et al. 2015), workshop, experience sampling method (ESM) (Hektner et al. 2007; van Berkel et al. 2016) and data collection of lighting control through DIGIDIM lighting control system (Helvar).

## RESULTING DESIGN FOR ADAPTIVE LIGHTING BASED ON KNOWLEDGE

Our lighting pilot research was part of a larger case study in which the layout of the studied knowledge work environment was redesigned and piloted.

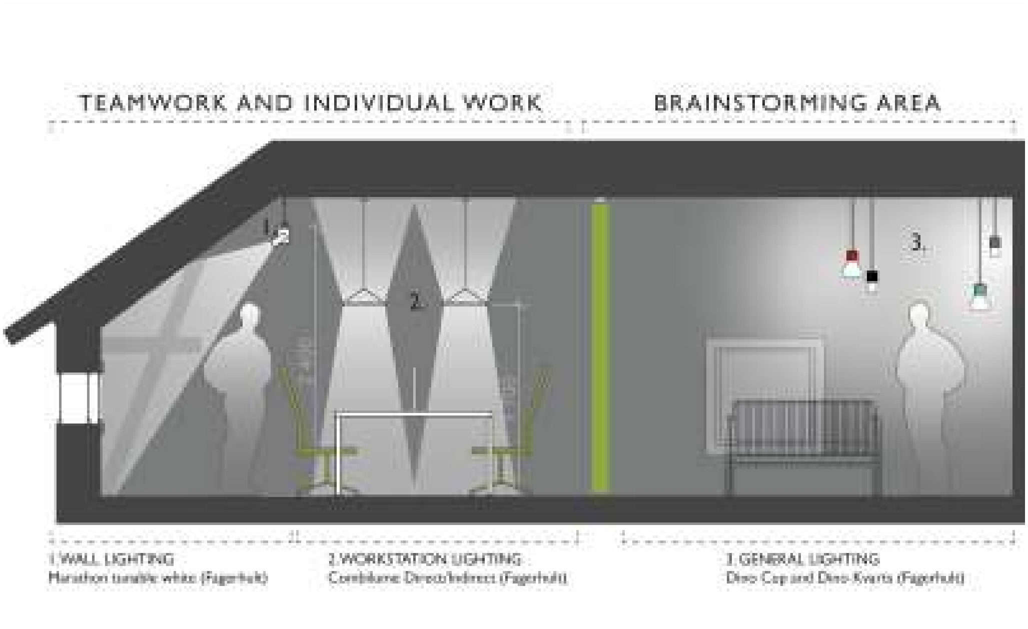



Figure 1
Schematic presentation of lighting design for the pilot study.

Figure 2
Dynamic changes of artificial lighting can be applied to knowledge work environment


Therefore, we were able to build genuinely user-controllable lighting on a personal level. As the layout of office and lighting were designed simultaneous, each workstation was designed with an individually controllable luminaire. Furthermore, we chose LED luminaires with DALI control and colour temperature control properties to enable dynamic lighting setup in the research area.

Lighting in the research area was studied and designed with 3D modelling and rendering software 3ds Max. During the design process of adaptive lighting behaviour the following aspects were considered:

1. Circadian rhythm - dynamic changes in illumination levels and colour temperature of daylight
2. Adaptivity on organizational level - programmed lighting supports daily routines
3. Adaptivity on individual level - daily routines and personal user-control of lighting

The outcome of the lighting design is described in Figure 1 and it consists of three main features: workstation lighting (1) and wall lighting (2) in teamwork and individual work areas and general lighting (3) in brainstorming area.

## *Dynamic lighting supports organization's daily activities*

Understanding the organizational routines of a typical workday can be used to enhance the lighting design to support knowledge workers' well-being and productivity. Organizational routines may include daily meetings, breaks and other designated periods of activity, such as brainstorming sessions. These routines can be supported programming changes of light intensity or color temperature with varying length. For example, during daily morning meetings, the alerting effects of bright and cool light can be implemented during pre-defined times through programmed pulses (e.g. 30 mins) of light with dynamic increase of illuminance and change of color temperature of light. On the other hand, to support creativity and innovation during brainstorming session, it has been shown that dim illumination supports exploration and creative processes better than bright light (Steidle and Werth 2013). These situations can be supported through programmed situations, which users can activate through lighting control system. In this case study, we implemented brief pulses of high illuminance with cool color temperature in pre-programmed dynamic workstation lighting during morning and afternoon periods. The combination of daylight simulation changes and organizational routine supporting changes were programmed using programmable DALI lighting system DIGIDIM (Helvar) and the designed lighting was implemented to research area during pilot weeks 1 to 12.

### *Individual control of lighting enables personal lighting*

At the end of week 5, we explained participants about the dynamic changes in color temperature of light and in illuminance levels, which were used in pre-programmed lighting. They were also instructed how to use SceneSet application installed in their smartphones to control lighting during the following weeks of pilot (pilot weeks 6 to 12). The application contained both pre-programmed changes and manual lighting control. Participants were able to override the programmed dynamic lighting by applying static lighting settings to teamwork and brainstorming areas. The lighting control was divided as follows:

**Personal workstation lighting.** Personal preferences for lighting in work environment have been shown to differ greatly in terms of illuminance level and color temperature (Moore et al. 2003). In our pilot study, participants were able to control their workstation lighting individually. The pre-programmed options included static lighting scenes if 250 lx, 500lx and 1000 lx with color temperatures of 3000 K, 4000 K and 5000 K, respectively. In addition, there were a dynamic lighting scene of pulse of high illuminance with cool color temperature for one hour. Furthermore, there was a possibility to set manually both illuminance level and color temperature.

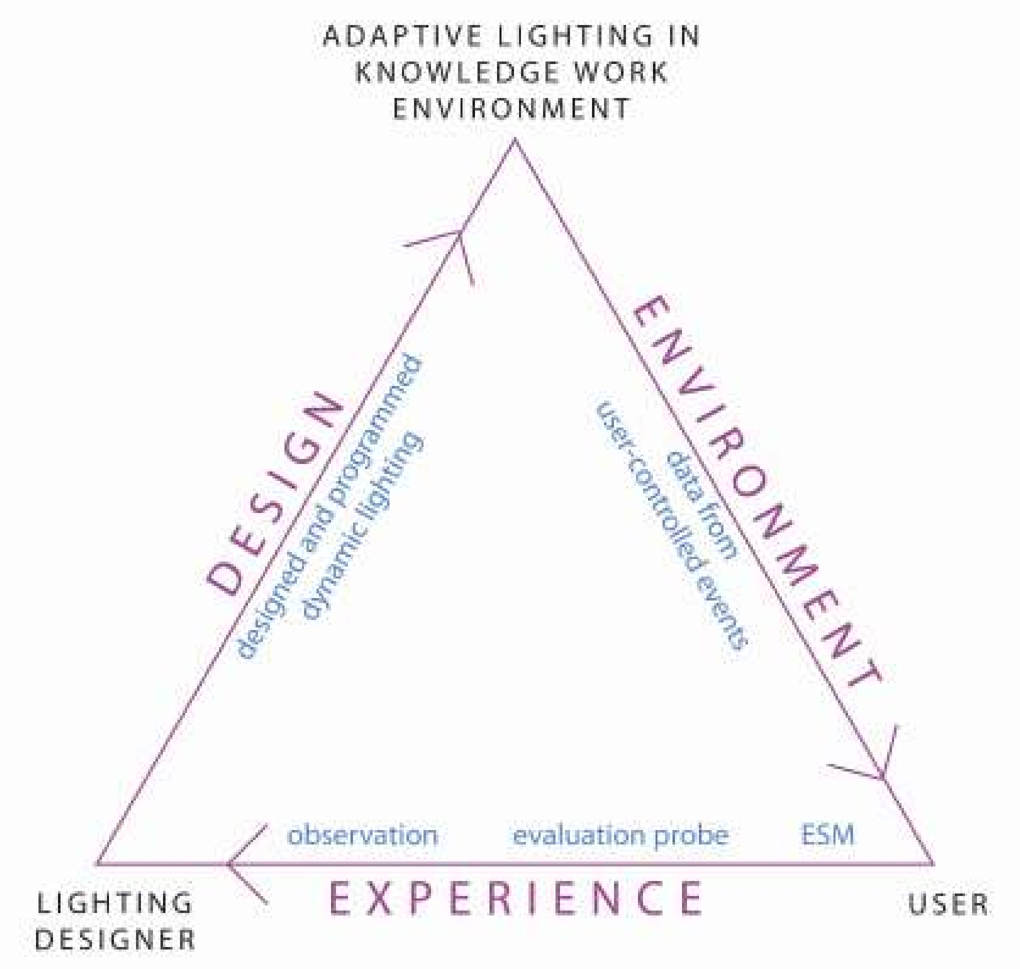
**Wall lighting in teamwork area.** The wall lighting and workstation lighting function together to create the office lighting. Wall luminance has been shown to effect on workplane illuminance level preferences (Chraibi et al. 2017). Wall illuminance has more impact on the atmosphere when compared to illuminance at workstations. In this study, participants were able to control the group of spot luminaires creating wall lighting in similar fashion as their workstation lighting. In addition, a pulse of high illuminance with cool color temperature was implemented in wall lighting options during the second phase of pilot.

**General lighting in brainstorming area.** The luminaires in brainstorming area had fixed color temperature of 3000 K or 4000 K. Participants were able to adjust the lighting in brainstorming area from pre-programmed option of 3000 K luminaires only, 4000 K luminaires only, or both group of luminaires, resulting in three different atmospheres in space. This enabled participants to find the suitable atmosphere for group activities and individual working in the brainstorming area.

### *Data collection methods for evaluation and improved lighting design*

To understand the effect of lighting for participants of the study and their experience of light and personal lighting control, we collected data through evaluation probes and workshops, ESM and direct data from light control situation through a gateway tool that accesses the DIGIDIM lighting control system. The results of pilot evaluation will be published elsewhere (Markkanen and Pihlajaniemi et al. 2017, unpublished results). In this pilot, we used evaluation probes to collect data during the intervention. At the end of pilot, we also organized a workshop to discuss with participants their experiences of pilot, including dynamic lighting and user-control of lighting. These methods generated rich qualitative data on participants' experiences of piloted adaptive lighting. Gained knowledge is beneficial in developing lighting design in forthcoming knowledge work environment pilots. Importantly, such qualita-

Figure 3
User-centric approach to design adaptive lighting in knowledge work environment




tive research methods often generate design inspiration from the users of the environment and point out events and experiences designers and researchers may not be aware of.

In this pilot, we also applied ESM method (Visuri and van Berkel et al. unpublished results) to study the users' motives to control the lighting. This was organized by giving participants smartphones with application that opened a short query every time participants used SceneSet application to control the lighting. Furthermore, we also used a gateway tool developed by Helvar to collect data of each individual lighting control event applied by the participants of the study from DIGIDIM lighting control system.

## DISCUSSION AND CONCLUSIONS

When lighting design of knowledge work environment is based on standard recommendations, it relies on knowledge that has not been adapted to the specific needs of users and the restrictions the architecture or the environment provides. The lighting technologies that enable adaptive lighting are still relatively novel and not yet commonly used. Occupancy based lighting control and daylight sensors are considered import energy saving options. However, creating atmospheres that support different tasks and situations in knowledge work environments should be also considered important, as they promote users well-being and comfort. Contemporary knowledge work environments promote collaboration and shared desk policies. Noise and lack of assigned desk have been shown to decrease users' satisfaction towards their environment (Wohlers and Hertel 2017). Adaptive user-controlled lighting provides knowledge workers an opportunity to control their own surroundings, which has positive effects on mood, well-being and productivity and increases users' satisfaction to their environment (Veitch et al. 2013).

In this paper, we present an user-centric approach to design adaptive lighting in knowledge work environment, which combines design and evaluation of implemented lighting design. The used evaluation methods facilitate iterative lighting design process that enables genuine user-centric design by means of gaining knowledge of users' experiences and motives to adapt lighting to their desired needs. Our approach is presented in Figure 3.

The daily situations of researched case organization were determined using qualitative research methods and taken into account when designing lighting for implemented pilot intervention. Three levels of adaptive lighting were considered in the lighting design process: First, the positive features of natural daylight were implemented in dynamic lighting design of piloted work environment. These included dynamic change of illuminance levels and color temperature. Implementing positive qualities of daylight in interior is specifically important for environments where natural daylight is scarce and during months, when the length of day is short. Second, organization's daily activities were analyzed and alertness promoting brief light pulses were implemented to dynamic lighting design for workstation lighting in teamwork area. Third, participants were able to control the lighting of shared environment and their assigned workstations in the second phase of the pilot study. In addition to enhanced user satisfaction to their environment (Veitch et al 2013), the user-control of lighting provides means to collect data on the lighting situations generated by the users. Furthermore, we applied ESM method to make inquiries on participants' motives to apply changes to dynamic lighting.

The design and evaluation set-up presented here provides tools for lighting designers that enable reaction to users changing needs and preferences. The presented pilot case system gives user control of their work environment and also creative means to explore and test how lighting can support their daily situations. Importantly, evaluative methods serve as communication tools between the users and designer. Both ESM data and lighting control event data are available through remote online access for designers and researchers. In future systems, online access to such a system would enable modifications to lighting design. Lighting designer is able to make changes into previously programmed dynamic lighting and pre-defined user-controllable lighting situations. In addition, based on gained knowledge and user-controlled situations, the designer would be able to create new dynamic lighting situations. Learning from our pilot, the critical point in system described above, is the users' readiness to use the system and to actively modify the lighting to support different daily situations. New research and development of easy to use and intuitive user interfaces are deemed necessary.

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# Learning by Merging 3D Modeling for CAAD with the Interactive Applications

## *Bearing walls, Vaults, Domes as Case study*

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*The development and the innovation of tools, techniques and digital applications represent a challenge for those who are in charge of architectural education to keep up with this development. This is because these techniques provide potentials that are not available in the traditional method of teaching. This raises an important question: can these tools and techniques help to achieve the targeted outcomes of education? This research paper discusses how to integrate both digital 3D models, of CAAD, and interactive applications for the development of architectural education curriculum. To test this, a case study has been conducted on the subject of building construction, for the second year at the faculty of engineering, specifically, the bearing walls construction system. In addition, this study has been divided into three parts. Through the first part, the scientific content of the curriculum, which tackles the bearing walls, has been prepared. The second part shows how to convert the scientific content into an interactive content in which the students learn through the experiment and the simulation of the traditional construction methods as the students a acquire construction skills and the ability to imagine different structural complexities. The third part includes the creation of both the application and the software containing the interactive curriculum. Workshop for the students has been held as a case study to test the effectiveness of this development and to recognize the pros and cons. The results confirmed the importance of integrating this applications into architectural education.*

**Keywords:** *CAAD, 3D modeling , Building Construction, Interactive applications, Bearing walls systems*

## INTRODUCTION

Is there a need for the development of the current teaching methods, especially in the light of the development of CAAD programs and the availability of many sites and interactive educational applications? Is it possible that CAAD programs can be assisting programs in education and creativity? Moreover, what is the students' reaction towards the modern methods of education? What are their advantages and disadvantages? The research, in order to answer these questions, clarifies the importance of the development and the usage of CAAD programs in architectural education as traditional teaching methods depend on the second dimension and, in some cases, such as hand sketches, they show the third dimension. Whereas some CAAD programs depend on 3D, 4D, 5D, 6D, 7D (Czmoch & Pękala, 2014) which are very important dimensions in the study of the effectiveness and the efficiency of the design and constructive elements. However, the study will focus on 3D models, of many of CAAD programs, integrated with an interactive educational application. The research supposes that teaching through these programs and applications will complete what is missing in the traditional methods.

## METHODOLOGY

The research depends on three integrated approaches. The first approach is the inductive approach through which the previous studies, dealing with scientific experiments and applications, have been reviewed. These scientific experiments and applications have been conducted to use both 3D models of CAAD and interactive applications in architecture to benefit from their advantages and avoid its disadvantages.

The second approach is the practical approach. This approach completes what has been achieved by the inductive approach. It is divided into three sections. The first section will tackle the presentation of the scientific material, bearing walls systems, depending on the books of architecture history, which include the development of construction using this method. In addition, it depends on the books of architectural construction, which deal with the types, the methods and the materials of construction used in building bearing walls. This forms the database for both the course and interactive application. The objective of the database is that the students learn how to classify all structural elements according to their structural nature and to link them to their architectural function. Whereas the second section depends on the conversion of the prepared scientific content into an interactive content. This section depends on the methods of preparing the interactive materials and their organization to achieve the objectives and learning outcomes, which will be carried out in the third section. The third section includes the preparation of the interactive exercises through which the students learn, using 3D Models, previously prepared with CAAD. The students gain scientific and practical knowledge through trial and error and through providing the right solutions.

The third approach is the case study which will show the extent to which the students take the advantage of the development of the former Course referred to, as the study is related to the students at the faculty of engineering, the university of Al Azhar. The results have been analyzed through observation, questionnaire.

## BACKGROUND

Previous studies are divided into two sections: the first one tackles the usage of 3D models of CAAD in the development of curriculums. The second section tackles the usage of interactive applications as being tools, to develop professional practice, and educational tools.

### *firstly: the usage of 3D models of CAAD in the development of curriculums*

Many studies, which were conducted, tackled the development of curriculums, through 3D models of CAAD, according to their technical and informational development. The case study shows some of them, according to the ways of their usage, as follows:

A case study was conducted by professor Maia Engle, in cooperation with Professor Gerhard Schmitt, both of whom are from Swiss Federal Institute of Technology ETH, Zurich.They prepared an interactive approach, for many digital designs, through which they demonstrate the future of design through CAAD. The approach consisted of thirty-three innovative projects and it was divided into four main sections as follows: 1-Design in space and time. 2- Learning and Creative Collaboration. 3- Virtual Environments. 4- IT and design practice.

The idea of the approach depended on how CAAD can be a tool for innovation and creativity in design. It greatly focused on the interaction between the designer and the computer to achieve the aesthetic aspects. The approach was supported with 3D models and animation for each project so that students can learn, through the animation sequences, the ways of exterior and interior digital design, graphic design and Information technology. (Engeli, 2001)

Both Gianluca Cattoli and Simon Garagnani conducted another case study in Italy, at the University of Bologna. They trained the students to make models of many historical buildings, in the form of practical exercises with different levels. This was applied through scientific methodology which aimed at learning by practicing and participating. They divided the students into groups, each of whom was required to simulate a building of architectural and constructional value. At the end of the course, an evaluation of the students work was made. The result was that they all succeeded in learning the basics of designing and simulating many historical buildings (Garagnani & Gianluca, 2015).

Another study was carried out by both Zoja Veide and Veronika Strozheva, from Riga Technical University. They developed the course of construction calculation in the civil engineering department. They used visualization to help students understand the geometrical problems. In this course, they used programs of Archicad, Revit and CAD, associating the used models with augmented reality, which helped the students to gain experience through experiment and practice. The content of the subject was divided into four modules, one of which was to teach geometric modeling. The period of the course was 32 hours, ten of which had been allocated for practical exercises on the previously mentioned programs (Zoja Veide, 2015).

Zhigang Shen and Wayne Jensen, both of whom were from The Durham School of Architectural Engineering and Construction, the university of Nebraska-Lincoln, carried out another study. The two researchers taught students sustainability through BIM programs. They prepared an approach including both sustainability systems and the way of their application on the different types of buildings. Moreover, it included how to apply modeling of buildings, by BIM, and energy simulation, through the programs of energy calculation. It showed how to analyze the rates of its availability and the effectiveness of environmental treatments. The design course has been linked to the environmental control course in order that students could apply ideas and test their impact on the efficiency of their designs (Zhigang Shen, 2012) (P.E., 2014).

many case studies for the development of curriculums were conducted through parametric modeling. One of them was conducted by Joshue Vermillion and Antonieta Angulo. They prepared a new course depending on teaching the strategies of thinking through parametric design integrated with traditional curriculums, at the university of Ball. One of its advantages was that the students were able to associate the elements of the project in a unified model according to the different changes, i.e, material performance, sustainability and structure form. The students were able to evaluate their work with digital ways, through modeling methods, surface, solid, rendering and digital fabrication. The digital culture was reflected on their designs. (Angulo & Vermillion, 2012).

Analyzing the previous studies, we find that they clearly depended on 3D modeling and used it in architectural education in various ways according to different subjects. The experiments varied widely using digital media, animation augmented reality and other techniques which help to teach. The researcher considers that the usage of these techniques reflects their emergence during the period before which the interactive applications appear. The usage of the interactive applications is a trend that has spread in many educational branches and professional practice.

### *Secondly: Using interactive applications to develop professional practice*

In the context of the inductive approach, many interactive applications have been monitored and developed in many professional and educational aspects, including a study by The site, Arch daily www.archdaily.com, which is one of the specialized sites in the presentation of everything related to architectural engineering, such as projects, products and scientific articles. It showed the most important applications from which architects can benefit. These applications have various uses and objectives and five of which were chosen according to their advantages as follows:

1- Auto desk formit application helps architects and students to put the initial ideas of the conceptual masses to be developed easily. It provides multiplicity of tools that facilitate 3D modeling. In this purpose, the tablet devices and mobiles are used and drawing is made only by fingers.

2- Rhino 3D application is used to show ideas that have been implemented through the Rhino program for the parametric design. It has been designed for both architects and clients.

3- Graphsoft BIMX application is used to show the implemented projects by BIM programs to follow the development of designs with the ability to review and identify the clashes that occur in the construction site, through virtual reality. It has been designed for both site engineers and clients.

4- Magic plan application is used to take the dimensions of real spaces through the mobile camera turning them into 2D graphics and drawings in order to be exported later to the various drawing programs.

5- Sketchbook application enables designers to draw sketches on tablet devices anywhere, which many similar applications do. The applications simulate the same traditional methods of drawings. So, interactive applications can be considered as assisting tools for the designer. It is also a means to review and exchange ideas and to measure space dimensions. In addition to the previous applications, there are educational applications which target the undergraduate students. The researcher has monitored many of these applications which tackle many subjects, but he has focused on the applications which deal with both architectural construction of bearing walls and the history of architecture. By monitoring these applications and downloading them from the "google store", they are found to be non- interactive applications, i.e, they only display the scientific content in a simplified form, which resembles the same traditional methods, but the only difference is that they can be loaded on mobile phones and tablets. Therefore, the research seeks to design an interactive educational application as follows:

## INTERACTIVE APPLICATION

The researcher prepared an interactive application which is called "3D Arch Learning", after he had conducted tests and a questionnaire related to the students' awareness of the scientific content of architectural construction subject, of second year undergraduate students. It was found that the curriculum and the used teaching aids weren't sufficient. Depending on that, the idea of interactive applications appeared as a means through which different educational aids and methods can be combined in one place, and linked to each other with the possibility to measure the level of students according to the achievement of different learning outcomes.

### *what are the learning outcomes for which the application will be designed?*

The application is designed to achieve the learning outcomes according to the national academic standers (Abd Alwahab & Al baz, 2009). Learning outcomes are phrases that describe what the student should know and be able to perform and achieve by the end of studying a particular course or an educational program. Through the case study of the architectural construction subject of the second year, specifically the bearing wall system, it was found that the curriculum doesn't achieve the required learning outcomes, namely: cognitive domain, the affective domain and the psychomotor domain. It was found that the students drew the structural system according to what they learned. But by testing their ability to understand, compose, apply and analyze, they didn't meet these cognitive aspects, the matter that has been solved in the preparation of the application and the scientific material, which is to achieve the cognitive, affective, and psychomotor outcomes through the application.

## *the scientific material of the application*

The scientific content is divided into three sections: the theoretical section, the practical section and the interactive exercises, which are included in the application interface.

**firstly, the theoretical content.** The scientific content has been prepared according to many scientific classifications as follows: 1- The history of the development of the bearing walls system throughout the previous civilization. 2- The classification of the structural elements of the bearing walls according to their nature and their constructive function. 3- Realistic models of the most famous domes and vaults, throughout history, and their constructive analysis.The theoretical content targets the level of understanding related to the cognitive aspect. But this is one level of this aspect, so a section, which is the practical content, is added.

**secondly, the practical content.** It has been prepared to contain various educational videos containing: 1- Educational videos showing the ways of building the structural elements of the bearing walls, domes, vaults and cross vaults using different building materials. 2- Educational videos illustrating the ways of modeling the structural elements in the CAAD programs, specifically, 3D max program.The practical content targets the levels of understanding and the composition of the cognitive side, but this isn't sufficient to achieve the rest of the required learning outcomes in the curriculum. Therefore, the third part, which is the interactive exercises, is added.

**The interactive Exercises.** The interactive exercises are considered as an educational tool that helps the students to learn, through trial and errors, and helps the lecturer to know and determine the level of the students' understanding of the theoretical and practical content. The aim of the interactive exercises is to deal with all learning outcomes: cognitive, affective and psychomotor domains. The interactive exercises are divided into three separate levels:

Firstly: the skill of arranging different stages of building.

Secondly: the skill of selecting the appropriate structural elements.

Thirdly: the skill of linking the structural elements to the appropriate space shape.

In order to transform the theoretical and practical content into an interactive content, coordination with programmer has been made. The stages, upon which the interactive exercises were created, were as follows:

1- Studying analysis 2- Gather requirements 3- System analysis and design 4- Development(Coding) 5- Testing & debugging

**Firstly: The exercise related to the skills of arranging different stages of construction.** The aim of this interactive exercise is to teach the students how to build and implement buildings with the bearing walls system. This exercise has been carried out on a model of the most famous historical buildings, which is Mohammed Ali mosque (see Figure 1). A model, consisting of nine stages, has been built. Each stage illustrates how to build the construction elements of the mosque. Tools have been added to help students understand three things: The technique of building walls, vaults and cross vaults.

The students learn How to model them in a three-dimensional image. The students' ability to un-

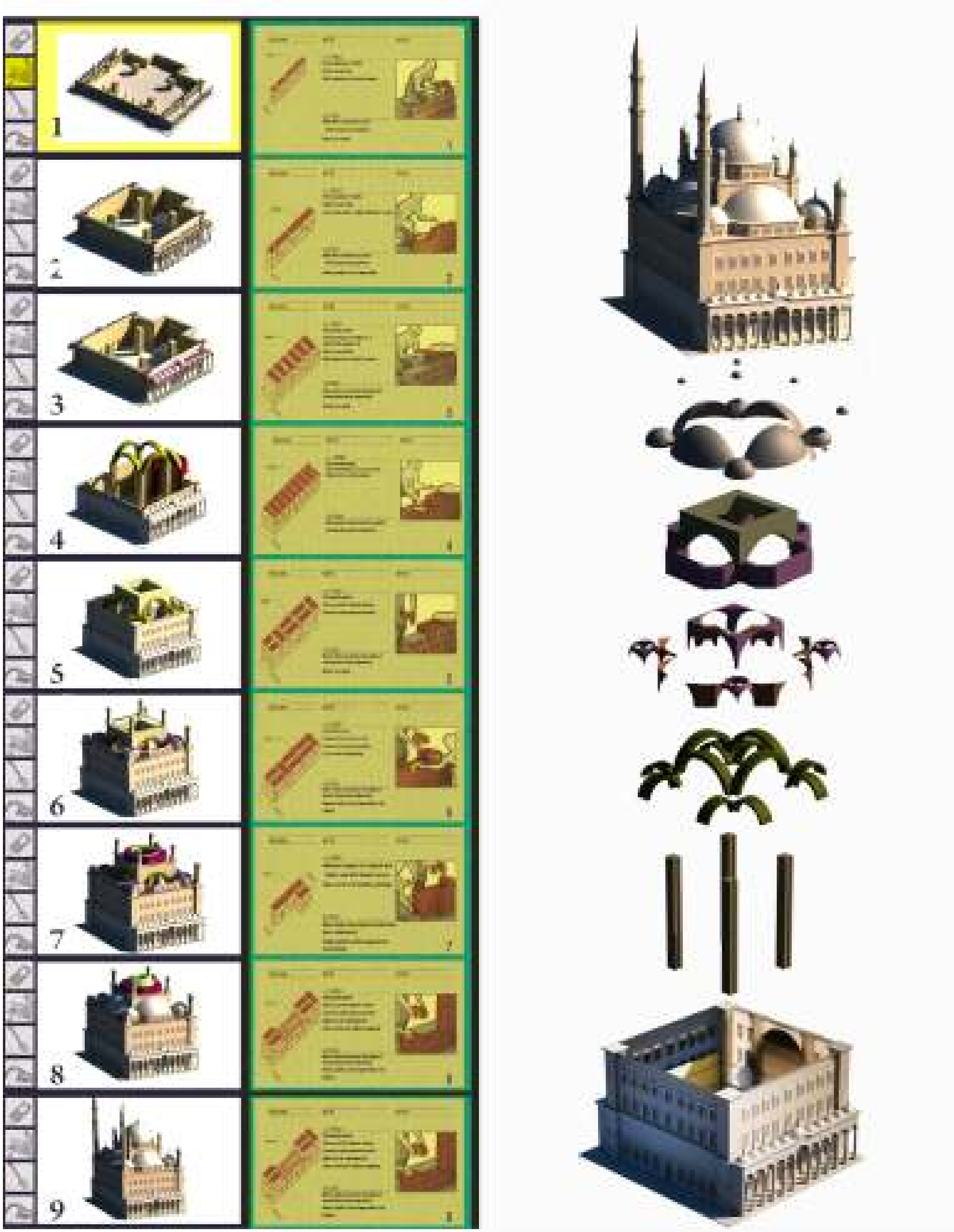

Figure 1
A model of an interactive exercises illustrating the stages of building the mosque with the bearing walls system

derstand the construction stages has been tested by the application interface. Drag and Drop has been done in a logical order until the correct stages of building the mosque have been completed.

This exercise targets both the levels of the cognitive domain (application, analysis, synthesis, evaluation) and the levels of the affective Domain (attention, response, assessment) and the levels of the psychomotor domain (observation and practice) (see Figure 1) illustrate the interactive exercise interface.

**Secondly: the exercise related to the skill of selecting the appropriate structural elements.** The purpose of this exercise is to teach the students to choose the suitable structure elements. The application presents many structural elements as alternatives. The student is to select among them. The structural elements are shown in the form of either architectural columns of different styles or different types of domes and vaults according to both the architectural style and the time period. It's available for the student to choose among the different structural elements. This exercise is associated with the third exercise that represents the first stage (stage 1 structural elements), which is the composition of the structural elements (see Figure 2).

**Thirdly: the exercise related to the skill of linking the structural elements to the appropriate space shape.** This exercise represents the second stage (3D model). It is the stage of linking the structural elements to each other and showing them in two forms:

The first form is the stages of building and the second form is the final composition after meeting the building conditions. The third and fourth stage are implemented through another application which is (Insta VR). It is an interactive application that receives images produced by the system of 360 degrees and turns them into an integrated scene showing the floors, walls and ceiling. The application helps to show the various stages of the development of the construction and associate them with realistic models to add comparison between the final form and the construction stages. (see Figure 2) illustrates the second interactive exercise interface.

## THE APPLICATION TEST

The application was tested by a workshop for the second-year students at the faculty of engineering, Al Azhar university. The study sample consisted of 85 students. The workshop completes what has been studied in the academic lectures, which consisted of 24 lectures and 42 hours divided into two terms. The workshop has been prepared after the usage of traditional teaching methods, and measuring their results. Then, the workshop has been conducted to measure the targeted learning outcomes achieved through the application. The workshop consisted of three stages:

The first stage: teaching the students the ways of building using bearing walls system through sketches and educational videos.

The second stage: teaching the students the methods of modeling domes and vaults through 3D max.

The third stage: The use of the interactive application by the students. The rubrics which represents the basic rules for judging performance level has been applied. It is a descriptive measurement to determine the level of what the students know and can perform. These measurements tell the lecturer, who is responsible for the evaluation, the characteristics or marks that he is looking for in the students' work.They also show how to evaluate this work depending on the rubrics. (Abd Alwahab & Al baz, 2009).

The extent, to which the students responded to the three stages of the workshop, has been monitored, through observation and questionnaire, from one hand, and through the availability of evidence, on the other hand. The following questions have been posed as a part of the questionnaire:

1- What is the order of the three learning stages used in the workshop according to the concept of the bearing wall systems? 2- Has the interactive application, as an educational tool, helped to clarify the construction methods of the bearing wall system?

3- What are the advantages and disadvantages of the application? 4- Is the interactive application

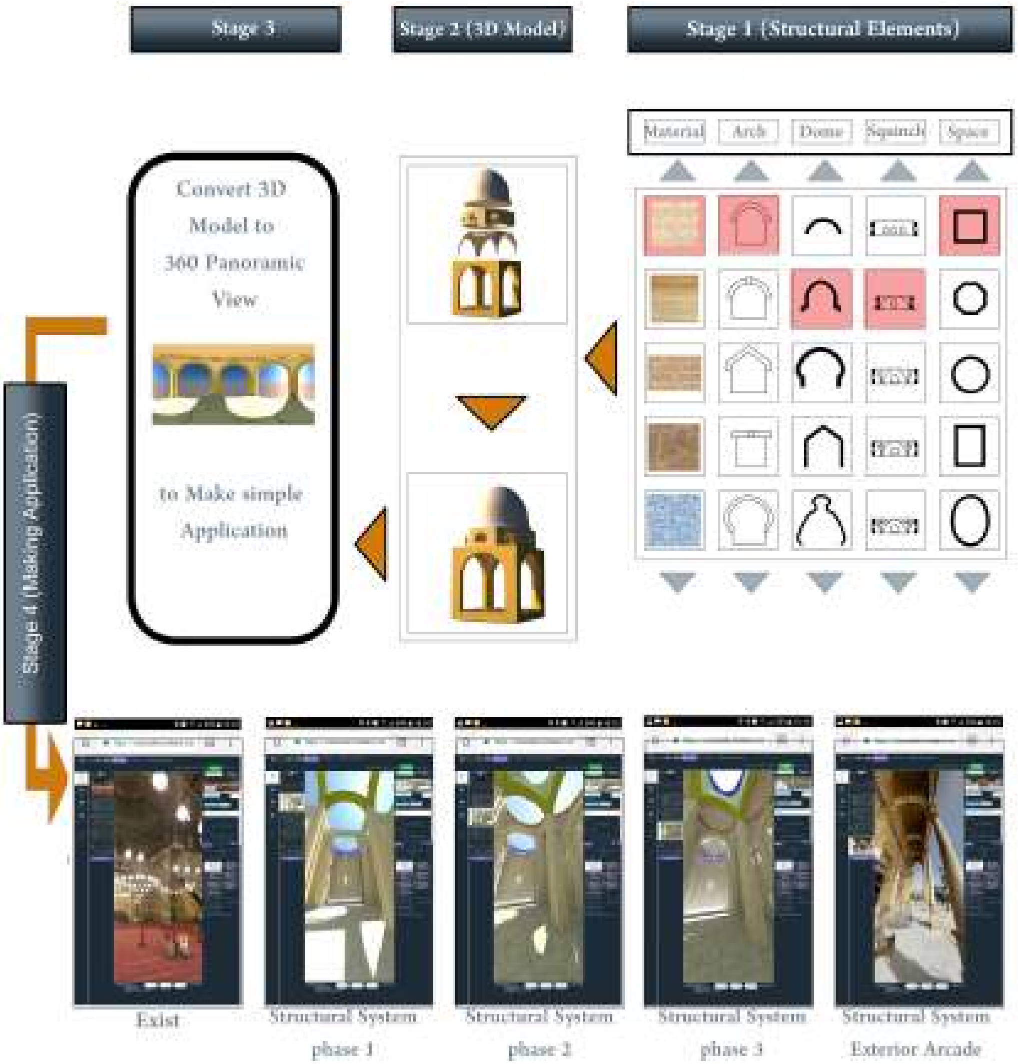


Figure 2
the four stages of the interactive exercises

sufficient to learn the structural system? 5- Did learning 3D modeling help understand the structural systems? 6- Did the integration of 3D models with the interactive application and 360-degree display help to understand the construction stages of bearing walls system? 7- Are the previous methods sufficient to understand the structural system?

Table 1
The statistic of the case study

| | |
|---|---|
| No. of enrolled Students | 85 |
| Hours of Lectures | 42 |
| Duration in months | 7 |
| Lecturer | 3 |
| Teaching assistant | 4 |
| Laptops Used | 85 |
| Students who successfully passed the 3D workshop | 53 |
| Student Selection for the best explanition Method inorder | 1-Application<br>2- 3D Models<br>3- Traditional methods |

## THE RESULTS WERE AS FOLLOWS

1- After monitoring the results of the questionnaire, after using the application, and comparing them with the results of the first questionnaire, which was conducted before using the application, it was found that the students arranged the means of explanation and education as follows:

The interactive application came in the first place. The results were based on the fact that it is an easy means that doesn't need previous skills. It was found that the interactive exercises helped the students to understand the ways of composing the construction system of the bearing walls. The students were able, through trial and error, to build the structural composition correctly (see Table1).

Teaching 3D modeling came in the second place. However, 85% of the students thought that it needed to be studied and practiced in advance. In comparison with the interactive application, it is considered as an important and complementary element. Its integration with the second application, Insta VR, to show the 360 degree structural elements, helped the students understand structural relationships, especially, when the three-dimensional models of CAAD were linked to the existing structure building.

Traditional methods came in the third place. According to the questionnaire, the reason was that these methods helped to understand drawing methods but didn't help to facilitate the imagination of reciprocal relations among structural elements, as clearly as, in the interactive application and 3D models

2- the study confirmed the research hypothesis that learning by merging 3D modeling of CAAD with the interactive applications completes what is lacking in the traditional methods. The targeted learning outcomes have been achieved in a varying rate. The scientific content, prepared for the interactive application, helped in achieving the outcomes of the cognitive domain by 70% whereas the knowledge level was achieved by 65%. The comprehension level was 58%, the application level was 70%, the analysis level was 75%, the synthesis level was 80% and finally, the evaluation level was 40% (see Figure 3). The results have come with these rates because the application is in the preliminary stage. The goal, in the future, is to develop the application to allow the students to design and compose according to what they have learnt and to use structural elements that aren't linked to the curriculum. But they may depend on what they have search for, so that the students acquire the skills of knowledge and creativity. The students will be able to upload their work on the application and, consequently, learning is achieved through practice and participation.

3- one of the advantages of the interactive application is that it is continuously scalable and testable, which can achieve more learning outcomes. The used methodology can be applied on the rest of the construction systems, in the same course, and other subjects.

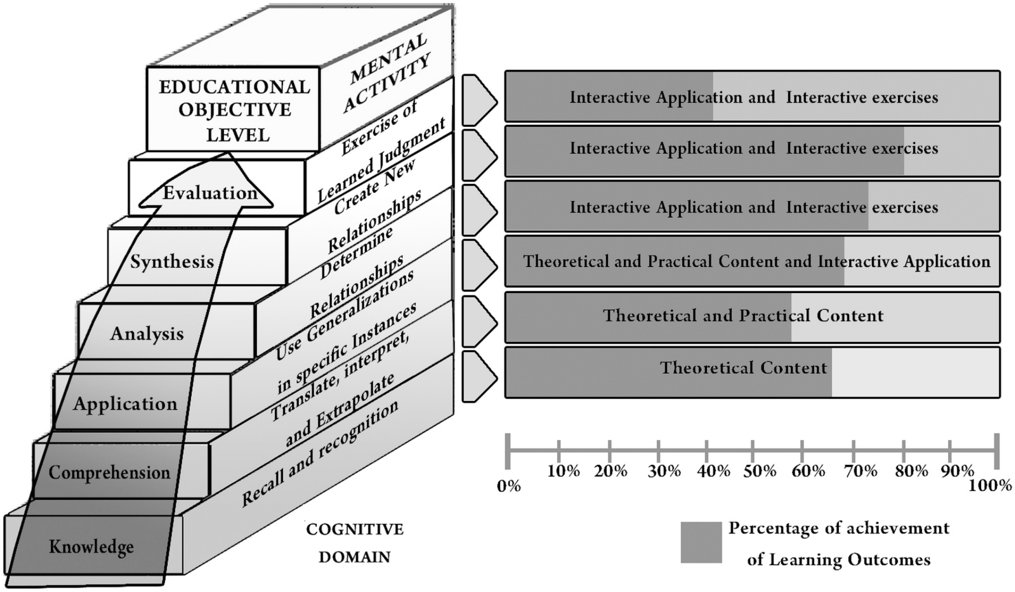


Figure 3
An evaluation of the cognitive learning outcomes

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# Teaching architecture students to code

## *Thrills and spills*

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*This paper will present the introduction of computer programming for design to students at the Leicester School of Architecture (LSA). It will describe the course and teachings, explain the trials and tribulations, and illustrate the results. An important weight on students of architecture, when it comes to the inclusion of coding into their architectural education, is the pressure of meeting certain professional criteria. The MArch Architecure course results in a professional level award that is prescribed by the ARB, and accredited by the RIBA for Part II exemption from their examinations. Consequently, students are required to articulate through their design work that they have met the learning outcomes associated with the stipulated professional criteria. Given the task of meeting the learning outcomes is challenging enough, the pressure of then learning to code, and to apply that skill to the design process in the course of the traditional process is a pressure few students of architecture seem willing to take on. The paper will conclude with a discussion as to the merits of coding and reason why students of architecture should learn to code.*

**Keywords:** *Programming, Code, Processing, Teaching, Architectural Education*

## INTRODUCTION

This paper will present the introduction of computer programming for design to students at the Leicester School of Architecture (LSA). It will describe the course and teachings, explain the trials and tribulations, and illustrate the results. The course has been taught for three years, commencing as part of a specialised stream of the MA Architectural Design course (2014-15), before becoming a component of the MArch Architecture course in 2015-16, whereby the course has become a module adjunct to the design studio; promoting algorithmic design thinking in correlation to traditional and contemporary methods of production and design thinking. An important weight on students of architecture, when it comes to the inclusion of coding into their architectural education, is the pressure of meeting certain professional criteria. The MArch Architecture course results in a professional level award that is prescribed by the ARB, and accredited by the RIBA for Part II exemption from their examinations. Consequently students are required to articulate through their design work that they have met the learning outcomes associated with the stipulated professional criteria. See the QAA

Subject Benchmark Statement for Architecture (Boddington et al. 2010). Given the task of meeting the learning outcomes is challenging enough, the pressure of then learning to code, and to apply that skill to the design process in the course of meeting these criteria is a pressure few students of architecture seem willing to take on. This is understandable because learning to programme is a challenge that requires a mind-set quite different from the traditional design studio (see Vannini 2016), and why would someone wish to struggle with connecting two random points to draw a line when they can quite easily do it with a pen and paper; and thereby focus on developing and articulating their design proposal. The paper will conclude with a discussion as to the merits of coding and reason why students of architecture should learn to code.

## BACKGROUND

Computer coding was introduced to students at LSA in the academic year 2014-15. It was offered as an option to learn coding for the purpose of using the computer as a tool to simulate parallelism and thereby generate architectural scenarios through a decentralised process of production. Until that time the manner in which computation was utilised in the school was quite traditional. Whilst it was incorporated and applied in the design process the computer was typically used for 3D modelling, graphics and visualisation. Rhino, the favoured modelling software, was, and remains to be, encouraged and students are adept in its use through studio tutorials, workshops and self-directed learning. Whilst workshops in Grasshopper are delivered students tend to adhere to 3D modelling software as a means to produce representations of their designs, rather than use the capacities of such tools to enable them to explore and form find: or as Ranulph Glanville would say to produce "models of, as opposed to models for". A specialist studio was introduced in the MArch Architecture course this academic year (2016-17), concerned with morphogenesis and parametric modelling techniques (led by Gudjon Thor Erlendsson), so this trend is changing and LSA students are becoming more computer savvy. The school emphasises the craft of making, and promotes, through studio teaching, craft-oriented and digital production techniques. Its mix of analogue and digital fabrication techniques, with a strong design-led ethos has yielded a number of student awards, putting the school in company with internationally renowned leading schools of architecture. (See note 1). The intention behind introducing students to algorithmic design thinking and teaching them how to code is to promote the generation of architectural propositions through decentralised methods of pattern formation and form production (see Coates 2010), so as to (a) open up their way of thinking about architecture and the world and (b) experiment and test the potential of the computer as a tool for design.

## IMPLEMENTATION

Coding is taught as a short course, composed of several lessons, introducing up to 10 students with only basic computer skills and no coding experience to programming. Processing is the programming language taught. By the end of the course they are able to produce their own agent-based-modelling programs. To date no students have failed the module, and the majority of students achieve a merit or higher: due in large to the format and premise that the students are required to write their own program that generates some spatial composition. The nature of code is such that no mistakes can be made, else the program does nothing. So, so long as a student is able to write code and produce a short program that generates some spatial formation they are unlikely to fail the module. This is not to say it is an easy course. The majority of students experience a breakdown (see note 2) until their mind-set clicks: after all programming is a way of thinking. This short course has evolved over three years. It was implemented at first as part of a specialist computing stream to students on the MA course, during the academic year 2014-15, before it migrated the following year to the MArch Architecture course, as a specialist technology module. As part of the MA Architectural Design course the students coding ability became more advanced (compared with the following year when the course transferred to the MArch) and the manner in which they took to coding was more literate. Having learnt from the MA-MArch transition the course was adapted and the relevance to design studio revised for the current year (2016-17). The coding module took place in the first term of the MArch course; completed before the Christmas break. This differs from what was taught when the course was part of the MA. The MA students where first taught (in the Autumn term) NetLogo and given theory lectures introducing them to key concepts: self-organisation, emergence, decentralisation and agency. They then took the Processing course in the Spring term (after the Christmas break). So the MA students were better prepared for programming, as they were clued up: in terms of having both a theoretical grounding and a basic understanding of code before commencing with the Processing programming module.

## COURSE OUTLINE

The course starts with an introduction to the basics of computer programming, before going through a series of lessons to teach the Processing programming language, agent-based modelling and Object-Oriented Programming (OOP). The intention is that the students write a short OOP programme which generates 3-dimensional architectural spatial formations. Asked to investigate simple organisms, students are required to model a simple artificial organism that responds to differences in its environment which can be utilised to generate architectural spatial compositions.

Essentially students are taught coding through a series of weekly workshop oriented seminars, during which they are introduced to key concepts and taken through a series of exercises. Each of these workshop-seminars concludes with a task, requiring the student to produce their own processing sketch to illustrate they have learnt the principles presented in each lesson. This is also a mechanism prompting them to work through the lesson independently, and to urge them to complete the tasks as the course progresses because the module concludes with the above mentioned assignment: to produce an object-oriented agent-based program, whereby a cyber-organism of their devising generates a pattern, structure or form that has spatial qualities and is an emergent outcome of their agent's autonomous interaction with its environment. This agent-based modelling assignment is the peak of this short course which they present in the form of a report, including their outputs for the weekly tasks. The report thus illustrates their progression through the course, articulating their understanding and development. Consequently, as the weekly tasks form the basis of this report, students are encouraged to complete each task promptly, not only to ensure they are absorbing the lessons but also as a scheduling mechanism to provide them the time to focus on the concluding assignment.

Each workshop-seminar starts with a confab whereby students present their previous weeks task output, explaining their code and what it does. The group discusses the output, problems highlighted and successes are congratulated. Given each task must, in actuality be completed for the submission of the report, students are able to take on comments to revise and rework their weekly task codes. Students are strongly encouraged to review the lesson independently, and that an hour a day of coding is necessary, else the code-muscle weakens and each week will quickly become groundhog like; and it quickly becomes apparent to the students that the workload snowballs if they do not keep abreast of the developing syllabus. Students are also encouraged to meet up to go through lessons and exercises together, either with a code-buddy or as a group to prompt discourse about the tasks, and problems encountered; to counter them getting trapped by internal processes that prohibit seeing the wood for the trees. The confab and workshop-seminar environment promotes an inner-circle atmosphere and students tend to work openly with each other, supporting one another in the various glitches they encounter. At the end of the session the week's task is revealed and example output(s) presented.

The course runs for five weeks. Starting with the fundamentals of programming students learn how to write short programs that create dynamic patterns and then, having grasped the fundamentals of coding, they move to interaction and movement before learning about agents and finally object-oriented programming (OOP). The course outline presented below is as delivered this academic year (2016/17). It is a reincarnation of a course originally authored by Alasdair Turner, which the author took in 2009 at the Bartlett School of Graduate Studies. The course has been altered and adapted over the three years it has been taught at LSA; in response to the students, the authors intentions and how it aligned with the design studio module. An underlying aspect of the course is that it has been shoehorned into existing programme structures. As part of the MA it was offered as an aspect of the design studio module, whilst under the MArch it is offered as a specialist option in the History, Theory & Criticism module, which has both a humanities side and a technology side. In both circumstances the timetable did not allow for the course - at least not to provoke and prompt the students to go from zero to agent-based modelling coder in five weeks. The two-hour weekly seminar timetabled for five weeks was insufficient. The course is an elective and consequently, it was stressed at the outset of week 1 that the enthusiastic students had drawn the short straw and that a deal was to be struck if they were willing to "feel the pain". To achieve said transition the author was willing to put in the time if the students were, and proposed the weekly sessions took as long as needed: on the basis that he was keen to share and teach coding skills with the students, it would not only be fun, but that it was a new skill and would open the students up to another way of doing things, with the view that it could feed into their studio work: as well as being part of a pioneering way of doing architecture at LSA. Over the three years all students have voted to take the plunge, signing up to extended weekly sessions that generally last three-and-a-half to four hours.

**Week 1.** The first week is a crash course in the fundamentals of programming before explaining repetition and variation. The lesson starts with a short presentation and discussion regarding "Why Code?", before covering fundamentals of 'functions' and 'data', the Processing co-ordinate system, and an explanation of 'loops' and 'conditions'. Using colour and co-ordinates as variables students are taught how to control data. The first week's task is twofold, requiring one sketch that produces a composition of points and lines, and another that produces colourful patterns. See Figure 1.

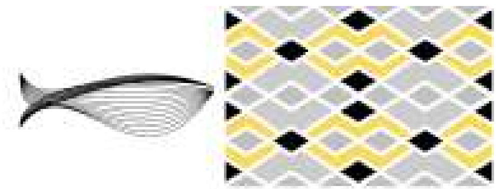


Figure 1
Week 1 sketches by MArch student Ka Leong (2015/16) that produces a composition of points and lines (left) and another (right) that produces a colourful pattern.

**Week 2.** The following week is about movement and change. Having learnt how to draw a shape primitively (opposed to using, say the "rect" command, to do so) in week 1, students are shown how to write their own function, enabling them to replicate their shapes more easily: i.e., less code. They then study how to manipulate these shapes through loops, altering local and global variables so that they shift and rotate. The output is to produce a sketch that generates a dynamic artwork. See Figure 2.

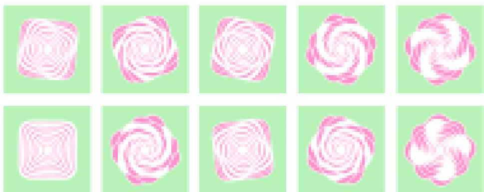


Figure 2
Week 2 sketch by MArch student Ka Leong (2015/16) that generates a dynamic artwork

**Week 3.** Students are shown how to stop and start shapes rotating use an event according to mouse clicks and key presses, so that their sketches become interactive, before they are introduced to classes.

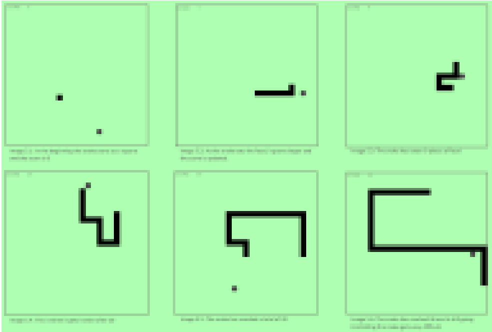


Figure 3
Week 3 task by 2016/17 student Aashiv Shah who created a simple two dimensional game, making his own version of the classic game 'SNAKE'.

The concept of grouping information into routines and sub-routines is emphasised so that they are able to organise their short programmes, grouping certain bits of data and functions together, to enable them to add and interact with shapes/objects that have different behaviours and respond differently to external events: like the press of the keyboard or click of the mouse to change direction. The aim being that they view their coded objects as characters that "know" what and where they are, and so respond accordingly to an event. They are required to write a short program in which an "object" has behaviour and responds to mouse/keyboard interaction. See Figure 3.

**Week 4.** This lesson introduces arrays. The notion of arrays is introduced, starting with fixed length arrays, first for lists of integers, and then for classes. Variable length arrays are then introduced so that they can add an arbitrary number of objects, which they can manipulate and interact with, before arrayLists are introduced. They are given a short sketch of variable 2D objects with behaviour which they are required to modify, amending the objects behaviour and transforming the sketch into 3D. They are introduced to libraries, at the end of the lesson so that they can either independently convert the sketch into 3D or use a plug-in: such as peasyCam.

**Week 5.** Students are shown how to manipulate and interact with their objects personally (with the click of the mouse) and with one another. They are introduced to the idea of agents, and agency to extend their coding to agent-based modelling. The object-oriented programming concept of composition is introduced to present the technique for creating more complex objects, and they study how we define an agent. The notion of an agent and agency crosses many disciplines, but the focus is on the computational notion of an agent; because that's what the course is concerned with. Jacob von Uexkull's concept of the "functional Cycle" (1957) is introduced to highlight an agent must be able to detect its environment in order to react to it.
A taxonomy of "agent" is presented (see Franklin and Graesser (1996), and Ingham (1997)) with the conclusion that an agent is situated and exhibits autonomous and cogent behaviour with respect to its environment and to each other.

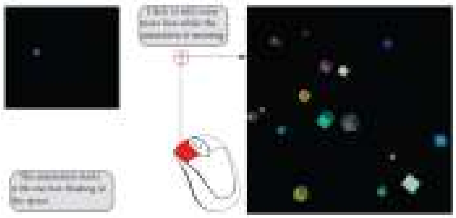
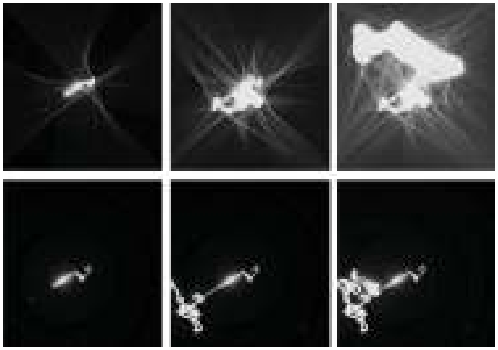


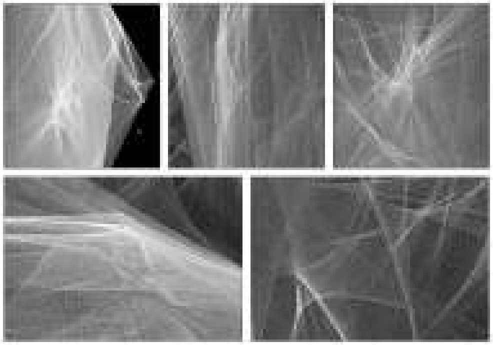
Figure 4
Week 4 sketch by Florian Mouafo (MArch 2016/17) in which spinning boxes that are attracted to/repelled by other boxes are added at the click of the mouse, to create an asteroid field.

The definition presented by Franklin and Graesser (1996) is adopted as a working definition, that: "An autonomous agent is a system situated within and a part of an environment that senses that environment and acts on it, over time, in pursuit of its own agenda and so as to effect what it senses in the future." Uexküll's functional cycle is thus used as a model to emphasise detector-effector interplay, explaining the congruence between an organism (agent) and its environment.

Looking at a simple ant inspired agent model we look first at a primitive method of movement using Moores Neighbourhood as a method of governing movement of a random walker: akin to how a turtle moves from patch to patch in NetLogo.



We then convert the method of walking to using PVectors. The lesson closes with a look at the object-oriented programming concept of composite objects and how an agent can interact with its environment. Students are then given the code for a random walking agent sketch and tasked to alter the agent's behaviour to generate an alternative output arising from the agent's interaction with its environment. They are also issued with the concluding assignment to write a programme, for which they are required to characterise an agent, which creates something through interaction with its environment.



By detecting differences in its environment which it reacts to, their autonomous agent must alter or affect its environment through its motion (shaping its environment as it moves) or by brute-force (moving and changing elements in its environment).

The aim is that their cyber-organism produces some pattern, structure or form which has spatial qualities and is an emergent outcome of its autonomous interaction with its environment. See figures 5 and 6, by 2016/17 MArch student Michael Roden, who, interested in how spiders sense vibrations, explored how the web acts like an amplifier enhancing spiders' capacity to detect, and replicated the spiders coupling with its web to locate food and survive.

## CORRELATION WITH THE DESIGN STUDIO

The coding course outlined above was for the first two years adjoined to the design studio. In its first year (MA students 2014/15) the course was integral to the design studio. With its transition to the MArch in 2015/16 students, who signed up to the authors design studio, were compelled to sign-up to the coding course, and in its third year (MArch 2016/17) the course was detached from the design studio; as the emphasis to design architectural projects through code appeared daunting for MArch students; who are compelled to respond to the constraints of the Part 2 architectural curriculum (QAA 2010). The MA is not vetted by the RIBA and so the design studio is at liberty to experiment and explore, with the luxury of being able to promote a more theoretical discourse given it is not constrained by vocational targets. During its application as part of the MA the course was submerged into the studio. The design studio commenced with Processing lessons, and so it drove the design thinking and process. The final output was thus not a report but a design project. The MA students were thus not bound to producing outputs each and every week; though in large they did. It meant that the learning was more fluid and embedded in a design discussion. Interestingly MA students seemed to struggle a little initially with some of the more advanced concepts (such as arrays and classes), even though they had the benefit of having worked with NetLogo in the previous term: during which they were introduced to key principles (self-organisation, emergence, distributed representation) and "played" with agents; so they had a heads-up. This was only appreciated in hindsight,

Figure 5
Two spider-agents; one that spins a web as it moves, thereby enhancing its sensorial domain, the other with just a field of view. The spider with the web (top) lasts longer and explores the majority of its environment.

Figure 6
And transcribed into 3D .

once the course was delivered to MArch students (2015/16), who seemed to lap up the initial weeks of the course, producing dynamic art sketches more impressive than their previous counterparts. However, having "twigged" the MA students use of Processing as a tool for their design project became ubiquitous and their coding projects surpassed the course content. The MA students design projects were driven by a code mind-set, and so their design projects were motivated by their coding abilities. They explored methods, utilised libraries and overcame technical problems independently: like how to enable an agent to recognise a 3D plane so that it changes direction and doesn't walk through a wall. The (2015/16) MArch students found the transition from using Processing as a drawing tool (to generate artsy dynamic outputs) to producing models that generate some sort of architectural/spatial composition through agent interaction more difficult. This is likely down to the fact that the MA cohort (2014/15) had more time and where not constrained by vocational criteria. The course they followed and the final output was the same but the format and schedule differed. The Processing course outlined above was delivered in MA studio time (for which a day was available!) and bled directly into the studio project which was to model a paramecium (i.e., build a 2D artificial creature that responded to differences in its environment), which they used to generate two-dimensional spatial compositions and developed into three-dimensions, to generate architectural compositions that express structure, space and form. (See Figure 7: top). The MArch students had the same brief as the MA students, but seemed to freeze when it came to using processing to drive their architectural projects, as they struggled to "let loose" and perceive, or consider, the output of their processing model as a basis for architectural thinking and a vehicle for designing. Consequently, the transition between their Processing work and their design project became moot: more an interesting exercise than an embedded aspect that informed their initial design process. (See Figure 7: bottom).

This third year the above Processing course was decoupled from the design studio, and students wishing to use their new coding skills were given the flexibility to test and try, whilst ensuring they progressed their design work by other methods in tandem. The result of this decoupling was that the MArch students appeared to relax; with regards the need to drive their design studio projects through Processing. The emphasis in the design studio was instead placed on algorithmic thinking: i.e., their design projects were driven by a rule based process (to emphasise results derived from cause and effect "systems"), which they were welcome to implement through analogue methods if they wished. The result of this decoupling was that the students were less troubled with regards the design studio and were more focused on the Processing course. The detachment seemed to allow them the space to focus on both individually and not worry about the coupling. Consequently, a few of the students freely utilised Processing in the early stages of their design studio projects to drive their conceptual thinking, and as an aid to generate outputs, which they exported into Rhino for further development. (See figure 8). Whilst few actually developed this further, to generate their final output, the fact that they freely utilised code in their design process was encouraging and suggests that there is an interest in using the computer in a more creative manner (i.e., "models for"), but that the vocational constraints and schedule, discourage architecture students because the vocational constraints pressure them to thinking more traditionally - or using more tried and tested methods. This is perhaps why (digital) architecture schools promote computational design through Masters courses as opposed through the vocational Part 1 and 2 (or equivalent courses). Whilst one might say this works, its a deterrent to experimenting with the machine as a creative device/engaging at the low level because completing a Masters thereafter (Part 2) not only amalgamates further time and expense, but is by that time somewhat detached from the "day job".

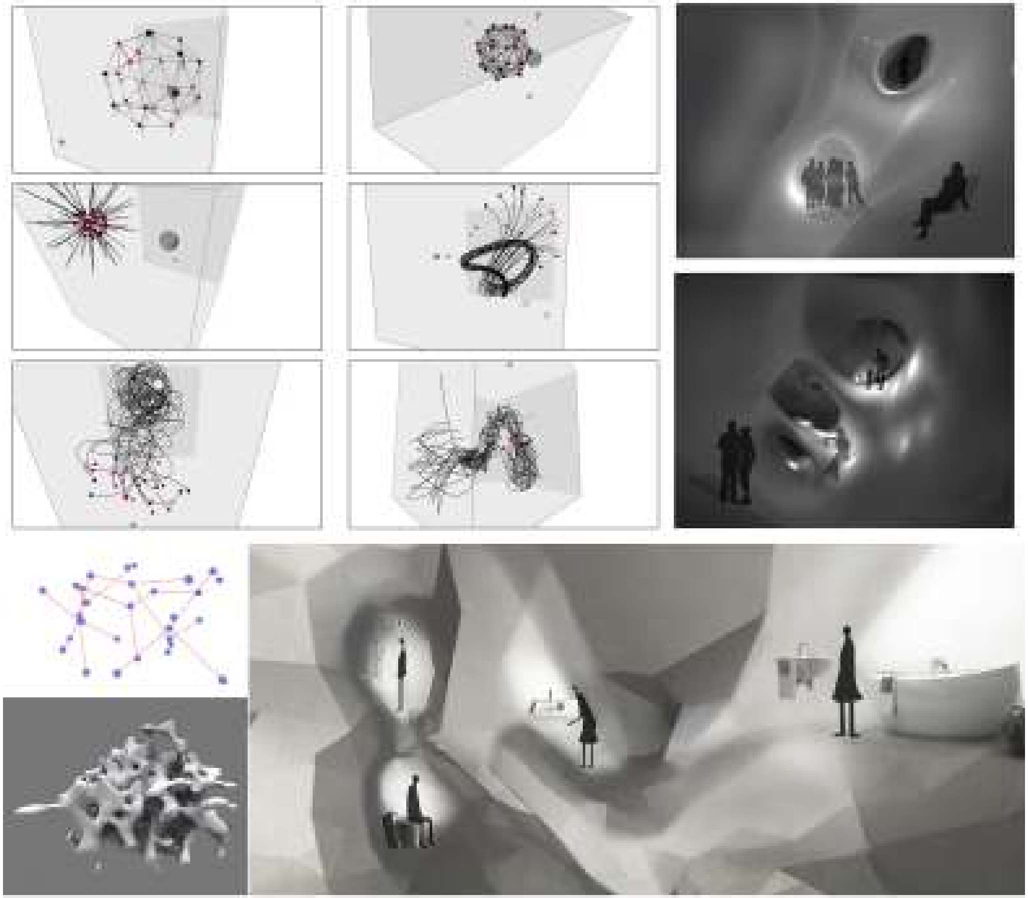


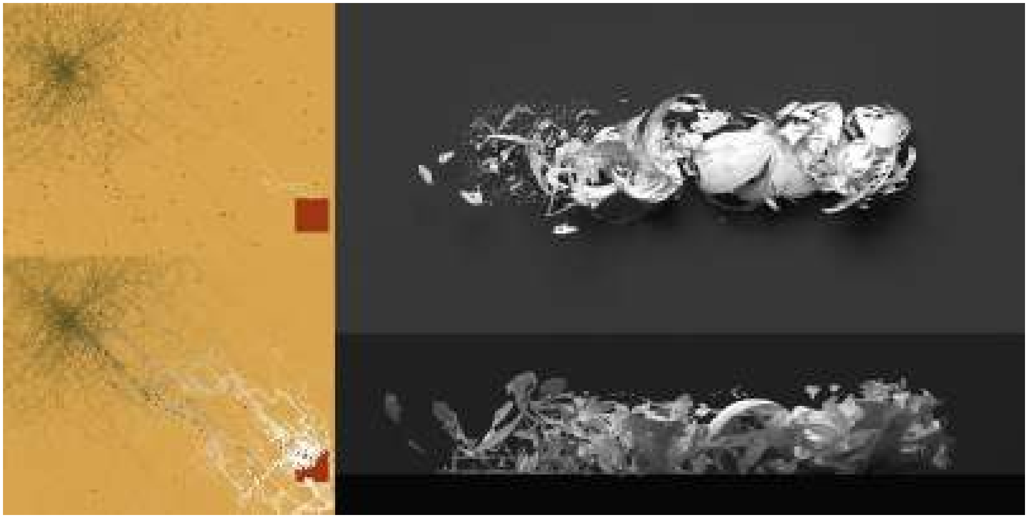
Figure 7
(Top) "Paramecium Drawing" by MA student (2014/15) Shen Guanlong (aka Jerry) derives inspiration from single-celled organisms that are attracted to light. The behaviour of which was used as a mechanism to draw and generate spatial compositions that materialise bottom-up. (Bottom) MArch student (2015/16) Ka Leoung uses an attract-repel network of nodes to generate a simple structure which a mesh is wrapped around (using toxi.geom) to inform a spatial scenario.

## TO CODE OR NOT TO CODE?

The fundamental question anyone interested in using computers as a medium for design must ask is whether to learn to code, or not. The underlying concern to this question is whether they should engage with the machine at a level typically reserved for computer scientists and nerds. Computers are a part of our everyday life, and computation has become an intrinsic aspect of architectural design today. But computers are typically background artefacts. Something we use in the process of doing something, which enables and enhances production and streamlines the way we do it. The vast majority of architects and designers use computers as a production tool. Fewer use computers as a tool for design. Fewer still use computers as a creative device - even in this age of digitalisation.

As a tool for design a user typically engages at the level of a CAD package (such as Rhino), to build a three-dimensional form using the in-built functions

Figure 8
March student (2016/17) Mark Ngo uses the pheromone trails generated by ant-like agents searching for food to generate a trail network which he exported into Rhino to produce a 3D spatial composition.



and procedures provided. Whilst using a 3D CAD package enables and enhances our design abilities it also constrains; keeping the user within a well-defined "design space". The user has the freedom to generate and build models but the manner in which they do so pertains to particular procedures and means dictated by the functionality of the program: i.e., the software designer felt they knew a better way than another program to do something in a particular way. A typical question a student may have when seeking to learn 3D modelling is which CAD software they should learn - because each package has its merits, functionality and thus particular ways of doing things. One may answer "learn any", because once you've learnt one you might crossover; and having understood the nuances of each platform be able to use whichever package best suits what you want to achieve. Whilst this is true, and not new, the issue is that the different packages require one to think in a particular way. 3D modelling packages, generally, do the same thing. They enable a user to build three-dimensional models, which they can animate and manipulate, but the functionality and ways and means of doing something is aligned to the developer's view of how something should be done. The same thing goes for visual programming languages, which enable students to construct diagrammatic programmes in an interactive way. Having learnt the graphic interface and functionality students can produce "something" quickly, with relative ease, and then simply play around. This provides a systems-oriented approach to "generating" something, but what the user gains in ease of programming they lose in being able to manipulate the "finer details". It is important to understand "algorithmic thinking" and the basics of programming, quite simply because it makes you build from the ground up. (See Burry 2011). Textual programming is empowering. It is the language of the computer scientist and it is necessary to "speak" this language. It is a question of communication and not of simply doing "something".

Steve Jobs said, "I think everybody... should learn how to program a computer because it teaches you how to think". (See URL reference: one minute in). The ability to code is liberating, because it enables you to get to the base of how to do something. To draw a line with a pen and paper is "natural", but using a computer to do the same thing is a complicated task. There is no kidding - code is difficult, time consuming and often daunting. But once you have figured out how to draw a line, and to copy, rotate, and offset that line the capacity to draw lines is enriched. The computer cannot and will not replace the qualities of a line drawn by hand but the capacity of the computer to do something repetitively and automate the process provides the "drawer" a freedom otherwise unknown. Speed and automation are key benefits, but the capacity to surrender to the process is liberating. For example; the addition of lines may change colour and an element of randomness may be combined into the mix. The lines could be animated, such that they move and have the capacity to affect and be affected by other lines. Once the "drawer" has figured out how to draw a circle the same process can be adapted to drawing circles, and then lines and circles; and so forth. In short the drawing of lines becomes an animated, dynamic and potentially self-organising and emergent process, which opens up a world of possibilities for the "drawer". In this way the machine is used creatively, because the only constraint is the "drawer". Additionally, the problem of having to work out how to draw a line in the first instance requires the "drawer" to think about the process of drawing lines. In short, programming how to draw a line mirrors the thought process and action of drawing lines. Learning to code empowers because it makes one think from the ground up.

### *Notes:*

1. LSA students have achieved 3 x RIBA awards at the RIBA president's medals in the past 5 years. A significant achievement paralleled only by four other schools of architecture: Bartlett School of Architecture, Royal College of Art, University of Sydney and London Metropolitan University.
2. Not literally - what occurs is that the students experience considerable frustration and fear that they cannot get to grips with code. They (reportedly ....and the author bears witness to the tired unkempt zombie looking beings the students become as the course progresses) spend long hours starring into space, wanting to throw their machine (and most likely the author) out the window.


## ACKNOWLEDGEMENTS

The author would like to acknowledge Alasdair Turner (author of the Processing course on which the course presented is founded) and the reviewers for their comments and suggestions, which have helped to improve the content of this paper. Not forgetting the students, who opted to take the course, and whose effort and input have made the course a delight to teach.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[1] https://www.youtube.com/watch?v=mCDkxUbalCw

# Early design stage automation in Architecture-Engineering-Construction (AEC) projects

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*The paper is dedicated to conceptual design stage in AEC projects since this stage defines most of further design and even construction. Conceptual design is less automated and more human depended part of a complex design process. It is reasonable to link modern construction design software with ideas generation techniques in order to enhance and automate design creativity and effectiveness. In the article we propose computer-aided automation of searching for new conceptual ideas and nontrivial solutions during early design stage in AEC projects using such TRIZ tools as Function Modelling and Trimming in BIM technology. For description of our approach we consider framed buildings.*

**Keywords:** *TRIZ, BIM, AEC, Function analysis, Trimming*

## INTRODUCTION

Early design stage in Architecture and Construction projects is a crucial part of sophisticated long-term design process. This stage is also known as Conceptual Design (CD) and here many fundamental and critical solutions are taken. The more smart and nontrivial solutions are taken during CD, the more technological, effective and less costly design we gain. Those solutions can be found by using different techniques of ideas generation, such as a morphological chart, synectics, brainstorming, TRIZ tools, etc. TRIZ is believed to be one of the most effective and well-structured problem-solving techniques (Altshuller 1999), (Salamatov 2005) and it is well applicable to architecture and construction (Conall Ó Catháin 2009), (Lin and Lee 2005), (Mohamed and AbouRizk 2003). "TRIZ" is the Russian acronym for the "Theory of Inventive Problem Solving." G.S. Altshuller and his colleagues developed the method between 1946 and 1985. The approach includes a number of tools, some of the most used are the Ideal Final Result and Ideality; Functional Modeling, Analysis and Trimming; the 40 Inventive Principles of Problem Solving. In our digital century it is reasonable to link modern construction design software with ideas generation techniques in order to enhance and automate design creativity. Nowadays Building Information Modelling (BIM) became popular stream in construction design. Existing BIM software have range of instruments enabling designers to bring all their knowledge and experience into projects but, however, those software do not support users in searching for nontrivial conceptual ideas for design. That is why the ideas generation stage is still a separate, not automated and human depended part of design. In the article we propose computer-aided automation of searching for new conceptual ideas and nontrivial solutions during early design stage in AEC projects using TRIZ tools in BIM technology. For description of our approach we will consider framed buildings.

## STATE OF THE ART

Linking engineering design software with ideas generation techniques and development of CAI (Computer-Aided-Invention) systems is still a researchable topic. (Ikovenko 2004) mentioned that merging TRIZ with other methods gave birth to several integrated methodologies based on TRIZ and it opened new horizons for CAI development to cover all the parts of those methods, both analytical and concept generating. Also (Bakker et al. 2011) explained the link that is missing between CAI and CAD (Computer-Aided Design) software. Furthermore, they proposed the integration of CAI and CAD software. Also (Noel 2001) suggested integrating TRIZ and CAD in order to increase design effectiveness and productivity. Also the review of existing literature in the field of architecture and construction showed that new technological advancements in AEC design has brought the "level of automation" as a pivotal factor in the success of projects. (Abrishami et al. 2013) show that extant literature has identified a significant knowledge gap concerning the key impact links and support mechanisms needed to overtly exploit computational design methods, especially BIM, throughout the conceptual design stage. Moreover, most of the respondents studied in the paper highlighted several deficiencies in the existing tools, whilst they asserted that such a purposeful BIM interface can offer comprehensive support for automation of the entire of AEC design and implementation phases, and particularly enhance the decision making process at the early design phases.

## DESCRIPTION OF THE APPROACH

According to [1] Autodesk Revit® was determined as a leader among the best BIM software products by customer satisfaction (based on user reviews) and scale (based on market share, vendor size, and social impact). Autodesk Revit is BIM software for architects, structural engineers, MEP engineers, designers and contractors. It allows users to design a building and structure and its components in 3D, annotate the model with 2D drafting elements, and access building information from the building model's database. Based on above, Autodesk Revit® was selected by the authors as the basic and most promising software for realization of a proposal for conceptual design stage automation in AEC projects. Moreover, this is the only software that has a built-in open source graphical programming tool for design which extends building information modeling with the data and logic environment of a graphical algorithm editor and enables users to significantly expand functionality of the software without having special knowledge of programming. The tool is called Dynamo. In our approach software is supposed to self-analyze Building Information Model and suggest solutions in order to improve the system. For that purpose we suggest to use the TRIZ Functional Modeling and rules of trimming. In order to teach software to extract a function model from BIM model we have built a special script with help of Dynamo. The script first automatically detects elements/components in BIM model and places them into an interaction matrix. The interaction matrix defines either elements interact with each other or not and shows all interaction between elements of the system. On the next step the software defines functions of elements in the Interaction Matrix. In building structures this functions are usually "holds". However, such functions as "bends", "expands", "compresses", "twists" etc. may take place. For identification of interactions the script also applies special rules. On the next step a function model diagram is automatically generated from the interaction matrix. This diagram shows a hierarchical structure of the components and the functions between them. Such function analysis helps to eliminate mental and thinking inertia since attention of designers is put on elements and functions. Also, the software helps to achieve a more complete and convenient workflow for design engineers as all is done within the BIM environment. Finally, having this overview is a prerequisite for performing other TRIZ tools, such as function ranking and trimming. Trimming is a method from TRIZ used to reduce the amount of system components without losing system functionality. The method is based on transferring functions performed by a component that should be trimmed to another component. The software uses rules of trimming for finding other components to perform this functionality, the component not performing any functions anymore can be removed (trimmed) from the function model without losing any functionality. As a result the software highlights the best candidates for trimming in the BIM model and design engineer can accept other decline those proposals. In function ranking functions of elements are ranked on their level of usefulness. In order to perform ranking we first have to identify a “target function” (for instance, “carry live load”). The higher rank belongs to the functions that are closer to the target function. So, the software chooses the furthest from the target functions as the candidates for trimming. There are also co-called “harmful functions” like “bends” or “twists” since bent or twisted elements require more materials in order to stay stable rather than tensioned ones and it may be wise to eliminate such function if it is demanded to design cheaper but equally stable structure. Function ranking offers the user a quick overview on the structure of a system and on the importance of distribution of functions. Such analysis during conceptual design enables engineers to automatically analyze the BIM model and easily obtain nontrivial design avoiding complex processes of topology optimization and structural analysis which are issues for further detailed design. As a case study we analyze a simple beam structural system.

## FUNCTION ANALYSIS OF A BIM MODEL

### *Interaction matrix*

Building the interaction matrix is the first step in the functional analysis. Here the position of elements in space, their geometric characteristics and functions are not taken into account. The matrix of interactions represents the model as a system of individual elements interacting with each other in order to perform the functions assigned to them. Identifying the presence of interaction between the elements of the system is the goal of this type of analysis. The aim of this part of the study is to automatically construct the interaction matrix based on the result of the BIM model analysis. In order to do this, the following tasks must be performed:

1. Analyze the BIM model for the presence of physical interaction between its components;
2. Output the result as the final interaction matrix in a user-friendly way.

**Algorithm for conducting analysis to identify interactions between elements.** As an illustrative example, we consider the following system, shown in Figure 1, consisting of three elements. The circuit can be represented as a sequential list of elements.

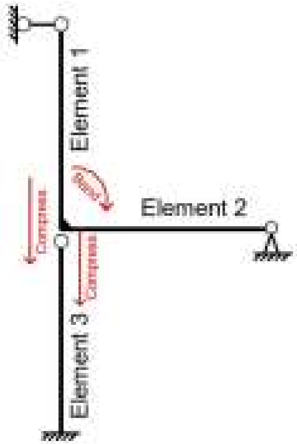



Figure 1
the circuit scheme

Further, each element of the list is sequentially examined with respect to the list of elements. Elements are (i) intersected, (ii) not intersected or (iii) self-intersected. Self-intersections of elements are excluded.

Based on the data obtained from the analysis of the interaction of elements, a matrix is constructed.

| | Element 1 | Element 2 | Element 3 |
|---|---|---|---|
| Element 1 | | ✓ | ✓ |
| Element 2 | ✓ | | ✓ |
| Element 3 | ✓ | ✓ | |

Figure 2
The matrix of interaction

| | Element 1 | Element 2 | Element 3 |
|---|---|---|---|
| Element 1 | | - | C |
| Element 2 | B | | C |
| Element 3 | - | - | |

Figure 3
The matrix of functions

**Output of the analysis result.** The table is automatically formed in an Excel file, which is generated after the script is run based on the analysis result of the BIM model elements. The output of the result in a text form is the most clear and understandable way.

## *Defining functions of elements*

The second step in the functional analysis is the construction of a matrix of functions of elements. When constructing the interaction matrix, we did not take into account the geometric characteristics of the elements, their position in space. The goal of constructing the interaction matrix was to reveal the fact of the physical interaction of the elements. The next step in the analysis is definition of the functions of the interacting elements relative to each other. Thus, we gradually go deeper into the analysis of the model, moving from the general to the particular.

**Algorithm of actions in determining the functions of elements.** Based on the data obtained during the construction of the interaction matrix we can judge the number of interactions in the model.

Let us return to our simplified model and consider the functions of the elements. Let us assume that the live load in our system acts along the Z axis and no other loads are applied to the model. Figure 1 shows that Element 1 compresses Element 3, and Element 2 bends Element 1 and compresses Element 3.

Further, for clarity of the results of the two previous analyzes, we represent the function table in the form of a matrix of functions. The elements are located vertically and horizontally, and their functions at the intersection. The following notations are used for the functions:

1. Compress - C;
2. Bend - B;
3. Stretch - S;
4. Torque - T;

**Defining functions by category of elements.** The purpose of defining the functions of the elements is to prepare the data for ranking the BIM model elements. Therefore, in this study, it was decided to take into account the functions of elements that require special attention: compression, bending, torsion.

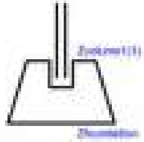
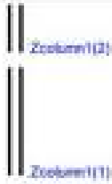
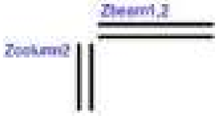
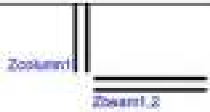
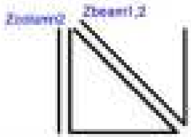
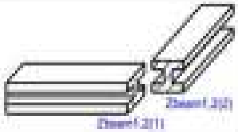
The Table 1 shows the functions that correspond to the interactions of elements of different categories. The categories were chosen according to the principle of the most common in framed systems.

| Category 1 | Category 2 | Hinged connected | Function |
|---|---|---|---|
| Foundation | Column | + | C |
| Foundation | Column | - | C + B |
| Column | Column | + | C |
| Column | Column | - | C + B |
| Column | Beam | + | C |
| Column | Beam | - | C + B |
| Beam | Slab | + | C |
| Beam | Slab | - | C + B |
| Beam | Beam | + | B |
| Beam | Beam | - | B + T |

Table 1
Functions of elements

In order to determine the functions of the elements programmatically, it is also required to specify the position in space, namely the coordinates of the elements in the BIM model. It is important to specify the coordinates of the bottom and top for the linear objects: beams, columns. And the lower level for the objects elements: foundations. A floor slab is also accepted as an object element, since the lower level at each point of the plate will be the same.

Table 2
Conditions of positioning of elements

| Category 1 | Category 2 | Condition | Scheme of interaction | Description |
|---|---|---|---|---|
| Foundation | Column | Zfoundation < Zcolumn1 |  | Column influences on foundation. Column has function. |
| Column (1) | Column (2) | Zcolumn1(1)< Zcolumn1(2) |   | Column (2) influences on Column (1). Column (2) has function. |
| Column | Beam | 1) If Zbeam1 = Zbeam2: | | Beam influences on column. Beam has function. |
| | | 1.1) Zcolumn2 = Zbeam1,2 |   | |
| | | 1.2) Zcolumn1 = Zbeam1(2) (only for rigid connection) |   | |
| | | 2) If not Zbeam1 = Zbeam2: | | |
| | | 2.1) Zcolumn2 = Zbeam1(2) |   | |
| Beam | Slab | Zbeam1(Zbeam2) < Zslab |   | Slab influences on beam. Slab has function. |
| Beam (1) | Beam (2) | Zbeam1,2(1,2)= Zbeam1,2(1,2) and Xbeam1(1)< Xbeam2(1)< Xbeam1(2) |  | Beam (2) influences on beam (1). Beam (2) has function. |

The functions of interest are appeared when conditions described in the Table 2 are met:

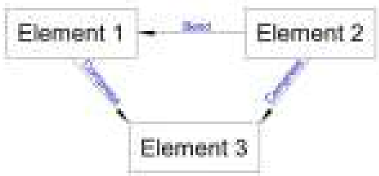



Figure 4
Functional model diagram

**Information output.** It is supposed to carry out the output of information by analogy with the matrix of interactions. After the script is run, the result is generated in the created Excel file.

### *Function diagram*

The construction of a function diagram is the third step in the functional analysis. The functional diagram displays the 3D model in 2-dimensional form, where each element is presented in the form of a block with the name of the element. Let us call it "block of the element". The interaction between them is displayed in the form of an arrow. Hereinafter - "arrow of interaction". The presence of an arrow between the blocks will indicate the presence of interaction between the elements and the direction of the arrow indicates the direction of the action. The nature of the interaction (functions), as a rule, is written above the arrows. Construction of the functional diagram is especially important for the analysis of complex systems with a large number of elements and functions.

Construction of the functional diagram is convenient for monitoring of unwanted functions and the state of the model after trimming when the function analysis is repeated. Let us construct a functional diagram for the model, which was considered earlier. This diagram is shown on Fig. 4.

The elements of the considered model are located in the same plane, so the construction of the functional diagram does not cause difficulties, however, when it comes to circuits which elements are placed in three planes OX, OY and OZ, it becomes necessary to adopt new rules due to the need to transform the usual three-dimensional space into a two-dimensional space.

**Function diagram generation. Common principles.** In order to continue this study, we develop a two-dimensional model into a three-dimensional one. To do this, we add several elements in the direction of the axis OY (see Figure 5).

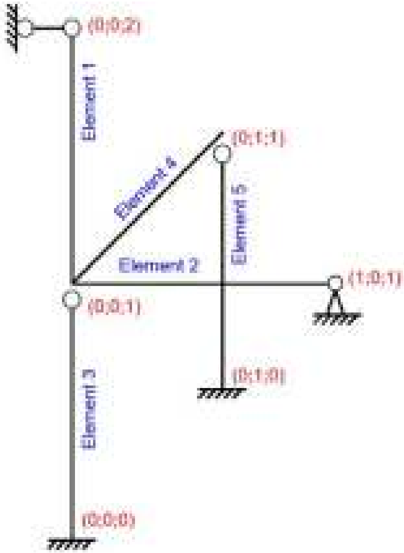



Figure 5
3D framed scheme

To place elements in the form of blocks in a functional diagram we need to group all the elements of the model according to a common principle. For this principle the Z coordinate of the lowest point of each element was chosen.

For the following categories of elements, most commonly encountered in framed building systems, the following levels are used in the analysis:

*Column- Zcolumn1;*
*Foundation - Zfoundation;*
*Floor slab - Zslab;*
*Beam - Zbeam1 or Zbeam2 (Choose a lower value)*

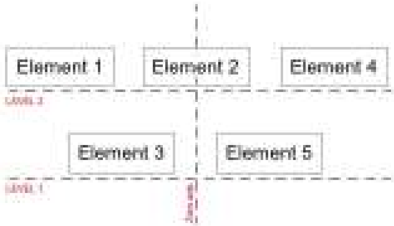



Figure 6
Placement of elements in a function model

| Exposed element / Influencing element | Element 1 | Element 2 | Element 3 | Element 4 | Element 5 |
|---|---|---|---|---|---|
| Element 1 | | - | C | - | - |
| Element 2 | B | - | C | - | - |
| Element 3 | - | - | - | - | - |
| Element 4 | B | - | C | - | C |
| Element 5 | - | - | - | - | - |

Figure 7
Matrix of functions

1. Let us take the length of each element of the model shown in Figure 5 is equal to 1m. The coordinates of the lower points of the elements are also shown in Figure 5;
2. Let us compose the table on the basis of the data from the model, in the first column of which the names of the elements are indicated and in the second one coordinate Z of the lower level of the element;
3. Let us group the contents of the table into levels equal to the Z coordinate, as shown in Table 3.
4. Let us place the blocks of the elements in the space of the diagram according to the detected levels. Elements are placed with an equal step symmetrically to the central axis (see Figure 6).

To create the arrows of interaction in functional diagram, let us consider the matrix of functions for the studied circuit. It consists of influencing elements vertically and of exposed ones horizontally. At the intersection of the horizontal and vertical axes are the functions of the acting element. It is necessary to read the matrix of functions from left to right, as indicated in Figure 7. Element 1 compresses Element 3. Thus, the arrow of interaction for interaction Element 1 - Element 3 will look as shown in Figure 8.

**Function diagram generation. Dynamo realization.** Implementation of this step by software is carried out by analyzing the elements of the BIM model.

1. The program extracts the coordinates of the bottom level of each individual element;
2. Based on the extracted data, the list of elements is divided into several sub-lists, all elements of the same list have a common Z coordinate. Each sub-list corresponds to a separate level in the functional diagram;
3. Next, a block family is created that is placed on the drawing view in Revit with an equal step along X in an amount equal to the number of elements in each separate sub-list and with an equal step along Y in an amount equal to the number of sub-lists;

Table 3
Position of elements

| Level in FD | Element's name | Z coordinate(m) |
|---|---|---|
| Level 1 | Element 3 | 0 |
| | Element 5 | |
| Level 2 | Element 1 | 1 |
| | Element 2 | |
| | Element 4 | |

4. The element name is written to the block parameter.

Thus, the functional diagram for the circuit will look like on the Figure 8.

In order to create arrows of interaction in Dynamo, a matrix of functions was used. The program performs the following algorithm of actions:

1. The matrix of the model function is analyzed. A list with "Element - Function - Element" elements is created;
2. On the functional diagram elements are searched for by name according to the list obtained;
3. A family is created based on the arrow line in Revit. A parameter is added to the family to which the function will be written later,
4. An interaction arrow is created from the influencing element to the exposed one. The arrow is created as a line in two clicks from one object to another. In order to find the point of the first and second clicks, the coordinates of blocks of the influencing and exposed elements in the list are tracked;

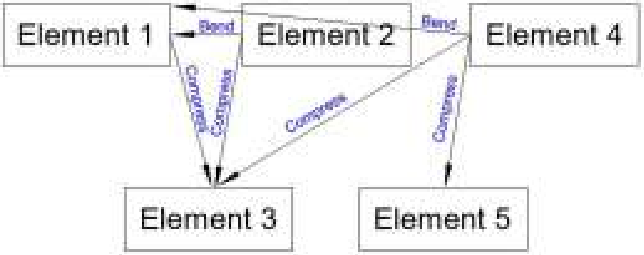



Figure 8
Function model of a BIM model of a framed structure

5. The function of the influencing element is written above the arrow.

### *Ranking*
Ranking is an analysis that precedes the main objective of functional analysis - trimming. It implies a discrete examination of the elements of the model under a number of criteria according to which the elements are assigned a rank. The higher the rank of the element, the higher its significance in the model and the higher the chance of remaining in the model after the trimming.

According to different ranking methods, the criteria for evaluating the model have different scales of evaluation: alphabetic, numerical and so on. The numbers obtained as a result of the ranking for the element are summed up, the letters are added to the number and can have their significance.

### *Formation of the first ranking rule*
**Closeness to a target function.** The work of the elements in the framed building system is, as a rule, reduced to one final goal. For example, the work of the beams is reduced to keeping the slab plate. In turn, these beams are supported by columns. From the above, we conclude that the work of beams and columns of the first floor is reduced to providing a stable position in the space of the first floor slab. Floor slab is needed in order to carry a live load, which includes the weight of people, equipment, etc. Thus, it can be said that the slab is the key element necessary to achieve the ultimate goal of design and operation.

We have combined all the elements into three main groups according to the degree of closeness to a target function:

1. Elements of category “A” - high importance of elements;
2. Elements of category “B” - the average significance of the elements;
3. Elements of category “C” - low significance.

In the framed systems, the following elements have been identified, the function of which is targeted, that is, the elements cannot be trimmed:

1. Foundations
2. Floor slabs
3. Roof slab

The listed elements belong to the first group and are marked with the letter “A”.

Elements of the second group are elements which work is aimed at helping to achieve a target function. These elements are marked with the letter “B”. These elements also have high significance in the model. Such elements can be identified through the following criteria:

1. The element interacts with the element that performs the target function;
2. The Z coordinate of the bottom point of the element is below the coordinate of the lowest point of the element that performs the target function

Elements that do not interact with the “target elements” or have the Z coordinate higher than the Z coordinate of the target element, refer to the third group and are marked with the letter “C”.

### *Formation of the second ranking rule*

**Harmful functions.** An important factor in the work of a structure is the function of its individual elements. Along with target functions, there are so-called harmful functions caused by certain factors. For example, the rigid connection of two columns provokes the appearance of compression and bending forces, and the hinged one - compression. The bending force will be harmful. The presence of harmful functions will also cause a decrease in the rank of the element. The following types of functions are assigned a certain number of points:

1. Compress - (-1);
2. Bend - (-2);
3. Torque - (-3)

Table 4
The results of ranking

| Element's name | Closeness to the target function | Presence of negative functions | Presence of positive functions | Overall result |
|---|---|---|---|---|
| Element 1 | C | -1 | | -1C |
| Element 2 | A | -3 | | -3A |
| Element 3 | B | | 6 | B+6 |
| Element 4 | C | -3 | | -3C |
| Element 5 | C | | 2 | C+2 |

### *Formation of the third ranking rule*

**Useful functions.** The third rule is the opposite to the second rule and take into account only positive functions, which include:

1. Stretch - 1;
2. Hold - 2.

Consider the circuit shown in Figure 5, let Element 2 performs a target function in the model. We will analyse it according to the rules presented above.

1. According to 1st prince of ranking, Elements 3 gets "B", because Element 2 has target function and Element 3 holds Element 2, Element 2 gets "A";
2. According to 2nd prince of ranking, Element 2 bends Element 1 and compress Element 3, Element 4 bends Element 1 and compress Element 3, so Elements 2, 4 gets (-3), Element 1 compresses Element 3 and gets (-1);
3. According to 3d prince of ranking, Element 3 and Element 5 have positive functions. Element 5 holds Element 4 and Element 3 holds Element 1, 4, 2

The results of the total ranking are given in Table. 4.

The rank of the elements is not the sum of the scores based on the results of evaluating the elements on three grounds. The rank of the element is represented as follows:

$$R = (-X)N(+Y) \quad (1)$$

where X is the total number of harmful functions performed by the element;
N - the letter designation of the group;
Y - the total number of positive functions performed by the element.

### *Trimming*

Trimming is the main goal of functional analysis. At this stage non-functional elements are "cut off" and the useful functions of the elements are transferred to other elements of the model.

Rules of trimming:

1. Removal of elements occurs only if they fall in the category "C";
2. Elements with harmful functions are highlighted in the model

After trimming, the circuit is transformed into the following:

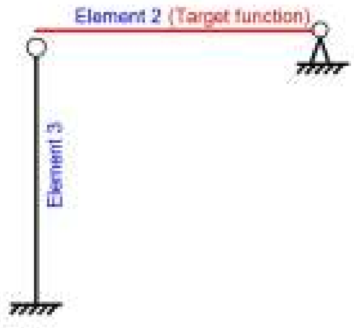



Figure 9
Circuit scheme after trimming

## CONCLUSION

In this research we obtained a result that allows designers to automatically analyse and exclude non-functional elements from the model and propose a solution to prevent unfavorable functions of its elements. The key advantage is that this analysis is being done on early design stage before deep structural analysis which is time and cost consuming.

## SUGGESTIONS FOR FURTHER WORK

After the function analysis has been done, we propose to analyse the trimmed model using another TRIZ tool called Contradiction analysis. This part of analysis is the final part of the conceptual design phase. Contradiction analysis includes 40 techniques to eliminate technical contradictions. A technical contradiction in TRIZ is a situation where an attempt to improve one characteristic of a technical system causes worsening of another. For more effective organization of use of techniques a special table has been developed. There are the characteristics of technical systems need to be improved and characteristics that are worsened. At the intersection of the table graphs the numbers of solutions are indicated which help to eliminate the arisen technical contradiction. For construction field the revision of all proposed technical characteristics was carried out in order to identify the methods most suitable for use in the construction area. Our goal is to implement these tools in the design process. To achieve this goal it was decided to link the possibilities of this tool with categories of the model's elements.

The software implementation of this tool should be implemented as follows:

1. Selection of the model element;
2. Selection of the worsening parameter;
3. Selection of the improving parameter;
4. Obtaining a number of solutions to the technical contradiction for the category of selected element.

Implementation of the 2nd and 3rd steps of the presented algorithm will be performed using Windows Form selection windows. Getting information about the element, analyzing the input data and output the result of the analysis will be done using the Dynamo visual programming tool based on the Revit software.

## ACKNOWLEDGEMENTS

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# CAAD EDUCATION - TOOLS

# Contrasting Publications in Design and Scientific Research

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*This paper explores the differences between `design' and `science' papers published at eCAADe conferences through use of automatic classification. The latter is conducted using a set of differentiating criteria (e.g. number of figures determines a paper to be either `design' or `science') which are calibrated with the help of a manual selection of papers from eCAADe 2015 as ground truth. Results show that we predict 83% of the papers correctly; experiments using data from eCAADe 2014 until eCAADe 2016 furthermore show the stability of our results. However, we are not so much after the development this automatic classification but rather want to characterize the two research cultures of design and science. This is achieved by taking a close look at the differentiating criteria, which can inform tools such as ProceeDings over possible future directions and adaptation needs.*

**Keywords:** *Differentiation, Design, Science, ProceeDings, CumInCAD*

## INTRODUCTION

Architectural conferences are inevitably caught between two very different research cultures: They must bring both “science” and “design” together, a process which is not seldomly done by having two proceedings volumes (one for the former, one for the latter). However, both ways differ with regards to the content (e.g. more or less use of figures or references). Another important difference is the way of referencing and giving credit (think: impact). To carefully characterize and contrast these two different cultures, with the expressed intent of being able to further develop and adapt the content guidelines of conferences in our field, we have conducted a study in which content content analysis was applied to papers:

- We exported all papers from ProceeDings (Wurzer, Martens and Grasl 2014), the web-based paper editing system eCAADe uses since 2014, and built up a publication graph (see section ‘Base Data’). Since ProceeDings stores each paper in a structured manner (e.g. figure, paragraph, enumeration, bullet point, reference to an article, etc.), there was a treasure-trove of semantic input which could be used to build up criteria that distinguish science from design. Additional metadata was retrieved from CuminCAD (Cumulative Index on CAD; Cerovsek and Martens 2016) so as to provide not only data about each individual paper but also about papers being referenced.

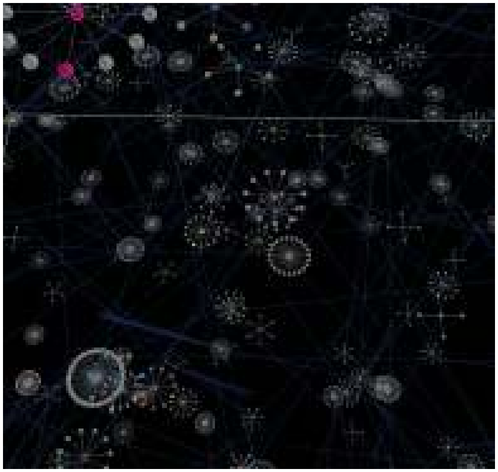

Figure 1
Graph representation of papers (NetLogo 3D showing papers and references as nodes, citations as edges).

- In order to automatically tag each paper as 'science' or 'design', all papers of eCAADe 2015 were first classified manually (see section 'Calibration', subsection Ground Truth). Most of these papers do not fit directly into these categories but are mixtures (n=148; science=24; design=22; other=102; see Figure 2). However, since the manual selection was carried out in a double-blind process, it is clear that only the most characteristic and undisputed examples were selected as ground truth.

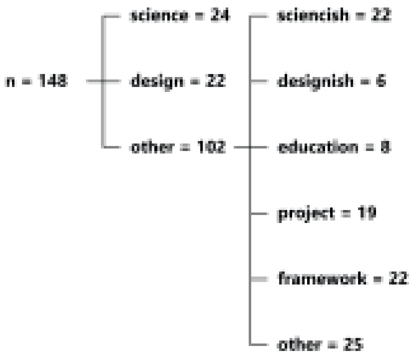


Figure 2
Decomposition of all eCAADe 2015 papers into science, design and other.

- Everything that is measurable in a paper and the graph it is embedded into can potentially serve as basis for a classification. However, there were far too many of these variables (in exact terms: 110) to be able to analyze each of these individually, even though much work was done in a statistical pre-study. Instead, we used a brute-force parameter sweep to find all variables which can serve as differentiating criteria (see section 'Calibration', subsection 'Fitting'). Only criteria which have predictive certainty - i.e. at least 65% of all papers can be explained using that measure, are selected as basis for classification.
- Applying all selected criteria yields a list of tuples of the form *(classification, certainty)*. Through application of majority voting, we find the most probable classification for each paper (see section 'Automatic Classification'). Furthermore, an overall measure for the quality of this classification is given by the mean of all certainties of the winning class. Application of this method on a publication graph built up from all papers of eCAADe 2014 and 2015 shows that our method can classify 83% of all papers within the ground truth correctly (see section 'Results'). The rest of the papers are classified as 57% science, 43% design. Applying our measure further, we find a fairly constant rate of 55% science vs. 45% design to be present in eCAADe even if we additionally take all papers of eCAADe 2016 into our publication graph.

However, the reason behind this paper lies not so much in the development of an automatic classification for science or design but rather in the question of *what motivations we can infer from the classifying variables*. Ample space is devoted to the discussion of these factors, since they can serve as basis for future development for tools such as ProceeDings (see section 'Discussion', subsections 'What scientists want' and 'What designers want').

## BASE DATA

This paper is based on structured data originating both from ProceeDings as well as CumInCAD:

- ProceeDings stores each paper as xml file. The different kinds of paragraphs (paragraph, bullet point, enumeration, figure, table, etc.) are technically represented as tags. These may be highly structured - as in the case of references or they might contain only text (see example further down in the text). It is the job of the analysis program to transform each paper into a graph representation (see Figure 1): For each paper, a node is allocated. The node is attributed with all metadata, such as: authors, the sequence of paragraph types used (e.g. title subtitle abstract keywords ...) and lengths of these paragraphs, in characters. Furthermore, all references of the paper are also allocated as nodes. For references that also exist in CumInCAD, there is additional metadata which can be attributed (id, authors, year, title, source, keywords, series etc.). However, the usual case is that we know only what was entered in the references, i.e. authors, title, source and year.

```
block with nested structure:
<inproceedings>
  <authors>
    <author>
      <initials>JRR</initials>
      <surname>Tolkien</surname>
    </author>
  </authors>
  ...
</inproceedings>

block containing only text:
<title>This is a test</title>
```

- Papers are linked to their references via edges. A reference is said to be *shared* if more than one paper references it. Since we deal with multiple conference year (eCAADe 2014-2016), it can also be that a paper references a previously-published paper. In that case, we check whether there is a common author in both paper, so as to account for self-citations (which can also be thought of as a continuation of work).
- In a further analysis step, our approach looks at each paragraph of a paper. It performs a content analysis, which considers each paragraph's length in proportion to the total paper body (or, in case of the references, the reference section). Furthermore, it counts the amount of standard headings, i.e. "introduction", "related work", "previous work", "background", "contribution", "idea", "conclusion(s)", "discussion", "motivation", "research question" and "methodology" - which are typical elements of every scientific paper and can thus distinguish a design paper from a scientific one to some extent.
- Manual classification into design or science is another piece of metadata that can be attributed to paper nodes. An in-depth description of the classification's logic is given in the next section (see 'Calibration', subsection 'Ground Truth').

## CALIBRATION

### *Ground Truth*

To classify papers into 'science' or 'design' is a hard task. We performed a double-blind selection process on all papers of eCAADe 2015 and only took papers into either category if both reviewers agreed. The logic behind the selection was as follows:

- Scientific papers must present an idea or hypothesis which is proven in the paper's main body. The presentation of the proof must be reproducible, i.e. there must be enough information regarding the process and input data (if this in the scope of a paper) such that it is clear how the authors came to a certain conclusion. Supporting material - such as algorithms, tables and illustrative figures, is indicative for such a kind of work. Furthermore, obtained results must be discussed and set into a perspective (think: relevance, quality of results and so on). Failing to produce one of these points makes a paper "sciencish" but not scientific (see Figure 2).

- Papers that are purely "design" bring forward inspirational work - typically in the form of built structures which are presented as such. They are not concerned with formal proof but present original work following an artistic logic. Most often, these papers can be spotted already by regarding the images - which will typically be photos of pavillons, installations, exhibitions and so forth. Furthermore, papers of this category often cite related artists in their figure captions (e.g. "work by ....", "photo by ....") but not in the references. Any attempt to put such a paper on a more formal basis - such as description of technology used, structural analysis of the end product(s) or so forth, makes a paper "designish" but not "design" in our classification (see Figure 2).

Further categories included project descriptions ("we did this, afterwards we did that"), education ("the students produced....; the workshop was about ....") and frameworks ("using our program, it is now possible to ...."). Even then, we were unable to capture all the knowledge that is present in the eCAADe conference, and have thus included an "other/other" category (see Figure 2).

Our classification stated that 24 papers were clearly "scientific" and 22 papers clearly "design" in the above sense. All further categorization was conducted for the sake of completeness, but did not enter our analysis. Papers other than design or science were marked as unclassified, so as to exclude them from the ground truth.

### *Fitting*

How does one select measures that have a high predictive quality with regards to whether a paper is "science" or "design"? The naive approach would be to come up with some intuitive rules, such as: Papers in design have a high number of graphics while scientific papers are generally text-based. However, such an approach turned out to be not adequate for classifying all papers, and further analysis showed that the variables we have are largely insignificant if we talk about statistics: 46 papers (ground truth) are not enough to determine a classification based e.g. on median, lower quartile and upper quartile. The second difficulty lay in the mere number of variables we can measure (110), which proved to be difficult to handle manually. Thus, we used an automatic variable selection and fitting process which gave us good results despite our limited set of ground truth samples:

- We assume that there is a differentiating threshold between science and design for every variable. This threshold is two-fold (refer to Figure 3): It is either so that all scientific papers have less than a certain value and all design papers have more or are equal, or vice versa.


Figure 3
Finding a threshold such that the amount of matched papers is maximal.

- To find the best threshold, we have to search through all possible values a variable might take. If its domain is [0, 1], our algorithm starts at 0 and ends at 1, incrementing by 0.01 (1 percentent) in every step . In all other cases, we have to search in between *(min - 1)* and *(max + 1)* since the variable is in the domain [0 ... N]. The best threshold is the one that can categorize the highest amount of papers found in the ground truth correctly. A formal description of this algorithm is given in due course as pseudocode.

```
======================================
PSEUDOCODE
======================================
fit all variables() {
  for each variable {
    if domain is [0..1] {
      fit(variable,0,1,0.01)
    } else { // domain is [0..N]
      fit(variable,
          min value of variable - 1,
          max value of variable + 1,
          1)
    }
  }
}

fit(variable, start, end, step) {
  n = number of papers classified '
   ↪ design' or 'science'
  best threshold := start
  best correctness := 0
  best estimate := science left,
   ↪ design right
  best certainty := 0
  for threshold := start to end
   ↪ incremented by step {

    // TRY SCIENCE LEFT, DESIGN RIGHT:
    correct = 0
    for each paper {
      seems to be science := variable
       ↪ < threshold
      seems to be design  := variable
       ↪ >= threshold
      if seems_to_be_science is not
       ↪ seems_to_be_design {
        // (CANNOT BE BOTH SCIENCE AND
         ↪  DESIGN)
        if (seems_to_be_science and
         ↪ ground truth says science)
         ↪  or
          (seems_to_be_design and
           ↪ ground truth says
           ↪ design) {
          // (PREDICTION AGREES WITH
           ↪ GROUND TRUTH)
          correct := correct + 1
        }
      }
    }
    if currect > best-correctness {
      best threshold := threshold
      best correctness := correct
      best estimate := science left,
       ↪ design right
      best certainty := best
       ↪ correctness / n
    }

    // TRY DESIGN LEFT, SCIENCE RIGHT:
    correct = 0
    for each paper {
      seems to be design := variable <
       ↪  threshold
      seems to be science  := variable
       ↪  >= threshold
      if seems to be science is not
       ↪ seems to be design {
        // (CANNOT BE BOTH SCIENCE AND
         ↪  DESIGN)
        if (seems to be science and
         ↪ ground truth says science)
         ↪  or
          (seems to be design and
           ↪ ground truth says
           ↪ design) {
          // (PREDICTION AGREES WITH
           ↪ GROUND TRUTH)
          correct := correct + 1
        }
      }
    }
    if currect > best-correctness {
      best threshold := threshold
      best correctness := correct
      best estimate := design left,
       ↪ science right
      best certainty := best
       ↪ correctness / n
    }
  }

  // (result is in best threshold,
  // best estimate, best certainty)
}
```

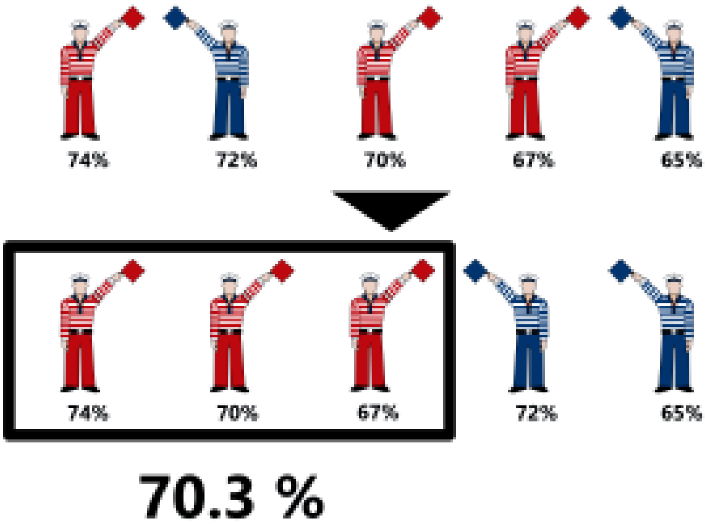

Figure 4
Papers are evaluated by a set of criteria, each yielding a category ('design' or 'science') and a certainty in percent. The overall category is the one with most votes, the overall certainty is given by the mean of certainties in that category.

- Depending on the amount of papers where prediction and ground truth match, we get a "certainty". Technically, this is the number of matching papers divided by all papers (see previous algorithm). By ranking these certainties as in Table 1, the final set of measures is determined. A measure that is 50% certain would make no sense, since it would equally predict and mis-predict. Thus, we have taken only measures above 65% certainty into account.

## AUTOMATIC CLASSIFICATION
Evaluating all criteria given in Table 1 yields tuples of the form *(classification, certainty)* for every one of them (see Figure 4 for a visualization). Through majority voting, we can then obtain the overall classification. Furthermore, all measures of that class have a certainty, the mean of which forms the overall certainty for the classification.

This certainty is less informative than one would assume: It is typically the mean of the certainties of all criteria - which in our calibration amounts to 68%. Deviations from this mean indicate a better or lesser degree of prediction, which could be used to further indicate the quality of the classification e.g. to end-users.

## RESULTS
Table 2 gives an overview of the experiments conducted with our data. In the calibration scenario, 46 papers from eCAADe 2015 were classified with 83% accuracy. The experiment was repeated for all other papers of eCAADe 2015. Since this dataset does not contain any papers which are purely 'design' or 'science', one would assume that the classification gives neither of both. However, this is not the case since the classification *will* categorize into 'design' or 'science' regardless of whether that makes sense, which is certainly one of the shortcomings of that approach. In that case, 57% of the papers were classificed as 'science' and the rest as design. This is a typical rate, which we also saw when repeating the experiment with data from eCAADe 2016 (see again Table 2).

Table 1
Measures ranked by certainty.

| Measure | Criterion | Rule | Domain | Certainty |
|---|---|---|---|---|
| 1 | Share of figures vs. other blocks in paper body | if value < 0.17 then science else design | [0..1] | 74% |
| 2 | Number of references | if value < 16 then design else science | [0..N] | 72% |
| 3 | Characters in paper body divided by number of figures plus 1 | if value < 2500 then design else science | [0..N] | 72% |
| 4 | Measure 3 divided by number of characters in body | if value < 0.109 then design else science | [0..1] | 70% |
| 5 | Number of figures in paper | if value < 9 then science else design | [0..N] | 70% |
| 6 | Share of heading 1 vs. other blocks in paper body | if value < 0.119 then science else design | [0..1] | 70% |
| 7 | Number of article references | if value < 5 then design else science | [0..N] | 70% |
| 8 | Share of heading 1 containing standard titles* vs. total number of heading 1 | if value < 0.34 then design else science | [0..1] | 70% |
| 9 | Number of characters in the whole paper | if value < 22500 then design else science | [0..N] | 67% |
| 10 | Number of characters in the references section | if value < 2000 then design else science | [0..N] | 67% |
| 11 | Number of tables in paper body | if value = 0 then design else science | [0..N] | 67% |
| 12 | Share of characters in abstract vs. characters in the paper's body | if value < 0.06 then science else design | [0..1] | 67% |
| 13 | Number of inproceedings references | if value < 2 then design else design | [0..N] | 67% |
| 14 | Number of blocks in paper | if value < 65 then design else science | [0..N] | 65% |
| 15 | Number of characters in paper body | if value < 18500 then design else science | [0..N] | 65% |
| 16 | Characters in paper body divided by number of figures and tables plus 1 | if value < 2500 then design else science | [0..N] | 65% |
| 17 | Measure 16 divided by number of characters in body | if value < 0.109 then design else science | [0..1] | 65% |
| 18 | Number of figures plus number of tables | if value < 9 then science else design | [0..1] | 65% |
| 19 | Number of formulas | if value = 0 then design else science | [0..N] | 65% |
| 20 | Share of the number of characters contained in paragraphs vs. total characters in paper body | if value < 0.67 then science else design | [0..1] | 65% |
| 21 | Share of characters in figure captions vs. chars in paper body | if value < 0.09 then design else science | [0..1] | 65% |
| 22 | Number of thesis references | if value = 0 then design else science | [0..N] | 65% |
| 23 | Share of article references vs. number of references | if value < 0.27 then design else science | [0..1] | 65% |
| 24 | Share of chars contained in article references vs. chars of reference section | if value < 0.28 then design else science | [0..1] | 65% |
| 25 | Share of references available in CuminCAD vs. number of references | if value < 0.23 then science else design | [0..1] | 65% |

| Scenario | Base Data | Investigated Papers | Science | Design | Remarks |
|---|---|---|---|---|---|
| 1 | graph consisting of eCAADe 2014 and 2015 papers together with all referenced papers. | all papers which were manually attributed 'design' or 'science' (ground truth, n=46) | 22 (48%) | 24 (52%) | comparison of manual classification with automated classification: 38/46 papers categorized correctly (83% accuracy). mean certainty 68%. |
| 2 | same as Scenario 1. | all papers excluding the ones of scenario 1 (n=231) | 131 (57%) | 100 (43%) | mean certainty: 68% |
| 3 | same as Scenario 1. | all papers (n=277) | 153 (55%) | 124 (45%) | mean certainty 68%. |
| 4 | graph of eCAADe 2015 and 2016 papers together with their references | all papers (n=289) | 160 (55%) | 129 (45%) | mean certainty 67% |
| 5 | eCAADe 2014, 2015 and 2016. | all papers (n=418) | 231 (55%) | 187 (45%) | mean certainty 67% |

Table 2
Conducted experiments (combination between loaded base data and nodes selected for analysis)

## DISCUSSION

Even though we can predict 83% of all papers in eCAADe 2015 correctly, it is clear that our calibration data is not statistically significant and we were not able to use that as general classification. However, in the scope of eCAADe 2015, we can nevertheless interpret the measures that helped us match all papers as intent of the authors, and infer some general remarks for the whole conference. If and to what extent these statements may also be applicable to other "CAAD" conferences remains to be studied in the future.

### *What designers want*

**A picture gallery.** The unusually high share of figures in the paper body (>= 0.17) tells us that there is a need for many figures. ProceeDings is currently very limited with regards to its abilities in layout, since figures may only be placed in a column or at the top/bottom of the page, spanning two columns. A further option which we also provide, the positioning of figures on an own page, might be a good match for this urge to put many figures into a paper: Combining many pictures into a single figure by use of an image editing software [or perhaps a "picture gallery" block which is to be implemented in the future] could let authors use even more photographic material without having to care about placement.

**Credits in addition to references.** To say that authors of design papers do not reference (number of references < 16) would blatantly ignore the fact that referencing works differently in those cases. Looking through these papers, one can see that most figure captions contain a part mentioning some source (typically the designer or architect who has created the structure or artwork being displayed). Thus, it might be beneficial to include an additional citation type [perhaps named *credit*], which can be counted in the same way as references. Another observation is that designers use more references from CumInCAD, so it might be beneficial to include an "insert reference from CumInCAD" functionality into ProceeDings in the future.

**Less text in the paper body, more in the abstract.** It is misleading to think that design papers have less text. The measure *(characters in a paper divided through the number of images plus 1)* only states that ratio between text and figures is somewhat smaller that in those papers, which is clear when one thinks about the purpose of such papers: Scientists use figures merely as illustration, while designers put figures in because they are the actual content and source of inspiration for others. However, the typical guidelines of conferences such as eCAADe state that figures should be used only in the former sense. It might be possible to devise another type of publication [maybe called a *graphical entry*] which capitalizes on the visual expression sought by designers. Other conferences furthermore have short papers accompanying posters, which could turn out as possible route in that sense. A further measure supporting this observation is the length of the abstract in comparison with the rest of the paper: Designers seem to like longer abstracts stating their motivation, while scientists try to use that only as a summary and expand the whole paper in the introduction.

**Less structure, more freedom.** There is a lack of standard headings when it comes to design papers. From looking through the papers, it is evident that this is a result of not presenting research in the classical sense - from 'introduction' to 'conclusions' - but rather describing the development of a final product and its reception e.g. in exhibitions. As eCAADe is also about education, it might be reasonable to adapt the content guidelines so as to accommodate reports of this nature. This might in turn also benefit the papers which we categorized as "project descriptions" or "education", which have a similar way of presenting their content.

### *What scientists want*

**Text, text, text.** Scientific papers have a high share of text in comparison with other material in the paper body (< 0.17) . The text import wizard of ProceeDings is clearly geared towards this way of writing, as is LaTeX: A low amount of text makes it difficult for to position figures, which is causing major complications during layouting.

**Tables and formulas.** Formulas are indicative for research papers, as are tables for giving supporting evidence . Both paragraph types are currently quite limited, since ProceeDings currently converts formulas from ASCIIMath [1] into LaTeX for compilation and allows only images as tables, which prohibits floating across multiple pages ["longtable" in LaTeX terms]. The first shortcoming could be alleviated by using the graphics generated by the ASCIIMath preview directly, the second by using a genuine table paragraph type. This type already exists in ProceeDings but was considered a bit too clumsy (it comes with a table editor that is fairly intuitive, however, rows and columns have to be added consecutively and it takes quite a time to paste text into these). One could offer both possibilities an have the authors choose either of them, and perhaps also implement an import from spreadsheets.

**A lot of references.** Scientific papers excel at their use of references: In almost every category (notably except URLs), scientists use more and higher-quality references (articles and proceedings rather than books). Currently, the import of references into ProceeDings is limited to BibTeX, which may be a limiting factor. However, one could invest some effort into text recognition, since it can be expected that authors would want to copy-and-paste citations from the web into our system. Another option would be to directly connect to citation indices such as CumInCAD, Google Scholar or CiteSeer, in order to get citation metadata quicker and in a more accurate fashion.

## RELATED WORK

Instead of presenting the related work in between the introduction and the idea, we have opted to put it here since the reader now knows about the extent of our work and can thus relate to this section more easily.

Autodesk Research has produced a similar research effort in their paper "Citeology - Visualizing Paper Genealogy" (Matejka, Grossman and Fitzmaurice 2012). The authors establish a visualization in which a selected paper can be traced back to the work it cites and the work these predecessors cite and also forth. In contrast to that effort, we have concentrated on content analysis and inference of some remarks concerning our conference, without the intended goal to propose a novel computational approach.

Cerovsek and Martens (2004) have used CumInCAD to build up a (chronological) citation graph and to infer statements on scientific information exchange, for example that the CAAD field uses "many more references" (p. 15) than other fields (taken from Open Citation Project 2002), and that most scientific ideas evolve over a period of 2 years (Figures 7 and 8 on p. 11).

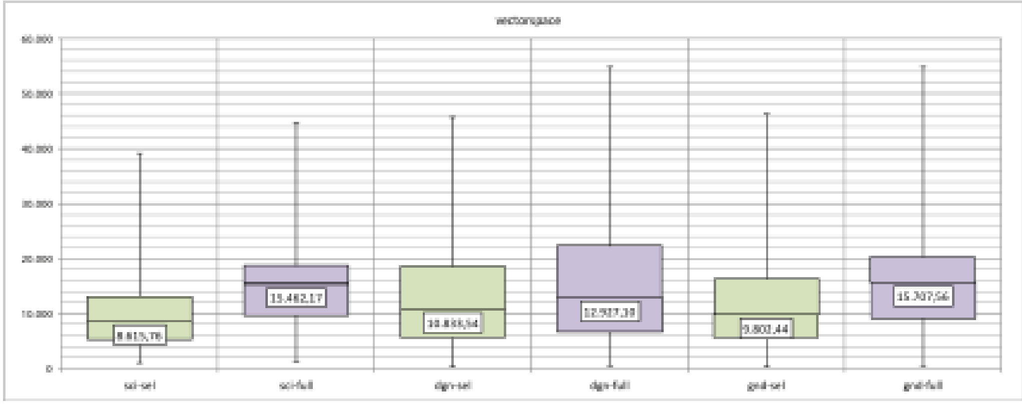


Figure 5
Relative euclidean distance between ground truth papers (within sci=science, dgn=design, or gnd=all) using our measures to build up a vector space (sel=top 25 selected measures as in Table 1, full=all 110 measures).

## FUTURE DIRECTIONS

One may obtain a vector for each paper by applying either all measures or just the ones selected for classification as given in Table 1. The resulting vector space may be used to calculate the euclidean distance between papers of the ground truth (see Figure 5). Results show that distances between science papers are less spread than design ones, and change significantly depending on whether we use all measures or just the ones selected for classification (see median of sci-sel vs. sci-full in Figure 5). As outlook, one could furthermore perform clustering, identify representative parsimonious "aggregated paper features" or conduct shopping basket analysis (people who read paper x also read papers ...), which would certainly yield interesting results.

## CONCLUSIONS

We know from practice that the research cultures of design and science need different modes of reporting about their work. To put this statement on a firmer basis, we have been conducting a study on all papers of eCAADe 2014-2016, using ProceeDings and CumInCAD as our data basis. Through use of automatic categorization into science and design, we were able to extract metainformation for both types. The results have been discussed and interpreted as possible future extension points for the ProceeDings system. As side-effect, we are now also able to categorize papers into 'design' and 'science' volumes, which is typical at least for the eCAADe conference.

## ACKNOWLEDGEMENTS

The team would like to acknowledge the contribution of Claudia Lorenz who invested valuable time in numerous discussions regarding statistical relevance.

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[1] http://asciimath.org

# The architectural gadget factory

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*The paper describes a course for architecture students in which by inventing things and products students enhance theirs skills in rapid prototyping, programming and manufacturing. A didactical background is specified in this context to prepare the students for a changing role in a broader professional environment. Different projects as outcomes of this course are described in detail.*

**Keywords:** *rapid prototyping, CAM, fab lab, DIY*

## INTRODUCTION

The project described is part of the architectural curriculum and integrated in the Virtual Engineering Laboratory (VEL) at our department. In the VEL we introduce on the one hand students to technologies, methods and applications of rapid prototyping (RP) processes, as it is common practice in many schools. Beyond this, we offer courses for graduate students where we extend the focus on tools and methods from other technical disciplines like electrical engineering, computer science and mechanical engineering. In this context we report on finished and ongoing projects in which architecture students have invented, planed and implemented different constructions, machines and setups in the broader sense of the popular open source fabrication laboratories (fab labs). The items the students have invented are in some cases close to architectural topics but can also fulfil requirements of everyday life or are built as a toy. We discuss the effects of this approach to the curriculum and identify positive impacts on creativity, construction capabilities, programming skills and interdisciplinary teamwork.

## DIDACTICAL BACKGROUND

The course format, its extent and the equipment of the Virtual Engineering Laboratory offer extraordinary possibilities to train students' skills in different ways. Since the students are free in choosing their topics, they are forced to position themselves in the fast changing and important environment of man-machine-interaction and technological developments. These processes strongly influence architecture and engineering in present and future. To handle their own tasks and to develop a product also helps to train organising a project in general, as they must collect all required sources, define a framework, set up a realistic timetable and resource management. Furthermore they have to find and involve external experts and work interdisciplinary to include knowledge and advices they are not able to acquire in the available time frame. The course format and the expected results encourage the students to work highly creative and unconventionally. The course profile and its spirit is therefore described as both playful and challenging by the students.
In this sense it offers a stimulating environment,

where skills in programming, engineering and manufacturing can be trained together with project management capabilities and design tasks at the same time. Also students extends their chances to establish themselves in a broader professional environment outside of a classical architecture. These experiments are based on the shifts currently taking place within the architectural profession and their implications for the curriculum of architecture schools and faculties. As a critical appraisal of the professional circumstances of architects reveals, the process of change, besides being economically driven, is primarily traceable to structural factors that will permanently transform the relevant vocational framework. While the statistical evidence for these trends is unequivocal, the notion of crisis is avoided in evaluating the situation facing architectural practices. Rather, the focus is on taking the persistently adverse business climate as a starting point for a close analysis of the profession and its potential reorientation, followed by the development of various scenarios marking out a broader remit plus attendant educational concept. This involves a critical examination of the prevailing conception of the profession and the educational approach embodied by university courses, together with a delineation of the specific potential offered by architects. The Course definition moves away from the traditional understanding of architectural services and highlights the fundamental capacity of the profession for tackling complex problems, also outside the construction sector. The following hypotheses are put forward and examined:

- In future, over 50% of graduates in the field of architecture are destined to work outside the traditional professional environment.
- The complex nature of the construction process promotes the acquisition of soft skills amenable to application in fields outside the construction industry.
- The acquisition of soft skills is of greater importance in architectural training than the teaching of hard skills.
- The ability to handle knowledge and information efficiently constitutes the core competency required by architects. The versatile use of IT tools plays a pivotal role in the acquisition of this skill.
- Start-to-finish digital product data modelling, as a common communication platform between design team members, and the ubiquitous computer-assisted processing of information represent the technologies that will shape all future activities of architects.

## ENVIRONMENT

Besides classic tools of a RP-laboratory as laser cutter, 3D-printer and 3D-Scanner the VEL observes developments in the discount and mid-range price segment of the electro and toy industry. Due to the ongoing decline in prices of electronic equipment and a stunning improvement of performance at the same time, this market is full of affordable and also powerful sensors, controllers or other mechanical and electronical components. The most popular item in this context is the Microsoft / PrimeSense Kinect sensor which has become the fastest-selling consumer device ever since its introduction in late 2010. This development has caused a fast growing community of independent and creative hobbyists, who are able to realise objects and services of high quality and good effectivity with only a low budget. Very often these developers are organised in so called fab labs or hackerspaces to benefit from shared ownership of tools and from interdisciplinary discussions and support. This development is well described and predicted by Gershenfeld (2005) and Anderson (2012) and can be observe on platforms like instructables [1] or hackerspaces.org [2]. The described process is accompanied by a simultaneous observable simplification of man-machine-interaction and also in the use of software and software development kits (SDK). Especially easy to use SDKs and programming environments (i.e. Scratch, Processing) make it possible for non-specialized persons to construct, build and test prototypes and address therefore a broader range of possible users.

Figure 1
Sonification of René Magritte, Sánchez Ramos and González Goas

## PROJECTS

In the past three years students in this course have produce about 30 machines, products, games or inventions in individual or group work. They have used objects, instruments and tools, which are normally not applied in design or planning processes, but seem to have potential to transport their principles into architectural frameworks.

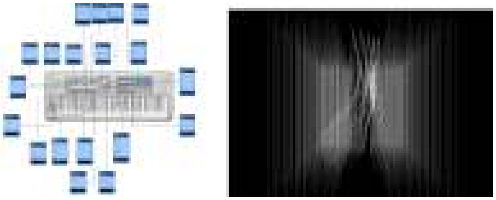

Figure 2
Connecting Midi signals with geometry, Maximilian Jüngling

These items have their origin in the games industry (e.g. MaKey-MaKey [3]), computer science (e.g. arduino [4]), electrical engineering (e.g. printed circuit board), medicine (e.g. brain computer interfaces), mechanical engineering, aircraft construction or other disciplines.

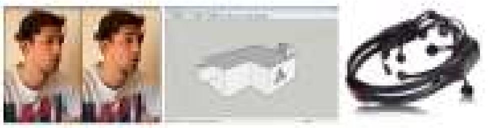

Figure 3
Mind controlled SketchUp, Arne Freyer, http://emotiv.com/

To realise connections between hardware components and user interactions the students have used easy accessible programming environments like Scratch [5], Processing [6] or built-in scripting languages. Typical results of finished projects are shortly described below.

### *See through sound*

The students used the invention kit MaKey-MaKey [3] based on Arduino technology [4] in combination with tools and methods of printed circuit board (PCB) production for electrical engineering to produce haptic representations of paintings for blind people. By touching this object, the item communicates with the visually impaired person by sending acoustic information and impressions about the painting itself. The connection between the MaKey-MaKey board and the sound systems was realised by using the Scratch programming interface [5] (see Figure 1).

### *Music and architecture*

The project combines a standard Midi Controller keyboard with an arbitrary 3D-geometry by connecting midi signals with specific geometrical parameters using the Processing environment [6]. By playing the keyboard the connected parameters of the objects (e.g. length, colour, position, etc.) change and lead to mutated spatial structures. The setup was then used to examine possible and meaningful relationships between musical and architectural elements (see Figure 2).

### *Drawing by brain*

The emotive brain computer interface (BCI, [7]) has been used to operate basic drawing functions of Google Sketchup modeller by probands thoughts. The student started his work by connecting the BCI to Sketchup using the Ruby application programming interface. He then analysed which classes of thoughts are suitable to keep up a firm connection between the BCI and the modeller. He tried then to combine this mental man-machine interaction with mimic elements and the built-in headtracker of the BCI (see Figure 3).

Figure 4
Telepresence robot in museums: prototype and evaluation (Jakob, Lennermann, Wolf)

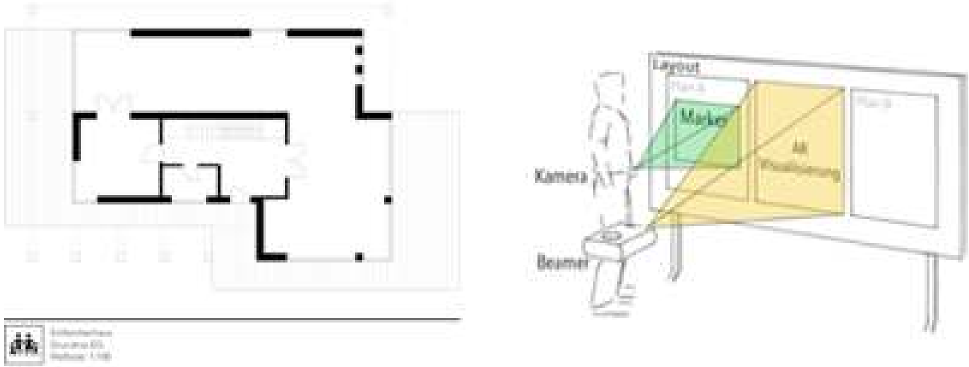


Figure 5
Augmented reality in presentation, Julia Schneider

### *Telepresence robotic system*
In this project students developed, constructed and evaluated a telepresence robot to grant disabled persons access to exhibitions in museums. They based their work on free available source code and affordable construction kits from the toy and game industry. After first tests with the prototype in the faculty building, they started to evaluate the concept with a more professional device in a local art museum.
In this environment the proband's feedback regarding the usability of the setup has been analysed and will be the background for future cooperation with museums in this context (see Figure 4).

### *Integrating augmented reality elements into classical presentations*
The student explored possibilities to combine augmented reality (AR) technologies with classical paper presentation of architecture. She used the AR SketchUp plugin by InglobeTechnologies [8] and tried to figure out, if geometric parts of the shown floor plans, sections or elevation on paper can be used as effective patterns and therefore as markers to be tracked by the plugin during presentations. To be able to act flexible she used a wireless webcam. It could be shown that common presentation of design project can benefit from integrated AR elements to enhance quality of dialogues between experts and laypersons (see Figure 5).

### *Living Rapid Prototyping*
This project is an interdisciplinary approach between rapid prototyping technologies and living materials in the field of biology. The thesis questions how the conjunction of digital and biological fabrication may look and to which opportunities this may lead for architecture in sense of biological and sustainable civil engineering.For all experiments the oyster mushroom (Pleurotua Ostreatus) was used in combination with wooden substrate offering shelter, nutrients and moisture. The focus lies on the mycelium roots and not on the fruiting bodies which normally refer to mushrooms. Test blocks made out of wooden substrate and mycelium were tested of their compressive strength. The results reveal that the compressive strength of mycelium blocks are comparable to the compressive strength of styrofoam and can be a sustainable substitute in some cases [9]. Despite the base material of mushroom substrate is made of wooden waste, it's not flammable [10]. Even exposed to a gas torch a mycelium block only starts to glow but not to burn. This is caused by the fact that

Figure 6
Cominig
3D-printing with
living materials,
Matthias Leschok

mycelium develops a dense polymer matrix while growing 2) and its cell walls are made of chitin 3), one of the most common biological building material which isn't flammable. To see if mycelium materials are usable on a larger scale a chair was designed and 3D printed. Therefore the enveloping surface of the chair was divided into segments. Afterwards the different parts have been filled up with mushroom substrate and have been weld.After a few days the mycelium starts to grow. Visible through the change of color, from brown (wood substrate) to white (mycelium). Waiting a few more days fruiting bodies are starting to grow searching for holes in the chair to break through and grow larger.From that point forward the chair was dried to get it's maximum load capacity. Only in a dried stadium mycelium roots have load bearing capacity, which finally makes the chair usable. The results of all experiments done in this thesis led to a final future vision, which combines artificial and man made structure with a natural cover. The symbiosis out of different knowledge sectors creates an optimised environment for humanity and nature.This vision shows, that with a minimal effort of initial investment (man-made structure) in combination with a living organism like mushrooms, a very complex result could be achieved. The man-made structure shows a reduced and industrial character, meanwhile the organic growth with its different growing processes rises very complex geometries with varying shapes. The structure is made out of different layers, each serving a different function. There is a reduced structure for load transfer, a control unit for the distributions of nutrients or water and a layer of fabric enabling the mycelium to grow on it. After temporarily fixing the structure the control unit starts to measure environmental conditions and adapt it's behaviour to it constantly. It's start pumping mycelium cells onto the fabric and enables specified growth on specified locations serving specified tasks. Is the building completely covered with mycelium the control unit stops feeding and starts the drying process [11], [12], [13], [14], [15] (see Figure 6).

## CONCLUSION

As positive impacts on student work and skills developmnet three effects could be pointed out as a first result: students have to observe technological developments and react on the appearance of new equiments, methods and principles . They have to be up to date about these developments and clear possible influences to architecture and design. Secondly the students get in contact with areas of expertise outside the architecture profession and can expand their possible fields of activities in the future. Alt last the project encourage students to train their creativity by inventing and creat object more intensively than in classical architecture projects.

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[15] https://vimeo.com/131353925

# The Role of VR as a New Game Changer in Computational Design Education

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*With the rapid advances in technology, virtual reality(VR) re-emerged as an affordable technology providing new potentials for virtual learning environments(VLE). Within the scope of this study, firstly a general perspective on potentials of VR to create an appropriate VLE is put forward regarding the potentials related with learning modalities. Then, VR as a VLE in architectural education is discussed and utilization of VR is revisited considering the fundamentals of education as how to enhance skills regarding creativity, furnish students to adopt future skills and how VR can be used to enhance design understanding as well as space perception and spatial relations. It is deliberated that instead of mirroring the real spaces, allowing students to understand the virtuality with its own constituents will broaden the understanding of space, spatial relations, scale, motion, and time both in physical and virtual. The dichotomy between physical and virtual materiality, the potentials and pitfalls in the process of transformation from real/physical to virtual - virtual to real/physical are discussed in relation with the student projects designed in the scope of Digital Design Studio course in Middle East Technical University. It is also shown that VR stimulates different learning modalities especially kinesthetic modality and helping students to develop creativity and metacognition about space and spatial relations.*

**Keywords:** *computational design education, virtual reality, digital tools, virtual learning environment*

Virtual reality, which is mostly correlated with advanced 3-D simulation and visualization technologies, has actually a long history dating back to 1930's to the first flight simulator designed by Edward Link. The bloom of the early wearable technologies in 1960's together with advances in computational power can be considered another turning point in VR. But the term VR in today's connotation is coined by Lanier who developed Visual Programming Languages(VPL) and related gears in 1987 [3]. Since then, Virtual Reality, Mixed Reality, Augmented Reality are the terms that are used to describe various technologies simulating/mimicking the real world in an immersive way.

The use of VR has found various implementations from entertainment to education and brought out from the closed doors of research centers, education facilities to daily life. The potentials of VR technologies have been well recognized in the entertainment industry such as cinema and gaming, in special trainings like flight, surgery or in exploring space, archaeology, museums, art and architecture and etc.

Starting from 2016, VR has re-emerged with new and innovative gears and applications such as Tilt Brush, Medium by Oculus, Minecraft VR, in a more affordable way. In addition to these, the increasing number of VR-ready applications in various areas makes its use more popular than before. Number of these implementations are increasing day by day with the rapid developments of software technologies accompanied by the enabling hardware. However, how VR will be benefitted in education is still a subject of research in various fields despite VR technologies brings in many innovative ways of its use.

## VIRTUAL REALITY (VR) AS VIRTUAL LEARNING ENVIRONMENT (VLE)

"How an ideal education should be" is another longtime debate among researchers and practitioners. It has been all acknowledged that education in any field is closely related with the current technologies. Yet, it is a fact that education cannot fully cope with the pace of technological developments due to its inertia. Although there are promising instructional technologies like online education, the internet as a medium of research and knowledge source, instructional videos on YouTube, distance learning, TED talks and etc., the use of VR and related technologies needs to be discussed further in education.

VR implementations are immersive experiences in computer generated/constructed environments aiming to improve cognitive skills and facilitating learning. Fleming and Mills in 1992 described the basic modalities of learning as visual, auditory, reading-writing and kinesthetic which today known as VARK [1](Fleming and Mills,1992). Since then, learning styles are subjects of discussion in development of curriculum and education strategies. Today, there are various models for learning styles yet, VARK is still a very widely used model. In this context, VR paves way to discuss more about its use in education more and more. VR experiences stimulate at least three modes of learning styles: visual, auditory and kinesthetic learning in the virtually designed environment. Among those learning modes, kinesthetic learning modality which is defined as "perceptual preference related to the use of experience and practice (simulated or real)"[1] can be achieved easily with today's VR technologies. Kinesthetic modality's key feature is the preference of learner to be connected to reality "either through concrete personal experiences, examples, practice or simulation" as stated by Fleming and Mills. In this modality, demonstrations, simulations, videos and movies of "real" things, as well as case studies, practice and applications can be included. Although kinesthetic learning is strongly linked with real experience, the "new real" of virtual reality offers new potentials in learning in a multimodal way.

VR is constructed by 3-D models, dynamic renderings, closed-loop interactions, inside-out perspective and enhanced sensory feedback (Wickens,1992). Therefore, when VR is used as a medium of learning/teaching replacing the real with the constructed, this new space and its spatial qualities require being more elaborately designed to achieve a better and more complete medium of education.

When virtual reality is employed as a virtual learning environment VLE, then in general four main components namely knowledge space, communication community, active action, and facility toolkit are required (Pan,et.al,2006). The "space" or "environment" in VR has an utmost importance since it is the "place of experience", or "medium of interaction" i.e. it is the immersive space mimicking the reality (Huang,et.al,2010) (Angulo and Velasco, 2014). Flight simulators, virtual surgery rooms, space travels, reconstructing the archaeological sites, museums are typical real-like examples of simulating different environments which enable learners to be actively engaging users and promoting active learning.

Most of the environments or event spaces in VR implementations are developed by mirroring the real ones through dynamic renderings. In this transformation, the constituents of the physical space are replaced by the ones in the virtual realm. Any feature related with materiality is depicted with the use of light and color, a pseudo-scale perception and motion are achieved by camera parameters, navigation and orientation through the agents deliberately constructed. In this sense, a typical VR environment is a flattened representation of real space where all the tactile and spatial features are limited with the rendering engine.

When VR is considered as a medium of learning as discussed above, the VR space which actually is not only just a space of interaction but it is the stimuli of learning, hence "how VR environment and its design should be in relation with the field" is still a question to be discussed.

## THE USE OF VR IN ARCHITECTURAL DESIGN EDUCATION

Architectural design education is built up on science, technology, engineering, art, and mathematics to create the base for design knowledge/skills. The diversity of the subject matters and the complexity of the design act make design education a controversial subject among researchers and practitioners. There are different approaches in defining the design, design process and design methods, showing remarkable disparities with each other and lack of consensus. Simon, Schön, Visser, Cross, Lawson are some of these names deliberating cognitive design theory aiming to clarify the design act. Discussions on the role of cognition in the design process cannot be isolated from the discussion on the role of creativity. Similar to the definition of design, there are many definitions of creativity. How creativity can be developed, learned is another important concern of architectural design education. Akın states that "Creativity arises under special conditions" (Akin and Akin,1996) therefore, architectural design education should also seek for these "special conditions".

The use of VR in design education with all its virtues as a stimulating learning environment can also contribute to providing those special conditions or "A-HA moments" as Akın describes. Chatfield an expert on digital technologies points out the role of VR in developing creative skills as

*"I'm actually slightly cynical about using virtual reality in education, in that I think people often get too excited at gadgets instead of thinking fully about what a great educational experience looks like. For me, perhaps the most exciting thing that could come of this type of technology is students themselves getting excited about, and using it to create things - and learn via the act of creating."* [2].

Although VR seems to be very promising, its use in design education is not as straight forward as it may be seen. Integration of VR into more tangible subjects like structure, engineering, history, modeling and etc. can easily be realized and VR can easily become a VLE for those subjects. However, when the core subjects like space, spatial qualities, and related issues are considered, then the question of "what is the VR space to teach the concept of space to architects?" is inevitable: "is it a replica of studio environment?".

The ambiguity between the concept and perception of architectural space and space constructed in the virtual realm either as a learning environment or as a space of experience makes to answer this question much more difficult. Thus, exploring the architectural space in a mimicked, conventional VR space is a dichotomy that should be questioned more. In this query, it is important to ask whether we need a specially constructed virtual environment as a replica of the physical environment as in most of VLE examples, or constructing a new space with the virtual materials of the VR regarding which cognitive skills and knowledge to be aimed at.

There is no agreement on how architectural design education should be, yet it is consented that architecture in its essence is the study of space, spatial relations; exploration of scale, material, contrast, texture, in-out, solid-void and more, mostly in the realm of physical world. The introduction of new digital and computational technologies has also been changing the definition of "space", and "its perception", and today physical and cyber-physical are two co-existing terms in the realm of architecture. Space becomes an elusive concept. This shift brings back the question of how design education should be achieved integrating these continuously developing technologies into the curriculum and what objectives should be aimed at. It is also necessary to question the "design studios" in relation with these technologies.

Design studios are inseparable part of architectural design education. These studios are "the locus of architectural design learning and teaching, a setting where students communicate with one another and receive comments from the tutor" as defined by Kvan and Yunyan (Kvan and Yunyan, 2005). Design studios with their own design cultures have long traditions and these are actually the environments where students are expected to amalgamate what they learn and to develop their own design skills and meta-cognition. Introduction of new instructional technologies into design studios is unavoidable but also it is not an easy task since studio learning is not only problem based but also student-centered and experiential aiming at developing creative and cognitive design skills. In this regard, two main question arise: what should be the new design studio with the advents of these new digital and computational technologies, and how those technologies are transforming the core subjects of design like space, model, material, scale and etc. In this quest, computational design and computational design studios with their media and problems introduce a new locus in the architectural design education.

Present study focuses on the second question and the use of VR is contemplated through different projects completed in METU Digital Design Studio.

## VR OR VLE IN UNDERSTANDING THE "SPACE": COMPUTATIONAL DESIGN STUDIO EXPERIENCE

Teaching computational design in architecture has a two-fold challenge: to teach design and to teach related computational technologies. It is also important to encourage learners to recognize the potentials/drawbacks of the digital medium, to help them to force the limits of the technology and the medium. Digital Design Studio aims to teach computational design paradigm with all the objectives of architectural education and related technologies. At the end of the studio, students are expected to develop computational thinking skills, to be able to use related technologies and to have a concrete understanding of space in any medium; real or virtual. In other words, students are expected to develop transferrable skills and knowledge in a mutual way both from virtual to real and from real to virtual to enhance their design understanding as well as space perception and spatial relations.

Computational design education requires new mindsets in order to grasp what process is and how the end product is related with this process. The resulting complex spatial relations and complex topologies are new kind of maze for students which is difficult to find a right way to go out. Therefore, computational education approaches should lead the students through their way to maximize their experience and to find their own way out. Several years of studio experience in our studio shows that problems assigned in the studio projects have utmost importance in this quest. It is observed that ill-defined and abstract problems giving no clue to or resemblance with the real life have resulted in more successful end products. It is also seen that in developing the computational design process, associating algorithms with a story is a powerful tool in understanding relations and transformations. These projects also force students to question the concept of space not as a reproduction but as a space of the digital realm with its constituents. The transformation from physical to virtual or from physical material to virtual material is mapped as follows

Table 1
Transformation table of real space parameters to virtual space

| REAL SPACE | VIRTUAL SPACE |
|---|---|
| material | immaterial mimicked by the texture |
| texture | mapping |
| scale | achieved via camera parameters relative to its environment |
| movement | illusion created by the relative motion of the surrounding objects |
| solid-void | mesh models enhanced by colliders |
| in-out | always in / no out |
| form | combination of points, curves, meshes |
| sound | sound |
| light | light |
| physical forces | local gravitational force (perpendicular to surfaces) |
| navigation | teleporting |
| existence | immersion |

This mapping helped students to develop an a priori knowledge for their design research.

In this context, VR offers several potentials in accordance with the objectives of the studio and the computational design education in general. How VR is included in the studio to achieve these objectives is explained below.

The project title given to students is “flying in, on, over boundless boundaries” as an ill-defined problem. Each student in the studio, re-defined and elaborated the problem in different ways not only in terms of defining the constraints of their designs but also in terms of representing their idea in the virtual environment. Regardless of the design approach of students, each project passed through four stages; storification, process design, translation to soft domain, developing the computational model appropriate for VR devices. Project named “When Daedalus Wakes Up in Modern World” is one of these projects which is present to illustrate the stages of design process and its transformation it into the VR environment.

Presented study is focused on the story of Daedalus, who is infamous for his maze, and student reproduced this story into the digital medium with a new understanding of dimension, levels, complexity, and existence by preserving the inevitable “no escape” rule. His reinterpretation innately forced by both opportunities and constraints of digital medium and virtual implementation environment. As a result, the student came up with new topologies in concurrence with redefining the physics of virtual environment. Even though the students are encouraged to explore the potentials of VE to reconstruct the user experience of designs, it is observed that students succeeded to alter and customize VE variables for a limited number of parameters and mimicked the rest of the real space parameters instinctively. Transcription of the design choices for the aforementioned student project is present in Table 2.

The second project is titled as ”Creation of the Creator”. As it is explained above, each student was freely redefining the problem. It is observed that in this phase of the project, students’ previous background and already developed skills plays an important role. Second student Ozan Yetkin redefined the problem based on his own experience and chose the building of Faculty of Architecture in which he studied for four years. This building completed in the beginning of 1960’s having a very strong image with vast openings and unpainted brutal concrete structures with various spatial relations, material qualities and changing scales strongly influences the students and visitors. It is very interesting to see the transformation of this physical space into virtual in Yetkin’s project. Yetkin, although he could perfectly reconstruct the building in the virtual medium, like all the other students in the studio preferred to transform and reconstruct it with the virtual materiality as shown in Table 2.

Actually, this transformation is summarizing the brickwork of virtual space in its own reality: the gen-

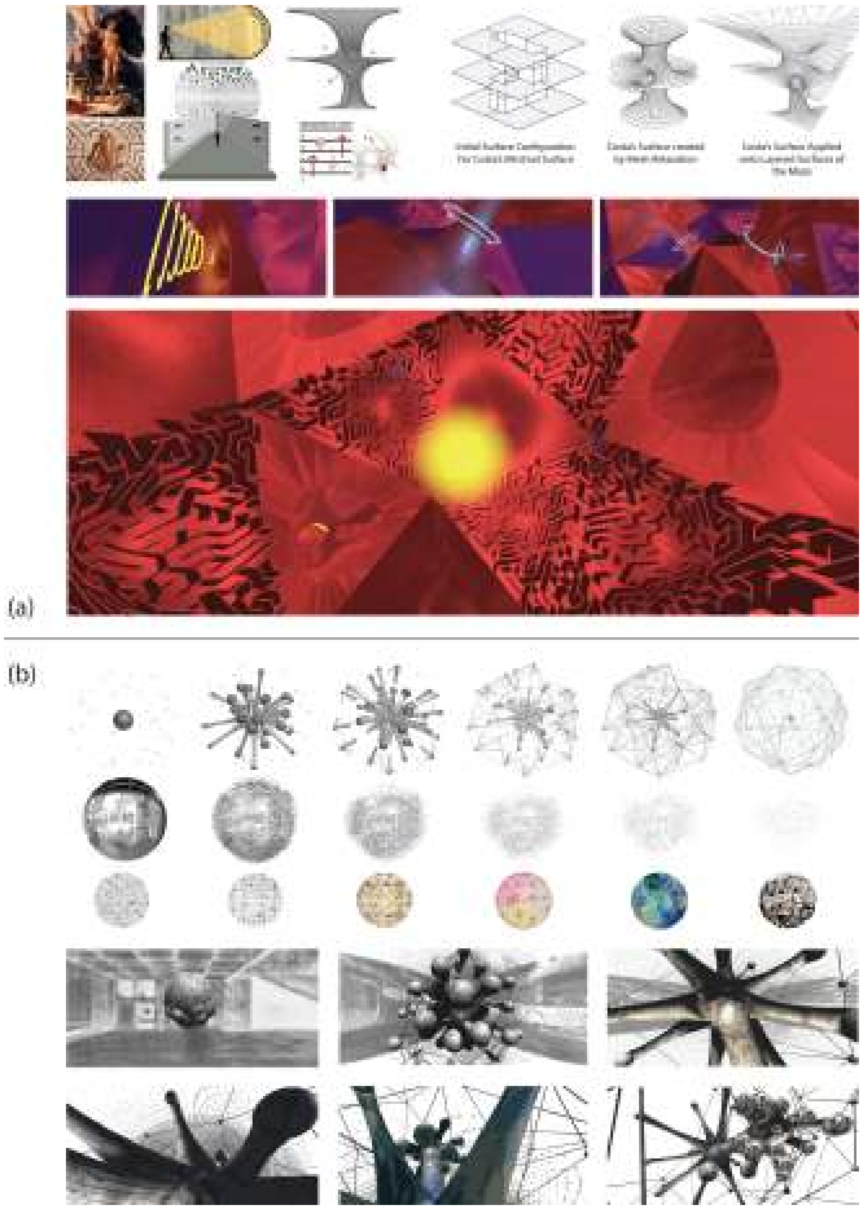

Figure 1
(a) “When Daedalus Wakes Up in Modern World” project by Cevdet Ege Çakır, (b) “Creation of the Creator” project by Ozan Yetkin

Table 2
Transformation table of real space parameters to virtual space (student projects)

| REAL SPACE | PROJECT 1 | PROJECT 2 | PROJECT 3 | PROJECT 4 | PROJECT 5 | PROJECT 6 |
|---|---|---|---|---|---|---|
| material | data construction of forms (points, wireframes, solid surfaces) | achieved by colours ( from asset store mostly?) | immateriality of the virtual space all elements are composed of one single material which is able to act anyway it is designed. | achieved by colors | Texture | reflection |
| texture | transition from abstract elements to the concrete (like from numbers to colored pixels and from pixels to photos and even videos) | achieved by colours ( from asset store mostly?) | all surfaces became screens which display different qualities. | achieved by images applied for the planets | PNG | reflection |
| scale | physical relation between elements | get reference from camera's scale (camera-Guangyadon) | NA | achieved by changes on the path's section dimensions | Distantness- Farness to the Spaces | |
| movement | perception of the motion, animation | achieved by mouse (time varying place on screen) | free movement in all directions | achieved by camera direction and speed | Gravitational Force by a Black Hole- Forced Animation | directionless |
| solid-void | density of forms and connections between them | achieved by visuality (I think you can see clearly the solid-void relation on planes but it cannot achieved clearly by wireframe boxes,I dont know should it be?) | void become solid while solid becoming void | N/A | NA | surface |
| in-out | construction of inside and outside experiment consecutively | wireframe structure for achieving borders but not sharp borders | it is possible to be inside and outside sometime in same objects. | achieved by changes on transparency of the surfaces | Closeness- Openness | monospace |
| form | central hierarchy to homogenous network | achieved by changeable visual forms | without under restraint of the physics of the reality any form can be generated. | achieved by morphing one 3D geometry into another one | Spaces Scattered From Explosion | sphere |
| sound | addition of new layers of sounds with new generations (like rhythm then rhythm+bass then rhythm+bass+treble/ melody...) | achieved by (soundbank) | NA | adding a track to the background | Sound of Radiation, Sound of Character | scan |
| physical forces | generation, a creative explosion | there is a thrust affect on my first plane ,when Guanyador flex came and touch the plane,the plane can get value on its height and grow vertically | designed forces | N/A | Explosion, Distance to Black Holes | |
| navigation | chosen movement path of the avatar | achieved by mouse and camera screen | NA | achieved by the camera direction | Forced Animation | light |
| existance | total experience of virtual reality | achieved by sound and visuality | experience | every change on the virtual galaxy gives the sense of existence to the user | Experiencing Multiple Existence- Camera Change | |

uine space of virtuality offering more potentials than simply mimicking the real environments through renderings. At this stage, the experience gained in VR environment should be reflected back to the perception of space in general (virtual or real) in order to develop a broader understanding of space and spatial relations. The studio experience that we have explores the ways and approaches to integrate this diversity and furnish student skills in that way.

## CONCLUSION

Today, Virtual Reality as an immersive experience is more popular than before with the advents of new and affordable technologies and applications. Its use as a learning environment-VLE is not a new idea and it has become an important component of instructional technologies. VR technologies and the virtual realms as a part of the learning process can respond different learning modalities of the students like aural, visual and kinesthetic and thus ease learners to develop new cognitive skills as acknowledged by many researchers.

In the case of architectural design education, the use of VR as a standalone technology or as a learning environment deserves to be explored more. Although what design is and what are the methods are still subjects of research, the core issues like space, spatial relations, materiality, scale and such are the loci of the architectural design education. Virtual space introduced by digital and computational technologies is a new space with its own materiality and with its own constituents. This brings a paradoxical dilemma of which space is the one experienced: the one replicated in the virtual realm or the one which is constructed with digital materials like light, sound, motion experienced through the gadgets/gears. In this paper, VR is considered as a new space and it is used as the medium of experience of virtuality rather than a pseudo-medium of experience of the physical one. In this context, real is mapped into virtual and this process is exemplified by the student projects. It is seen that when VR is liberated of being the replica of the real, students started to explore the concept of space, its relations, scale, and its meaning in a more creative and in-depth way. This exploration also helped students to re-consider physical space and its constituents and a meta-cognition of space is developed.

Today architectural education is responsible for furnishing students not only with professional skills but also with the future skills enabling students to adapt changing learning, design and production environments. The coming age will create its new ecosystem which is mostly named as the digital ecosystem in which virtuality will be more important than today. Hence incorporating those new technologies with their own realities is essential for all the professions.

## ACKNOWLEDGMENT

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# Computational and Modeling Tools

## *How effectively are Urban Designers and Planners using them Across the Design Development Process?*

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*Literature suggests that despite the increasing range and variety of computational tools and technologies, they have not really been employed for designing as extensively as it might be. This is due in part to the numerous challenges and impediments limiting their effective usage such as the methodological, procedural, and substantive factors and limitations, and skepticism about their impact of usage on the design process and outcome. The gap in our understanding of how advanced computational tools could support the design activities and design decision-making has expanded considerably to become a new area of inquiry with considerable room for the expansion of knowledge. This research is a single-case study that has been pursued in two phases: literature review and survey followed by analysis and discussion of the empirical results. The empirical observations were compared to the theoretical propositions and with results of similar research to highlight the areas and the extent to what the IT tools' usage have influenced the outcome of the design process. The comparison has helped highlight, explain, and justify the mechanism and improvements in the design outcome. Please write your abstract here by clicking this paragraph.*

**Keywords:** *Computational urban design, Urban Design Practice*

## INTRODUCTION

### *Research background*

The increased interest in a holistic, multi-disciplinary, and collaborative approach to urban design practice has multiple dimensions and challenges that require extensive and effective usage of analytical, communication, and dynamic visualization techniques (Batty, 2007). Literature suggests that despite the increasing range and variety of computational and modeling tools and technologies, they have not really been employed for designing as extensively as it might be (Al-Douri, 2013; Fraser and Bjornsson, 2004; Simpson, 2005). A recent study provided a critical evaluation of the vision, methods, and content of urban design plans in large North American cities. It showed that despite the considerable developments in computer-based technologies and analytical tools such as GIS, 3D modeling, and remote sensing, few of the plans that have been examined offer innovative ways for studying and interpreting the environment (Lehmann, 2006; Linovski and Loukaitou-Sideris, 2013). This underutilization and lack of sophistication of IT tools development and usage in the planning departments in US cities were highlighted in other studies such as Hammerlinck (2011), Hombeg (1994), and Klosterman (1997).

This is due primarily to numerous challenges and impediments that affect the effectiveness and impact of their usage on the quality of the design process and outcome. In particular, the developments in computational and modeling technologies have not been supported by similar methodological developments outlining their usage through the design process (Batty, 2007). Different types of representation fit different design phases, and different kinds of tools are suited to different parts of the process (Billger et al 2016; Marsall, 2015). Yet, one challenge concerns how different computer generated representations can be integrated into the process.

Modes of representations employed while designing frame our thinking and has a strong influence on the scheme's design (Angelova 2015; Carmona et al, 2010). Also, it can influence decision-making when it empowers a wider engagement of all stakeholders in the design process (Caliskan 2015). Hence, choosing the appropriate mode of representation and using it extensively should be given a special consideration in urban design practice. It is strongly recommended that urban planners and designers examine how a combination of computational tools could effectively support the decision-making process and ultimately help transform the group work from one way to multiple ways. This would influence how effectively designers design, communicate, evaluate and represent design proposals (Carmona et al, 2010; Neto, 2006).

## *Research Problem*

The entire range of advanced computational tools and interactive visualization technologies has not really been employed for designing across all design phases as extensively and effectively as it might be. The gap in our understanding of how they could support the design activities and decision-making has expanded considerably to become a new area of inquiry with considerable room for the expansion of knowledge (Kunze et al, 2012; Lewis et al 2012). The empirical research literature on the usage and impact of those tools on the design decision-making in real urban design and planning processes is sparse and rare (Billger et al 2016). A few studies were focused on their impact on the design outcome, but a systematic outlook at their impact on decision-making and on various activities across all design phases has to be empirically examined. Therefore, further studies are required to examine the methods, pattern, viability, and impact of the consistent usage of computational tools for design, decision-making, presentation, and evaluation (Carmona et al 2010; Derix et al, 2012).

## *Research objectives and questions*

This research departs from the hypothesis that computational tools may support design activities and result in improving various aspects of the decision-making process including participation, 2D, 3D and 4D design representations, and decision quality. (Appleton and Lovett 2005; McGrath, 2008; Carmona et al, 2010; Bosselmann, 2008; Al-Douri, 2006, 2010, 2013; kunze et al, 2012; Derix et al 2012).

Urban Planning and Design departments that have used computational tools in their practice may help to gather evidence regarding this hypothesis. This research has used the quantitative approach to examine the extents and methods with which those tools have been used in the Department of Planning and development in San Diego, CA. The objective of this research is twofold:

1. Investigating how urban designers and planners are using computational tools in support of various phases of the urban design process
2. Assessment of the impact of their usage of computational tools on the design and decision-making processes.

To attain these objectives, the study will address the following primary questions:

1. To what extent have urban designers and planners used the variety of computational tools and techniques and at what phases?
2. How has the usage of computational tools influenced the output of the design process?
3. What computational tools have designers used at each design phase?

## RESEARCH METHODS AND DATA COLLECTION

This research has been pursued in two phases. In the first phase, a review of related literature such as Angelova (2014), Marsall (2015), Billger et al (2016), Batty (2007), and Al-Douri (2010, 2013) among others was pursued to construct theoretical propositions to which the empirical results have been compared. In the second phase, an on-line questionnaire survey was forwarded to all urban designers and planners working at the Department of planning and development, City of San Diego, California, US to document, quantify, and assess the methods and extent with which they used computational tools across all design phases and to assess how their usage has influenced the outcome of the design process. The questionnaire consisted of four sections of closed-ended questions and one section of open-ended questions.

Question one asked designers to identify the extent to what they used computational techniques during the design process. The question listed twenty-nine techniques collated from reviewing related literature and categorized into four main functions, following the framework of Batty et al (1998). Question two asked designers to identify the extent to what they used computational tools at each design phase. The question listed four design phases with their constituent design activities as described by Cooper and Boyco's model (Cooper and Boyco 2010; Boyco et al, 2006). Question 3 asked designers to assess the extent to what they agree on the impact of using computation tools on decision-making and quality of the design outcome. There were 23 questions grouped in five major areas of impact based on literature review. Responses were measured on a five point scale ranging from Strongly Disagree (1) to Strongly Agree (5).

Table 1
Extent of usage of IT techniques and functions

For question four, the survey explored key design and technology issues by gathering the participants' perspectives on fourteen technologies commonly used in urban design activities. The list of technologies were compiled from the review of related literature and participants' feedback in a previous research which involved conducting series of interviews and focus groups (Slotterback and Hourdos, 2009; Al-Kodmany 2002, Simpson 2005, Al-Douri, 2010). The participants were asked to assess the extent and the phase(s) at which they use each of those technologies. The survey also explored two key issues identified in the literature as pertinent to computational tools usage in urban design activities: the level of expertise in its usage, and the field of practice. Respondents have been asked to indicate their level of expertise within a range that varies from non-user to advanced user.

A total of 19 invitations were sent to all potential participants listed in the Department's website. The response rate was 79% among whom 50% were self-identified as planners, 25% as urban designers, with the remainder consisting of people working in the related fields of architecture, GIS, environmental planning, and transportation planning. The distribution of response for these two questions (years of experience, and field of practice) is comparable to the characteristics of planners in the US planning departments (Slotterback 2011), thus suggesting a relatively representative sample.

The empirical observations were compared to the theoretical propositions and with results of similar research to highlight any patterns and consistencies that could highlight, explain, and justify the mechanism and improvements in the design outcome and output. The comparison has helped drive conclusions about the prospected future of IT tools usage in professional practice.

## EMPIRICAL FINDINGS AND JUSTIFICATIONS

The results of questions 1-4 in the questionnaire were discussed in light of the theoretical propositions and were compared to those of a previous study that was conducted in 2006 in an attempt to highlight any patterns in the extent of usage of IT tools over the years.

### *Extent and methods of usage of IT tools*

In question one, the IT techniques listed under each functionality were sorted in descending order according to the sum of responses with 'very high' 'high' and "sometimes" of each IT technique (Table 1). The results showed that the IT functionalities were employed with a variety of extents (Figure 1). They showed an extensive usage of the analytical and communication techniques, but only above-average usage of simulation & decision support and visualization techniques. These results are inconsistent with the literature premises concerning the low extent of IT tools usage in current urban design practice.

In the analytical functionality, the most extensively used techniques (rows 3.1-3.8, Table 1) appeared to have supported designers in a wide range of core design activities including analysis, synthesis, and alternatives generation. These results, compared to those of the 2006 study (46.2%), show a higher extent and more effective usage of the analytical techniques in core design and development activities, particularly at early design phases when their potential role in decision-making support is the highest.

In the communication functionality, the most extensively used techniques (rows 2.1-2.3, Table 1) were utilized as a communication platform to communicate 2D and 3D information within the design team and to represent and illustrate design products to the public. This is inconsistent with the theoretical proposition that most urban information systems fail to create conditions for communication and constructive dialog between professionals and decision makers and thus remain to serve only experts in long-term (Angelova et al 2015). Their usage, compared to the results of the 2006 study (71.7%), was higher in extent and effectiveness of supporting core design activities (Al-Douri 2013).

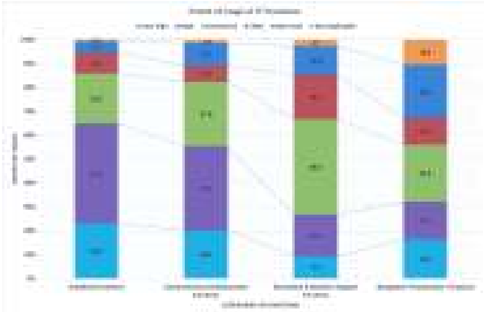


Figure 1
Extent of usage of IT techniques and functions

In the simulation and decision-support functionality, the most extensively used techniques (rows 4.1-

4.2, table 1) were used to support designers in creating a vision and physical development policies, designing the urban form, and modeling and testing proposed zoning. Although the extent of their usage is markedly higher than the results of the 2006 study (39.1%), their capabilities to support planners in dynamic simulation of the design decisions and changes over time have not been effectively used. This inadequacy is due, in part to three main reasons. First, the nature of urban codes that have limited the usage of simulation software to quantifiable design elements such as micro-climatic calculations (Derix 2012). The second reason is that simulation and decision-making tools only operate as a black box not as a collaborative design instrument which is essentially required for vision building. Finally, research has proven that in professional urban design workflows, continuous simulations that integrate many scales and temporal changes alienate designers and their heuristic tools (Derix et al 2012).

In the visualization functionality, most techniques were used with above-average level (rows 1.2-1.8, table 1). They involved dynamic visualization, animation and design alternatives assessment that could improve designers' abilities to view and analyze elements of the urban environment. However, the results showed a very limited usage of the real-time dynamic visualization technique (see row 1.9, Table 1) that could support the process of design generation. These results are consistent with those of the 2006 study (61.4%) and with the theoretical propositions regarding the above-average usage of visualization tools to represent design alternatives and to visualize complexities of the spatial structure at a variety of scales.

### *Extent of usage of IT tools at various design phases*

The results of question two were analyzed to highlight the patterns of IT tools usage at various phases of the design process. The design phases were sorted in descending order according to the combined number of respondents with "very high", "high" and "sometimes" levels (Table 2).

The highest extent of IT tools usage was at phases 2 and 1 and was characterized by "high" and "very high" usage at all design activities comprising those phases (Figure 2). The extent of usage though gradually declines across phases 3 and 4 and is characterized by the respondents' selective usage "sometimes" of IT tools to support certain design activities. This pattern is inconsistent with the results of the 2006 study which showed that IT tools usage was limited at the initial, analytical phase but has increased at the conceptual and design production phases (Al-Douri, 2013).

Table 2
Extent of usage of IT techniques and functions at each phase of the design development process

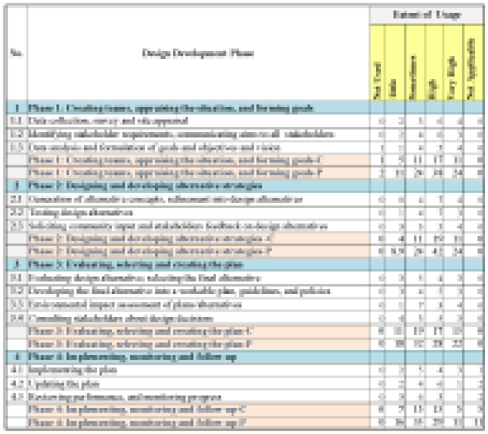
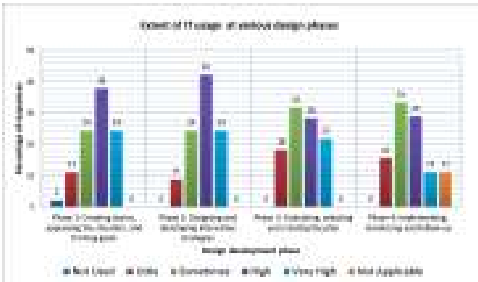


Figure 2
Extent of usage of IT techniques and functions at each phase of the design development process



This pattern of usage could be interpreted as a reflection of the planners' usage of the IT techniques that are most appropriate to each design phase. The most extensively used analytical and communication techniques (rows 3.1-3.8; and rows 2.1-2.3, Table 1) are central to the analytical and conceptual activities in phases 1 and 2. Conversely, the design activities that involved low extent of usage occurred at the advanced design phases that require selective usage of visualization and simulation & decision-support techniques. This pattern is in line with the argument regarding the planners' preference to use conventional 2D techniques over their 3D counterparts (Ryan 2007). It can also be viewed in line with the theoretical proposition that too much detail and visual realism in visualizations at the initial stages of the design process are often not necessary and can even be misleading, as that information will not be decided on until a later date (Billger et al 2016).

These results show that IT functions were used most extensively in the initial design phases when the impact of their usage on the quality of the design process and product would be at its highest. Such pattern provides evidence that IT techniques were effectively used to support designers in core design activities and may have ultimately increased the overall quality of the design product. However, their declining usage in phase four which typically requires extensive and effective communication and outreach is inconsistent with the mission of the planning department that emphasizes outreach to the Downtown's community and stakeholders.

The results may have been influenced by the design methodology. The conjecture-led cognitive nature implies that the analytical work in urban design practice does not represent the first and foremost phase in urban design thinking. Instead, it runs in parallel with the other consecutive steps: conjecturing, modeling, and testing in design (Çalışkan, 2012). In addition, the literature suggests that designing by alternative is not always applied in practice; alternative thinking in design is not taken as a cognitive tool to make design synthesis. Instead, it might be utilized as a communication tool to enhance the original design argumentation either against the external stakeholders or within the (design) group itself. Thus, the alignment of the extent of IT tools usage with the design phases and with the nature of the design methodology opens a wide range of possibilities to create new design techniques and activities.

### *Overall Impact of usage on the design process and product*

The results of question three were analyzed to assess the impact of IT tools usage on the design process and product. The areas of impact were sorted in descending order according to the combined number of "strongly agree" and "agree" responses (Table 3).

| No. | Impacts of IT tools usage | Assessment: Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree | Not Applicable |
|---|---|---|---|---|---|---|---|
| 1 | Communication and interactivity. The usage of IT tools has increased the following: | | | | | | |
| 1.1 | Efficiency of communication with planning teams and consultants | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 1.2 | The amount and diversity of information used in plan development | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 1.3 | Efficiency of communication with community and stakeholders | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 1.4 | Speed of conflict resolution among stakeholders and planners | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | Communication and interactivity | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | Communication and interactivity | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 2 | Cost. The usage of IT tools has: | | | | | | |
| 2.1 | Increased the cost of plan development | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 2.2 | Reduced the time required for plan development | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | Cost | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | Cost | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 3 | Ability to represent contextual complex data. The usage of IT tools has helped designers in: | | | | | | |
| 3.1 | Effective visualization of the scale and complexity of the urban form | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 3.2 | Switching between various urban scales (Zoom in and zoom out) | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 3.3 | Increased understanding of the complex relationship between various urban systems | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 3.4 | Relating the plans of individual sub-systems (eg. open spaces) to the entire system (city) | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | Ability to represent contextual complex data | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | Ability to represent contextual complex data | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 4 | Comprehensiveness of work. The usage of IT tools has helped designers in: | | | | | | |
| 4.1 | Management of more urban elements/subsystems | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 4.2 | Relating the plan to other planning scales (project scale, metropolitan, or regional sc | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 4.3 | Management of each element/subsystem comprehensively | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 4.4 | Analyzing the study area at multiple scales | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 4.5 | Generating a larger number of alternative solutions | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 4.6 | Underpinning alternative solutions with analytical findings | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 4.7 | Allocating more time to analytical tasks | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | Comprehensiveness of work | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | Comprehensiveness of work | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 5 | Decision-making process. The usage of IT tools has led to: | | | | | | |
| 5.1 | Allowed stakeholders to view a realistic model of the plan in its actual context | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 5.2 | Increased the quality of the final plan | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 5.3 | Improved the efficiency of the design and development process | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 5.4 | Helped planners relate plan strategies to the nature of the area problem | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 5.5 | Improved the efficiency of decision-making | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 5.6 | Increased the time allocated to creative thinking | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | Decision-making process | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | Decision-making process | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

Table 3
Assessment of the impact of IT tools usage on the design outcome and decision making

The results show three levels of impact: high (area 3), medium (area 1, 4, and 5), and low (area 2) (Figure 3). These results may be interpreted in light of the results of question 1 regarding the extensive usage of analytical techniques, and question 2 regarding the extensive usage of IT tools at phases 1 and 2. They are also consistent with the theoretical model proposed by Al-Kodmany (2002) which suggests that the highest impact of visualization tools is its ability to represent contextual complex data.

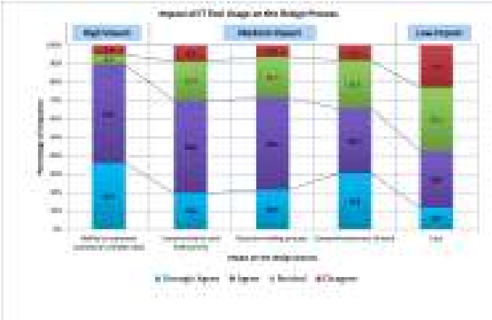


Figure 3
Assessment of the impact of IT tools usage on the design outcome and decision making: grouped in areas

Yet, the medium impact on the "communication and interactivity" area is a discrepancy that may have resulted from three interrelated factors. First, the available IT tools lack the high degree of interactivity that is required to create opportunities for communication and higher participation (Billger et al 2016). Second, the ineffective usage of IT tools as a communication platform to represent and illustrate design products to the public (rows 2.4-2.5, table 1). Ineffective communication does not allow professionals and decision-makers to combine efforts and collaborate at all design phases, particularly the early phases, and hence will reduce the quality of the plans (Angelova, 2015; Kunze et al 2012). Finally, the overall impact on communication requires addressing the challenge of developing the actual dialogue and collaboration process (Billger et al).

The average impact on the comprehensiveness of work (area 4), particularly the activities in rows 3.4-3.7 (Table 3), may have resulted from restriction in the planner's analytical vision and the urban analysis that is predominantly pursued with conventional 2D maps rather than 3D tools (Ahmed and Sekar, 2015). Also, the average impact on the decision-making process (area 5), particularly the activities in rows 5.5 and 5.6 (Table 3) may be interpreted in light of the study that was pursued to compare the benefits of the 3D methods of information interrogation over alternative 2D methods. The findings showed that the 2D resource allowed faster and more accurate decisions to be made, even though the 3D resource allowed a greater understanding of more specific information. The users believed that 3D resources allowed increased spatial awareness and subsequent understanding of information, and would, therefore, allow them to make quicker decisions (Ryan 2007). These results imply that it is essential for urban designers to use a combination of both 2D and 3D resources during the design process.

Finally, all areas of impact have involved activities that have been highly affected by the IT tools usage. Hence the results of this question were sorted in a descending order according to the sum of "agree" and "strongly disagree" (Figure 4). The six highest areas were related to increasing the spatial awareness, understanding the relation between the urban elements, and the efficiency of communication with the planning teams. This provides evidence that IT tools usage could support designers in pursuing core design activities and decision making that would ultimately affect the quality of the design product. Those tools would allow designers working at various scales and levels of abstraction and managing various urban subsystems in a hierarchical order at various phases of the design process.

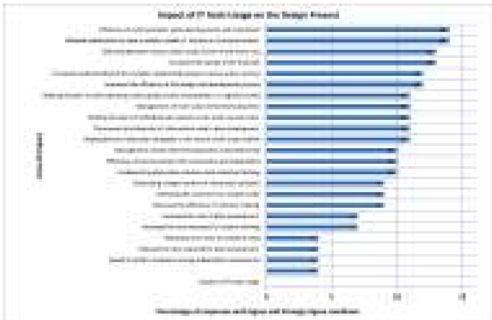
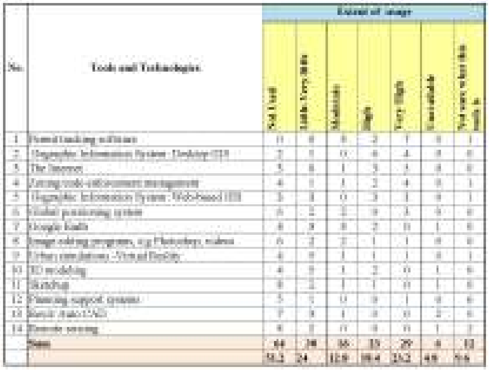


Figure 4
The impact of IT tools usage on the design outcome and decision making: listed in descending order

### *The IT tools used across the design phases*

The results of question 4.1 were listed in descending order according to the sum of the "very high", "high" and "moderate" responses (Table 4). The results of question 4.2 were listed in descending order according to the phases where IT tools were most extensively used (Table 5).



| No. | Tools and Technologies | Extent of usage: Not Used | Little/Very little | Moderate | High | Very High | Unavailable | Not sure what this tool is |
|---|---|---|---|---|---|---|---|---|
| 1 | Parcel tracking software | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 2 | Geographic Information System - Desktop GIS | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 3 | The Internet | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 4 | Zoning code enforcement management | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 5 | Geographic Information System - Web-based GIS | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 6 | Global positioning system | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 7 | Google Earth | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 8 | Image editing programs, e.g. Photoshop, videos | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 9 | Urban simulations - Virtual Reality | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 10 | 3D modeling | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 11 | Sketchup | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 12 | Planning support systems | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 13 | Revit/ Auto CAD | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 14 | Remote sensing | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | Sums | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

Table 4
The extent of usage of each IT tool and technology

| No. | Tools and Skills | Phase at which it was used most: Phase 1: [illegible] | Phase 2: [illegible] | Phase 3: [illegible] | Phase 4: [illegible] |
|---|---|---|---|---|---|
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

Table 5
Design phases at which each IT tool and technology was used the most

The results show two patterns. First, the IT tools that are typically used for analytical and communication functionalities, such as the Geographic information systems, the Internet, and software for plan implementation and management, are the most extensively used tools, and they were consistently used at the appropriate phases. Second, the IT tools that are used for visualization functionalities, particularly 3D modeling, such as VR/urban simulation, Sketchup, and 3D modeling are the most ineffectively used tools. They have been moderately used only in phases 2 and 3 where they could support a variety of visualization and decision-making activities (Table 4 and 5). Such ineffectiveness is due, in part to urban designers' reluctance to integrate 3D tools into various design activities due to the complexity of data integration, cost, skepticism of the impacts, and lack of appropriate skills (Ahmed and Sekar, 2015).

These results reflect those of question 1 regarding the high usage of analytical and communication techniques and the average usage of the decision-making and visualization functions (Table 1, Figure 1). The results also may explain the medium impact on the areas of decision-making and comprehensiveness of work (Table 2, Figure 2). In addition, these results provide evidence that planners perceive greater capacity and a likelihood of use and understanding of those technologies that focus on providing information such as project website, as opposed to stimulating discussion and interaction such as photo editing and GIS-based scenario evaluation (Slotterback 2011).

It must be noted though that the extent of usage of IT tools in each design phase is not correlated only with the quantity of tools used in it but also with the usage of the tool (s) that is/are most appropriate for each design activity and phase. This highlights the importance of increasing the planners' knowledge and skills of the capabilities, potential, and methods of IT tools usage to support the variety of design activities.

## CONCLUSIONS

The findings showed that IT functionalities were used with a wide variety of extents of usage at various design phases. The overall extent of IT tools' usage was between very high and above-average. These findings are inconsistent with the premise concerning the low extent of usage of IT tools in current urban design practice. The extent of IT tools usage varied along the design process. The highest extent was at phases 2 and 1 but it gradually declined across phases 3 and 4. This pattern is inconsistent with the theoretical propositions that IT tools usage is limited at the initial phases but increases at the design production phases.

The results have shown a variety of levels of impact of IT tools' usage on the design outcome and decision-making process. They provided evidence that IT tools usage could support designers in pursuing core design activities and decision making that would ultimately affect the quality of the design product.

The results provide evidence that the impact of IT tools usage on the urban design process and outcome is correlated with not only the extent of their usage, but also with a variety of procedural and substantive factors particularly the following:

- the planners' level of expertise with the capabilities and methods of usage of the variety of IT tools including data handling and representation, the choice of the appropriate tool and level of realism and detailing that best fit a specific purpose.
- the planning and development methodology employed
- The consistency and effectiveness with which IT tools are used across the design process.
- The capability of the available digital tools to visualize and represent different kinds of data.

The results have shown that the design methodology is the main factor that can affect the effectiveness of computational support in design decision-making. Thus, the alignment of the extent of IT tools usage with the design phases and with the nature of the design methodology opens a wide range of possibilities to create new design techniques and activities.

With the increased sophistication and usage of IT tools in urban design practice, particularly simulation and decision-support tools, the emphasis shifts from monolithic simulations to discrete simulations units for cross-scale distinct design aspects (Derix et al, 2012). Their increased interactivity offers a wide range of opportunities for designers and public to visualize and communicate the constituent plans and to increase design collaborations and enhance the quality of design and decision-making. On the other hand, emerging geospatial technologies such as GPS, remote sensing, BIM, cloud computing, wireless communications, and parametric modeling may be used to support a wide array of design activities (Drummond and French 2008; Marsall 2015). Their role, methods of usage, and potential support to urban designers at various phases of the design process have yet to be examined in future studies.

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# Development of parametric CAAD models for the additive manufacturing of scalable architectural models

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*Architecture models are an essential component of the development process and enable a physical representation of virtual designs. In addition to the conventional methods of model production using the machining of models made of wood, metal, plastic or glass, a number of additive manufacturing processes are now available. These new processes enable the additive manufacturing of architectural models directly from CAAD or BIM data. However, the boundary conditions applicable to the ability to manufacture models with additive manufacturing processes must also be considered. Such conditions include the minimum wall thickness, which depends on the applied additive manufacturing process and the materials used. Moreover, the need for the removal of support structures after the additive manufacturing process must also be considered. In general, a change in the scale of these models is only possible at very high effort. In order to allow these restrictions to be adequately incorporated into the CAAD model, this contribution develops a parametrized CAAD model that allows such boundary conditions to be modified and adapted while complying with the scale. Usability of this new method is illustrated and explained in detail in a case study. In addition, this article addresses the additive manufacturing processes including subsequent post-processing.*

**Keywords:** *Digital manufacturing, Parametric design, Architectural model*

## INTRODUCTION

The implementation of digital technologies in architecture has rapidly advanced in recent decades. In this, the advantages of this technology have been recognized early on and systematically analyzed (Mitchell, 1989). Thus, a series of tools are available today which support all phases of the virtual development of architectural projects from the design to the construction and even to the realistic representation with embedded environments. In the process, both challenging mathematical methods, such as e.g. the parametrization of design elements, and high-resolution display techniques, such as e.g. in rendering buildings, are applied (Armstrong, 2016).

Additive Manufacturing (AM), also called Digital manufacturing (DM), developed alongside this several years ago and has since established itself as a significant tool. This allows for virtual models to be converted to physical architectural models in short periods of time and at relatively low costs. Details of design elements as well as complete building complexes can be displayed in physical models with AM which are a critical decision-making tool for architects and developers. Due to this advantage, this procedure is also used today in related fields, such as e.g. archeology (Gibson et al., 2015). The application of AM has already been established for standard models in the field of architecture. Nevertheless, these applications are subject to some restrictions. Complex buildings with a multitude of different rooms, floors or even delicate design elements must undergo a laborious pre-processing phase so that this architectural model can be produced by means of AM.

In addition, these models have the disadvantage that they are generally only designed using one particuluar scale. Thus, a scaling of the model is not feasible because its physical conversion has become no longer possible due to various restrictions. Through the collaboration of digital development processes and additive manufacturing, the advantages of the rapid developments of both technologies in recent years can be reasonably combined and enhanced. In this article, the demands and restrictions in the AM of architectural models shall therefore first be outlined. Then a method is developed in order to be able to manage these current hindrances with the aid of a parametrization. Based on a case study, the application of the method is demonstrated and evaluated.

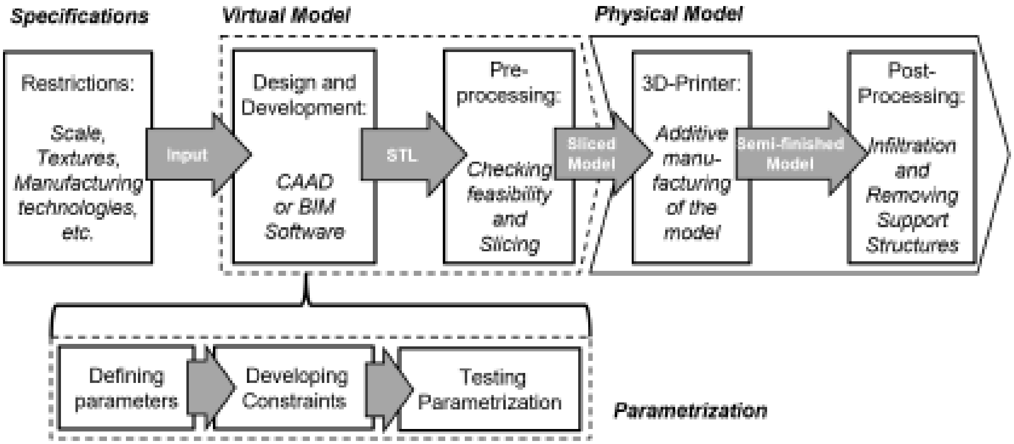
## LITERATURE REVIEW

The first process of additive manufacturing or 3D printing was developed with stereolithography approximately 30 years ago. Up to now, a large number of processes has been established, all of which are characterized by the layer-by-layer structuring (also called generative manufacturing) of the components and the direct implementation of CAAD using 3D printers. The processes used differ mainly in the joining technology of the layers and in the building material that is employed. For several years now, the use of the processes of additive manufacturing to implement architectural models has been investigated. For example, a very comprehensive study of the different technologies showed, that, despite the fact that costs are still high, rapid prototyping through the rapid implementation of models can significantly influence design (Ryder et al., 2002). However, it was demonstrated that the models are often still insufficient in terms of construction size and appearance (Gibson et al., 2002). Since then, significantly larger 3D printers have become available, and the costs have also decreased dramatically, mainly due to competition among the 3D printing service providers. For example, an up-to-date survey shows that the number of components manufactured with additive manufacturing processes has risen sharply in recent years (Wohlers, 2017).

The current range and operational performance of the different additive manufacturing processes, including the implementation of architectural concepts, is considerably increasing (Wong and Hernandez, 2012). Also a selection process using various criteria for finding a suitable process of additive manufacturing for architectural models is developed (Mançanares et al., 2014). The advantages of additive manufacturing are particularly important when complex shapes (such as delicate supports or organic shapes) are to be created as models. Thus, the additive manufacturing of complex buildings using AM can be simplified or even enabled with a methodical fragmentation. The implementation of this method could successfully be demonstrated in single colour models with the aid of Fused Deposition Modelling (FDM) or in multi-coloured models of larger building (e.g. industrial or administration building) with Binder Jetting (BJ) (Junk and Coté, 2013). Furthermore, additive manufacturing can be used in the manufacturing of models with organic and complex shapes in the topology optimization of bridges (Zerdad and Paulino, 2014).

The integration of AM is also an important aspect in the education of architects in order to push this technology forward. The use of additive manufacturing technologies to train students is therefore being examined in architectural design education. The advantages when using design versions are especially

Figure 1
Process steps from virtual to physical model while observing restrictions (above) and with additional parametrization (below)




emphasized in this (Silva and Lima, 2013). It was shown in a comprehensive study on the impact of this new technology on the training of architects that students are more integrated into the design process and also become more creative. Additionally, they are enthusiastic about the new ways in which models and prototypes can be generated and benefit from direct feedback through the physical, and therefore “tangible”, models (Celani, 2012). In this, the application of assembly kits for 3D printers can provide the students with a practical look into the technology. As a result, the students can learn in a short period of time how they can design and also additively manufacture architecture and landscape models (Junk and Matt, 2015).

## BOUNDARY CONDITIONS FOR THE ADDITIVE MANUFACTUIRNG OF ARCHITECTURAL MODELS

However, many boundary conditions and limitations must still be observed today in the generative manufacturing of architectural models. On the one hand, very few processes are able to create colored models, such that it is often the case that colors, labels and textures are not possible on the models. A further limitation is that the majority of the generative processes only work with a construction material. Usually, it is not possible to use different materials, such as masonry and glass fibers, in one model. Therefore, window fronts are often simply omitted and not shown in the models. In many processes, extensive supporting structures are also necessary in order to represent overhanging component areas in the first place. By means of a skillful placement, the support structure can be avoided with simple components; however, this is not possible for complex building models. Such support structure is usually generated automatically during the pre-processing of the CAAD data prior to the additive manufacturing process (see figure 1, above).

After the additive manufacturing process, however, it has to be removed manually or chemically. With the BJ process, the excess plaster powder has to be vacuumed, and the models are then infiltrated to increase strength. For example, with the FDM process, support structures (made of plastic filament) have to be removed (e.g. by cutting or using an alkaline bath). For this purpose, it is often necessary that the support structures are accessible, for example, with a cutting tool. This accessibility is often not avail-

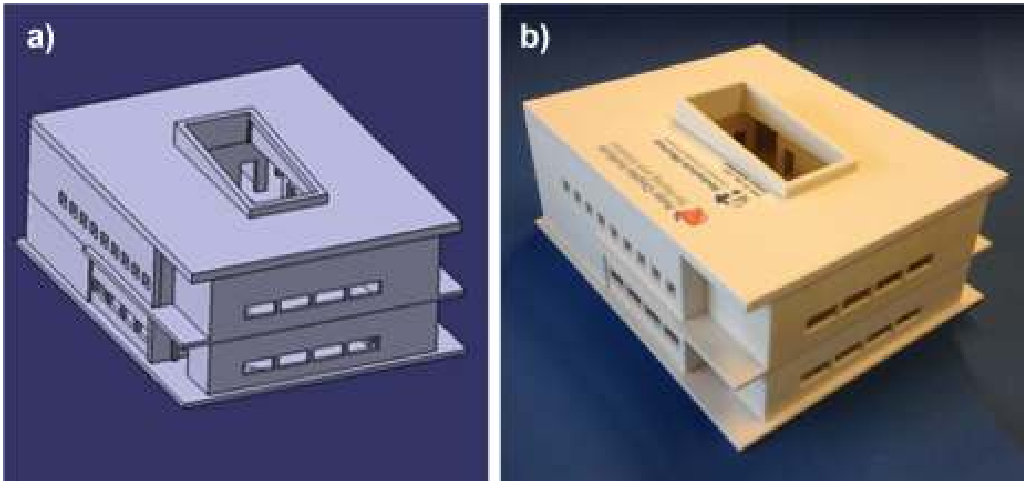



Figure 2
Example for a "rigid" model: University building in CAAD (a) and 3D-printed architectural model (b) using Binder Jetting (scale 1:100)

able, or it has to be achieved by splitting up the CAAD model. Finally, minimum wall thicknesses must be observed for all processes. This leads to the fact that important details can no longer be represented, in particular in small-scale models. Such details must also then be omitted. Alternatively, the details and wall thicknesses can be scaled in the masonry. However, this leads to a distortion of the scale. In order to be able to represent the interior of buildings, the models usually must be divided. For this purpose, different division strategies can be applied; for example, a division based on the floors or the function of the buildings.

## LIMITATIONS OF "RIGID" ARCHITECTURAL MODELS

When implementing virtual CAAD data in physical models, different process steps are executed. In doing so, CAAD data are initially transferred to the data preparation software via an STL-interface. Today, the STL format is often used as the interface. This format presents a simple reproduction of the geometry using triangles (including directional normals), and is included in many CAAD software packages, as it is license-free. At this time, new data formats (such as AMF and 3MF) that can transmit color information in addition to geometry are under development. However, such new formats are not yet widely used. In the course of data preparation, the model is divided into individual layers. Further more, additional information, such as inscriptions and logos, can be added to the data set.

A feasibility test is also possible. For example, there can be a check regarding whether all triangles are correctly aligned and whether there are "holes" in the model. There can also be a check regarding whether the minimum wall thickness for 3D printing is sufficient. This can lead to the fact that 3D printing is not possible, especially with models that are highly reduced in scale. In such cases, many software packages offer the automatic correction of data. Subsequent modifications, such as the scaling of certain areas (for example, only the wall thickness, but not the load-bearing ceilings) or the cutting out of certain areas, is either not possible or only possible with time-consuming additional work. Further more, a return of the modified data to the CAAD system is only pos-

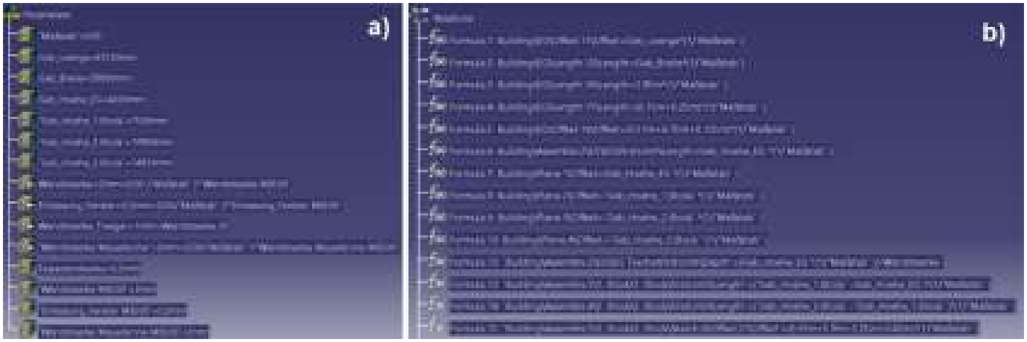



Figure 3
Screenshot from CAAD-System: list of parameters (a) and list of formulas (extract) from parametrization (b)

sible to a very limited extent, since only simple geometry information is transmitted in the STL format. With this format, complex information, such a construction history, textures or materials, can no longer be traced. Thus, the result of this data preparation is a "rigid model", which can be printed only on one scale and can only be modified to a very limited extent. This is transferred as print data to the 3D printer, and can then be built up layer by layer. After the completion of this 3D-Printing process, the architectural models are taken up and reworked during the post-processing according to the processes used.

To illustrate a "rigid model", an example of an architectural model a research building for one of the university departments, which studies heart diseases, (see figure 2) manufactured using BJ processes, is described. The model was built at a scale of 1:100, which means that no significant changes in wall thickness were necessary. The model consists of three parts: the first floor with laboratories, a second floor with offices and storage rooms, and a flat roof with a vitrified cover over the atrium. The individual parts of the model can be disassembled, allowing the accurate assessment of the internal structure of the individual floors. In this case, the doors, windows and the vitrified cover of the atrium were presented as openings in the model. This way, viewers have a chance to look inside the building. In addition, this kind of model allows to simulate the progress of direct sunlight throughout the building. In addition, the logos of the university and the institute are displayed on the roof. This application is performed in preprocessing.

## IMPLEMENTATION OF SCALABLE ARCHITECTURAL MODELS

In order to overcome the disadvantages of "rigid models", a parametrized model has been developed (see figure 1, below). In doing so, all of the essential dimensions of the virtual model are already provided in the CAAD system with parameters, such that they can be varied independently of each other. Thus, when the scale of an architectural model is modified, the outer and inner dimensions can be scaled. However, the wall thicknesses are not scaled to the same extent, in order to continue to ensure the ability to produce by means of 3D printing.

A four-storey university building with an integrated experimental hall is used as an example of the application of parametrised models. On the one hand, there was a difficulty in that a particularly small scale was chosen. Thus, many details had to be adapted or modified. In addition, a special texture of the facade was required. Moreover, some details of the experimental hall (for example, roof construction, roof structures and visitors' balconies) are to be represented in spite of the large reduction in size. However, it should also be possible to produce the model

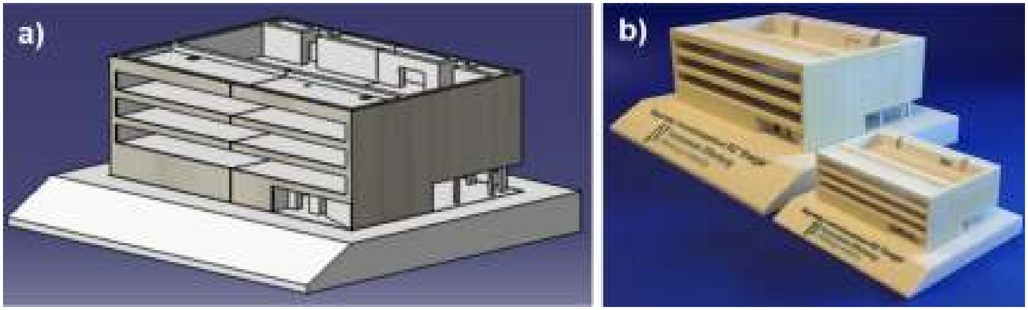



Figure 4
Example for a scalable model: University building with wooden texture in CAAD (a) and paramitrized and scaled model made of Binder Jetting (b) in Scale 1:250 (left) and 1:500 (right)

on a larger scale, without having to once again significantly rework the CAAD model. Parametrization makes it possible to select specific dimensions and to vary them. This allows the details of the building to be modified according to the chosen scale, such that the requirements for 3D printing are met. In addition to the simpler feasibility, parametrization also results in cost advantages, since the parameters can be adapted to different scales within a few seconds. A modification of a ”rigid” model in the CAAD or during data preparation usually requires several hours.

## PROCESS STEPS IN PARAMETRIZATION

The parametrization in the presented mehtod runs in various process steps (see figure 1 below). In this example, CATIA Version 5 was used to create the CAAD model. This CAAD software provides the determination of individual parameters. These parameters can be either fixed or variable. The most important single parameter is the “scale”. Based on the scale entered by the user, all dimensions are adjusted in the virtual model. Using a formula editor, the individual parameters can then be linked by mathematical formulas (constraints or relations). Within the course of parametrization, all necessary parameters are first selected and recorded as such in the CAAD system. Ultimately, it can be determined which parameters should be changed in the scaling. These parameters are then combined with the aid of the relations to the scale or among each other. In the case of a change in the scale, the parameters are automatically adapted with the aid of the relations. Finally, comprehensive tests are performed to check if all necessary dimensions have been adapted relative to the guidelines assisted by the boundary conditions. In addition, errors in the formulation of the relations are also regularly recognized in these tests, and the formulations are then revised and optimized.

For the demonstration, a multi-purpose building of the Offenburg University that houses both office and utility rooms (experimental hall) is created with the new method. In this case, the particular challenge is that a very small standard of 1:500 should be converted. In this extreme case, many details could no longer be represented due to the small dimensions. On the other hand, certain minimal wall thicknesses must be adhered to in order to ensure the printability. The model is divided into two parts to be able to remove powder from the interior during postprocessing. Furthermore, the model user has the option here of taking out the parts of the model and identifying the internal structure of the building. A base plate is additionally developed which serves as a mounting for the two parts of model.

A total of 15 independent parameters were defined in the parametrization (see figure 3). The façade should also be an expressly realistic design. Therefore, this is provided with specific parameters as a separate partial model to enable individual setting of the façade texture. A total of 290 relations allow for a very detailed adaption of the CAAD model to different scales and requirements. The generation of the parameters and relations involve an additional expenditure of circa 25 hours. This expenditure is, however, justified because with the change of a parameter, namely the scale, all necessary changes in the model are performed since these are no longer combined with each other by relations. An example of the application is illustrated in the multi-purpose building in two scales 1:500 and 1:250 in figure 4. The Binder Jetting process is implemented in the digital manufacturing of the architectural model because a colourful representation of the façade texture is possible. A further advantage of this additive manufacturing process is that the powder used for layerwise construction of the model simultaneously serves as a support material. The powder can be easily removed using compressed air. The removed powder can be completely reused so that no waste is generated. In other AM methods, e.g. FDM, it would be necessary to integrate supports in such an architectural model. These supports would have to be removed from the model with a lot of effort during postprocessing.

## CONCLUSIONS AND OUTLOOK

Today, additive manufacturing processes provide a sophisticated technology for the manufacturing of architectural models. Therefore, this technology is applied in many areas of architecture and civil engineering as well as in the education of university students. Yet, the models are, as a rule, restricted to a specific scale. A simple scaling, particularly a reduction of the scale, is not possible because, in doing so, important criteria for the feasibility (e.g. minimum wall thickness) would not be fulfilled.

In this contibution a method was developed and successfully tested, which allows to overcome these disadvantages by parametrisation. For this, a specific number of parameters is determined. All dimensions crucial to the Digital Manufacturing of the CAAD model are then linked with each other via relations. Depending on the complexity of the design, a large number of relations could then be necessary. It can be shown on the basis of this case study that in using this new method, a scaling of the architectural model is easily convertible. For this, only the change of one single parameter is necessary, i.e. the virtual model can be scaled within seconds.

In the further development of the method, the focus is on the integration of further additive manufacturing technologies. Thus, the restrictions in various additive manufacturing processes are rather diverse (e.g. is a support structure necessary or not). Consequently, the relations in the model must also be adapted to these process-specific restrictions. Additionally, the generation and testing of relations should be simplified by future work. This testing is still carried out experimentally today. It should be investigated to what extent the application of methods from computer science and numerical mathematics (for example, generic algorithms and data mining) can reduce this time-consuming effort.

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# CITY MODELLING AND GIS

# Parametric master planning via topological analysis using GIS data

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*This paper discusses parametricism in regards to urban planning and infrastructure. The objective is to bridge GIS data (using FLUX) and the parametric design process together into urban master planning. Creating a tool which generates the infrastructure and grid system automatically using specified manual user inputs, allowing for further generation of 3D forms from the block patterns. It also critically analyses the traditional master planning approach of grid system division in regards to topography, and how classical urban designers did not consider topographical constraints when a square grid system was employed to structure a city. The analysis of existing parametric master plans will also show that data driven planning has not put topography as a significant hierarchical. Through case studies using the developed tool, a clearer understanding of how topography can shape infrastructure can be understood. The analysis of topography is the main driving data iteration point which generates the infrastructure, grid, and division systems.*

**Keywords:** *Master Plan, Parametricism, Urban Design, GIS Data, Topography Optimisation, FLUX*

## INTRODUCTION

As population around the world increases, the demand for new cities and the redevelopment of existing cities also increases, both complementary to each other creating a supply and demand chain. New approaches of urban design and planning need to be considered (Verebes, 2014), to offer a resilient form of urban development where the rapid growth of population density will be progressively allocated in respect of the balance between built, social, and natural environment. Arguably Parametric Urbanism could offer a solution to hosting billions of people into new cities and interesting approaches as Computational Urbanism (Verebes, 2014); Morphogenetic Urbanism (Trummer, 2009) or as Digital Cities (Leach, 2009). Still there is another dimension. The conventional process of urban development treats buildings as isolated objects in the landscape, not as part of the larger fabric of streets, squares, and viable' open space. Decisions about growth patterns are made traditionally from two-dimensional land-use plans, without considering the three-dimensional relationships between buildings, spaces, geology, and without a real understanding of social and human behaviour (Trancik, 1986) Critics argued that traditional master planning is static and rigid. They were developed as a method for long-term planning of infrastructure and services in regards to relatively slow growing cities in developed countries (Clarke, 1992).


Figure 1
Screenshot of FLUX's user interface.

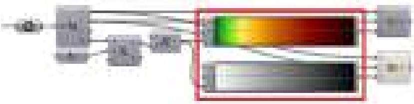

Figure 2
Grasshopper script for gradient calculation. Greyscale and Coloured output

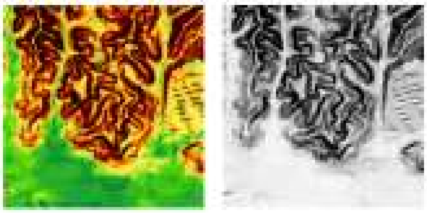

Figure 3
Coloured and grayscale image sample map produced by the Vector Angle calculation.

One significant criticism was the notion of master planning centred on the production of plans on paper, with little attention to implementation (Njoh, 2008). The traditional master planning technique thus became an end in itself, often separate from development controls and tertiary data factors (Todes, Karam, Klug, Malaza, 2010). Geographic Information System (GIS) offers an analytical collection of data about the three dimensional relationships between buildings, spaces, and geology, as extensively discussed and examined by Bonham - Carter (1995) or Malczewski (1999). However, Parametricism and GIS in conjunction with each other have only recently been used to form a thoughtful design process, which reflects on the natural environment to create a meaningful urban master plan. This research is the first to advocate extracting Geographic Information Data to create a new parametric method for the development of resilient cities.

## OBSERVATIONS AND RESEARCH QUESTION

Using GIS datasets and extracting data structures can be a very long and tedious process where certain programs and file types have different structures and capabilities. The limitation with GIS is that only certain regions have full datasets and the other lacking regions are extremely difficult to extract usable and meaningful data from. This paper is not only a theoretical development process, it is also an exercise in adapting to current technological advancements in commercially accessible industries.

A selection of projects has been carefully examined which have utilised GIS data to generate a solution for managing urban change and master planning.

From Estefania Tapias and Shubham Soni's 'Building-up urban open spaces from shadow range analyses', which addresses master planning in regards to sunlight optimisation utilising GIS data.

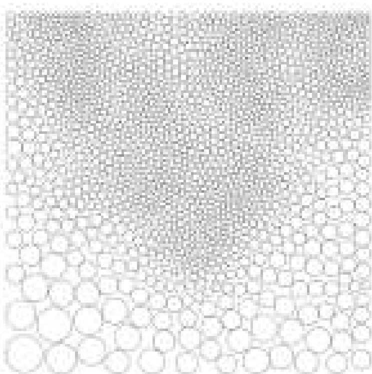

Figure 4
Circle packing based on image map.

To José Beirão, Pedro Arrobas, and José Duarte's 'Parametric Urban Design: Joining morphology and urban indicators in a single interactive model', where the GIS data of existing road infrastructure was the catalyst for the master plan.
In particular, the joint venture collaboration between dotA and Shanghai Tongji Urban Planning and Design Institute's 'Kaili Ethnic Cultural Compound' research project is the project that is similar to the research methodology of this paper. As an alternative to conventional masterplanning practices, this project transcends the inertia of two-dimensional planning with a new three-dimensional mode of planning. The research team explored a set of techniques for intelligent massing in relation to environment information and local vernacular architectural morphologies (Verebes, 2014).
The team at dotA and Shanghai Tongji only used topography analysis as a specified gradient to generate building typologies. This paper draws on and evolves the notion of topographical analysis further from the examined projects, asking the question of:

> *"Can a method of design or a process of design be created to bridge GIS data and Parametricism, whilst reflecting on the importance of the natural environment which is represented through topography?"*

### *Research objectives*

The aim of the research is to create and test a method or process of design which implements and bridges both GIS data and Parametricism to form a singular design dimension. In detail the objectives are the following seven items:

- to access and use GIS datasets effectively;
- to analyse topographical gradients;
- to develop infrastructure from topographical analysis;
- to generate a hybrid block system derived from the infrastructure development;
- to generate building typologies and structures within the block fabric;
- to analyse performance criteria and reiteratively design parameters; and
- to optimise performance using existing data as adaptive inputs.

## METHODOLOGY

The paper critically analyses traditional master planning approach of grid system division in regards to topography through literature review. To underline the importance of the natural conditions in urban design, knowledge has been evaluated and adopted from existing research projects. Based on the literature review the research employs an agile software development method. The following steps, described in greater detail in the paper, respond to the prior listed objectives and research question:

**SITE EXTRACTOR.** Selecting a site area or site boundary using google maps in the browser based system, the Site Extractor accesses OSM's public database and collates every available data stream. The selected site with the collated data is then sent to a FLUX project file, where it is saved to the cloud and

Figure 5
Explanation of Lloyd's algorithm through different iterations.

available to be viewed on a browser and/or downloaded by FLUX component add-ons in various programs. (see Figure 1)

Figure 6
Culled point cloud corresponding to the gradient image map and Voronoi tessellation applied to that point cloud.

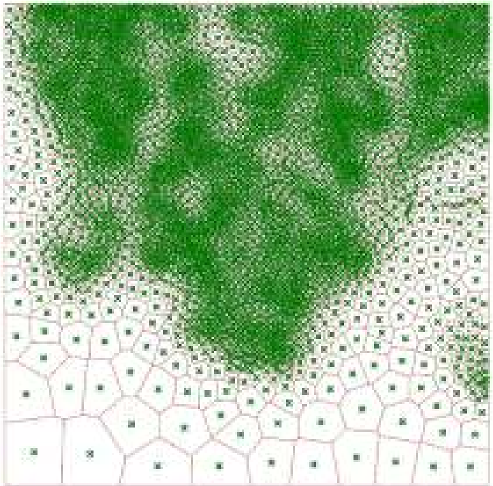

Figure 7
5 iterations of Voronoi relaxation is applied using Lloyd's algorithm.

**ANALYSIS OF MESH GRADIENTS THROUGH MESH REMAPPING.** A Vector Angle calculation is produced between the rising gradients of the mesh. The angle relationship of the vectors is then assigned a colour from a colour gradient chart which then assigns that specified colour back to the face of the mesh. The raw mesh downloaded from FLUX has enough subdivisions that it produces a good base for a colour image map from the colour gradient chart. (see Figure 2)

Concept and method of image sampling to represent topography and landscape has been drawn from Michael Batty (2005), it has also been reappropriated and developed upon to custom fit into the present mesh gradient analysis process.

**ANALYSIS OF TOPOGRAPHY USING REMAPPED MESH IMAGE SAMPLE.** Taking the remapped mesh image sample, the gradient analysis is expanded further allowing for a usable base for parametric design. This phase is the bridge between GIS data and Parametricism. It is critical that this phase be as accurate as possible, whilst creating a meaningful and plausible approach. (see Figure 3)

**EVOLUTIONARY RECURSIVE SUBDIVISION FOR TOPOGRAPHICALREPRESENTATION.** To use the gradient analysis from the remapped mesh image sample, the image map outputted is subdivided into cells that correlate to the gradient. This allows for an easier parametric design process, which allows the optimisation of infrastructure around specific gradients, culling the gradients that at too high to build on, and creating exclusions so that only lower slopes or flat ground is utilised.

Figure 8
Voronoi cell analysis with culled cells that are steeper than 1:5 and specific gradient range selection from the Voronoi tessellation.

There are many plausible methods to calculate cell sizes which corresponds to the gradient.

However, for this tool only two systems have been utilised and compared, the logic behind the two systems is to quickly compute an outcome so that an iterative design process can be achieved, where the original topography mesh could be changed and the script for the tool would immediately change and produce a cell distribution accordingly. (see Figure 4)

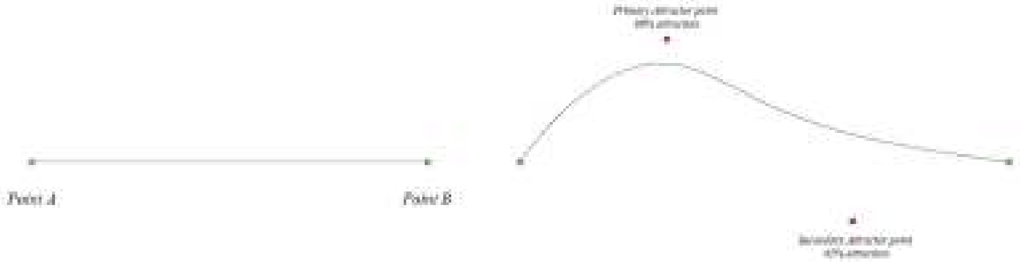


Figure 9
Infrastructure points A and B connected by a line or curve, this line is then pulled by a Primary and a Secondary attractor point.

Circle packing the image map utilises a gravity based push-pull simulation system. Scattering a specified amount of cells onto the gradient map, the cells fight for space pushing and increasing in size where the gradient is flatter, and decreasing in size where the gradient or slope is higher. This computational method has many disadvantages. The iterations it takes for every cell to be settled in place is approximately the same amount of specified cells for the simulation. This process also creates cells that do not fully join on the perimeters of each cell, this is due to the shape and natural limitation of a circle.
This limitation creates gaps between each cell which can never be filled even with exponentially smaller cells to fill each gap.

Using Lloyd's algorithm which is also known as Voronoi Iteration or Voronoi Relaxation, is an algorithm derived to compute and generate uniformly spaced convex cells from a set of points, in this application, it is used to compute evenly spaced distances between each centroidal point located in within each cell.The advantage of using Lloyd's algorithm is based on the principle of Voronoi subdivision, the most critical being that there is no empty space between neighbouring cells.Lloyd's algorithm also differs from circle packing) by the way each cell is generated and computed. Based on a point cloud system, a Voronoi function computes the distance between every point and the neighbouring points from that specific point. It then creates a cell tessellation equidistant from each individual point with the point cloud. (see Figure 5)

The time to compute Lloyd's algorithm increases exponentially when the population of points increases. However, the computation time for this method is significantly faster than circle packing when calculating the same iterations and point densities. (see Figure 6)

Figure 10
Test of Methodology on Case Study Golden Gate Park with generated infrastructure using the attraction system .

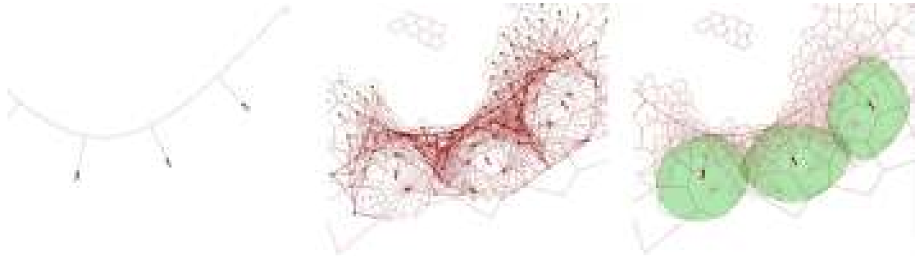

Figure 11
The three layers of process in order to create block distribution.

**EQUIDISTANT REORGANIZATION OF THE CELLULAR MATRIX TO PRODUCE AGRADIENT IMAGE MAP.** Using a grid system to distribute points onto the image map, a culling system is used to distribute points only to areas that are coloured, the darker the colour on the image map, the more points that populate the area. Taking the culled point cloud, a Voronoi tessellation is applied. The density of the culling system can also be changed based on parametric sliders. The denser the point cloud, the more accurate the analysis of the gradient map will be. (see Figure 7)

**POINTS DENSITY CALIBRATION AND GRADIENTS SELECTION.** Once a usable Voronoi tessellation through a user specified density and iteration amount has been computed, the user can specify gradients ranges to be utilised or removed. A gradient selection system has been designed to cull specific gradients using the Voronoi Cell Size formula. The culling process also allows for a specific gradient to be chosen and utilised. This is useful if the user wants to generate infrastructure on a specific slope within the topography and site.
However, the computing time for following processes may be slowed due to the population of the point system, an issue easily solved by switching onto a more powerful machine (most work was conducted on a laptop). (see Figure 8)

**INFRASTRUCTURE GENERATION.** The basic objective for infrastructure generation is the connection of manually inputted points, Point A (source) to Point B (destination). A straight curve or joining line is created between the points, however this curve can be further dictated by attractor points generated by the gradient analysis or manually specified points.

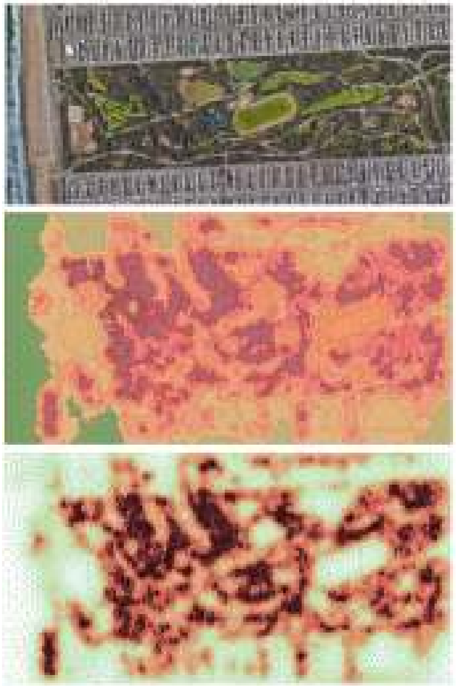

Figure 12
Aerial photograph of site (left), Gradient analysis represented through cell colour (middle), Voronoi cell layers corresponding to gradients (right).

There are three types of Attractor points; Primary, Secondary, and User defined. An Attractor point is used to pull the infrastructure curve towards it. Attractor point types are given weighted attraction percentages or pull strength and this can be manu-

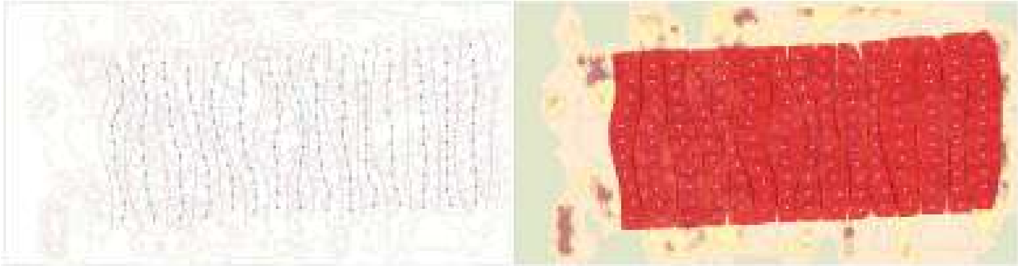

Figure 13
Block generation from pulled infrastructure lines from Figure 9.

ally adjusted through parametric sliders. The curve responds by losing its initial linearity and becomes more organically shaped by the gradients of the surrounding. (see Figure 9)

**INFRASTRUCTURE OPTIMIZATION WITH CELLS SELECTION.** Removing or culling the cells with high gradients, and/or choosing specific gradients for infrastructure generation. A systematic method of urban network generation is created that can be applied to any site. (see Figure 10)

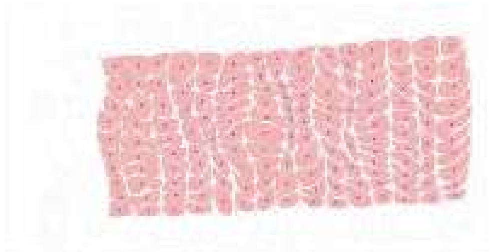

Figure 14
Cleaned block distribution or dynamic grid system.

**BLOCK DISTRIBUTION.** Similarly to the infrastructure generation, gradients are analysed according to the steepness of the slope and put into individual cell groups, corresponding to the size of the gradient. The cells within each group of gradients is assigned an attraction value or percentage, with the largest cell or flatter gradient group assigned the highest attraction values. The smallest cell group with the steepest gradients is conversely assigned the lowest attraction values. These individual sets of gradient cells are then used to create an interpolated polyline from a point which is offset from the infrastructure line. The range of the attraction between the point and the groups of cells is equal to the distance between the offset curve and the infrastructure line. This poly-line generation is dictated by the attraction values assigned to each individual gradient group. (see Figure 11)

After each set of polylines has been generated, an intersection or dividing process is implemented between different offset points (if there is more than one offset point). Based on each individual gradient set, an evenly spaced perimeter line is created between the infrastructure offset points. Then a smoothing, offset, and fillet process is employed to generate the final grid subdivisions or block distribution.

**BLOCK SUBDIVISION AND BUILDING TOPOLOGY GENERATION.** This is the current stage of research and development of the tool. Basic extrusions of the block patterns can generate building typologies. Taking the block boundaries within the grid system, there could also be a consideration for generating further building divisions or creating a plaza typology with communal domains within each block. Furthermore cellular autonomously based generation algorithms can also be implemented to create optimised typologies. (see Figure 12)

### *Testing of hypothesis*

In order to properly investigate the developed methods, sites or test area had to be specifically chosen to maximise and test the effectiveness of the process.

Golden Gate Park, San Francisco, California, was the ideal site for a case study and implementation. The greenfield site is situated within a densely populated area with various topographical gradients ranging from low to high elevations. (see Figure 13)


Figure 15
Different steps of methodology to analyse the site, Twin Peaks, San Francisco.

The rectangular site boundaries (existing road infrastructure) dividing the park from the already existing buildings also allows for an easier understanding of the context, between the contrasting built and natural environments. Apart from the benefits from the geographical location, there is also an advantage of the site due to the available data sets that have been collectively added on OSM (Open Street Maps).
Using FLUX and the FLUX Site Extractor to choose the specified site boundaries, it allows the tool to select and analyse the topography automatically, in real time. This cannot be done in regions where topographical information has yet to be added in OSM, Australia for example. Using a site which has already been developed, the developed methods are used to test and analyse how the topography is used within the existing infrastructure. (see Figure 14)

This creates a critical analysis of the existing built environment and tests the validity of the tool through the analysis of topography. *Twin Peaks, San Francisco* presented a strategic location (interesting topographical formation, closeness to natural features, surrounded by an existing high-density settlement) in which a critical analysis could be performed.
For this site test, the accuracy of the topography analysis was very important to demonstrate the validity of the script.
Adjusting Voronoi density for the sampling process increases the accuracy but reaches a point where the density becomes too dense and redundant, where a lower population of points could equally represent the same outcome as a much more populated model.

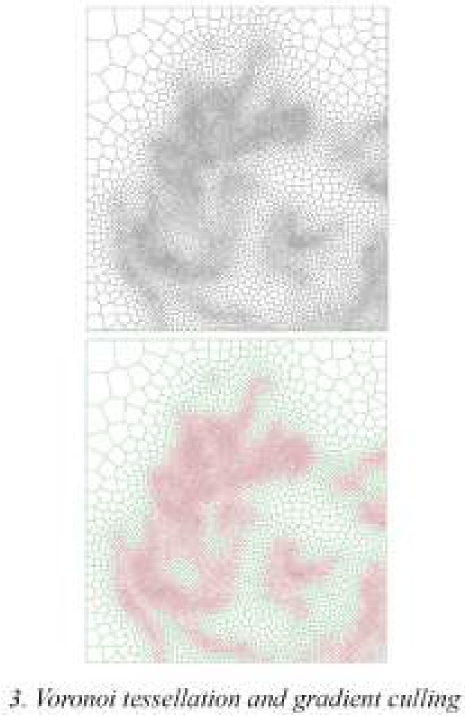


Figure 16
Culled cell representation of gradient analysis

The high gradient topography of *Twin Peaks* had already been developed with various residential build-

ings, this meant that the land these buildings were built upon were relatively flat. The outcome of the topography analysis displayed that not only did the script recognize the already existing flat topography where the residential buildings are located, but it also displayed similar flat gradients which had not been developed and could potentially be developed.
This does not only validate the topography analysis of greenfield sites which could lead to development, but also existing sites where potential developments could be realized. (see Figure 15)

The *Twin Peaks* topography analysis method could possibly be applied to any project with the available GIS data, and could potentially change the outcome or influence the design process from the original concept.
Using the outcome of this test as a data set strengthens and compliments a thoughtful approach towards development on any topography. (see Figure 16 and 17)

## *Evaluation and discussion*

The generated shapes of the infrastructure curves were less dynamic than anticipated and the whole digital process took longer than predicted. Too much user options created too much free choice in terms of parametric sliders and specifying points. This is not necessarily a disadvantage but it does require the user to spend more time to setting up the correct values.The critical analysis of topography can be evidently seen through the case studies, which is important in reflecting upon the research objectives and research questions. Most importantly, the case study in San Francisco demonstrates that the proposed methodology is valid, and that the process produces a workflow that can be applied when considering urban master planning.

## *Significance of research and Conclusion*

The significance of this research is a proof of concept in regards to the idea of designing cities in the digital age. Compared to conventional master planning design processes the use of data such as topographical information to create infrastructure that is context and environment aware is a stark change to a traditional grid system. It allows planners and city designers to adapt and consider a possible alternate design outcome that has a clear optimisation goal. In conclusion, through an iterative testing and design methodology, it is possible to not only theorise but to potentially realise a context tailored master plan that reflects on the topography of the site. Ultimately, this creates a discussion between the classical notions and ideas behind master planning with GIS design processes, both demonstrating how it is possible for a city master plan to not only be optimised but to also have a meaningful design.

## ACKNOWLEDGMENT

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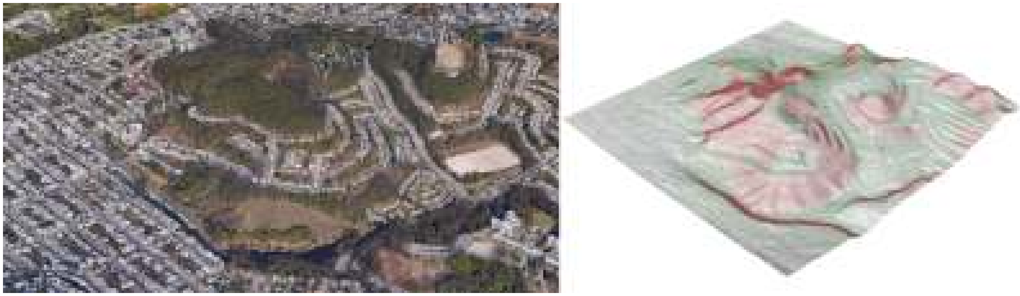

Figure 17
Aerial photograph of Twin Peaks (left) and Representation of the steep gradients of the site through a user specified gradient level (right).

bedded into the firm. We are grateful for the support Grimshaw has given and acknowledge the supervision support of Erik Escalante and Romain Guillot in order to submit the Bachelor thesis.

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# Urban Pinboard

## *Development of a platform to access open source data to optimise urban planning performance*

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*In this paper we present our research to design and develop `Urban Pinboard', a platform to optimise urban planning process and performance. We argue that second machine age general purpose technologies can now be accessed for city modelling. Based on the observation that: GIS does offer a depository that can display urban data; data sets exist but often stored at different locations; there is a discrepancy of access to planning information; and the data often are not accessible to private / public sector and the general public on one location, Urban Pinboard aims to address these problems as an integrated digital platform that enables the public, private and community sectors to connect by contributing ideas, comments and proposals on all planning issues in a single platform. The paper outlines the background research, methodology and introduces the Urban Pinboard's features to create a single source of truth for planning data.*

**Keywords:** *Software development, web-based GIS platform, Urban Planning, planning data*

### INTRODUCTION AND BACKGROUND

The maturation of the Internet has made possible the confluence of powerful technologies in which freely accessible software libraries automate many tasks (Brynjolfsson, McAfee, 2014). Low cost database technologies, storage, transmission and replication mean that massive data sets can now be accessed for city modelling. At present GIS does offer a depository that can display urban data; government agencies and others provide websites that store i.e. planning data, but often datasets are not on one and the same site and a user has to search at different locations to get all information; further there is a discrepancy of access to planning information; and finally data such as the private and public sector and the general public are not able to access the same information on one location leading to miscommunication and potential delays in planning processes hence there is no single source of truth.

#### *Planning*

The built environment is arguably designed and constructed by multiple, diverse entities that span academia, government, industry and the community. Whilst successful outcomes rely on effective collaboration between these entities, such collaboration is hard. Different paradigms and competing goals mean that many planning decisions are politically contested. Exacerbating the political challenge is the difficulty of describing the built environment comprehensively. It is a complex physical entity, but cannot be understood as that only. The legal reality of a city needs to be described and represented, as do its economic and demographic aspects. The organization, manipulation and visualization of spatial data is not a novel problem and an enormous amount of work has been done in this field under the umbrella term GIS (Davis, 2001).

### *Full featured GIS*

GIS is a mature technology with an evolved ecosystem of products and technologies. Despite the promise of GIS to present data cleanly and comprehensively, GIS has largely remained the domain of technical experts. This is driven by a number of factors such as: Open source solutions - PostGIS, Qgis despite their active, welcoming and helpful communities are technically difficult, limiting their uptake; and proprietary software like Esri, CityEngine are both technically difficult and also expensive.

### *Light weight web GIS*

More recently GIS has become more accessible to a community of non-experts. Google Maps provided a digital map designed for the masses in 2005. This is a lightweight geographical information system which exposes some algorithms - distance and way-finding - as well as the overlaying abstract information on the base map - such as traffic speed. The success of this product has lead to a greater market understanding of key GIS interactions and concepts (such as layers). This has lead to a virtuous circle where web GIS apps are able to assume a more technically literate market and thus increase the complexity of their offer. The visualizations shown on platforms like Mapbox are evidence of this. Crucially graphics and browser technology has evolved to the point where almost any device can display convincing 3D environments.

### *Community Interaction*

At the same time the way community interact with each other and with institutions has changed rapidly with the advent of social media. The cost of interaction - both direct and diffuse - and of information - has fallen rapidly. Facebook, Twitter and other social media platforms host more than just individuals. They are platform for a wide variety of interactions between multiple sectors. Governments, professions and businesses are able to seek feedback on their activities and policies far more cheaply and rapidly.

### *The opportunity and the need*

These two trends (1) a mass knowledge and technology ecosystem that makes public consumption of complex spatial data feasible and (2) an understanding of social media and rapid, de-siloed communication - provide an opportunity to change the way city planning is performed. Better GIS tools are able to provide clearer, more instantaneous evidence and information about problems, and social media platforms enable deep community engagement in the design process.

## OBSERVATIONS AND RESEARCH QUESTION

Based on the above listed background the paper makes the following observations:

- GIS platforms and their commercial licences are costly, hence they are mainly used within the AEC profession and consequently are not necessarily openly available to the general public.
- Still there are developments to address this issue and offer open source free GIS platforms such as the websites 'Mapbox' or 'Esri' to name but two, but these platforms are as well professional focused but not towards use of the general public.
- Further the above mentioned website platforms focus on purely technical problems but not on problems of governance, design and consensus.

- On the other hand of the spectrum websites like 'Social Pinpoint' are providing community engagement via a software solution but they often lack the data richness of GIS platforms like 'Mapbox' or 'Esri'.
- Yet one can argue that web technology has matured and one can get de facto standardisation of formats hence data transfer between different organizations (community vs. GIS) is cheap and feasible.
- At the same time web users of the general public are familiar with navigating maps on the internet through an exposure to Google Maps and others and therefore able to utilize GIS like tools.
- Further web browser allows complex information to be displayed visually and in 3D, here Kelly and Donegan (2015) deftly make the argument that: "Three-dimensional visualisation tools are much more effective at conveying what proposed new housing will actually be like. [As] one Australian state government official said that: this tool is moving us from year-long to hour-long negotiations".
- Yet if the use of GIS offers potentials one can notice that even architects and designers that are proficient in CAD make limited use of City data and web technologies in their design process due to the difficulties of accessing GIS data.
- Lastly built form data transfer has improved (through platforms like flux.io), however the potential for designers create, share and market algorithms has not been realized. Direct model to API communication happens within design firms, but not across design firms.

When reviewing and analysing these observations the researchers concluded that, speaking here general, two main types of data depositories exist: Data rich and interface poor or Data poor and interface rich (advanced), meaning they either have a large amount of data and these with a high level of accuracy - but with a user unfriendly interface; or the other way around, the interface has a higher level of quality and could be used by the general public - but the data stored at the backend are from a lower quality. A further disadvantage is that most platforms present data and the built environment in 2D as a map but not as a 3D model. Hence the research proposes two questions:

- *Can one use currently available web technologies to source and combine disparate, disconnected, high quality data and provide a single, 3D user interface to that data which is legible to the public, design professionals and government users?*
- *Could such a shared platform enable a new business model for architects and consultants where they provide their services as API calls across a network?*

Consequently the paper provides background into the multiplicity of available urban data and urban data platforms in order evaluate what exists at presents, and based on these findings propose and develop a platform of one's own meeting the objectives listed in the observations.

## METHODOLOGY

The research project employed a three-folded methodology.

Firstly, the team conducted a review of existing platforms such as 'Esri ArcGis', 'Qgis', 'Nicta National Map', 'F4 maps', 'Mapbox', 'Leaflet' and 'Postgis', to name but the most commonly known platforms in order to gain a broad understanding of the state of play in the field. This was supported through an extensive literature review in GIS, Big Data, urban planning tools and similar outlined in greater detail in the final paper. Through evaluating and reviewing the above and other platforms the researchers could classify them in taxonomy to identify a need for a platform to access open source data and algorithm to optimise urban planning performance. Classification criteria were items such as maximising the chance of community engagement the tool needed to be browser based and not require complex installation; establishing that the tool supported 3D, as the built environment is three dimensional and to seek community engagement this needed to be recognised; or that social media integration was a critical item. Through this taxonomy we could establish that full featured platforms like Qgis or ArcGis were not solutions. Further Google maps, Leaflet, Mapbox and Esri provided browser based mapping services which could be integrated with social media technologies but Google maps and Leaflet did not offer a 3D environment to an extend the project need. Mapbox and Esri provided aspects of 3D mapping, with Esri's being the most comprehensive.

Secondly, the team conducted a survey and interviewed ˜ 100 potential users from the private sector (architecture, planning, developers), the public sector (state government, local councils) and the general public (community groups) in order to understand and evaluate how these three target groups planned to use the proposed 'Urban Pinboard' platform. The private and public sectors were asked about their technology workflows, their data collection and storage methods and the integration of this data into their work, their understanding of 'open data' and the 'collaborative economy', and the integration of API's and other shared platforms into their work.This component of the surveys revealed that many firms in the private sector and some Local Councils are moving towards more open and integrated processes and platforms in their everyday workflows, and that there is a need for more authoritative and centralised data sources.Other topics covered in the survey included the public consultation process, in particular the time, costs and processes associated with engagement from the private sector to the Government and the community. As well as the communities expectations for consultation, and barriers to true consultation and feedback throughout the life of a proposal. The findings confirmed the need for more expressive communication of built form in the consultation process to the general public, lower costs and time allowances for consultation from the private sector to the community sector, as well as more opportunity for direct feedback in a timely and targeted manner from the community.

Thirdly, findings of the team were peer-reviewed and evaluated through weekly meetings by an advisory team comprising developers and urban planners. The advisory board evaluated and tested in these meetings whether 'Urban Pinboard' could lead to better design outcomes by facilitating collaborative, evidence based design processes.The conclusions of the advisory team indicated that more direct and comprehensive consultation with a larger segment of the community through an online 3D platform was likely to lead to more targeted feedback on the design of spaces and buildings, and would encourage a collaborative solution. Additionally, they identified that the opportunity for the community to interrogate the context of a proposal through the data layers provided on Urban Pinboard was likely to lead to greater understanding of the proposal, and would also encourage the private sector to deliver more evidence based planning and design.

Based on the three-fold methodology the team started developing the 'Urban Pinboard' platform using agile software development principles (Collier, 2011). This was motivated through the mixed nature of the project development team comprising a mixture of: architects, urban designers and computational designers working in a practice; academics from computational design; a software development team with a quantity surveying background; and a national urban development institute as client. Hence 'Urban Pinboard' needed to evolve through the collaborative effort of this diverse, self-organized and cross-functional team mixture.

## URBAN PINBOARD

Urban Pinboard (urbanpinboard.com/app) is an integrated digital platform that enables the public, private and community sectors to connect by contributing ideas, comments and proposals on all planning issues in a single platform. Urban Pinboard is the product of City Live Labs, a national innovation competi-

tion hosted by Urban Development Institute of Australia NSW Chapter, with the architecture / urban design firm Cox Architecture, Sydney and the academic partner University of New South Wales / Computational Design as winner of the competition (City Live Labs, 2016). Urban Pinboard was developed by the AAM group, a Geospatial Services company with offices in Australasia specialising in the collection, analysis, presentation and delivery of geospatial information.
The research team took as premised that planning issues may be physical, visual, acoustic, strategic and political and they could be local or regional. Further they may be quantitative and/or qualitative. Hence Urban Pinboard was developed to be a data and knowledge rich resource that has the ability to raise the urban IQ of the city and as a result, produce more informed decision making and smart city transformation. Further Urban Pinboard is founded on open urban data, with the latest qualitative and quantitative urban data constantly being inputted by all sectors to become a universal resource and collaboration platform. Examples of urban data that may be harnessed and integrated within Urban Pinboard may include:

- Community Input: local knowledge and insight that already exists but is normally locked away. I.e. lack of amenities in a certain area; lack of performance of certain infrastructure; ideas for new developments or programs; public perspective on policies or infrastructure investment;
- Government Policy: Local Government and State Government Policies / Plans translated into a legible digital / spatial format that general public understands.
- Professional Input: Research or studies prepared for a particular area by professionals. i.e. flooding studies; site survey information, traffic studies; ideas for new developments, improvements, collaborations.
- Other Urban Data: Big Data of Cities - Theory and Politics surrounding data;
- Policy-making urban data: land use and geographic data, Census & demographic data, traffic - mobility & flow data; Other types of urban data from social media and twitter to noise, urban lights and urban heat; Public and Open Data (or commercialised data).

The development team sees Urban Pinboard as an urban data marketplace, where commercialised data could be exchanged or purchased through plug-in applications integrated with the platform.
Once on Urban Pinboard, data and ideas can be responded to or elaborated on by others from any sector, providing equal opportunities to be connected (See also Figures below).

Figure 1
User specific login to Urban Pinboard on the top right of the interface © Industry&Co

The digital platform enables participants to respond by sharing their own views on the data they see, regardless of their physical proximity to the matter being proposed or addressed.

Figure 2
Screen capture showing the Urban Pinboard interface © Industry&Co.

Participants can share their ideas and responses via connected platforms such as social media, in order for those ideas to gain momentum and reach wider audiences. Urban Pinboard has sophisticated voting and ranking systems to allow popular ideas and data to be brought forward to gain more momentum and become a project or action Still it also could function as a tool used by a development or developer team. In listing some, but not all, features and functions Urban Pinboard can / is:

- *User login with user specific interfaces.* Urban Pinboard caters for different users ranging, as listed above from the private and public sector to the general public. Naturally each group has different expectations and skills they will bring to Urban Pinboard. To give an example, a community member might only want to see projects that are under DA (Design Approval) and alter the shadows to see if the new development overshadows his/her site, but do not want to engage into further tools such as uploading a DA, as an architect might like to do, or do a query for suitable sites, as a developer might do. Hence each user group has specific tools available to their individual needs. Users can login via registering an account or via using their Facebook or Twitter credentials (See Figure 1).
- *A browser based 3D representation of the physical city, including buildings and terrain.* Urban Pinboard is able to render 3D buildings in real-time as well as the terrain (See Figure 2) This 3D map is frequently updated by the geo surveyors at AAM, the back end developer of Urban Pinboard to assure that 3D map is up to date. Users can choose different base maps such as Streets, Satellite, hybrid or topography. Again, this gives specific user groups the opportunity to engage in a preferred way with Urban Pinboard and to allow general public users to navigate via a map system they are comfortable with through their use of Google Maps.
- *Multiple layers of data.* It includes multiple layers of data that are pulled from a variety of sources - including planning controls, demographic and/or transport data (See Figure 3). These data are displayed in a variety of ways, and overlay on the 3D representation of the cities or councils of interest. For the council used in beta version (Parramatta City Council in NSW, Australia) this results into ˜ 800 layer sets with several sub layers underneath. The data were grouped into main fields of interest with sublayers, as well different users will get access to some or all data depending on their login credentials.

Figure 3
Screen capture showing the data layer function on the right side of the user interface © Industry&Co

- *Filter,search and layer tools.* Filters, search and layer tools to easily navigate and control the display of data. These tools are widely used in web GIS and need little introduction. Urban Pinboard has more numerous data layers than something like Google Maps and so layers are organized into subcategories. An interesting feature for users from the public sector in particular developers is the 'query' function. (See Figure 4)Here a developer can search for sites that meets certain requirements i.e regulations such as no heritage, a particular FSR, etc. in combination with soil and ground information in order to assess and evaluate potential costs to develop the site.

Figure 4
Query function in Urban Pinboard with a general query option or as shown in the right side of the interface with a architect specific query © Industry&Co.

Figure 5
Proposed project can be presented on Urban Pinboard via renderings or video clips in order to give community and council a better understanding of the proposal (right side of interface) © Industry&Co.

- *Uploading proposed buildings by designers or developers.* A developer or architect can use Urban Pinboard to upload a proposed building which would then be visible to the public, in 3D, in its context (See Figure 5). Urban Pinboard also allows developers to upload text and images and create a panel to display their project in a traditional manner. Further, the multiple built form options per project can be uploaded which increases the value of engagement. The potential to upload proposals prior to a DA submission offers an interesting option for a developer to engage with the community. A proposal can be tested upon the response from the community, i.e does the community care less about if the building is taller than the planning regulation allow because it offers extra public space. This feedback can be collected and evaluated via the browse, comment and vote function outlined below.
- *Understand buildings in their 'data context'.* All users can turn on data layers to understand buildings in its 'data context' - all the physical and nonphysical information that is meaningful to evaluating the project's suitability. Some of the data layers - particularly those representing legal zoning constraints - are hosted by the relevant custodian and pulled at time of use. This ensures data integrity.
- *Browse, comment and vote on proposals.* Ability for the public to browse proposals, and comment and vote on them, providing feedback to the developer as well as the government directly through the platform. The comments are organized in threads according to each project option.
- *Showcase 3rd party apps on Urban Pinboard.* Developers and government users can use Urban Pinboard to run analysis via 3rd party apps to develop a deeper understanding of the building. (See Figure 6) This serves two functions. First it allows focused specialized uses of the Urban Pinboard platform which increases the number of experts contributing to the platform. Secondly it provides the possibility for consultants to derive income from Urban Pinboard which creates an incentive to engage.

Figure 6
Screen capture showing 3rd party app 'Kinesis', which provides a modelled estimate of parking allowance and their effect on transport expenditure per resident. © Industry&Co

- *Urban Pinboard as a marketplace.* 3rd party data vendors can use Urban Pinboard as a marketplace to sell their data, these could

be static but also real-time data. A benefit of a web-based platform is that Urban Pinboard can consume a wide variety of spatial data formats, and so is well placed to display data collected and stored elsewhere from the private sector, as shown on the example Kinesis (See Figure 6) as well as public sector like universities such as UNSW's City Data (www.citydata.be.unsw.edu.au) or others.
- *Community orientated functions*. Reservations against neighbouring new developments are often associated with the question of overshadowing. Where as planning permission often only require a proof on the summer and winter solstice Urban Pinboard offers a feedback for any day of the year at any site. Thus members of the community can easily evaluate if their property is overshadowed at any day and time during the year. (See Figure 7)

Figure 7
Shadow function to enable community members to assess overshadowing of the property. © Industry&Co

## EVALUATION AND NEXT STEPS

At present Urban Pinboard exists as a beta version with one council, Parramatta in New South Wales, Australia, represented through its spatial, economic and social data. Over the next months we are planning to cover most of Greater Sydney to then extend Urban Pinboard further to the state of New South Wales and finally Australia, with the potential to extend the project to Australasia. Where as 3D building information can be provided by our partner AAM , the collection and access to data for all proposed regions will remain the main challenge of this project. Initiatives like National Map in Australia (www.nationalmap.gov.au ) are a step in the right direction to better access data for planning and APIs can feed data from the platform directly into Urban Pinboard and updates can happen instantly. Still to often data is scattered over several platforms and we hope that Urban Pinboard can play a role in collecting and visualising data from different sources to make them available to a wider community. This is where we see the greatest strength of Urban Pinboard as we understand and see it as an interface to access data but not a data storage. When reflecting on the observations and the research question and evaluate the result we argue that Urban Pinboard has provided a single,3D user interface to that data which is legible to the public, design professionals and government users as well as that it has the potential to become a shared platform that enables new business model for architects and consultants. Further we see the following benefits for the private, community and public sector.

### *Private Sector Benefits*

Urban Pinboard will provide local insight and knowledge to developers, as well as all professionals and consultants. These inputs can be considered and incorporated into their proposals or professional outputs which are more likely to be favoured by both public sector and community sector through the collaborative process. As a result, the timing required to undertake formal community engagement processes and for development applications to be assessed has the potential to be significantly reduced.

### *Community Sector Benefits*

Urban Pinboard will provide easy access to essential data and knowledge of areas where communities live or are interested in, allowing them to be more educated and more 'intelligent' in addressing urban challenges. Communities will be encouraged in several stages to interact with Government and the private sector on service solutions and to improve outcome for their areas, creating attractive communities as a result.

### *Public Sector Benefits*

Urban Pinboard can become the main tool for all government agencies to engage and communicate with the other sectors. The nature of it being digital, legible and accessible, allows them to communicate much more efficiently than ever before, hence providing them with significant economic, as well as social benefits.

Yet to definitely answer and argue for these benefits with confidence Urban Pinboard needs to be applied and tested on case studies in each of the three sectors.

### *Next Steps - Community Engagement 4.0*

Before rolling out Urban Pinboard to further councils and thus a state-wide platform the team aims to conduct tests. This first test concentrates on how Urban Pinboard performs for community and the general public. There is evidence that in periods of rapid growth large projects often face opposition from community. Here research suggests that opposition often arises due to a lack of trust and limited understanding of the development process. As argued in the background chapter of this paper legally planning documents are available to the public during the consultation phase and ultimately, a community or individuals may decide to oppose a project, not because they disagree with the proposal, but because they simply do not understand it. To address this significant challenge, Community Engagement 4.0, the first test project funded by Urban Growth NSW, a large developer proposes the following research questions: "Can Cities 4.0 principles (Web 2.0, social media, open data and computational design) technologies help better communicate planning concepts to the public through a digital representation of planning data using Urban Pinboard?" The project aims to add emerging technologies to Urban Pinboard as they present engagement opportunities to government that can demonstrate public sector innovation through collaboration with key stakeholders. This is relevant as research argues that Cities 4.0 principles (Web 2.0, social media, open data, computational design) can harness "digital disruptive trends of automation, internet of things (IoT), cloud computing, virtual reality, 3D modelling, and other cyber-physical systems" to "fundamentally change city planning, design, construction, governance, financing and operations" (Cities 4.0 Summit, 2017). These emerging concepts offer new opportunities for cost effective, customised and engaging ways to communicate development projects to the community. The full scope and potential of Cities 4.0 concepts is not yet sufficiently understood when focussing on community engagement. To conclude next steps aims to achieve:

- Identification of efficient ways for collecting, analysing and storing social media data and digitised information on community engagement;
- Using virtual reality or 3D modelling via the UrbanPinboard platform to assist in explaining planning concepts to the public; and
- Forecasting community behaviour through machine learning.

## ACKNOWLEDGEMENT

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# Rethinking the Urban Design Process from a Data Perspective

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*Urban design always requires the processing of large amounts of data from multi-disciplinary sources during the decision-making stages. However, unfamiliar multi-disciplinary data sets can only lead to confusion and uncertainty. This research proposes a data-driven approach for supporting the urban design process. A hybrid data mining method is used to cluster, classify and rank solution-instances according to geometrical properties and energy performance. An urban design case study is used to demonstrate the proposed method with respect to two performance issues: solar heat gains and natural ventilation. The result shows that the method addressing both familiar and unfamiliar data can effectively guide the designer during the design process.*

**Keywords:** *energy performance, S3VM, decision tree, familiar and unfamiliar*

## 1. INTRODUCTION

Urban design is traditionally a heuristics problem solving process, involving different data acquisition and analysis techniques with the aim to establish a more evidence-informed design process. Schön (1983) described the design process as exhibiting "see-move-see" cycles, which involve preparing drafts to be evaluated, revised, and refined. Lawson (2005) further pointed out that urban design as a mechanism includes three parts: analysis, synthesis and evaluation. Meanwhile, the urban design process always includes some gratuitous proposals, which might bring a degree of randomness during the design stages. Though there has been substantial research on this iterative urban design process, the general conclusion has been that systematic design methods are not applicable to urban design (Cross 2006).

The rapid urbanization in the tropics has brought many challenges for urban designers to deal with the relationship between humans and the physical environment. Of growing concern to urban designers is the rapid change in urban climate associated with urbanization. At the same time, urban energy performance is highly impacted by the urban climate. And urban design has a significant influence on energy consumption for buildings and transportation, irrespective of the socio-economic context (Emmanuel 2005). Hence urban energy performance becomes an important aspect during the design process. Research of urban energy performance in the recent past has revealed a series of causal relationships between a wide range of urban variables and climate (Ratti et al. 2005; Stewart and Oke 2012). These range from urban geometry to human behaviour, from anthropogenic heat to thermal characteristics of urban surfaces, and from obstruction of wind flow to lack of vegetation. As concluded by Emmanuel (2005), from the climate perspective, there are mainly two mitigation strategies for pursuing energy efficiency during the urban design process at the neighbourhood/district level: 1) radiation reduction during the day, and 2) ventilative cooling at night.

Furthermore, as in other hot-humid tropical climate contexts, urban design in Singapore needs to consider the impact of a number of variables to achieve energy efficient design, including: 1) location; 2) building/site orientation and dimensions; 3) size and height of individual buildings; 3) existence of high-rise buildings; 4) street orientation; 5) availability, size and distribution of open areas and green belts (Givoni 1998). However, the research problem remains how to manipulate urban geometry to achieve energy efficient design with respect to the "move" step in the urban design process.

Hence the objective of this research is going to develop a hybrid data mining method for design data to guide the design process on energy-related urban performance aspects. Furthermore, the design data also relate to many other planning data and policies, thus including both familiar and unfamiliar data. Hence, to achieve this aim, we will reconsider and improve energy performance assessment during the urban design process from a data perspective.

The proposed method is expected to guide and inform urban designers to achieve energy efficient designs through an intuitive process. Each of the iterations will output a recommendation list of the design parameters for reference, which is sorted by energy performance priority. Furthermore, the output will identify which performance aspect should be focused on at the next design step. As a proof of concept, this research adopts an urban design studio to demonstrate the proposed method. This paper also expands on the problem statement and gives a brief overview of the literature review on urban variables. The model sites which are used in this case study could be replaced or modified by the designers for different design contexts. It will also outline and discuss further developments necessary to fully address the problem statement identified and to become readily usable as an urban design support tool within education and, possibly, practice.

## 2. LITERATURE REVIEW

Following on the energy crisis from the end of the seventies, many design projects and researches were carried out to understand energy consumption for urban design. Knowles & Ralph (1981) discussed architectural and urban design applications from the variables of solar envelopes. Subsequent researches started to investigate the energy performance of urban design considering climate variables (Akbari and Taha 1992; Owens and Susan 1986). From the mid-nineties, designers and researchers began to consider energy performance not only from a single perspective such as climate, morphology, etc., but also from multiple perspectives. They realized that the multifaceted relationship between energy performance variables and urban environment variables is the key to promote energy efficiency within urban practice. The whole urban system comprises many systems which are too complex to be quantified and represented in numbers and models (Yeang 1995). However, it appears there is no limit to include numerous variables into the analysis to quantify the urban impact on energy performance and vice versa. With the development of information technologies, the regression models for understanding design variables became more complex. Givoni (1998) and Littlefair et al. (2000) conducted research in both building and urban design located in different climate regions. They refined the design methods from an environment perspective and generated regression models for human comfort and the effects of urban form on climatology. Kikegawa et al. (2003) used the observed data with regression models to address the significance of regional meteorological conditions and its interactions with buildings on evaluating impacts of urban-heat-island on buildings' energy demand on a citywide scale. Ratti, Baker and Steemers (2005) pointed out that urban designers/researchers need to understand the building energy use as a comprehensive regression model of urban form, building design, energy system efficiency and occupant behaviour.

To address the abundancy of variables, new data analysis methods were proposed for the design process as well. Hanna (2007) implemented several techniques from machine learning and space syntax to define architectural archetypes. Liu and Seto (2008) built a method to simulate and predict urban growth from historical urban growth data. Gil, Montenegro, Beirao, and Duarte (2009) implemented a data mining method to extract descriptions of street and block typologies using attributes related to the morphology and density of urban blocks and street mobility. D'Oca and Hong (2014) developed a framework combining statistical analysis with two data mining techniques, clustering and association rules, to identify occupant behaviour patterns of window opening and closing in a naturally ventilated office building.

In conclusion, while supervised learning methods (regression models) are extensively used to deal with the abundance of design data/variables, and recent research explores the possibility of unsupervised (data mining) learning methods to handle with these kinds of data, there is lack of research on applying semi-supervised learning methods to deal with both labelled (familiar) and unlabelled (unfamiliar) data sets. Hence this research addresses the question of how semi-supervised learning methods can solve data issues during the urban design process. Specifically, in comparison with a supervised algorithm that uses only familiar data, will the semi-supervised learning methods have a more accurate prediction by considering the unfamiliar data points as well?

## 3. RESEARCH METHODOLOGY

The proposed method includes four iterative steps (Figure 1): 1) Design Variables & Parameters. This data includes the influencing data from different domain subjects. The variables and parameters will change between different design stages. 2) Similarity (Fréchet distance). The similarity between the familiar and other data variables (population, weather, economic, etc.) is checked. 3) Semi-Supervised Support Vector Machines (S3VMs). This classification method is carried out to separate the result of similarity as positive or negative energy performance. 4) Decision Tree (C4.5). All variables are recalculated by their information gain ratio with respect to the two issues: solar heat gains and natural ventilation. This result will help designers to identify which variable is the most important in the current design stages.

### *3.1 DESIGN VARIABLES AND PARAMETERS*

The influence of urban variables on energy performance is obvious from previous researches (Bueno et al. 2012; Ignatius et al. 2016; Jusuf et al. 2007; Ratti et al. 2005; Wong et al. 2011), and the key urban design and planning strategies to reduce energy use and thermal discomfort variables are: site coverage ratio, façade to site ratio, sensible anthropogenic heat, albedo (the ratio of reflected radiation from the surface to incident radiation) and emissivity (relative ability of the surface to emit energy by radiation).

### *3.2 SIMILARITY (FRECHET DISTANCE)*

The Frechet Distance was first defined by Maurice Frechet in 1906 as a measure of similarity between two parametric curves (Buchin, Buchin, and Wenk 2008; Eiter and Mannila 1994). Subsequently, it has become a standard measure between parametric curves used in many areas. The Frechet distance is typically explained as the relationship between a person and a dog connected by a leash walking along two curves and hoping to keep the leash as short as possible. The maximum length the leash reaches is the value of the Frechet distance. The standard definition for the Frechet distance (Alt and Godau 1995): Given two curves, A, B in a metric space, the Frechet distance, dF (*A, B*) is defined as:

$$d_F(A,B) = \mathrm{inf}_{\alpha,\beta} \max_{t\in[0,1]} \{d(A((t)), B((t)))\} \tag{1}$$

where $\alpha$, $\beta$ range over all monotone parameteriza-

Figure 1
The four steps of proposed systemic method

tions and *d()* represents the Euclidean distance, and *inf* is the *infimum*.

### *3.3 SEMI-SUPERVISED SUPPORT VECTOR MACHINES (S3VMS)*

Semi-Supervised Support Vector Machines (S3VMs) are developed from Support Vector Machines (SVMs). SVMs rely on training data to generate a separating hyperplane that splits the given data into two different classes. SVMs are formulated into optimization problems to find a series of weights and a constant b, which together represent the separating plane. Such a decision boundary is defined as (Bennett and Demiriz 1999):

$$f(x) = w^T x + b \tag{2}$$

where $w^T$ is the parameter vector that specifies the orientation and scale of the decision boundary, and b is an offset parameter.

However, traditional SVMs require the data to be labelled before classification analysis. Considering the limitation of the SVMs, this research adopts the S3VM to deal with the data during the design process, specifically, the software SVM-light (Joachims 1999).

### *3.4 DECISION TREE (C4.5)*

The decision tree method C4.5 is proposed for the classification issues, because it adopts a simple hierarchical structure that aids user understanding and decision making. The C4.5 algorithm includes the information gain ratio concept, which is defined as follows (Quinlan 1993):

$$\text{GainRatio}(p, T) = \frac{\text{Gain}(p, T)}{\text{SplitInfo}(p, T)} \tag{3}$$

$$\text{SplitInfo}(p, T) = -\sum_{j=1}^{n} \left\{ p^{'}\left(\frac{j}{p}\right) \cdot \log\left(p^{'}\left(\frac{j}{p}\right)\right)\right\} \tag{4}$$

where $p^{'}\left(\frac{j}{p}\right)$ is the proportion of elements present at the position p, taking the value of the j-th test. The information gain ratio is independent of the distribution of examples inside the different classes.

## 4. CASE STUDY - RETHINKING URBAN PRACTICES FOR JURONG VISION 2050

The case study for this research stems from an international, collaborative design studio (Winter School) involving over 170 students and 30 design tutors, organized by the International Forum on Urbanism (IFoU), in which the first author participated as designer from energy performance perspective.

The brief was to develop proposals for the transformation of Jurong Industrial Estate (JIE), a 5000-ha industrial area in the west of Singapore from an almost mono-functional, segregated and fragmented, polluted industrial area into a major catchment area for future population growth that integrates clean industrial plants with green lungs, attractive housing and vibrant urbanity for one million people. During the IFoU winter school, designers were divided into teams, who then worked intensively together to develop urban visions and proposals for a scenario of 100% renewable energy system by 2050.

The design case study focuses on sustainable energy production, consumption and distribution within the built environment. The design process is elaborated on two levels: On a macro scale (urban level), new approaches of energy exchange, circulation and balancing are investigated, while on a micro scale (precinct and block level), design explorations focuses on energy efficient building structures, natural ventilation, optimal daylight access and the integration of technologies for sustainable energy production. To identify the features of the proposed method, two design scenarios are described and compared in the following paragraph.

### *4.1 CONVENTIONAL DESIGN METHOD*

**4.1.1. Macro-scale design stage.** The designers follow the idea of urban acupuncture to deal with the energy issues. Just as the practice of acupuncture is aimed at relieving stress in the human body, the goal of urban acupuncture is to relieve stress in the built environment. Due to the five-element theory of Chinese philosophy, the designers chose five sites from this area which also was figurative as "material energy" system. Each site is improved from the concept of the definition of the element. In this design, the definitions of the elements are: "earth" represents underground space, "metal" means reinforced frame pier, "wood" refers to green space and residential area, "water" implies hydropower and "fire" indicates the energy plants. In the meantime, designers carefully consider energy consumption flow through analysis of aggregate urban environmental, social, economic and ecological factors. The final decision of the selected sites is shown in Figure 2.

**4.1.2. Micro-scale design stage.** The designers selected one node "wood" for the integration of industrial and residential areas. Two main aspects were considered for the design: 1) radiation reduction during the day, and 2) ventilative cooling at pedestrian level and indoors. Designers compared the site with Punggol New Town which is developed as an energy


Figure 2
The five important nodes identified by designers

efficient residential area in Singapore, and completed the masterplan and concept design as shown in Figure 3a. Furthermore, a building typology is proposed based on their energy performance as shown in Figure 3b.

### 4.2 HYBRID DATA MINING METHOD

Before applying the hybrid data mining method to the design data, the designers need to specify what is the familiar data and unfamiliar data. In this case study, the familiar data will always refer to the spatial variables from macro-scale to micro-scale. The unfamiliar data will include the population structure, economic structure and industrial structure from Punggol New Town (Table 1).

Hence, based on the different design solutions, the final estimated values of the three categories will always be compared and classified during the S3VM step. The detailed design scenarios are described below.

**4.2.1. Macro-scale stage.** Considering the preview dataset, we denote the designer not as an expert but as a novice who only is familiar with the urban environmental data which contains fundamental information of geography and transportation. The nodes selection will go through the proposed method: 1) Familiar design variables: crossroads points (more than four boundaries), bus stop points. 2) Similarity: Because designers want to identify the isolated sites, the number of bus stops inside the circle should be as few as possible. And the curvature of the roads will also be compared with an empty crossroad. The radius of the circle is 200 m. 3) S3VM: compare the selected nodes for their prominence with the social and economic data sets. 4) C4.5: Ranking the select sites based on the information gain ratio.The detailed calculation steps are shown in Figure 4. Population density is analysed in Figure 5. The final important nodes are also shown in Figure 5.

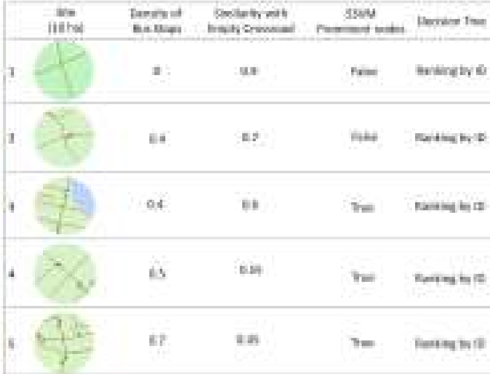

Figure 4
The five nodes calculated by proposed method

**4.2.2. Micro-scale stage.** As in the previous design process, the designers choose node 3 which is the "wood" node, to explore the design proposals from an energy perspective. Unfortunately, the designers are still only familiar with the spatial geometry data. They have no knowledge on the impact the weather or economic conditions will have on the energy performance. Hence the proposed method at the first step will be redefined such that the familiar data only contain the variables: site coverage, massing height, massing location and green area. Bueno et al (2012) has listed the values of key urban design variables from energy perspectives in Punggol New Town (Table 2).

Considering the values from Table 2 and the total area of this new site (64 ha), designers start to draw any forms as they like. However, there are two rules to consider a) site coverage ratio and b) single plot area. This design area total is 64 ha, hence the residential area should no more than 24.32 ha from Table 2. And as the plot area always is around 6 ha, hence the proposed residential area in this area will be split into four parts. The site area also can be divided into nine subsites, which means that the site coverage decision-making problem becomes a math problem: how to insert the four residential areas into the nine subsites to achieve the maximum energy performance and comfort. But the total number of possible combinations is 126, which is too many for designers to decide manually. Then considering sim-

Figure 3
a) Micro site proposal for Jurong Bird Park site and b) design for massing structure and layout


Table 1
The urban design data from energy perspectives in Punggol New Town.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Ethnic Group | Chinese | Malays | Indians | Others | | | | | |
| | 75.35% | 15.03% | 6.80% | 1.94% | | | | | |
| Marital Status | Single | Married | Widowed | Divorced | | | | | |
| | 18.36% | 73.91% | 3.50% | 4.23% | | | | | |
| Religion | No Religion | Islam | Hinduism | Buddhism | Taoism | Sikhism | Catholic | Christians | Other |
| | 21.47% | 13.25% | 4.85% | 34.50% | 9.41% | 0.72% | 6.63% | 11.58% | 0.48% |
| Highest Qualification Attained | No qualification | Primary | Lower Secondary | Secondary | Post-secondary | Polytechnic | University | Professional | |
| | 8.98% | 4.26% | 6.39% | 15.30% | 8.38% | 13.42% | 34.45% | 9.29% | |
| Age Group | 0~4 | 5~9 | 10~14 | 15~19 | 20~24 | 25~29 | 30~34 | | |
| | 12.68% | 8.95% | 5.80% | 3.08% | 3.13% | 6.27% | 16.88% | | |
| | 35~39 | 40~44 | 45~49 | 50~54 | 55~59 | 60~64 | 65 + | | |
| | 12.86% | 8.88% | 5.32% | 4.65% | 3.73% | 3.21% | 5.57% | | |
| Monthly Income from Work | <1k | 1k~1.5K | 1.5k~2K | 2k~2.5K | 2.5k~3K | 3k~4K | 4k~5K | 5k~6k | |
| | 5.97% | 5.31% | 4.64% | 4.98% | 5.88% | 11.77% | 10.38% | 10.32% | |
| | 6k~7k | 7k~8K | 8k~9K | 9k~10K | 10k~11K | 11k~12K | >12k | | |
| | 9.12% | 8.13% | 6.30% | 4.64% | 2.82% | 2.49% | 7.83% | | |
| Industry | Manufacturing | Construction | Wholesale & Retail Trade | Transportation & Storage | Accomodation & Food Service | Information & Communication | Financial & Insurance Service | Real Estate Service | Professional Service |
| | 6500 | 2700 | 10100 | 6100 | 2800 | 3100 | 5200 | 1800 | 5400 |
| | Administrative & support Service | Public Administration & Education | Health & Social Sevices | Arts, Entertainment & Recreation | Other Community, Social & personal Services | Others | | | |
| | 2200 | 8600 | 2500 | 3100 | 2300 | 700 | | | |

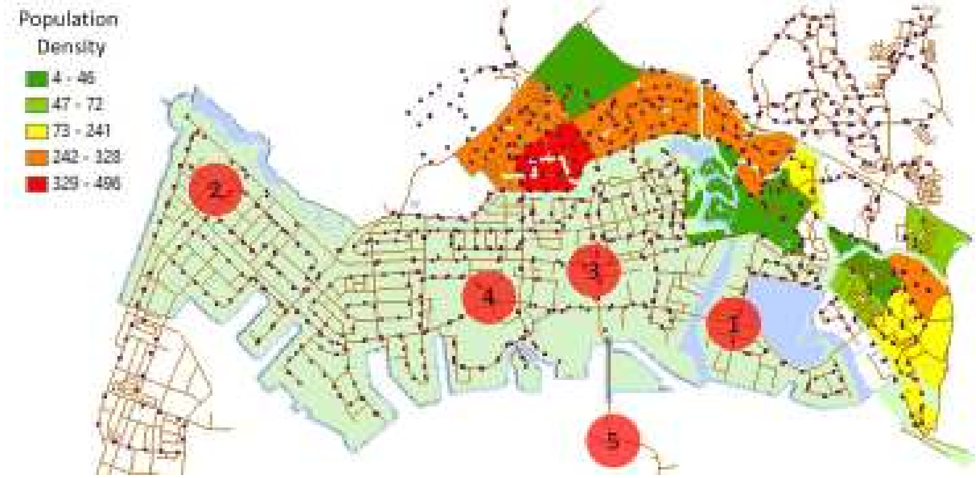


Figure 5
The five important nodes identified by proposed method

ilar sites in Punggol New Town as a model, two sites Treelodge@Punggol and Punggol Water Park are selected to compare for similarity. The curvature is generated by linking all the centre points of the residential areas. The drawing with the highest similarity value is selected as site coverage proposal. S3VM will help to classify whether the proposed site coverage is sufficient for the future increased population and economic. Finally, the decision tree will rank the design parameters for designers to consider for the next step. Figure 6 lists a single initiative progress of the site coverage decision-making stage. After the decision of site coverage is confirmed, the decision tree suggested to consider massing layout in a single

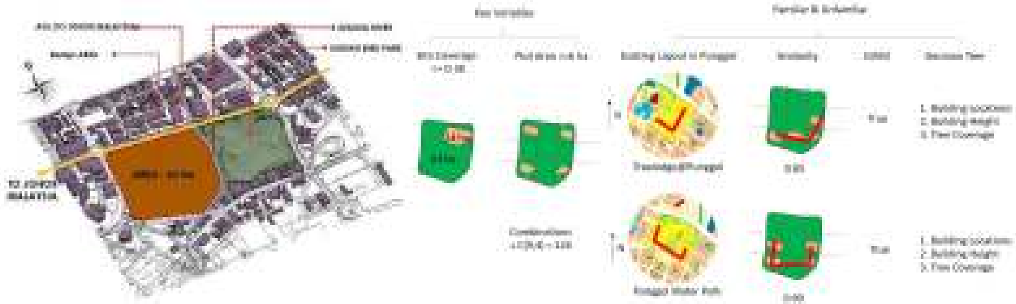

Figure 6
Decision of site coverage process by proposed method.

Table 2
The key urban design variables in Punggol New Town.

| Location | Tree coverage | Average building height | Site coverage ratio | Facade-to-site ratio | Sensible anthropogenic heat |
|---|---|---|---|---|---|
| Punggol New Town Singapore | 0.19 | 26 | 0.38 | 1.55 | commercial area: 10<br>residential area: 4 |

plot. Also from Table 2, there is a limitation for the façade-to-site ratio. Because the single plot area is 6 ha, and the perimeter and area of a typical residential building in Singapore is 90 m and 700 m2, it means that if the height is 26 m, the maximum number of buildings in a single plot is 39. Hence here the single plot also is separated into 600 sub slots (100 m2 per slot). Then the decision of massing layout also becomes a mathematic problem which is how to insert the massing to achieve the maximum energy performance and comfortable again. The plot models are also selected from the Punggol New Town area, and the calculation process is shown in Figure 7. Hence the same calculation process is also applied on the decision of tree coverage. And the final micro-scale design proposal is shown in Figure 8.

### 4.3. COMPARISON AND DISCUSSION

From the above mentioned urban design case study, the conventional design method and the proposed hybrid data mining method are compared in Figure 89. There are two important points which should be discussed further. First, both design processes used the same available datasets which are collected from

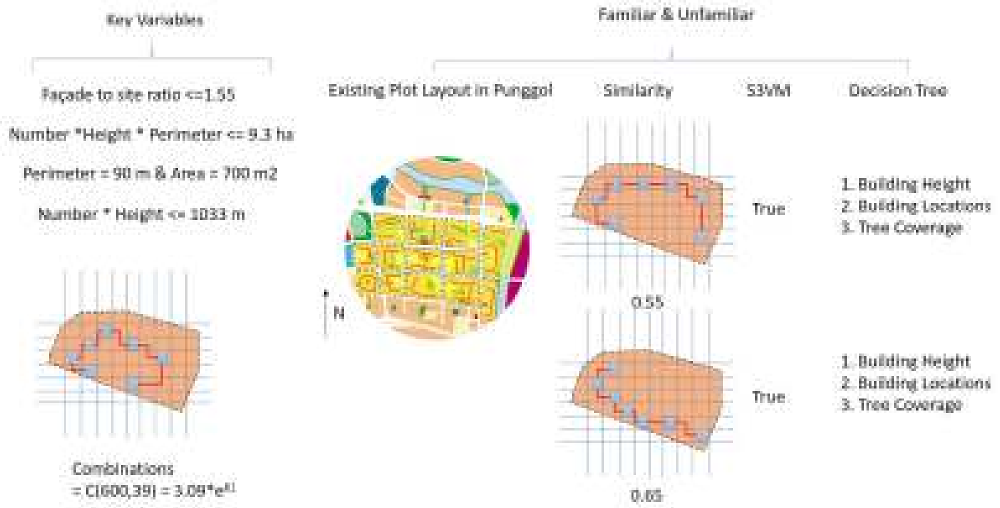


Figure 7
Decision of massing layout by proposed method.

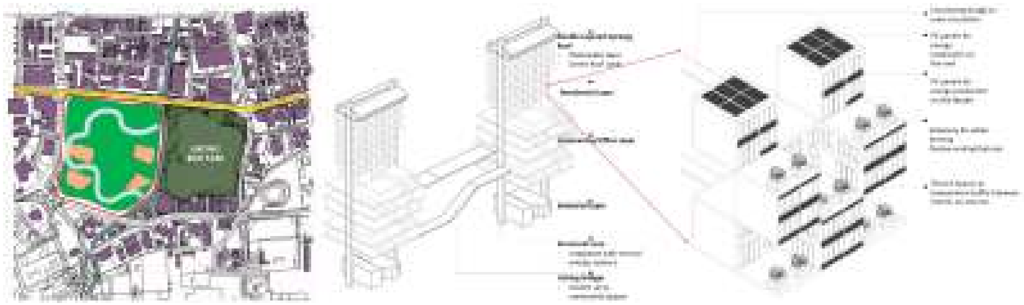

Figure 8
The final micro-scale site design proposal for massing structure and layout.

| Data Source | | Design Objective | Conventional | | Hybrid | |
|---|---|---|---|---|---|---|
| | | | Method | Result | Method | Result |
| Macro-Scale Stage | Spatial<br>Social<br>Economic<br>Ecological<br>Weather | 100% renewable energy system | Urban Acupuncture | Concept is accepted, but lack of data to prove it. | Familiar & Unfamiliar | Concept is accepted, and the data of population, economic and transportatio n also prove it |
| Micro-Scale Stage | Spatial<br>Social<br>Economic<br>Ecological<br>Weather | 100% renewable energy system | Rule of Thumb | Total energy consumption are reduced by 75% in 2050,<br><br>Energy production from PV cover 70%. | Familiar & Unfamiliar | Total energy consumption are reduced by 79.1% in 2050,<br><br>Energy production from PV cover 85%. |

Figure 9
Comparison between two design methods

public websites. The only difference is the design method. The conventional design method could be extended to any other regression models (like Gravity Model, Urban Energy System), which require the designers to pass all the assumptions as input data to evaluate the design solutions. But the proposed data mining method will allow the designers to improve the design process by skipping the data which is unfamiliar by them. The proposed method allows designers to simply focus on the design variables which are familiar to them, while keeping track of the design quality through the unfamiliar data. Hence back to the design "see-move-see" cycles, the proposed method removes the burden of data from multi-disciplinary sources. Secondly, considering the design results from the two methods, both design proposals were evaluated with respect to the total PV cell area and total energy consumption at the site. The present total energy consumption of the Jurong Industrial Estate is 2567.84 Ktoe (EMA 2016). And the annual average solar radiation on tilted panels (shadings not included) is 1663 kwh/m2. Then the conventional design method achieves the reduction of energy consumption by 75%, and the energy production of PV could cover 70% of the total energy consumption in the year 2050 with a total panel area of 3352140.379 m2. The PV area is estimated from built-up (roof, façade, etc) and open space (8% of natural space). In the meantime, the final design by the data mining method reduces present energy consumption by 79.1% and increases the energy production of PV (3686820.70 m2) to 85% of the final estimated energy consumption in 2050. Hence the results demonstrate the possibility of applying this hybrid data mining method as a complementary decision-making approach for energy performance aspects in the urban design process. The proposed method is able to prioritize the design variables to guide designers at the micro-scale stage. Furthermore, the conventional design result needs an expert to explain the design proposals and the audience also needs the relevant knowledge to understand the evaluation progress. On the contrary, the design proposals from the second method could be explained with data analysis results as evidenced by novices. In summary, this proposed data mining method is able to make the urban design process from an energy perspective more trackable and transparent.

## 5. CONCLUSION

The objective of this research is to create a hybrid data mining method to help designers solving decision-making problems during the urban design process. The proposed method mainly includes three parts: similarity calculation, classification (S3VM) and decision tree (C4.5). The main difference with the conventional regression model is that the design data is separated into two groups: familiar and unfamiliar. The proposed data mining method could allow designers to improve their design without fully understanding all the knowledge. The case study also shows the possibility to apply this data mining method as a complement considering energy performance into urban design processes.

In the future, we will evaluate this method with other design perspectives: accessibility, mobility, greenery etc. Additionally, the proposed method will also be further developed to become readily usable as an urban design support tool.

## ACKNOWLEDGEMENTS

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# Advanced tools and algorithms for parametric landscape urbanism

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*In the last decades, urban design has been influenced by its relationship with landscape. This has led to a new approach formalised and called Landscape Urbanism. Defining specific reading and analysis instruments together with proper design methods, capable of a transdisciplinary dialogue with geography, plant and biological world's languages, landscape urbanism can undoubtedly obtain more performing purposes than the ones achieved by traditional urban planning. Moreover, new digital tools are appearing, providing urbanism with new instruments for an advanced and interactive way to design cities in close relationship with landscape. The process starts with the acquisition of large quantity of data, like georeferenced maps in conjunction with relevant information about the territory, such as traffic and atmospheric pollution data, important buildings and monuments or significant landscape elements (rivers, mountains, etc.). All this information is combined onto multiple layers in order to be used by different design algorithms, connected by multi-dimensional arrays, whose reciprocal relations are dynamically controlled by architects and engineers. We will present here the case study of an ecological and regenerative infrastructure for the city of Bergamo designed on the basis of these principles, using a convenient combination of parametric tools.*

**Keywords:** *algorithmic city planning, landscape urbanism, post-urban architecture*

## INTRODUCTION

During the last two decades, the idea of landscape has been assumed as a generative model for urban design. This concept has been proposed and supported not only by a great interpreter of contemporary architecture like Rem Koolhaas, but it has permeated a large number of theories worldwide that are constituting a disciplinary advancement along this path. Perhaps, the most complete and interesting work on the historical and disciplinary formalisation of such approach is due to Charles Waldheim (Waldheim 2016), who himself defined it as Landscape Urbanism. This is why the perspective from which we look at the interface between engineering and architecture leads us to recognize urbanism, and especially landscape urbanism, as the exemplary place of such disciplinary hybridization. An inhabitable future for that urban environments that we call post-urban - not only the traditional peripheries but also suburbs and new conurbations of larger towns - is possible only by devising and designing new eco-infrastructural systems, infrastructures for urban regeneration, multitasking infrastructures, systematic Green, living accessibility, etc., and a de-engineering building process that can recover the disorder of empty spaces, non-places, and sites of a lost naturalness. And what could be the tools allowing us to achieve these purposes, other than those managing georeferenced maps, and parameterizations of geographical data, in combination with additional algorithmic tools to control the growth of cities? In our case the latter are some tools that have been developed in engineering for structural form-finding applications, the popular parametric 3D modeling software Rhinoceros and Grasshopper with plugins like Elk and Meerkat. These tools, used together, contribute to define the so called Parametric Urbanism. There can be several ways for these meta-objects to connect with each other (Otto 2009). A rule based on their reciprocal distance can be defined, or a model of their distribution on a surface can be identified in a similar way. Their density can be hypothesised depending on the type of the studied object (human being, animal, building, etc.), and so on. In addition to bi or three-dimensional distributions, it is also possible to consider and conveniently model the behaviour of people, animal or other "unpredictable" beings, organised in single entities or in crowds, like in (Waldrop 1993) and (Canetti 1984). All this information is then converted into mathematical objects. The effectiveness of the entire procedure relies on the accuracy of the various mathematical models and on the way they interact with each other. The methodological part of this work derives from the chapter "A-Astrazione/E-Strazione: Per una metrica qualitativa dello spazio urbano" written by V. Paris in (Pizzigoni 2017). This study starts from the analysis of the city of Bergamo and its relation with the territory, seen through the presence of the Morla river that becomes the element through which the entire regenerative process can begin.

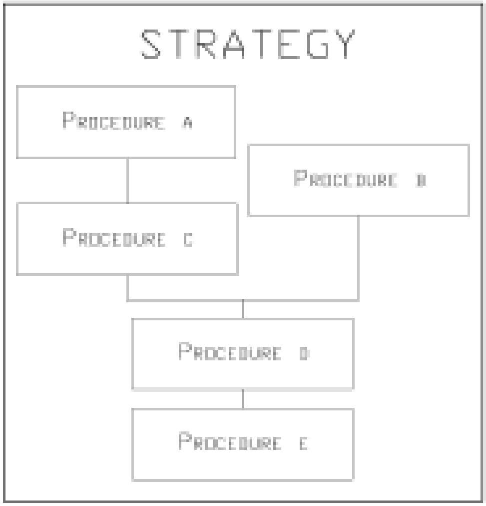



Figure 1
Representation of a possible strategy

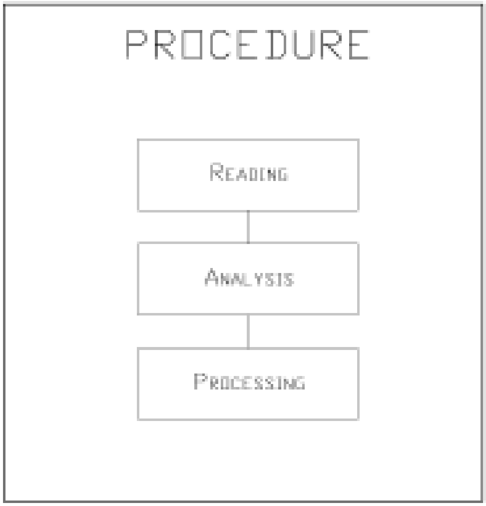



Figure 2
Representation of a procedure and its phases

## THE SEARCH FOR AN OPERATIVE METHOD

The chorography of Morla river, with both its natural and urban topography, characterizes not only the place and the space, but it also becomes the founding element of all produced maps. The adoption of different viewpoints identifies different narrations that can be far from each other in many respects, but that share three factors: two physical - the urban area and Morla's hydrography - and one operational. The development of the latter needs our attention [1], and this research is focused on the identification of design strategies capable of abstracting and extracting data in order to reveal and represent hidden relations inside urban space. First of all, it must be defined the meaning of the term *strategy* and the concept of *procedure*, the latter being the basis of the strategy itself. A *procedure* must be intended as an algorithm, whose scope is the description and the virtual representation of a physical, social or environmental phenomenon. Every *procedure* is constituted by a logical sequence of mathematical operations and it possesses specific variables, input and output. In particular, it should be capable of restoring the consequentiality of all the elements that represent physical phenomena or real entities. With the term *strategy* we refer to a vision (see Figure 1), a priori defined through a series of subjective choices and strictly related to the design process and to the concept itself. A *strategy* identifies one or more procedures that are related to each other. This approach implies the need to develop complex readings and analyses, creating logical connections between them in order to provide a better comprehension of urban phenomena. Every logical step has to be made explicit in a formula, in a mathematical model or in a sequence of smaller steps. In order to achieve this, it is requested a description of the city's social and evolutional phenomena which should be beyond a simple static representation. The adoption of such a methodology shifts the design effort to a more abstract level, where connections, networks, time and places of diversities become dominant. We are required to operate on two different levels. A first abstract and methodological level, containing a set of verified procedures, capable of obtaining a result. A second level, seen as a synthetic model, recalling a Batty's definition (Batty 2007), represents the bridge between real and virtual and must be capable of foreseeing all possible scenarios with good accuracy.

## PROCEDURE

In theory, every *procedure* can be specified in three phases: *reading*, *analysis* and *processing* (see Figure 2). The algorithms that constitute its single steps should have some common characteristics in order to verify their congruity through some form of output in every moment of the process. Other properties may belong only to specific situations. As previously said, procedures are algorithms with a precise purpose, describing and composing traces deriving from acquired data. Given these conditions, a natural question is: what should be the task of a designer? Where should its individual actions and technical skills take place? The efficiency of this phase of design work depends on the current knowledge in computer science and architecture, but the possibility of describing the complexity of urban space needs skills in several disciplines which are barely capable of interfacing with each other. As an example, it can be noted how difficult can be the interaction between architectural design and structural engineering, so strictly connected in the traditions of the past. Ability of comprehension, dialogue, synthesis, sensitivity for the reading of the present, are fundamental and necessary gifts not only for the single designer, but especially for heterogeneous working groups, where different and complex skills have to dialogue, interact and deal with each other in order to pursue a common goal.

## THE MAKING OF A PROCEDURE

The first phase of this study is about the reading and the analysis of regional [2, 3] and municipal [4]) open data, integrated with the ones coming from OpenStreetMap (OpenStreetMap 2017). The gathered information is managed by algorithms capable of providing a numerical or graphical representation. In particular, the research is focused on the determination of an ordered set of instructions whose aim is the correct reading of shape file [5] or spreadsheet data. This choice has been followed because the former represents the standard for GIS systems, so these procedures can acquire data and use them in georeferenced environments. At the end of the *reading* phase, for simplicity's sake, we can imagine that data are organized in different layers, each of them corresponding to different classes of elements. Later, at the *analysis* stage, the needed information is extracted and organised in order to achieve the objectives defined in the strategy adopted by the designer. At last, every procedure is characterized by the *processing* logical-sequential group, constituted by algorithms which have the goal to relate layers one to each other. This last phase necessarily needs to produce a graphical output.

## STRATEGIES: EXAMPLES AND CLASSIFICATION

We present some examples derived from the different *strategies* adopted during this research, stating their objectives and describing some details. The first *strategy* here considered deals with the *analysis of the entombed parts of the Morla river* (see Figure 3). This strategy is based on three *procedures*. The first one, whose scope is the materialisation of the chorography of the surveyed area, retrieves the layout of the Morla and of the built environment from a shape file (reading phase). Afterward, it extracts from the previously obtained data a series of points, or nodes, and organises them in layers (analysis phase). Finally, nodes are adequately connected to each other those nodes in order to materialise the buildings and the Morla's riverbed (processing phase). The second *procedure*, similar to the first one, acquires the information related to the covered sections of the river, providing their geometry. The third procedure collects the data about the outflow and the flow rate of the river (return period of 20 years) and it represents them by a series of diagrams. Together, the three *procedures* give an overall view of the state (quantitative and qualitative) of the entombed parts of the river inside the urban environment. In this case, the adopted *strategy* has a purely informational function. Other *procedures* have the aim to identify temporal phenomena and criticalities through the processing of layers and their data.

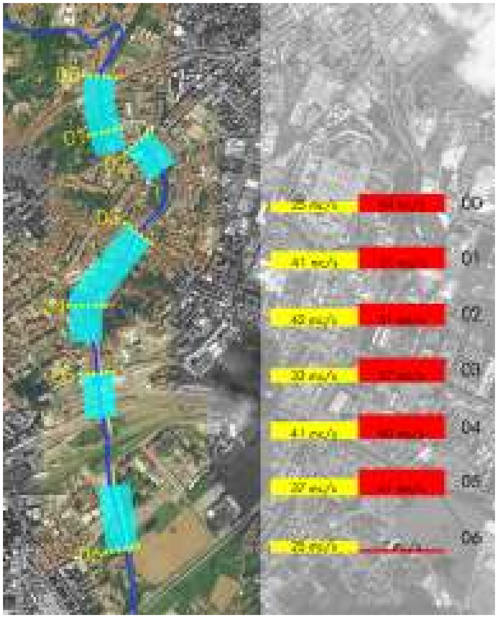
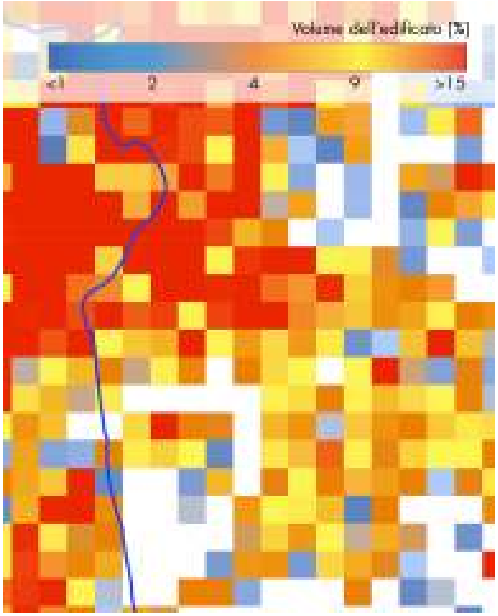



Figure 3
Strategy: analysis of the entombed parts of the Morla river. On the right column it can be observed the ratio between the outflow and the flow rate of the river (return period of 20 years). It can be noted that five of six sections are undersized

After this first and simple strategy, we present two more strategies, less simple, that can *determine the buildings total volume and urban density* (see Figures 4 and 5). In each case, a survey has been run by adopting a support matrix, constituted by 100 metres wide square cells, which have allowed us to read and analyse specific phenomena. The adoption of this grid allows us to focus the attention on the very subject of the survey (*buildings total volume and urban density*), filtering the unnecessary elements. In this way the diagram represents only the geographical distribution of a specific element. The first of these two *strategies* divides the total volume of the buildings contained inside a cell by the cell's area.

Figure 4
Strategy: determination of the total built volume in a given area. The diagram shows the zones where the ratio between built volumes and relative area is more than 15%. Regions with greater population's concentration can be easily found

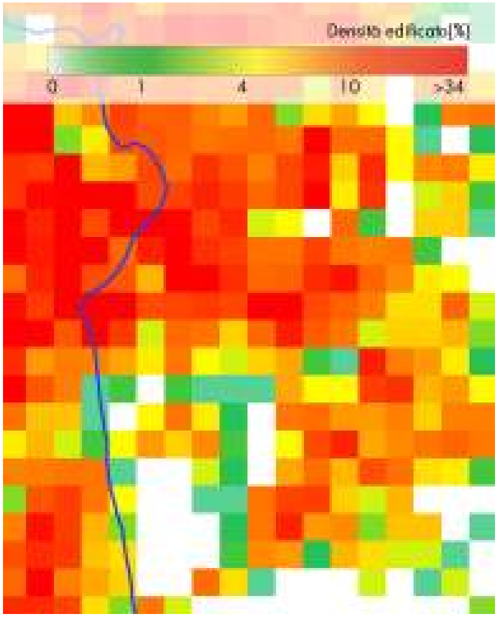
Figure 5
Strategy: evaluation of urban density for a given area



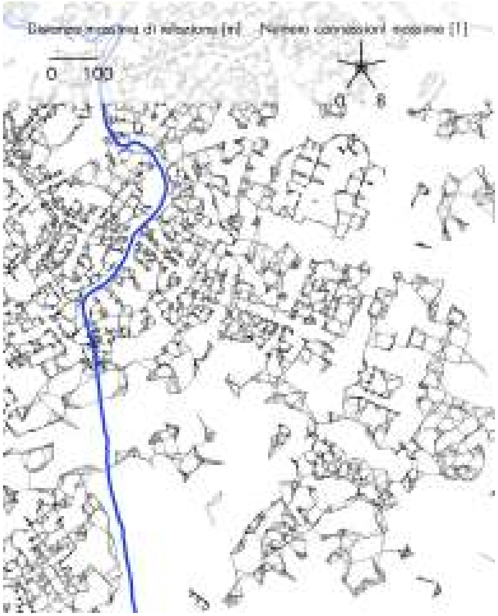

In the figure, every element of the grid assumes a different colour in relation to this ratio. In particular, completely red elements correspond to the highest ratios. If we look at the diagram, the cells identifying the ancient part of Bergamo, constituted by small-medium buildings being very close to each other, are red. The cells containing big and isolated buildings are in a similar condition, being also coloured in red.

The next *strategy* (see Figure 5) is aimed at the representation of the urban density. As for the previous case, we use a support matrix with 100 metres wide square cells. Their colour changes according to the number of buildings belonging to each of them. In this way, it is possible to distinguish between historical and recent buildings. This property derives from the characteristics of the *procedures* and their combinations for the *strategy*'s tuning up. For a better comprehension of what it has been asserted, we report below a short logical scheme:

1. Import the necessary (for an urban representation) geometrical information from an external database;
2. Geometrically identify every building (e.g. determining the centre of every area);
3. Define a contextual space around every building (e.g. a circumference of a given radius);
4. Find the interference between points of geometrical identification (in this case, the count of all points included in the area of every circumference);
5. Draw the survey diagram (e.g. a square grid);
6. Sum all the value determined at the step n. 4 (expression of a density);
7. Define a connections' domain through a mathematical filter and identify potential incoherent values;
8. Redefine the domain in relation to the survey area;
9. Represent with a legend every value associated with a cell.




The key for the pursuit of the *strategy* is contained in the 4th point. As a matter of fact, every contextual space contains a different number of objects. In close proximity to the historical part of the city there is a greater number of elements than in recent built area, independently from the built volume. From this observation, we can have a cartographic representation (see Figure 5) capable of expressing qualitative environmental values, like urban density.




The last consideration suggests the development of an analysis based on a proximity logic. It is the case of the *strategy: network of potential relationships* (see Figure 6). This strategy represents the network of buildings' potential relationships, that is to say the maximum number of connections that can be achieved between people living among two neighbouring buildings. For the pursuit of this scope we used the first four points of the previous strategy and, only at last, the fifth. In this way it is possible to formulate a variation of the scheme whose aim is to connect all nodes belonging to the same cluster. At the current state, this system of relations is purely theoretical, since it does not consider the roads and their directions. However, in the diagram it can be noted the difference between the residential and the industrial parts of the city.

Having put into a relation all the phenomena presented in the previous *strategies* (see Figures 4, 5 and 6), it is now possible to identify a further *strategy* which can describe the *probability of a relationship*. These terms can identify an urban quality and a possible concept design, deriving its value from the volume of buildings, their position and the network showing the potential connections between them.

Figure 6
Strategy: network of potential relationships and proximity logics

Figure 7
Strategy: vehicular traffic in the city of Bergamo

A relational value-quality can so be defined in geometrical terms until a prefiguration of a formal model. If we suppose a certain volume per person and if we compare it with the total volume of a building, it is possible to evaluate the potential number of people living in the considered area. Then, if we consider a population's distribution proportional to the network of potential relationships and if we group it in sets governed by a spatial proximity's variable, it is possible to define the strategy expressed in Figure 7. It shows a scenario, representing the probability that two or more people can be in the same place and get in touch with each other. The map can so describe the attractiveness of a place, giving the possibility to identify a forecasting strategy.

If we summarize the whole itinerary, we can identify three different levels:

1. The first corresponds to the simple visualisation of all gathered data, and it is the more intuitive level that can be expressed through other tools (e.g. GIS as seen in Figure 3).
2. The second characterizes the analysis and processing of the information, relating multiple strategies to each other (see Figures 4, 5 and 6).
3. The third level is the most design related, since it involves the creation of a series of possible scenario or master plan. The model processing is not simple and not automatic, since it involves the description of different behaviours and the interaction of complex systems, material and immaterial. It needs a synthesis, guided also by subjective choices, like the ones that are the basis of a project.

Here below we show some strategies developed by the students of the Architectural Design course held by prof. A. Pizzigoni at the University of Bergamo. Strategy developed by Andrea Mazzoleni and Matteo Rigamonti (see Figure 7). This strategy deals with the vehicular traffic of the city of Bergamo. The diagram highlights the most critical hours and their related air and noise pollution. The strategy is organised as follows:

1. Import urban geometrical data from external databases;
2. Geometrical identification of the roads on the map;
3. Import of town traffic from an external file of the municipality of Bergamo;
4. Associate roads with their relative traffic;
5. Define a three-dimensional mesh depending on the traffic flow;
6. Define a series of isolines on the map;
7. Represent the obtained values using a chromatic scale on the map.

Figure 8
Soft mobility and new cableway design, 1st part

Strategy developed by Marta Caltran and Luciana Melillo (see Figures 8 and 9). This strategy is about the temporal analysis of soft mobility along the Morla river. The adopted parameters are: time, distance and speed (by walking or by bicycle). This strategy ends with the proposal of a new cableway along the same river:

1. Import urban geometrical data from external databases;
2. Compare current data about greenways located in the area with the ones planned by the city of Bergamo;


Figure 9
Soft mobility and new cableway design, 2nd part

3. Locate the intersections of the designed cableway with the current greenway of the territory;
4. Select the best intersections for tourism and cultural scope;
5. Evaluate travel time starting from the previous selected points;
6. Prepare a diagram based on a 10 minutes travel time for different transport systems;
7. Define a possible route by cableway nearby the Morla river's path;
8. Calculate new distances depending on various transport systems based on an acceptable 10 minutes travel time;
9. Graphically represent the distances found on step n. 8 for cyclists and pedestrians;
10. Calculate travel time for the new designed area depending on various transport systems;
11. Assess the most important traffic flows depending on the main buildings of the city of Bergamo;
12. Foresee a "maximum flow" scenario with a total of 95,442 people per day;
13. Evaluate travel time by non-sustainable transport systems (cars, etc.);
14. Compare non-sustainable and sustainable travel time to go from a stop to the next one of the new cablewy;
15. Analysis report.

Strategy developed by Giuseppe Traettino and Roberto Lo Giudice (see Figure 10). This strategy analyses the noise pollution nearby the Morla river, showing the influence of the river itself on Bergamo district. Noise level is represented from green (low noise levels) to red (high noise levels).

1. Choose adequate layers for noisy area representation;
2. Assign weight to layers depending on their influence on the territory;
3. Create and overlap the area of influence obtained by layers evaluation;
4. Assess the influence of the river on the noise levels (the entombed parts do not provide any improvement);
5. Create the final diagram.

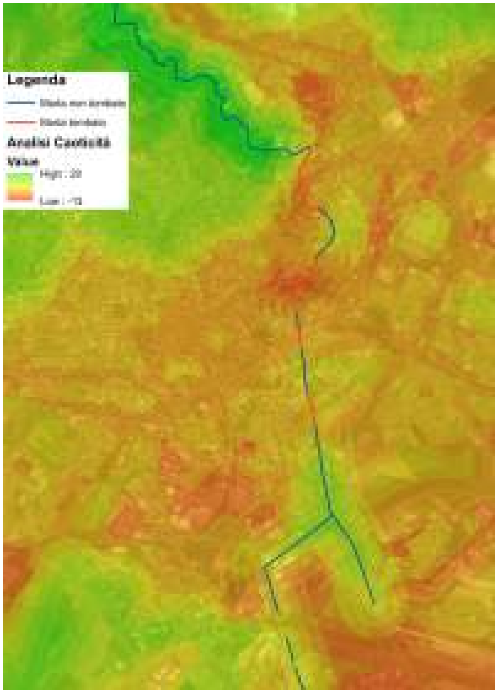



Figure 10
Noise pollution strategy

## CONCLUSIONS

This work shows new operative and design possibilities for Landscape Urbanism that, although at a beginning state, have a great potential. The post-urban space can be represented through a dynamic cartography, capable of describing time and motion. Nowadays, free and easier access to data, together with powerful processing tools, enables the possibility to go beyond a conventional cartographic document, which has been treated until now just as abstract analytical object. A digital parametric tool can be fundamental during the design process, maximising the efficiencies and optimising the forms, thanks to the capability of instantly showing the results related to different scenario depending on the weight of the various selected variables.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# Merging the Physical and Digital Layer of Public Space

## *The PobleJoc Installation Case Study*

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*Traditional approaches in public space design tend to bring order and control hindering the creation of expressive spaces that can host and stimulate social dynamics in the neighborhood.The aim of this project is to develop points of disorder, providing opportunities for imagination and spontaneity, by testing the potential of overlapping the digital and physical urban layers.The PobleJoc installation aims to activate the public space enhancing citizens participation and creativity.*

**Keywords:** *augmented reality, urban design, participatory design*

## INTRODUCTION

The city of Barcelona, during the last three decades, has dedicated much work to reshaping its public space, developing, through several interventions in the historic city centre, waterfront and peripheries, an approach known as the Barcelona Model for Urban Regeneration. The Barcelona Model has driven and shaped the transition from the industrial model to the tertiary and leisure city models in the whole of Europe. The city has embraced the potential of technology as a means to once again be at the forefront of innovation. Barcelona was the first city to win the award for European Capital of Innovation in 2014, also known as the "iCapital" of Europe, "for introducing the use of new technologies to bring the city closer to citizens". This opens the debate on how advanced technologies can help to enhance existing public space, fostering creativity and exchange, as well as citizen participation, both with respect to the design and inhabitation of its spaces.

Traditional approaches in public space design tend to bring order and control hindering the creation of expressive spaces that can host and stimulate social dynamics in the neighborhood. Sennett recommends, in order to surpass the issues related to over control, the development of points of disorder in public space allowing to implement zones of unexpected experiences and activities (Sennett, 1990). The points of disorder become areas of creativity and change (Amin and Thrift, 2002). These points of disorder in public space, through attentive design, can conjoin and allow for the creation of opportunities finally enhancing the urban spatial qualities of the area (Graham and Thrift, 2007). This paper explores how the integration of digital technologies and participatory design strategies can result in the creation of expressive public spaces and forms of self-organization, enabling the citizens to organize activities and modify their public space according to their real time needs and desires.

## THE SUPERBLOCK AS A FLEXIBLE PUBLIC SPACE

Through the implementation of new technological developments urban spatial quality and the related experience within it can be enhanced, providing fertile ground for creativity. In this sense there is potential to transform existing static urban spaces, thanks to the application of new tools, into dynamic spaces that can respond to the citizens' needs and desires.

Ubiquitous computing allows us to embed technology in our everyday life in such ways that it is becoming an integral part of our environment. Objects are interacting with us, building skins are becoming interfaces and architecture is becoming an evolutionary organism, able to react in real time to multiple agents, such as the environment, time or user needs.

Within the framework of "Active Public Space" (APS), a project co-funded by the Creative Europe Programme of the European Union, under development since 2015, a profound study of the activation of public space has been developed, in particular addressing the relation between public space and new technologies. The Active Public Space project includes several actions, among which the development of publications, workshops, a symposium, and an itinerant exhibition. These activities are developed by the Institute of Advanced Architecture of Catalonia (IAAC), the Centre for Central European Architecture (CCEA) and the University of Applied Arts Vienna (UAAV). As part of these actions, the PobleJoc workshop was held at IAAC between the 5th and the 7th of September 2016, oriented to the development of the Poble Joc installation, to be placed in the Superilla pilot area in the Poble Nou district of Barcelona.

The Superilla pilot is a small scale pilot project of the Superilla plan for Barcelona, developed by Agencia de Ecologia Urbana, as part of the Urban Mobility Plan of Barcelona 2013-2018. The plan aims at closing two thirds of Barcelona's roads to traffic, an urgency brought on by the high levels of traffic pollution in the city. This intervention allows to create new pedestrian areas and consequently new spaces for citizens. If implemented, the plan will greatly increase the public space availability in the city of Barcelona and it is therefore an important opportunity to test new principles to design the area. In order to study innovative solutions for this new public space, five schools of Architecture in Barcelona were invited to set up an one-week workshop as well as installations in the area. During the workshop, IAAC students participated in the development of the PobleJoc installation for the Superilla aera.

Figure 1
Urban Furniture Modules

## THE POBLEJOC INSTALLATION

The aim of the urban intervention designed by IAAC was to bring new life to this public space and provide opportunities for imagination, spontaneity and social interaction. This was further enhanced by the creation of a dynamic platform, allowing to engage the community and multiply their experience informing them on environmental factors and related events.
The installation included:

- Digitally fabricated furniture modules on wheels, that could be moved by citizens reshaping the space according to their needs;
- An online calendar for organizing the activities;

- An augmented reality application, which could give real time information on the activities related to each furniture;
- A system of drones detecting the movements of the furnitures, which were mapped and projected during the night on one of the furniture modules.

By integrating the digital and physical layers, a new public space which was responsive to the citizens' needs was developed, creating an unpredictable surprising space constantly shifting and changing.

The PobleJoc installation was designed as an Urban Game. The urban furniture included: a bench incorporating a tree, an urban orchard, a market stall, a ping pong table and a screen, which were all mobile. The elements were sorted with the aim of responding to the following needs: rest and interaction, production, exchange, play, audiovisuals. (see Figures 1 and 2)

Figure 2
Reconfiguring Urban Modules

The space configurations were also mapped using a drone, in order to extract data on the space dynamics. During the night the data was projected on the screen, offering a new point of view on the public space, revealing hidden spatial dynamics.

As part of the PobleJoc installation, an augmented reality application was developed, which was used to digitally overlay information about the activities and functions of the installation. Using a QR code, the users could download the application (freely available on the Android platform) and use it to get more information on each module of the installation. By pointing their phone cameras to physical markers available on each module, digital information was overlaid on them regarding the program and location of different activities related with the installation, as well as related general information about the city. By introducing this digital layer to the installation, the aim was to provide a second level of interaction, through information and social media.

The following data could be visualized using the augmented reality application (see Figure 3):

- Screen tag: general info on the project; 3D model of the superilla;
- Bench tag: twitter feeds with the Superilla hashtag;
- Pods general tag: info on urban agriculture in Barcelona;
- Pods specific tags (one tag per plant): nutritional value and general information about plants;
- Table tennis general tag: map with sports locations around the area;
- Table tennis specific tags: calories burned, optimum temperature and relevant time of the day to practice sports;
- Market tag: market's weekly schedule.

The installation aroused curiosity between the citizens and the PobleJoc app was downloaded numerous times. The elements of the PobleJoc installation became for a week empowerment tools enabling people to express their creativity and adapt the public space to their needs.

## MERGING THE PHYSICAL AND DIGITAL URBAN LAYERS

Augmenting the physical layer of the urban fabric with the continuously and rapidly growing digital layer of our urban life has been envisioned for decades. With ubiquitous and mobile computing and the recent advancements of available technology, the interweaving of the physical and the digital layers of the urban space is becoming a reality. To-


Figure 3
AR app visualizing
Twitter hashtags

day, there are numerous applications of Augmented Reality (AR) in the city using smartphone devices.

In the domain of design and planning, information and communication technologies (ICT) offer great opportunities in participatory processes as they allow people to better visualize projects and participate in the development process. AR and ICT tools are also applied widely in cultural heritage sites to enrich the experience of the visitors.

They are also very valuable in enhancing education and awareness of the public, such as the example of the TunnelVision project in New York City's subway system. TunnelVision allows users to point their phone at one of the many New York City transit maps and explore city open data that is overlaid onto the physical map. Users can explore city Census data such as income levels by region, real-estate prices, etc. and can also observe real-time data such as the number of commuters entering train stations by activating a visualization of New York's smart transit data feeds.

Figure 4
Users Participation

The Poble Joc installation tries to not just superpose a new layer of information, but to create a vibrant dy-

Figure 5
Reclaimed Public
Space

namic between the digital and physical layer, helping citizens to make decisions, share information and leading to new participatory designs and spatial configurations. For example, reading information about the growth of vegetables and their nutritional value people can decide what vegetables to cultivate in the orchard module and where to place it in the public space, according to their solar needs or people can decide to organize activities in the market module, sharing them in the market's weekly schedule.

This project demonstrates design values central to participation through augmented reality.It is a process which balances the digital and physical channels of communication. It emphasizes the power of experience gathering the local community in a physical space and a virtual space simultaneously and it promotes sustainability and reproducibility through tracking and analysis of the urban fabric. Through our installation, we have managed to engage the public in a participatory design and extract meaningful information on their perception and aspiration of the reclaimed public space. Moreover, PobleJoc is a proposal and a stepping stone for the development of augmented public spaces that through merging the digital and physical urban layers enable user participation and adaptation in the urban environment. (see Figure 4)

## CONCLUSIONS

The aim of this project was to develop what Sennett calls points of disorder, providing opportunities for imagination and spontaneity, by testing the potential of overlapping the digital and physical urban layers. The very dynamic nature of urban public life requires experimentation with creative mechanisms that engage the community and enrich their experience in urban public space. For this reason, PobleJoc tested open systems and creative points that would leave the space unfinished and offer new possibilities. (see Figure 5)

During its implementation period the PobleJoc installation activated the public space enhancing citizens creativity. Systems merging digital and physical layers should be further tested, but through the PobleJoc installation they demonstrated to be a good starting point for the continuous shaping of urban public space to meet the changing needs of communities.

## ACKNOWLEDGMENTS

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# Generative computational tools for the design of Urban Morphology

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*Today more than 50% of the population is located in cities. This is an essential need, considering the facilities that urban life offers in contrast to the rural one. But, despite the benefits this migration brings to the individuals, it is also associated with some degree of unpredicted behavior which harms the community. In the recent years Albania, like most developing countries, has been facing problems with both informality and the inability to come up with concrete design solutions to adapt quick changes. From this perspective, this paper illustrates a research done to encompass new tools in the urban design practice of Albania for the overcoming of the current design difficulties.It describes a new approach to assess the problematics in the city of Tirana, and implement an algorithmic procedure which creates urban design proposals similar but not limited to the existing ones. Together with other evaluation tools, these new proposals can be tested in terms of energy efficiency, solar access and ventilation performance with the ultimate goal of creating a unified work model which not only will speed up the process but also improve its overall design efficiency.*

**Keywords:** *Parametric Urbanism, Urban Morphology, Sustainability*

## INTRODUCTION

Urban design involves a multitude of elements., thus it requires a lot of time and effort to predict an end result. As a consequence, in order to deal with the infrastructural sprawl in Albania, many proposals have just an outline of the end product to maintain the needed flexibility for the eventual changes. To continue, these issues are so problematic that by the time a solution is found, new complications might emerge, which themselves would require extra time to be solved and also further interventions in the original proposals. Thus, conventional ways of city planning in this country, bring non-flexibility, which in the process of urbanization is never ending. To address these issues, a new approach may be needed, which is able to compute variables faster and more accurately, is adaptive to the changes, and requires less efforts spent

As a result, the solution this paper proposes is the usage of parametric design tools to automatize the major part of the design process. By hypothetically assuming that these tools can indeed drastically shorten calculation times and aid designers, the paper tries to assess a new and easy way of doing so.

Specifically, the Grasshopper plugin for Rhinoceros was used, though any scripting language available in other CAD applications will do as good.

To deliver a concrete model, research was done only on the morphological aspect of a neighborhood based on the context of Tirana. Other constrains like social, political or legal, pose difficulties to manage from the parametric design point of view. On the contrary, urban morphology is the part of urban design which is quantifiable, thus manageable in terms of mathematical relations and therefore suitable for algorithmic processing. Morphological parameters alone have proven to influence other practices which deal with comfort, sustainability, lighting and ventilation. The breakdown of this elements will serve as input for the script to generate the desired urban patterns but also as the criteria to evaluate their overall efficiency.

## HISTORICAL AND ACTUAL CONTEXT

After the 90's Albania has been facing multiple problematics with land administration however, differently from other countries, here we may find it as a result of a more particular issue. For fifty years, being in a rigid dictatorial system, Albanian citizens had lost all their belongings to the central power together with their sense of private property. People lived in groups of two to three families under the same shelter due to the lack of habitations. With the removal of the communist system, these citizens found themselves unprepared and with no monetary or land capitals. Dwelling for millions of citizens without jobs were needed, together with assets to generate income. Land seen as free was occupied and buildings were erected without concerning about the urban environment. The newly developed state couldn't re-establish order, thus following for a transitional period of time the "laissez faire" principles bringing cities to slump conditions. These new created slumps became impossible to deal with, and often are the reason for diseases, disorders and social problematics. Tirana, as the capital, was in the center of this disorder, and is by far the most damaged city due to informality. People were allowed to build, and later houses were legalized, only to form the most unsustainable development with one story villas occupying land which is very valuable in a small territory like Albania. Tirana has always been the center of attention in planning, where the major territorial developments involved it as a pilot project. The number of inhabitants is more than 2/5 of the entire Albanian population. Nevertheless, despite all the efforts the situation is not changing. The issue can be addressed to the poor management of the initial state, which by bringing the city to the current situation makes it challenging to adapt. The study hypotheses is that the situation can improve if new modern tools are implemented in the urban design phase


Figure 1
Arial view of Tirana + Site (Google)

As case study, an area of 430.000 m2 plot is taken in consideration, located only 3.5 km from the historical and economical center of the city. It is important to note that despite the informality of this zone, the urban pattern is structured. This because the occupied land, being previously an agriculture land, created a sort of ordered sprawl due to the existence of the irrigation system. This will serve as one of the inputs for the script, for the sake of maintain the said order and preserve some beneficial existing infrastructure. The surrounding neighborhoods which are already developed lack unity between each other and within themselves. This context varies from urban blocks to tower typologies which will be part of the generated design models. (see Figure 1)

## DEVELOPMENT OF THE FRAMEWORK

For the continuation of the project, it was uneasy to state beforehand which topological pattern was better performing in the current situation. Moreover, if this "universal" working model is to be implemented in other cities of Albania, there is no way to develop a one fit all solution. The advantage of parametric tools lays in the fact that if instructed properly, can develop multiple proposals which can then be tested to find the most convenient solution for a given site. The tower typology together with the urban block are taken as reference to create either uniform morphological neighborhoods or mixed systems between towers and blocks. The research sets as goal the creation of five different proposals trying to include most possible scenarios in Albania. The scenarios are namely: a- Tower typology with strict rectangular grid, b- Mixed typology, Towers and Urban Blocks with strict rectangular grid, c- Urban Blocks with strict rectangular grid, d- Urban Blocks with random pattern of streets, e- Urban Blocks with random pattern of streets + predefined major circulation axis. Other remaining combinations like Tower typology with random pattern of streets are seen as uninfluential, thus not taken into account

The second step consists of breaking down the structure of these proposals in order not only to create the input for the script to run, but also to have the criteria by which these proposals will be tested to find the most successful proposal for a given site, and, furthermore to find the most appropriate variation of the successful proposal. Multiple elements are studied like building height, width, length, surface to volume ratio of the building, proportions, density, site coverage of different elements, solar and wind orientation, porosity of the neighborhood and sinuosity of the roads. All these parameters will influence the design in such a way to promote natural light and ventilation, thus increasing sustainability. In order to channelize the focus on finding which urban morphology performs best in terms of efficiency and natural light/ventilation access, it is necessary to maintain some of these parameters unchanged during the whole experiment as well as across all proposals. Namely: building width, building height and road dimensions are set in the initial stage and remain fixed. The towers will have dimensions of 20x30m while the urban block will have a width of 14m in order to have a minimum passive to non-passive ratio. [Steadman et. al., 2000]. The building height will remain random across all the proposals specifically between 7-9 floors in order to have better ventilation [Ng 2010] improved solar access [Cheng et. al., 2006], and also a sustainable high density [Salat & Nowacki, 2010]. The height of the floor, which directly influences the passive zone of an apartment will be 3 m [Ratti, Baker & Steems, 2005], which also complies with the actual regulations in the Tirana urban development policy. The road dimension will be 20m from building to building (including pedestrian and vehicular) in order to have an Height/Width ratio of 1.2 which is favorable for good ventilation [Ng, 2010]. Also, this angle between 46-53 degrees is appropriate for non-solar extrusion proposals. The rectangular street patterns will be rotated from the Y axis with approximately 30 degree to follow the predominant wind flow in summer for better ventilation during hot days. On the other hand the specific factors which are taken in consideration and which vary from case to case constitute on elements like building distance, shape of the buildings, orientation and street pattern. (see Figures 2, 3, 4, 5 and 6)

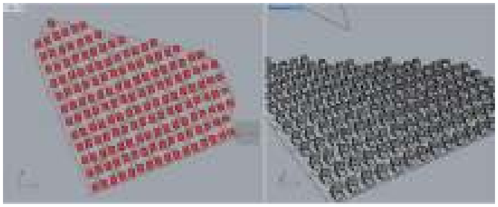

Figure 2
Tower typology with strict rectangular grid

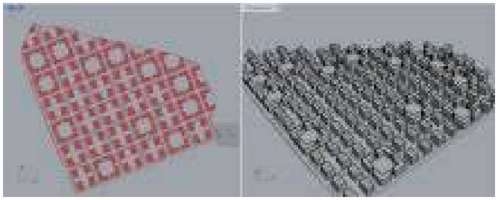

Figure 3
Mixed typology, Towers and Urban Blocks with strict rectangular grid

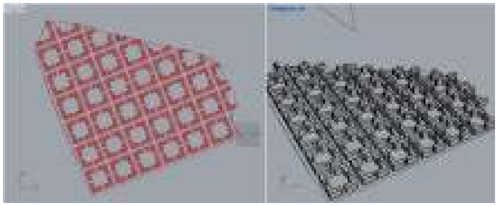

Figure 4
Urban Blocks with strict rectangular grid

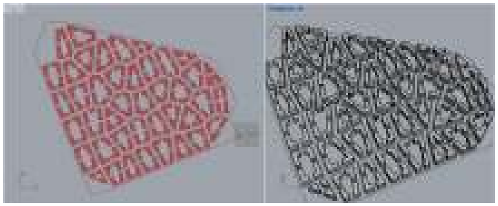

Figure 5
Urban Blocks with random pattern of streets

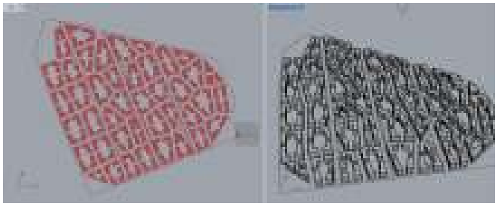

Figure 6
Urban Blocks with random pattern of streets + predefined major circulation axis

## SOFTWARE INSTRUCTION

Following the development of the framework for generating the proposals, research was carried out to determine basic parameters of the surrounding existing models, in order to unify the existing with the proposals. An average plot area of urban blocks was extracted from different cases and inserted as the first input in the script. Based on this average plot area, the number of plots which will fit in the given site is defined. The script then creates a rectangular grid, with as many subdivisions as the number of plots which is rotated in order for its axis to overlap with the prevailing winds. The new grid will serve as the base for the a, b and c proposals. For the development of the random urban patterns namely d and e, the script extracts the centroids of the generated rectangular plots which are then shifted randomly in the X and Y direction. These new points will serve as centers for a voronoi structure which will partition the plane into regions with areas near to the average plot area. (see Figure 7) After the base structure for both the major typologies is set, the program performs the remaining commands of offsetting the roads, creating the building patterns and extruding the 3d shapes based on the rules above mentioned. In the end, a rule runs which eliminates all the 3d volumes with a base area lower than 350m2. After the full generation of the proposals, the script extracts all the necessary data for each proposal like overall area of the occupied by roads, landscape, and surface coverage, general volume of the buildings, surface exposed together with annual radiation and ventilation data, taken respectively form Autodesk Ecotect and Autodesk Flow Design.

## SELECTION OF THE MODEL

In order to select the best solution for this site, it is necessary to compare the proposals in scientific quantifiable terms. The patterns are evaluated in four major categories like: efficiency from morphology, efficiency from site usage, solar exposure performance and natural ventilation exposure.

Data about Floor Area ratio, Surface to Volume ratio are directly calculated within the script where

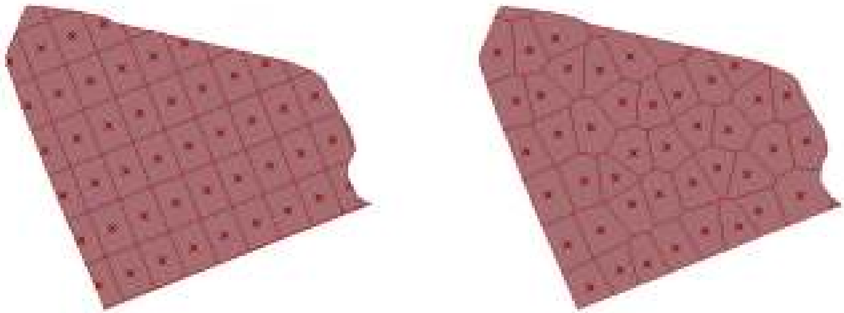

Figure 7
Software
instruction

the Floor Area Ratio is preferred to be 1.6 to 1.8 for having both a high density together with good solar access [Capeluto and Shaviv, 2001] while the Surface to Volume ratio is preferred to be high in order to have less energy loss. The site usage area informs the user of the denser environments which is generally preferable for higher efficiency.

Regarding the solar exposure elements like thermal gains are not considered since depend on other factors like material absorption, insulation etc. The focus remains in the building exposure as a broader term since this characteristic is inherited to the building by its morphological construction and sun orientation. This criterion selects buildings which receive the less amount of heat/light during summer when it is not needed and the most during winter.

The final step involves quantifying the ventilation exposure in terms of porosity (total open volume/total volume of the site) [Adolphe, 2001], Width of airflows (building height/street width) [Ng 2010] and air tunnel simulations. The greater the porosity the greater space for wind to flow while the greater the H/W ratio the slower the wind flow will be on the ground. On the other side, the wind tunnel simulation can only process graphic results which are enough to determine a successful proposal. (see Figure 8)

As a final result a table is constructed where for each optimal factor a given proposal receives a “+” whereas for inconvenient factors it receives a “-”. Since it would be impossible to create a ponderated value system which can select the best proposal across all possible given sites, due to the high number of possible scenarios, it is thought to let this part of the process unautomated. This also gives the opportunity of the user to use his design experience as well as take in consideration other social factors which otherwise would not be possible to calculate. (see Table 1)

Figure 8
Selection method
from top to bottom:
Monthly incident
radiation, Site
usage in %, Wind
tunnel of one
proposal

## CONCLUSIONS

The final table (see Table 1) displays all the output generated from the process. However the final decision remains to urban designer. By also taking in consideration other design factors like economical, cultural or environmental the selection process will be complete. For Tirana, which is subjected to a hot climate, pattern 1 seems to perform best. Not only it has the highest amount of absorbed radiation in winter and the lowest in summer, but also has the highest ratio of exposed area which makes it easier to cool down during the days. On the other has it also has the lowest density which translates in cost. All these specific factors supported by the exact mathematical data provided by the script create an enhanced habitat for the urban designer to operate

To conclude, the research started with the question, if the computational design tools could aid urban designers come up with fast and reliable proposals. The answer is in the affirmative where for the whole part of this work, a process of task automation was created and urban technical data was translated into understandable visual graphs, all of which required little or no time. Continuing in this field many scenarios can be achieved which makes possible a real natural selection of the best proposal. The benefit of this method, as opposed to manual techniques, is that at each phase of development and design variation, both the input and output data are tabulated and easily accessible. This research constitutes a step forward in rethinking the Albanian planning culture and hopefully in other developing countries. Further work may include the development of a larger platform in order to encompass other design influential factors as well as more automatization in the stages of data collecting.

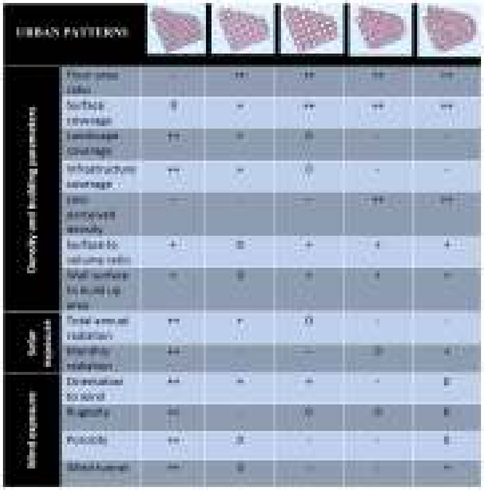

Figure 9
Breakdown structure of the final results

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# CITY MODELLING TOOLS

# Towards a modular design strategy for urban masterplanning

## *Experiences from a parametric urban design studio on emerging cities in Ethiopia*

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*In emerging countries there is a need for rapid urban planning, since they are confronted by unprecedented wave of urbanization. This need is even bigger since usually there is no adequate number of professional educated urban planners in these countries. Therefore, we investigate in this paper how to develop a set of methods that allow to generate urban fabric semi-automatically. The challenge is to come up with a generative planning model that adapts to multiple boundary conditions.Through a modular design strategy generative methods are applied by students in an urban design studio in order to combine them into more complex planning strategies for small cities in the emerging country of Ethiopia. The modular approach allows to break down planning into sub-issues to better deal with the overarching problem. For testing the implemented generative urban design strategies various cities are generated at different locations in Ethiopia with various topographic situations. Their underlying design strategies and modular approach are discussed in this paper.*

**Keywords:** *Urban Design, Planning Systems, Modules, Teaching, Emerging Country*

## INTRODUCTION

The design of a city is a complex task, involving the definition of numerous elements and the consideration of many performance criteria. Especially in emerging countries facing rapid population growth and urbanisation it is a challenge for urban planners to continuously envision new neighbourhoods or entire cities in a minimum of time while ensuring maximum quality. Computational methods can therefore offer valuable support, either regarding the rapid generation of variants (see e.g. Weber et al., 2009; Beiaro, 2012; Duarte & Beiaro, 2011) of the evaluation of variants by analysing different criteria, such as accessibility (see e.g. Karimi, 2012; Sevtsuk & Mekonnen, 2012), visibility (see e.g. Czyńska & Rubinowicz, 2015; Yang et al., 2007) or energy demand (see e.g. Ratti et al., 2005; Robinson et al., 2009).

To efficiently design sustainable spatial structures it is necessary to equip urban planners with the skills to use these methods effectively. Educating students of architecture and urbanism we set up a course (urban design studio with accompanying seminars) that enables them not only to use, but also to adapt and develop such methods and to apply them on a case study in Ethiopia.

Ethiopia is currently trying to adapt to its rapid urban growth by fostering the development of thousands of new small cities (with approximately 10.000 inhabitants) in the coming years (GTP-II, 2015)[1]. This challenging task served as the background for our design studio, namely to develop a method for rapidly creating plan for the sustainable development of these small cities. The focus therefore has been the spatial morphology of the city. This refers to the physical overground elements of a city, such as streets, plots, public spaces and buildings. These elements are of greatest importance in planning, since they - once built - persist over long periods of time and greatly influence the behaviour of the urban user.

The goal of the course was to develop a computer-based design strategy, which rapidly creates solutions that are adapted to varying environmental parameters (such as topography or existing streets and buildings) and which integrates the perspective of the urban users (movement patterns and land use). The students should learn how to approach the high challenges of urbanisation through new planning methods while considering quality of urban space, resources and limited amount of time. To get an understanding for relevant criteria of emerging cities the students got to know the context through an excursion to Ethiopia, discussion with local people, lectures and literature. Beside, the students got equipped with basic skills for parametric modeling and computational urban analysis. The former served for the rapid generation of urban models. The latter focuses on methods how to analyse a city quantitatively (e.g. density, walkability, centrality). With this knowledge they then had to conceptualize and implement a computationally supported city planning method and apply it to different cases. In this paper, we put special focus on the design strategy, that the students developed. This strategy is based on modular thinking, helping to handle the complexity of urban planning. In the following we briefly discuss the modular approach, present exemplarily three students works and finally briefly discuss the challenges and potentials of this approach in education as well as for the practice of urban design.

## MODULAR DESIGN STRATEGY

The challenge for designing a city stems from the high number elements it is made of (such as streets and buildings). Between these elements there are many relations (such as adjacency or walking distance). Both, the form of these elements and the relation between them are influencing the performance of a city in terms of social, economic and ecological criteria (such as lively, costs or energy consumption). Although a city can be evaluated only by taking into account all elements ("the whole is more than the sum of its parts"), during design considering all elements at once is hardly possible, due to human's cognitive capacity and the fact that elements are often highly interdependent. Thus a certain structure for simplifying the problem needs to be introduced. This structure often is referred to as a design strategy and can take several forms (see e.g. Lawson, 2006). One strategy, that is rarely used in design, well known in the field of programming, is "Divide & Conquer" (D&C). In D&C one divides a problem into several subproblems until they are solvable. By solving all subproblems the original problem becomes solved.

However, this causes problems in the case of design, since solutions that one created for solving subproblems might not be compatible to each other on a higher level. For example, the requirements for an urban neighborhood are to promote social interaction and ensure privacy. The former can be achieved by a well connected street network, the latter by a cul-de-sac street network. The contradiction in this example occurs by the fact that the design variable that was used to solve the two problems (requirements) was the same (the street network). This lead to two different ways for defining the design variable. In order to combine both solutions a new solution needs to be created. (see Figure 1)

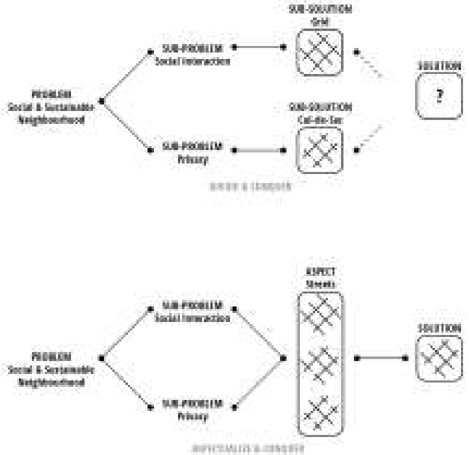



Figure 1
Comparison Divide & Conquer to Aspectualize & Conquer

In order to make the D&C-strategy applicable for design Bertel, Freksa and Vrachliotis (2004) introduced an adapted version of D&C, namely “Aspectualize & Conquer” (A&C). Thereby the decomposition is not into disjoint parts, but is based on the notion of a problem’s aspects, whereby aspects “provide criteria for the making the selection, and choosing the right aspects must thus be seen as a key factor for successful solving of design processes” (ibid., p. 273). If we take the example from before, we would define the design variable “street network” as an aspect. This aspect is then processed in order to promote social interaction and ensurance of privacy. Thus, in synthesis both problems are regarded at the same time with no need for changing the design variable.

The idea of dividing the task of designing a city into several aspects was the starting point for our design studio. We asked the students to identify certain aspects and create computational modules for each. These modules shall be capable of generating a certain outcome (such as a street network) by certain requirements. Therefore, the students had to define (1) which input is needed for each aspect, (2) how it processes these inputs and (3) how the aspects relate to each other. Regarding the first issue, they had to clarify what are essential boundary conditions for an aspect and what are performance criteria that are applicable to that aspect. For example, a street network is based on existing streets and topography and shall ensure high accessibility. The second issue is about the algorithm for creating a solution. Therefore, each module can consist of generative and evaluative parts as well as of optimization procedures. For example, a simple module for creating a street network can consist of a grid-generator, an accessibility analysis (e.g. space syntax) and an evolutionary algorithm for varying the grid dimensions in order to achieve a high accessibility. Regarding the third issue, the students had to define a sequence in which these modules are processed. For example, the definition of land use can be based on the street network (e.g. locate commercial land use in highly central locations) or the street network can be based on an afore defined land use plan (e.g. main streets are passing through commercial land use zones). In the following the strategies that the students developed are presented.

## IMPLEMENTATION AND EXAMPLES

The generative algorithms for the cities presented in the following were made by a group of students during a one semester urban design studio. The students were introduced to urban analysis methods for understanding the performance criteria used for the evaluation of the designs, to programming in C#, as well as to parametric design by using the software

Grasshopper for Rhino3D and our self-developed DecodingSpaces components (Schneider, Bielik & König, 2011; König, 2015). The latter provide a set of methods for generating and analysing street networks, street blocks, plot subdivisions.

The groups of students (3 students each) had to think in abstract systems to create a parametric, modular city design. They had to set their own priorities and goals in the boundaries of the course outline. The creation of their generative strategies started by defining the performance criteria and the relationships to each of the three aspects (street network, street blocks, land use). By iteratively improving the design strategy they developed and arranged the modules.

The outcome of this process was different in every group. In the following the work of three student groups is described with particular focus on the modular design strategy. All student projects can be accessed in an online documentation [2] and on demonstration videos explainingthe functionality of their concept [3].

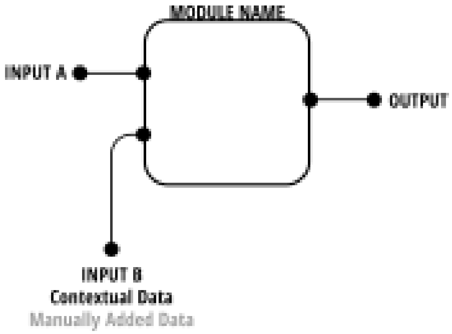



Figure 2
Scheme showing how to read the visualised modular design strategies of the student groups.

To compare the strategies, they are visualised as shown in figure 2. Input A is data that is transferred from other modules. Input B is data that is applied through other contextual or manually added data to influence the procedure of the module. The module itself generates and/or evaluates the spatial organisation of an aspect in relation to the given performance criteria like walkability or density. It then outputs new data like geometries of streets or buildings.

### *Group 1 - Vector-field approach*

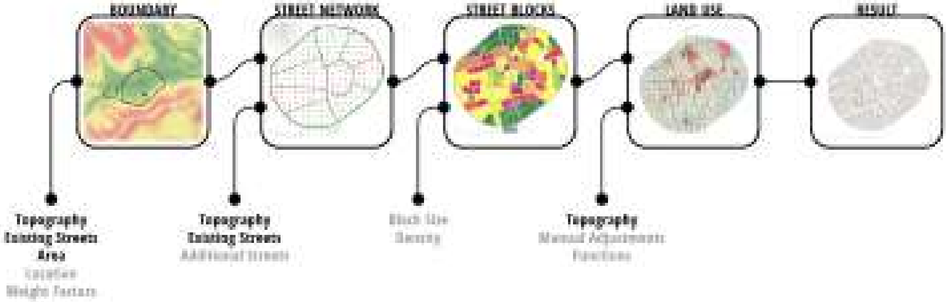
The focus of this group was to establish a street network that relates to the topography and useful allocation of functions such as schools, churches or hospitals. The group developed four different modules, namely Boundary, Street Network, Street Blocks and Land Use (see Figure 3). They used a linear design strategy, starting from the boundary of the city, followed by the generation of the street network, the analysis of street blocks and lastly the assignment of functions. As a base to generate their city they chose to use vector fields that contain information about the topography and existing road network. The approach to generate the streets is comparable to the work of Chen et al. (2008).

The module "Boundary" defines the border of the city, which limits the area in which it shall grow. Its input data is the topography, existing streets, the needed area as well as manually added data such as location and weighting factors for the strength of the influence of existing streets and/or topography on the shape of the city. Its output is a curve that defines the boundary. The calculation is done by growing the boundary on a vector field in the direction with the least threshold until the needed area is reached.

The module "Street Network" requires the city boundary as input and makes use of the topography, existing streets and manually added streets to define a vector field. New artery streets grow then on top of this vector field and divide the city into several parts. This process was optimised by the group to get equally sized subareas. The output is a list of curves defining the main street network.

The module "Street Blocks" creates the remaining streets inside of the main street network that define the city blocks. Its inputs are the street network and manually defined densities and block sizes. The algorithm again uses the vector field to distribute points that are connected through a Delaunay-Triangulation. The triangulated street seg-

Figure 3
Modules and their sequential order of Group 1 - Vector-field approach




ments are then thinned out depending on the angle towards each other to achieve a more grid like network. Curves of the whole street network are the output.

The last module "Land Use" allocates functions such as schools, churches, commerce, hospitals or public buildings on site. It needs a street network and topography as input and can be manually adjusted by the group. Since this component defines greatly the social structure of the city it needs a well defined street network. The group therefore had to iterate and improve on the aforementioned modules. The streets and the street blocks are then analysed regarding several criteria (block size, altitude, accessibility, centrality). Based on these criteria certain uses are located on specific blocks (such as a church on the highest point of the city, or the municipality on the most central street block). The module's output is a map with land-use labels for each street block and placeholder geometries of the respective buildings.

### *Group 2 - Force-based approach*

The priorities of this group were equally distributed on land use and the main street network. Both modules can be independently developed. Afterwards a module for creating secondary street grid follows. Lastly a second land use-module defines the detailed allocation of uses. The generation of the city is mainly done with force-based algorithms. Forces can be slope of topography or the location and connectivity of certain land uses. Each force has an objective like keeping a certain area, staying close to a point or keeping lines in a certain angle. They have different strengths and try to pull the geometry towards their objective. In competition with other forces they either reach their objective or they pull as much as they have strength. In this way the geometry is deformed until all forces find a state of equilibrium. In Figure 4 the sequence of modules is displayed. The group developed five modules, namely Boundary, Land Use, Street Network, Street Blocks and Land Use 2.

Similar to Group 1, the module "Boundary" generates a curve as an output that defines the limits of the city. It does so by applying forces on it such as occupying a defined area of square meters and flatness of the topography.

The module "Land Use" requires the city boundary as input as well as required land uses with their respective sizes and adjacencies between each other. Furthermore they can have preferred locations such as high places, sloped or flat terrain or the center of the city. These connections are forces and work like springs trying to bring interconnected functions close to each other. When the forces do not have enough strength anymore to pull and the functions do not move anymore, their locations can be used as an output.

Module "Street Network" generates a primary street grid based on the city boundary. Additional inputs are topography and existing streets. Streets are created by forcing the street lines to adapt to the topography, keeping them as horizontal as possible

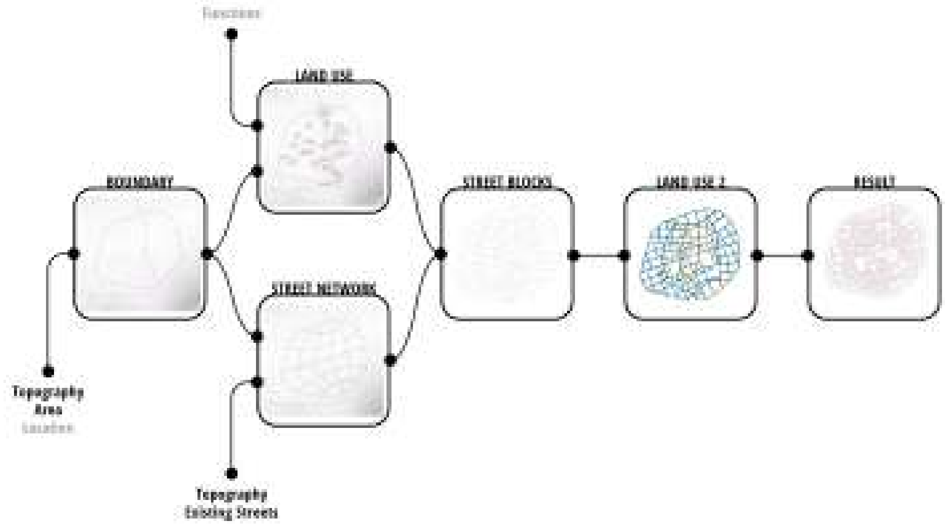



Figure 4
Modules and their sequential order of Group 2 - Force-based approach

while leaving enough space between border and existing streets of the city for buildings. The output are curves in form of a deformed street grid

The module “Street Blocks” combines the modules “Street Network” and “Land Use”. It creates grids inside of the main street structure that serve as street blocks. If certain land uses need more space then blocks will be merged into a bigger one. The output are curves defining the whole street network.

Lastly, module “Land Use 2” allocates commercial land use and residential densities. The group decided that these land uses are more dependent on the street network than others, since they need to be at highly integrated (frequented) locations in the case of commercial use and rather unfrequented locations in the case of residential use. Therefore the module analyses the street network through Space Syntax methods and allocates the functions.

### *Group 3 - Watershed approach*

The third group decided to put main emphasis on water infrastructure as a necessary resource for the development of the city. They created four modules: Street Network, Street Blocks, Land Use 1 and Land Use 2 that sequentially build up on each other (figure 5).

The input of the module “Street Network” are topography, existing roads, a manually specified location and the water rundown. Compared to the other groups this module gets along without having a specified city boundary and solves it in this module. The priority clearly lies on the resource of water by using the water rundown to define street locations. This affects all other modules in the sequence.

Module “Street Blocks” takes the water street network as input. Since those streets follow the water running down the hills, horizontal street networks are missing. Therefore they are added parallel to the existing street in a distance of 60m to subdivide the street network into blocks (in order to have lots on both sides with a depth of 30m). If these blocks are longer than 200m they are again subdivided, to ensure walkability (see Sevtsuk et al., 2016).

The module “Land Use 1” uses the whole street network to allocate subcenters by a predefined number. Their location is defined by Space Syntax measure (Integration at Radius 400m, referring to locally well accessible places). Afterwards module "Land Use 2" adds more functions to the city by finding locations around the subcenters for a list of land-uses with certain sizes, adjacencies and distances to each other.

### *Application to different cases*

After each group developed their design strategy they were able to generate cities not only on one specific site but on many. For the course they had to create plans for three different sites in Ethiopia namely Haro Welabu, Fefa Dildiy, Anko Golma. The results can be seen as figure-ground plans in figure 6. The comparison shows how the design adapts to different contexts like the topography while inheriting the logics of the strategy.

## DISCUSSION

Bertel et al. (2004) point out that A&C relies on well chosen aspects and their sequential order needs clear prioritization. The designer needs to decide what information is most important and which aspect should have more influence than another. By defining the generative strategy in relation to their performance criteria each of the student groups developed a different approach. All groups considered with various weightings that the street network is highly influenced by the environment especially the topography, that the properties of street blocks depend on the street network and that land use distribution needs most information from other aspects. The street network was prioritized by nearly all of the groups as a base for the allocation of functions. Only group two has calculated the land use at the same time as streets. The geometries however differ greatly and were produced either through a vector field, forces or water rundown or simple rectangular grids.

With the introduction of the aforementioned aspects in our course we saw the advantage of defining the scope of our computer-based modules: one module would deal with only one aspect making it exchangeable with other modules of the same. As expected, the information that the produced modules handle and need as input and give as output are similar. It would be therefore possible to exchange the modules of street network and block in a group, since they both need boundaries and then create their streets. But even in between groups modules could be shared. For example force-based generation of geometries could be combined with modules that use vector fields or water rundown.This shows us that the flexibility and exchangeability of modules can also be advantageous in urban planning, but with the demand of a planner to prioritize the sequence of modules. On the other hand we also realized that not all modules are exchangeable, since they need different information and are dependent on other modules. Group two therefore tried to run land use calculation and street network independently from each other, preferring flexibility, but

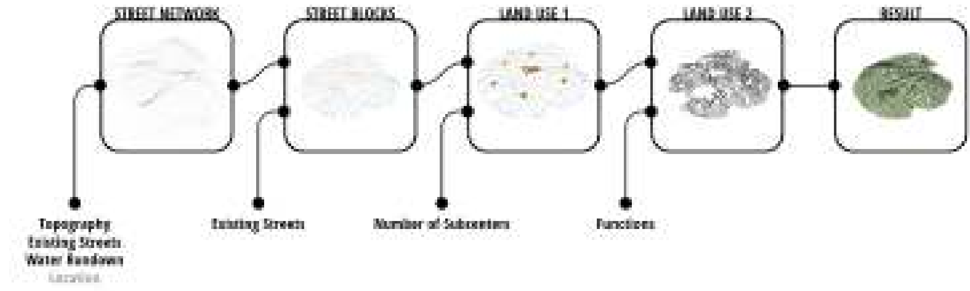



Figure 5
Modules and their sequential order of Group 3 - Watershed approach

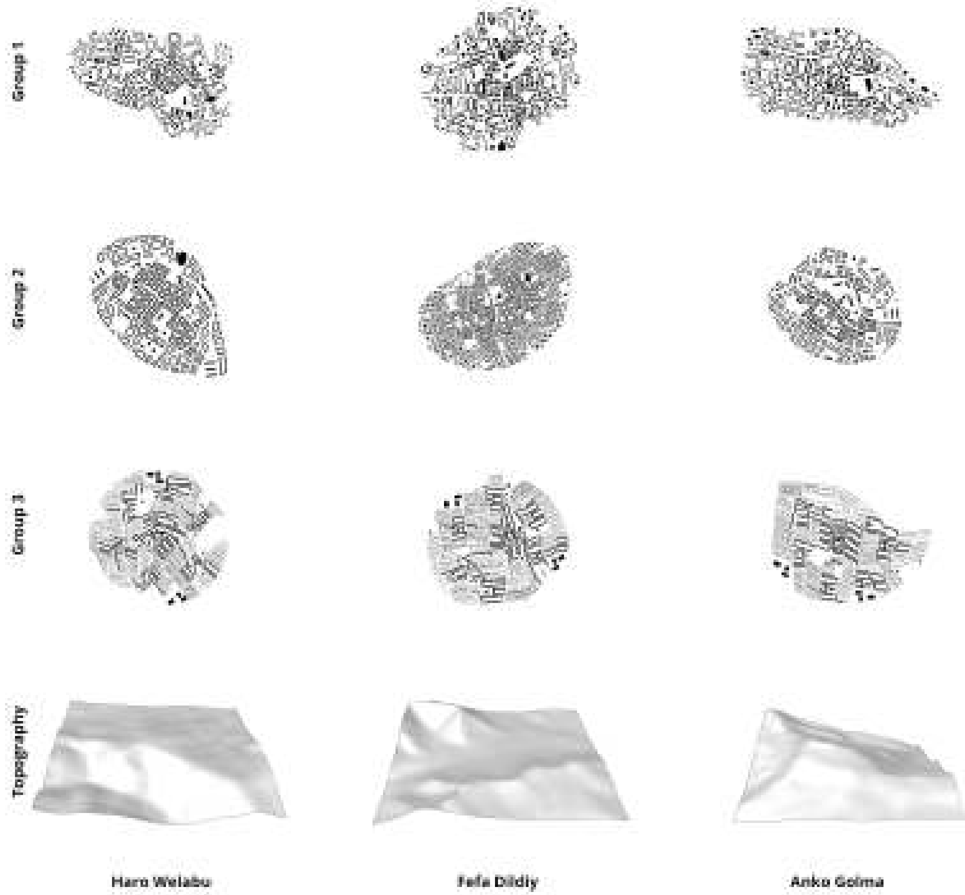



Figure 6
Design Strategy applied to different villages. From left to right: Haro Welabu, Fefa Dildiy and Anko Golma.

reducing information for the allocation of functions. The issue of parallel and sequential modules is shown in figure 7. Modules can be arranged independently from each other running parallel which allows to flexibly exchange them, but with the need to combine their information later, or modules can be arranged in sequential dependency with one gaining information from the other

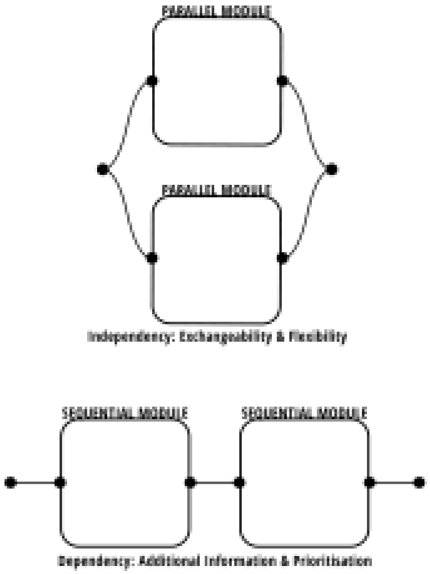



Figure 7
Independent modules can run in parallel with more flexibility. Dependent modules run in sequence and need information from another.

## CONCLUSION

The group results show the possibilities for educating architecture and urbanism students without prior knowledge in programming or computational design in one semester. The division of the main problem into sub-aspects helped the students to understand and grasp the complexity of a city better. It also assisted in the development of a design strategy, since the aspects could be easily translated into modules that generate the cities. By creating a computer-based method the strategies can be applied to not one but many locations in Ethiopia, and through the flexibility of modules the design strategy can be easily adapted to different contexts. The designer automates repetitive design tasks by translating them into modules. The exchangeability of the modules lets the designer try out different procedures in a fast pace. Simply said, a module is outsourcing repetitive tasks of the designer to give him more time to plan, design and explore the solution space. This automation capacitates one with more time to iterate over many designs, making the process itself semi-automated. The course therefore made the students understand, how important such a rapid generation of cities can assist planning processes in emerging countries like Ethiopia.

An interesting observation was that the parameterized but closed components prepared by the supervisors for special purposes like generation of street networks, parcels and buildings were usually replaced by the students own algorithms. There was obviously a need for understanding and adapting the procedures in detail in contrast to using black box parameterized generative models. This demand for keeping the control over the generative process conflicts with the inherent logic of generative design methods, since more sophisticated algorithms may create urban designs more automatically and eventually lead to another level of control as expressed by Kelly (1995).

## OUTLOOK

Modules have certain advantages like the exchangeability, automation of tasks and straightforward application on planning aspects. They need clear attention on ordering their sequence and the compatibility between each other. Linearly computed, they can produce results fast and could iterate over many solutions fast. However after setting up the sequence there is no iteration in the sequence itself. Modules stay in a fixed information of flow and do not communicate backwards. Parallel computing could show alternatives, like for example Carl Hewitt's Actor Model (1973), which would let the aspects communicate and influence each other.

Furtheron an analysis and comparison of performance of the generated designs could quantitatively characterise the effectiveness of the design strategies. It would assist the iteration of design solutions and would add the analysis to the framework of formulation and generation of design as described by Duarte, Montenegro and Gil (2012).

## ACKNOWLEDGEMENT

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# The role of Open Data in identifying and evaluating the Livability of Urban Space

## *Importance and Method*

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*The past decade has experienced a staggering rise of data-aided analysis that facilitate understanding the impact of socio-economic flux and socially oriented activities towards the quality and livability of space. Evaluating urban environments is not only important from the planners' perspective, but has larger implications for the residents themselves. In this paper we argue that the livability of a city or a neighborhood is not necessarily described by conventional, authoritative data, such as income, crime, education level etc., but the combination with ephemeral data layers, related to human perception and desire, can be more effective in capturing the dynamics of space. Implementing methods that are considered disassociated with urban analytics, we attempt to go beyond the conventions in understanding the dynamics that drive socio-economic phenomena and construct lived space. Our objective is to create methodologies of anticipating and evaluating urban environment by re-patterning different datasets and taking advantage of their combinatory potential.*

**Keywords:** *Livability, Data-aided Analysis, Open Data, Human Factor*

## INTRODUCTION

Urban design practice has been significantly influenced by the development of tools and platforms that have set the scene for new ways of understanding place and space. Current data streams have allowed planners to view the city as a constantly transforming and unpredictable environment. This paper will focus on the development of alternative urban computing methodologies that are non-deterministic and attempt to provide new insight in mapping the complexity of the urban environment. The research builds on the term of mapping as James Corner defines it. Corner suggests ways in which mapping acts may emancipate potential and reveal hidden, invisible layers (Corner 1999). Under this scope, we create a case study that attempts to evaluate the livability of space in Oakland, San Francisco Bay Area, through a set of collected data sets. We implemented a data - driven process utilizing multiple databases that offer opportunities to author urban data through subjective observation and crowd sourced survey techniques. We formulated an accumulative analysis that operates at different scales, regional and local, in an attempt to show, through

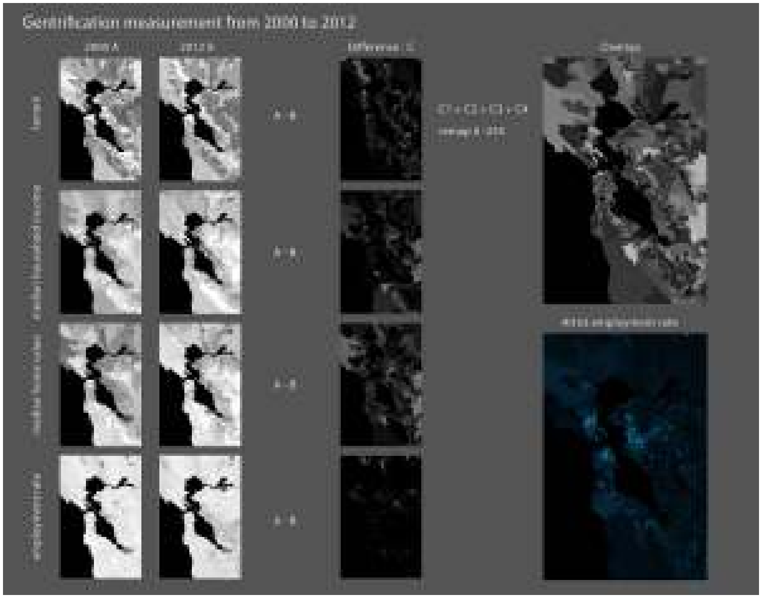


Figure 1
Census Data Analysis method. Data Analyzed: Tenure, Median Household Income, Median Home Value, Employment Rate, Overlaid with Artists employment rate

the lens of new and old ideas, how the city can be better understood nowadays. In order to provide an informative framework for our research on data-driven mapping methodologies, we will analyze the groundwork of some fundamental topics and problematic that influenced our approach on data and design. This research combines different methods that operate at different scales, including that of neighborhood. In the following section we will analyze terms such as livability, accessibility, neighborhood and displacement and attempt to provide an understanding of their interrelation. Finally, we will emphasize on the role of data in mapping processes and its contribution to the current state of the art.

## KEY TERMINOLOGY

### *Livability and Accessibility*

Livability is identified as the ability of an urban area to maintain and improve its viability and vitality, to attract investment and to remain alive. It is a temporal phenomenon measured across multiple dimensions. It relies on various factors, such as population demographics, employment, entertainment, parking, transportation, crime, safety, affordability etc. These are important aspects to determine quality of life and are profoundly influenced by the built environment. Complexity, balance and diversity in the built environment, not in form of segregation however, can influence how a community forms and how people relate to it. In this research livability relates more in identifying the quality of life in the urban environment, rather than being a set of criteria for a ranking system. As identifying livability is a multifaceted concept we introduce another term that is key to the livability of space. This term is accessibility, which implicitly or explicitly underlies many measures of livability. Accessibility can be identified as the ability of an individual or group to access equal amount of opportunities and resources. Accessibility is important to investigate whether the built environment is evolving towards an equal state of services, and other opportunities or in favor of certain socio-economic groups over others.

### Neighborhood and Community

The notion of neighborhood is one that planners and scholars usually presuppose as consistent, however, its role in the urban environment has been debated upon. The neighborhood is understood as the physical building block of the city for both "social and political" organization (Sampson 2011), and thus, combines physical and non-physical attributes. Based on these theories, neighborhood change was a natural process of population relocation and competition for space, until a state of new equilibrium is established. These ideas about neighborhood presented a deterministic model, where neighborhoods can be categorized based on simplified criteria such as their residents' financial status etc. However, neighborhoods are not introverted, autonomous clusters and the mechanisms of neighborhood change do not rely on exclusively external factors.

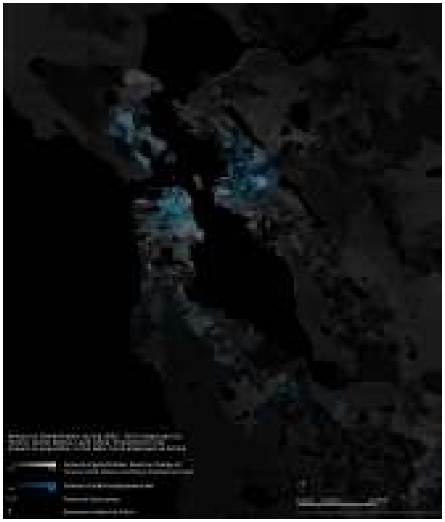

Figure 2
San Francisco Bay Area Gentrification Rate based of delta values between 2000 and 2012 on Tenure, Median Household Income, Median Home Value and Employments rate , overlaid with Artists employment rate

According to Jane Jacobs, nowadays people identify a neighborhood by a landmark in the city because it has become intimate from daily encounter (Jacobs 1961). The key that creates the notion of a neighborhood is diversity and identity. She argues that people tend to avoid visiting places that do not represent any variation either in function or aesthetics (Jacobs 1961). Although the modern way of living has urged people to be mobile, for example, their place of work does not coincide with their place for entertainment or home, people tend to care about the district that surrounds their home if it meets certain criteria that fit their lifestyle. The stability of a neighborhood relies on its capacity to absorb opportunities and sustain its diverse character. The term neighborhood can be described as an instance of organized complexity (Jacobs 1961), a network of numerous connections, where transformations can occur unexpectedly. Apart from a territorially bounded entity, neighborhoods embody series of overlapping social networks, where a diverse mix of people and processes has its own self-organizing dynamic.

### Urban Displacement - Expulsion

Under the lens of an economic perspective, livability is a key characteristic that attracts people with talent and capital leading to an economic growth. However, city dwellers are not all rich and talented and their growing populations should not be deprived of the opportunity for personal growth and a good quality of life. In this sense, when a neighborhood undergoes change in favor of certain groups, this phenomenon is called gentrification. Gentrification is broadly defined as the process of improving and renovating previously deteriorated neighborhoods by the middle or upper class, often by displacing low-income families and small businesses. The first documented use of the term "gentrification" (Glass 1964)) describes the influx of a "gentry" in lower income neighborhoods. It is a complicated process that does not rely on binary and linear explanations (Owens 2012). Early studies identified two main categories that cause gentrification: private capital investment for profit-seeking and people flow that refers to individual lifestyle preferences. Gentrification does not result in negative effects, as it can also be regarded as a tool for revitalization. When revitalization occurs from existing residents, who seek to improve their neighborhood conditions, the result can be constructive in enforcing the neighborhood stability. This condition is called incumbent upgrading or "unslumming" as Jane Jacobs defines it (Jacobs 1961). However, when revitalization causes displacement and expulsion of current residents and a decline in neighborhood diversity, then neighborhoods gradually become segregated by income, due in part to macro-level increases in income inequality as well as decline of job opportunities (Freeman 1990). Hence, neighborhood stability is compromised because the opportunities have been narrowed down to a very limited range of financial status and lifestyle. Displacement is identified as the biggest negative impact of concern resulting from neighborhood revitalization. Displacement occurs when any household is forced to move from its residence, usually because of eviction and unaffordable rent increase. However, tracking unwilling displacement can be challenging to categorize, as researcher have faced limitations regarding data availability and data comprehension. Gentrification recalibrates terms such as safety, affordability, aesthetics etc. towards upgraded standards that may be regarded as improvement on the surface, but have a negative effect on lower income society. Gentrification alters not only the social fabric, but also the physical makeup of a neighborhood, such as its identity, local culture, indigenous characteristics and traditions preserved by the local residents.

## RECENT COMPUTATIONAL TOOLS - THE ROLE OF DATA

One of the most important tools in urban analytics and visualization is GIS (Geographic Information System), which has made possible to visualize information at a certain timeframe. GIS has offered a common language analysis tool between urban planners, as well as a useful representation tool for the public that breaks down the complexity and enhances understanding and decision-making on their sides. GIS can visualize time-space paths in a static mode using a model of space and time that shows the entire path within a geographic space and a fixed domain of time (Forer 1998). This has greatly lowered the cost of data accumulation and improved the accuracy of these data (Smyth 2001). The most common space aggregation in GIS is Census tracts, which is a zoning system that defines artificial boundaries. Others can be school districts, or political units such as municipalities, counties or physically defined regions. This division principle is proven useful in describing common characteristics or common policies that apply in a certain tract.

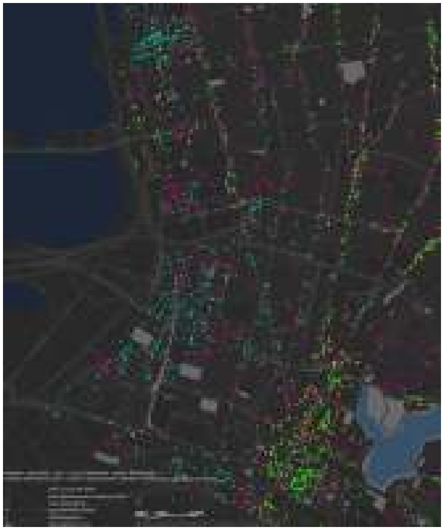

Figure 3
Oakland: Industrial buildings, Lofts, Businesses related to Artists, Fitness, Stylish cafe/restaurants. Data combination from Open Data Platforms and Amazon Mechanical Turk

However, the "coarseness", created by spatially aggregated tracts can be a barrier in understanding the spatial heterogeneity of many important social variables that occurs at a more local scale. In this sense measuring the average of each value over the total population obscures a level of detail. As cities are becoming more instrumented and networked, more data is being generated about the urban environment and its residents, allowing urban designers to access the local scale fabric of the city, opening up new research directions for understanding the city (Sassen 1998). Going beyond traditional data sources, such as Census, which is fairly static and updated only every 10 years, we encourage designers to engage with other types of data that capture the ephemeral side, such as, people's desires, trends etc. It is important for designers and planners to recognize the opportunities for making better sense of public space through technology. One of the key benefits of adopting a data-driven approach to urban analytics surveys is the ability to see a combination of datasets in context with each other, and to detect temporal and spatial patterns. The following section describes the case study that attempts to analyze the multidimensional nature of livability or expulsion.

## CASE STUDY

### *Introduction*

As mentioned in the main introduction, this case study will focus on analyzing the factors that affect the livability of space. The case study involves a combination of three different methods in an attempt to provide a holistic understanding of the flux in the urban environment. This case study will use a series of maps at different, suitable scales to visualize all the data collected from all the three methods. We employed James' Corner principle in combining data sets in a creative way that could uncover realities previously unseen even across exhausted, over studied grounds, such as the Bay Area (Corner 1999). In order to get a better understanding of the overlapped data sets, we first created a geo-located 3d space in the software Processing, were multiple data sets can be displayed at the same time on an map. When such illustrations are examined closely, every data point has a value, but when they are looked at more generally, only trends and patterns can be observed (Tufte 1990). In particular, changes of degree in a factor are displayed with a gradient of the same color, changes of type are displayed with different colors and the general vocabulary of visual styles is communicated with dots, lines and areas. One important dimension in this survey is scale as livability can be affected strongly by smaller-scale changes. The livability of two neighboring houses on the same street could be assessed very differently. As our target is to mirror the image of the diverse city, whose neighborhoods, although they are bound together as one unit, when examined, they start to reveal deviations. The problem of mapping those populations adequately, both to reveal the ongoing inequalities and spatial flux within the city, we are operating at mainly two different scales.

### *Census Data Analysis*

The first method is based on a Census GIS data analysis to identify the areas that have altered their character the last 10 years, based on authoritative parameters associated with livability and life quality, such as tenure status, land value, income and employment rate. The Geographic Information System, or GIS, allows for very fast accumulation of Census data that represent multiple categories relevant to our study. However, for domain specific categories, such as population, income, educational level, transport etc. surveys are conducted every few years, using a limited spatial and temporal sampling framework. As a first step, we identified all the green areas, parks etc. in the entire Bay Area and excluded them from the calculations, as they would have compromised the results of the survey.

The initial survey was done for the county of San Francisco based on an assumption that most changes would occur there. Soon it became apparent that most suitable scale for this kind of data set display, is an urban scale, that of the entire Bay Area, because this data has low spatial resolution and hence, refers to large scale surveys, where comparison would make more sense. As a second stage of the process we re-collected data for the entire San Francisco Bay Area. The Census data that we collected consists of a combined data set from 2000 to 2012 that compares tenure, median household income, median home value and employment rate. Through calculations we generated the delta of these data sets respectively and remapped the values in a series of grey scale maps. The term delta stands for the difference/amount of change that was observed in every county of the Bay Area for every data set respectively. The amount of change was visualized in a series of grey scale maps that range from 0 - 255, where black color represents lowest amount of change and white color highest amount of change. The 4 maps that represent the amount of change in tenure, median household income, median home value and employment rate were weighted and overlapped on a single map that represents the amount of change of the combined data sets (Figure 1). In order to enrich the process, we added an additional layer of information, that of artists' employment rate. Artists' community is considered highly associated with real estate flux. Previous surveys in the field have established artists as agents of urban gentrification, for the reason that low-income artists tend to revalorize unproductive spaces, since they are affordable, and, as a result, increase the attractiveness of urban space. Artists make the first move into post-industrial, post-welfare neighborhoods. Soon they attract the hipster movement before, eventually, being displaced by them and their new middle-class neighbors. Both participate in the cycle of exploring, developing new potential sites for capital investment. Hence, the combined data set of the other categories is overlapped with artist employment rate Census data, as a contributing factor in tenure shift (Figure 2). All the relevant data was collected from government websites in .csv format, then imported to Microsoft Excel for the calculations to be performed (delta calculation) and then re-exported in .csv spreadsheets that were imported in Grasshopper and visualized in the Processing model space created for this purpose.

### *Open Data Platforms - Google API and craigslist.org*

The second method operates at a local level analysis in Oakland and Emeryville. The data resources for this research derive from open data platforms (data that is freely accessible), such as Google API, Google Places and collective, open-data platforms where users post all kinds of requests (sell and buy, real estate etc.), such as "craigslist.org". Our database is articulated by tracing certain populations and services categories that reflect activity and flux of the built environment.

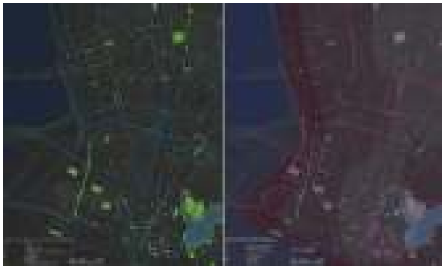

Figure 4
Oakland: Street Trees, Parks, Education, Religious spaces, Medical, Public Transport (left), Oakland: Walkability, Pavement condition, Injuries

The targeted population involves artists and their activity in Oakland. The targeted services are directly related to the urban quality, such as crime reports, accidents and pedestrian network, street trees and parks, schools, education points, medical and religious spaces. The same logic as in the first method is applied in this method as well. The artist population is considered as the frontline of gentrification. The main difference of this method in comparison to the previous one is that the data accumulation derives from open data platforms by defining an equivalent keyword query. Although we are dealing with the same group of people (artists), the data come from an entirely different type of source. We argue that for the artist community particularly, this data source describes more effectively the activity of this group, as most of the people are freelancers or unemployed, however they actively pursue real estate for their studio or advertise artwork exhibitions etc. This activity would be completely masked by the Census data set, however it is revealed at this stage of the process, since Google places and "craigslist.org" allow for every request is geo-located. In detail about the method itself, using Google API and "craigslist.org", we performed multiple requests at a daily basis, in order to collect all the necessary data. The keyword queries were related to temporal requests and offers regarding real estate for artists' studios, gallery spaces, events, artists' resources, artwork sale, exhibitions, FAQ etc. (Figure 3). Regarding the services analyses, we divided the data sets in 3 categories. The first depicts amenities such as access to education, religion, health and green areas, as well as the street trees that definitely improve the urban environment in terms of walkability, microclimate and aesthetic (Figure 4). The second set depicts crime reports for the years 2010 and 2013 (Figure 5). The third depicts car dependency zones, car injuries report, pavement condition and parking spaces (Figure 4). The data accumulated was formatted in .csv format same as with the Census data process and visualized as nodes on the same context.

### *Human factor*

The third method operates at building scale and embraces a human based approach, where human perception and subjectivity are considered a qualitative source of data that can unveil qualities that the other processes overlook. In order to allocate a group of people for crowd sourcing, we utilized a human-based outsourcing platform called Amazon Mechanical Turk. Amazon Mechanical Turk is a crowdsourcing Internet marketplace, operated by Amazon, enabling individuals to coordinate the use of human intelligence to perform tasks that computers are currently unable to do. It is an on-demand large sample of users that executes large assignments over a given period of time. In our case, a large group was given two different sets of questions. The first set targets human subjectivity, where the users were asked subjective questions in order to rate certain neighborhoods based on Google Street View viewpoints. This research takes advantage of human subjectivity when it comes to rating an area based on personal interpretation of safety, affordability and infrastructure condition, qualities that vary significantly even among neighboring blocks, however the amount or the frequency of variation may have a significant role (Figure 6). The second set targets the collection of detail features (e.g. the presence of: expensive loft housing, abandoned buildings, industrial buildings, trees, fitness studios, contemporary, stylish cafes etc.) that are encountered in the areas of interest using the same Google Street View viewpoints. These features are time consuming to collect manually therefore; this tool is proven convenient as it succeeds in collecting this information in short time. The areas of interest are Oakland and Emeryville, which were chosen because they are transforming from a crime area into an urban, entertainment and commercial attractor point. The questions were submitted to Amazon Mechanical Turk through a template in .json format. The questions were structured in a way that the answers would be easy to process and to visualize, such as numerical (scale 1 - 10), binary (yes/no) or choice (tick the box), while we avoided completely answers in a form of text. The answers we received were in .json format so we transformed them into .csv format and then imported to Grasshopper and Processing same in the previous two methods.

Figure 5
Oakland: Crime reports 2010 (left), 2013 (right)

### *Evaluation*

The results of the three surveys were overlapped when the data sets where relating, for example the second with the third method present very interrelated data sets (artists businesses with industrial building, loft, fitness and café abundance). It is difficult to argue that either a Census-based or an open-data, subjective based perspective is more appropriate. Each perspective provides a different lens through which to view transition towards more or less livable environments. For example, using a human-based perspective alone may lead us to commit to something, which is entirely subjective, by ig-

Figure 6
Oakland: Amazon Mechanical Turk crowdsourced survey on Infrastructure condition (left), Safety (middle) and Affordability (right)

noring holistic factors that emerge at aggregate levels. All census-based and open-data based perspectives are necessary for appropriate analysis of livability. Each method presents certain advantages. The Census data analysis provides an overview of the context over a significant time span (2000 - 2012) and helps us understand major socio-economic shifts that affect tenure, which then affects the local market and the standards of living in the area. The open data analysis depicts the ephemeral layer of relationships that take place in the urban environment, which is impossible to be described by authoritative data, however it is more relevant to the actual conditions, revealing virtual changes and dynamics for the near future. The third method enriches the process with user personal feedback about ranking the environment of a neighborhood as it currently stands. The project aims to provide a calibrated understanding of the multiple grains of constructed space through top down and bottom up methods, as well as to offer a tool of visualizing dynamical characteristics of the urban environment that tie with livability. Our research balances the traditional census data analysis with more dynamic layers of collective platforms and crowdsourcing. Whichever method is considered more or less descriptive of the reality, it is worth examining all the conduits and corridors available to us, by which this change is being delivered. Looking at urban issues through maps can give us several hints about spatial and social transformations, in which we can think upon, as visualized information provokes feedback, either logical or emotional (Corner 1999). Throughout this entire process we can assess certain findings:

**1.** Based on the Census data search, nearly half of Bay Area census tracts are undergoing some form of neighborhood transformation and displacement.

**2.** The data accumulated from the open data research depict a significant artists' movement regarding art studio rent requests, artwork sale and creative services in general in the entire Bay Area and especially in the post industrial areas of Oakland.

**3.** Studying Oakland at a local street view scale, we can assess that the area is undergoing disperse development that presents high contradictions related to infrastructure condition, affordability and safety. The results from the crowdsourcing survey vary significantly in building block scale. We notice significant contradictions on the results of the crowed sourced research regarding infrastructure condition, safety and affordability perception of the participants. Some of the findings depict areas of new development (last 3-4 years) that are yet islanded off because the surrounding area is significantly undermined. However, this contradiction reveals certain dynamics regarding the future, further re-development of the area, as well as the areas that accumulate similar features (Figure 7). The former "industrial areas," in west and southeast Oakland stand in sharp contrast to newly constructed luxury apartment buildings. This illuminates an economic disruption of the city that speaks of individual cases of displacement or on the edge of eviction.

Figure 7
Oakland: Industrial buildings, Lofts and Businesses related to Artists overlaid with neighborhood infrastructure and safety comparison from Amazon Mechanical Turk survey. High contradiction: White, No Contradiction: Black

**4.** Any sense of continuity of the same character because of proximity is not necessarily a criterion to rely upon. One reason is that some relationships are different across neighborhoods; for example, a person's access to education or higher economic status may vary significantly. This creates contextually different responses to the same stimuli. Many livability measures assume that the resources and opportunities at a place are perfectly available to individuals who live close to that location. However, factors other than proximity can affect the ability of individuals to obtain resources and opportunities. For example, an individual who lives in a recently upgraded neighborhood might no longer be able to afford the services of the neighborhood. This means that measuring only based on proximity can overestimate livability and mask individual inequality in the benefits obtained from resources and opportunities.

**5.** Certain re-developed areas have uniform functional identity, such as Emeryville, as they present excessive duplication of the most profitable uses (malls, restaurants) or present a standard combination of functions, for example artist studio, loft, fitness and café are appearing within the same block (Figure 3).

**6.** Although crime rate has reduced significantly over the years, which allows us to assume that the city becomes safer, public infrastructure is not continuous across all neighborhoods. Poor quality street infrastructure is observed in the areas that are not undergoing reformation, however they are the most undermined (West Oakland).

**7.** Oakland presents a good foundation for a more walkable, active city, as the green network of street trees and parks would contribute very positively towards that scenario. Street trees network is continuous for the most part of the city, which allows us to assume that if the authorities invested towards an equally good public infrastructure condition (uninterrupted pavement, traffic control, accessible ramps etc.), this would significantly contribute to a walkable city. This establishment of relationships does not depict equal accessibility to opportunities towards more livable space. Although it creates more visual order, as many areas are undergoing significant upgrading, this aesthetic ordering might not have a social correlation. For example, lower income families were in fact disproportionately effected by foreclosures and former residents were expulsed as residence became unsustainable. For these areas, social structure and social stability are inversely proportional to visual order. This condition is known to be establishing in Oakland, which was significantly undermined in the past few years, however the challenge is not only to identify the problem, but also to find the ways to analyze by mapping its characteristics it and communicate it visually to its extents. Understanding the shifts of urban space and finding the patterns that drive them is a big challenge. We support that close engagement with technology leads us to explore numerous research methods, which have a way of contributing to meaningful connections inside data networks. We find inspiration in the combination of the traditional ways of space categorization by investigating the relationship of home value, income, transportation etc. with a bottom-up, participative approach in which individuals provide more ephemeral social elements of neighborhoods. We believe that the composite association between them leads to a more informed decision-making and a more qualitative image of the city that reflects subjective aspects of urban planning (Batty 2013). As some of the above methods open the possibility to operate at a fine spatial scale, examining the city building by building, they provide the context for a more fine-grained understanding of neighborhood characteristics, conflicts and relationships that reveal the heterogeneous characteristics of the city. Although it is impossible to predict precisely how and where changes will occur in the future, new combinations of data can create new knowledge and capacity for discovery that often comes from unlikely places. Throughout the entire survey the key aspect that brings all the results together is open data. In order for our process to have a meaningful insight, it required putting data in context waith other data, compare different timeframes and different scales, as accessible data by itself does not necessarily help us better understand, and interact with, our cities. Open data allow for evidence-based decisions, analyze patterns and solve complex problems. We believe that the key to improve policymaking is engaging people to collaborate and use information to become more active in society. This would be a first step towards the equalization of power between citizens and stakeholders and the collaborative constructions of urban space, as well as a step to understand the unique challenges that the city faces.

## FUTURE WORK

Future development of the project would be to find ways to enrich the process with user feedback data that will improve decision-making and will also affect policy making. One way to achieve that is the incorporation of social media feeds, such as Facebook and Twitter that would refine the tool by adding the feedback of targeted users and potential residents of the area. In the years to come, it is vital to understand that as technology improves, the amount of data increases and designers should problematize on the cases where data provides unique understandings they couldn't have had otherwise or cases where it creates confusion that hinders designers' perception. The main challenges would be to identify whether we have enough data to create assumptions, whether we have the right type of data to support our claim and whether we can visualize urban space in ways that are perceived by everyone.

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# Human-driven and machine-driven decisions in urban design and architecture

## *A comparison of two different methods in finding solutions to a complex problem*

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*The authors of the paper research the aspects of two approaches in human-computer collaboration to solve an urban scale problem: positioning a new cycling-pedestrian bridge in the city of Warsaw. The first approach is a machine-driven stochastic optimization combined with the shortest walk algorithm; the second one is a human-centered process involving an interactive table as a way of communication and data input. Both approaches were explored as part of a one-week student workshop. The article covers the undertaken techniques in detail and presents the outcomes of both studies. It concludes with a reflection on the necessity to inspire a discussion about the future of the architecture among apprentices of the profession: with all the potential threats and opportunities deriving from computer automation.*

**Keywords:** *interface, TUI, optimization, PSO, generative design, programming*

The question of potential collaboration between two intelligent but dissimilar systems - the man and the machine - was raised long before humanity had reached its current technical development. In contrast to visions of intelligent machines being a menace to humanity and Mumford's pessimistic thoughts on technology being a limitation to human spirit, Nicholas Negroponte in 'The Architecture Machine' (Negroponte 1973) presented guidelines for good practices in possible human-machine interactions, disproving general distrust and opening the possibility for future symbiosis.

Negroponte distinguishes two ways of involving computers in a design process: it can be either computerized or computer-aided. As computerized process we understand a situation in which a problem is presented to the machine (with all necessary initial data) as input and a solution is calculated in an uninterrupted way and submitted as output - final and accurate. A computer-aided process, on the other hand, can be explained as a dialogue, in which the machine provides user with constant feedback during work but does not impose solutions. The user specifies his own criteria and follows his or her intuition, taking advantage of computer's fast local calculations.

The authors investigated the aspects of computerized and computer-aided design as part of a one-week student workshop, during which the participants were to investigate walking and cycling accessibility within the city of Warsaw and to enhance connections by diminishing distances on the street network between two sides of the river: by finding optimal position of a new bridge or bridges. The question of *optimal*, however, was supposed to be tackled with two different approaches.

The first approach to the problem was a machine-driven stochastic optimization combined with the shortest walk algorithm; the second one was based on tester's city experience and involved an interactive table as a way of communication and inputting data. The article covers the undertaken techniques in detail and presents the outcomes of both studies.

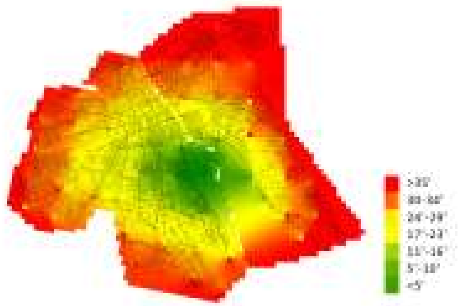

Figure 1
Global Accessibility for the present situation. Gradient colour indicates the average time needed to access other point on the map.

## THE TASK: CYCLING INFRASTRUCTURE IN WARSAW

The city growth model of Warsaw shares many similarities with other European cities. Rome, Budapest, London or Belgrade has grown simultaneously and unevenly on two sides of a river. In Warsaw the first bridge connecting two sides of Vistula appeared as late as in the 16th century. Before that point, crossing the river was only possible on boat. The wooden bridge lasted for thirty years. Due to geographical position and unstable political situation the next bridge was not built until mid-18th century. For the next centuries Praga, the town on the east side of Vistula, suffered from the lack of connection with Warsaw. Nowadays, there are ten bridges connecting the two parts of the city,but only two of them are equipped with safe bike paths. Not surprisingly, the citizens prefer to use the closest bridge rather than the cyclist-friendly: According to studies run by the local government [1] Poniatowskiego Bridge, with no cycling infrastructure, has more users than Siekierkowski or Świętokrzyski bridges, both equipped with cycle lanes and direct connection to city bike network.

Contemporary cities are facing problems related to climate changes. Reducing energy consumption and carbon emission are key elements to protect the environment. One of the most energy intensive city activities is individual motorized transport. Facilitating walking, cycling and public transport is a very effective method to decrease carbon emission. (Mitlin & Satterthwaite 1994).

The objective undertaken during the workshop was to research potential positions for a new cycling-pedestrian bridge or bridges to enhance the connectivity and to promote sustainable transport methods.

We took into account three concepts while conducting preliminary research: Local Accessibility, Global Accessibility and Average Distance. Local Accessibility is defined as a topological distance, on the city network, from a given location to a network of points which is defined by centerpoints of a square grid of 300 by 300 meters. The Global Accessibility is calculated as a average product of all the distances on the city grid. Accessibility Distance is calculated as a average topological distance to all the grid points in the absolute distance smaller than 1 500m.

The topological distance is measured on a map generated from the Open Street Maps platform. We converted data to the network of the city. The grid consists of all class of roads and its links (excluding highways), footpaths, squares and bicycle lanes. To measure accessibility, we calculated topological distances using A* algorithm. The cost of each connection was estimated taking into account the length of the connection and an average cycling speed in Warsaw (15-20 kmph). Preliminary accessibility studies (Figure 1) revealed that some parts of Warsaw (Powiśle, Saska Kępa, Gocław) considered as central are poorly connected whereas others, especially the ones constructed after second world war, are generally well-connected.

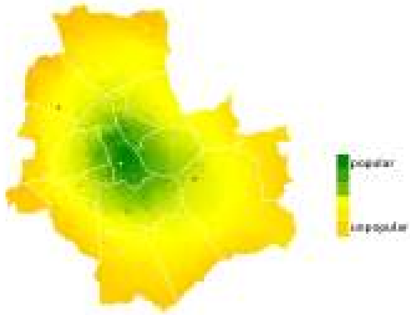


Figure 2
Attractiveness Map.

To understand the population distribution and people flow, we used two databases:

- Strava Heat Map (a community built database that maps information about bicycle and pedestrian activity) and local government information on number of inhabitants per district.
- The Heat Map reveals communication patterns in the city. Surprisingly while analyzing the intensity of the flows on the bridges, it appears that it does not respond neither to their design nor to the traffic rules. It confirms that the bike network is weak and people tend to use the shortest way rather than safe or designated one.

Interpolated data served as a reference for inhabitants flows and conformed Attractiveness Map (Figure 2). The interpolated data hierarchies the possible position of the bridges favoring the connection between the more popular areas.

Apparently Warsaw Escarpment creates a strong border for the cyclist, so there is a demand for a lower bridge and an upper bridge. The upper essentially connects the existing city grid on the left side overpassing part of the city, a very similar strategy has been applied to Poniatowski Bridge, and allows high-speed connection. The lower links to riverbanks and could be use for the low-speed, recreational bicycle connection.

To verify design concepts, we invited local activists, foundations and experts. After meeting with Warszawska Masa Krytyczna (the Warsaw Critical Mass) local biking community a potential need for two bridges was also considered. (Figure 3)

## MACHINE-CENTERED APPROACH: OPTIMIZATION

Most of urban planning and design problems are characterized by high complexity, numerous parties and aspects involved. Traditional methods are looking for a compromise, but due to the lack of information and relatively slow solving process they may be inefficient. Applying Artificial Intelligence in such class of problems reduces the computation time and allows to consider more options and/or solution based on a larger data base.

Figure 3
The workshop involved local cycling communities like Masa Krytyczna.

Optimization problem was analyzed in three different scenarios - only the upper bridge was added to the system, only the lower bridge was added to the system, both bridges were added to the system. To enhance Global Accessibility two objectives has been declared. The position of the new bridge is to reduce topological distance between all the points on the predefined grid and favors the more popular zones. To enhance local accessibility only the topological distance is to be reduced.

According to Michalewicz and Fogel (2004) a difficult optimization problem occurs when:

- a high number of solution is possible and reviewing them is high time consuming; problem cannot be simplified because any simplification leads to useless or distorted solutions;
- might have multiple optimal solutions. Urban problems tends to be impossible to solve using analytical methods.

For such complexity of problems heuristic methods can be employed. This technique does not guarantee to find the optimal solution but is capable of finding one of the fittest solution.

For finding the most optimal solution optimization solver based on Swarm Intelligence was used. The algorithm, introduced in 1995 by Kennedy and Eberhart, is a stochastic alternative to evolutionary methods. The algorithm mimics the behavior executed by the individuals in a system such as school of fish or flock of birds while searching for the best location (global optima). The instruction depends neither on the initial state nor on the gradient information. The fact that it depends only on the value of objective function makes it computationally less expensive (faster) and much simpler to implement comparing to evolutionary algorithms. (Patnaik et al, 2012). A Grasshopper plug-in Silvereye is the first implementation of Particle Swarm Optimization into design field. The tool is significantly faster than others and it uses other classes of algorithms (Cichocka, 2016).

For modeling the problem the Global Accessibility was declared as $D_{GA} = \frac{\prod_{i=0}^{n} d_i}{n}$, where $D_{GA}$ stands for Global Accessibility [m], $\prod_{i=0}^{n} d_i$ is the product of multiplication of all distances and $n$ is the number of connections.

The objective was to minimize Global Accessibility.

Three iterations of optimization has been performed, each had 20 iteration and the initial swarm size of 20 elements. The PSO initializes with an arbitrarily dispersed set of particles assigned with random velocities. The elements fly in an n-dimensional space, then cluster together to finally converge to a global minimum area. The particle movement in the solution landscape reflects the flying experience of the individual and its neighbourhood in the swarm.

| Bridge Location | Accessibility Distance* [m] | Enhancement |
|---|---|---|
| Current Situation | 1 991 | |
| City Hall Proposal | 1 908 | -83 |
| Lower Position | 1 845 | -146 |
| Upper Position | 1 817 | -174 |
| Two Bridges | 1 775 | -216 |

Table 1
The comparison of Accessibility Distances in different scenarios.

We have reviewed and analysed new connections planned by the City Hall. It appears that they are going to enhance to Global Accessibility - a new bridge in a trace of a historical wooden one by 4% (distance shorter by 83m) and a bike path on The Łazienkowski Bridge by 9 % (distance shorter by 196m).

Additionally, three schemes concluded in very similar position of the bridges (see Table 1 and Figure 4), close to the Łazienkowski Bridge that is scheduled to open in late 2017. The new link between two sides of the river is going to reduce the time needed for crossing from Praga to Warsaw downtown up to 21 minutes and significantly enhances the Global Accessibility. The optimized solution roughly shares the abutment position with Łazienkowski Bridge. In order to further validate the location of the bridge more data should be implemented and A* algorithm should be enriched with the more information such as user preference, detailed topography (ideally three-dimensional shortest walk ) or city bike station position.

While modelling the optimization problem, a threat of over-constraining or discretizing problem appeared. Since the city center and bank of left-side of Vistula is much better developed and situated on the escarpment the number of possible access points for the upper-bridge is limited and discrete. The possible position is almost entirely defined by the existing city grid, only far-south and far-north banks, neighbouring with Siekierkowski and Grota-Roweckiego bridges, are undeveloped. Praga's riverside is much less developed so the problem is mostly continuous. The lower bridge could be positioned on any location on the both side of the river.

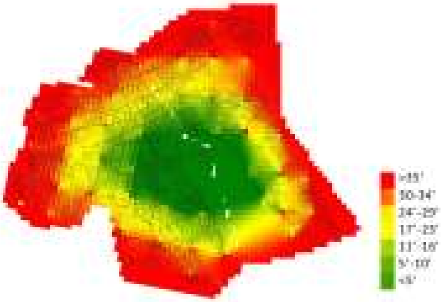

Figure 4
Global Accessibility Map with two bridges. Gradient colour indicates the average time needed to access other point on the map.

## HUMAN-CENTERED APPROACH: A DEDICATED INTERFACE

In 1970s Negroponte accentuated the importance of an architect in the process of translating human needs into design language. In this process, he defined a machine (a computer) as a virtual partner with the ability to suggest alternative solutions, pointing out emerging collisions, but never imposing calculated solutions. He underlined the need to adjust the abilities of a computer to the specificity of human actions - not the other way around - and predicted a shift in the field of interfaces from a counterintuitive set of knobs and buttons towards processes based on human language. (Negroponte 1973)

In our opinion, there is still a lot of research required to fully enhance the way architects use computers in their work. Software solutions that are available today along with computers' increasing calculation capabilities provide users with mechanisms to easily model, edit, analyze, present and share architectural projects. However, the use of possibly inadequate peripheral devices in the process of architectural and urban design may lead to difficulties in the use of CAD tools. Also the threat of skeuomorphic approach arises, technology providers are having difficulties breaking designer habits and produce pencil-like, drawing board-like devices rather than proposing a new approach.

As means for testing computer-aided approach we decided to use InteracTable - a low-cost Tangible User Interface (TUI) designed and prototyped by Jacek Markusiewicz with the assistance of students Jakub Andrzejewski, Kacper Karpiński and Damian Lachtara. The device is a table-like structure in which the tabletop was replaced with a translucent glass panel with a dual objective: to create possibility for backlit projection and at the same time to provide user with working space. The table is equipped with a camera placed above the glass panel for capturing elements that are handled by users, while the projector responsible for computer-user feedback is placed below its surface.

The direct inspiration for designing InteracTable was Reactable project - an innovative multi-user musical instrument. Reactable was conceived at Pompeu Fabra University in Barcelona as an attempt to create an intuitive tool for synthesizing music with no additional peripheral devices needed. (Jordá et al. 2005) While designing InteracTable, a series of design decisions has been made to adapt the concept of Reactable to architectural and urban design purposes, such as using a rectangular shape for the workspace instead of a circular one , and placing the camera responsible for image capturing above the table, instead of below it, to be able to implement different types of interaction.

The workflow undertaken during Warsaw Summer School 2016 was divided into three phases, and controlled by three different programs: (1) ReacTIVision (an open-source framework developed by Martin Kaltenbrunner and Ross Bencina for image recognition in the Reactable project), (2) a Grasshopper definition and (3) a custom application developed in Unity3d. (Figure 5)

The first phase is the process of inputting data. A user places physical elements on the translucent surface of InteracTable with a map of the city projected onto it. Each physical element is equipped with a fiducial marker optimized for ReacTIVision image processing algorithm. There are three types of these elements: (Figure 6)

- The home symbol: the starting point. By placing this element on the projected map of Warsaw, the user defines their virtual location. It is the position from which accessibility to all areas is calculated.
- The knob: defining the maximum cycling distance. By rotating this element, a user defines the longest distance they are willing to cycle. This value varies depending on the user's physical conditions and the purpose of bicycle use. It may be e.g. set to higher values when testing cycling accessibility for recreational reasons, while for everyday commuting the maximum distance may decrease.
- Pairs of arrows: start- and endpoints of new connections. By placing two arrow-like objects on the table, the user proposes new linear cycling paths. Multiple sets can be used in the process to design both bridges and new in-city links.

The camera captures the configuration of elements that is then interpreted by ReacTIVision software (phase 1) to obtain each element's location and rotation on the table. The coordinates are then sent to the Grasshopper definition (the second phase) via User Datagram Protocol (UDP - a transmission model that enables communication between devices and programs within the same network).

The Grasshopper definition (phase 2) was developed by the workshop participants under the supervision of Adrian Krężlik. This part of the process is re-

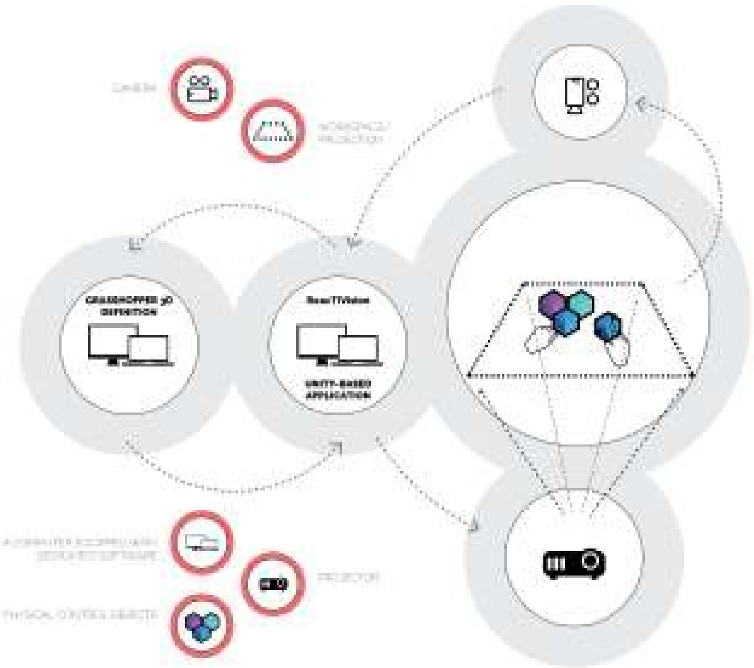


Figure 5
A scheme presenting the workflow based on the interactive table.

sponsible for calculating cycling accessibility of different areas of Warsaw based on data received from the user. It implements Dijkstra's algorithm (using Shortest Walk plugin for Grasshopper) to calculate connections through pre-defined network of cycling lanes and cycling-friendly streets. Each city area is then assigned a color that indicates the level of accessibility and the color map is sent using UDP to the application developed in Unity3d (phase 3).

Figure 6
Prototyping the interactive elements of the interface.

The Unity-based software (phase 3) was developed during the workshop under the supervision of Jacek Markusiewicz and is responsible for displaying live feedback on InteracTable workspace. The city plan has been divided into roughly 30 000 small regions of similar area. The accessibility to each of these regions is estimated by measuring the shortest path length from its center to the starting point (home symbol location). If such length exceeds the maximum desired cycling distance, then the area is assigned white color. Otherwise the color is interpolated between red and orange proportionally to the length of the path. The feedback is provided almost instantaneously (125-500ms between changes made by the user and the update of color map on the screen).

Every participant of the workshop was assigned a task to propose one or more new bridge connections across Vistula river according to their own criteria. We observed different approaches. Some students were commuting to work or school using a bicycle on a daily basis, while others used bicycles exclusively for recreational purposes. Most participants were defining the starting points in either the areas with biggest population or the ones that are believed to lack bicycle infrastructure. Some however were placing the home symbol subjectively - around their houses, schools or working places. All users performed accessibility analyses for multiple starting points and multiple configurations of proposed connections attempting to compare accessibility data for:

- Current situation - with no new links
- Their subjective design proposal - where the user simulated new connections in places he or she intuitively considered advantageous
- The city authorities' proposal
- The seemingly incorrect situation - where new links were proposed in location that the user considered illogical.

We conducted a simple survey, in which we asked every table user to select a new location for a bicycle bridge or bridges across Vistula river. We received 27 answers (10 workshop participants, 2 tutors, 15 guests on the workshop outcome presentation - see Figure 7). The most popular answer was a link in the vicinity of Poniatowski Bridge (central Warsaw - 13/27 answers). Other indicated solutions were: the proximity of Łazienkowski Bridge (south central Warsaw - 6 answers), the confirmation of the city authorities' proposal between Karowa Street and Okrzei Street (Old Town - 3 answers), a double connection linking both river boulevards and Warsaw Escarpment on the left side of the river with the right bank confirming the optimization results (near Łazienkowski Bridge - 3 answers) and a link between Łazienkowski and Siekierkowski Bridge (south Warsaw - 2 answers).


Figure 7
The interaction with the interface during workshop's results presentation.

## DISCUSSION

The solutions originated from the process are the following:

1. For machine-driven approach:

- Upper Bride, extending Ludna Street at the level of escarpment, going over Wioślarska Street, crossing the river to Walecznych Street over Wał Miedzeszyński,
- A possible additional lower bridge, close to trace of Łazienkowski, connecting Vistula Boulevard (around Czerniakowski Port) with Saska Kępa

2. For user-centered approach: a single cycling bridge in the vicinity of Poniatowski Bridge. (Figure 8)

The similarity of these results may be interpreted as a complementary validation of both approaches, but it also raised a question among the participants of the workshop about the role of human decisions in architectural and urban processes. These processes are traditionally considered as creative and it is hard to imagine they can exist when devoid of human aspect. (Meltzer 2014; [2]) However, recent history shows that unimaginable scenarios have to be taken into account. Levy and Murnane in their visionary "The New Division of Labour" made many accurate predictions about potentially automated human jobs. Interestingly enough they presented the job of a truck driver as unlikely to be replaced by a computer. The world of science needed only a decade to defy this forecast by switching the status of driverless cars' vision from "highly unlikely" to "very close future". (Levy and Murnane 2004 after Harari 2015)

There is no reason to assume with full certainty that the job of an architect or urbanist will not undergo automation at least to certain extent. In this context, optimization can be the first step to introduce computer-performed tasks in architecture, where many agents - including investors - often look for efficient solutions over individual approach. Implementing solutions like PSO in the workflow provides data-valid solutions in relatively short time.

Then why bother involving people in a process when it can be fully automated by an algorithm? One opinion may be that it is not always the solution that matters the most but the process itself. When working on a problem - either as individual architects, a group of designers or part of a larger community in participatory design - we take part in a cultural process that enhances one's social and often environmental awareness. Receiving a ready solution does not give us reasons to rethink our future goals or to resolve potential ethical dilemmas. Distinguishing good or bad solutions in architecture and city planning does not come from pure data. The popular example of whether a driverless car can face moral decisions (Greenemeier 2016; [3]) shows how vague our own priorities can be - not to mention priorities that may be consider as optimal by a machine. While taking decisions collectively, humans act as multiple independent algorithms and - even if some of us come to incorrect solutions - the final decision is probable to meet shared priorities thanks to negotiations and mutual validation. Decisions made by a computer, if not programmed correctly, can have serious consequences.

However, maybe the question should be exactly the opposite: should we spend our resources on programming computers to work on tasks that human are able to perform just as well? There are many situ-

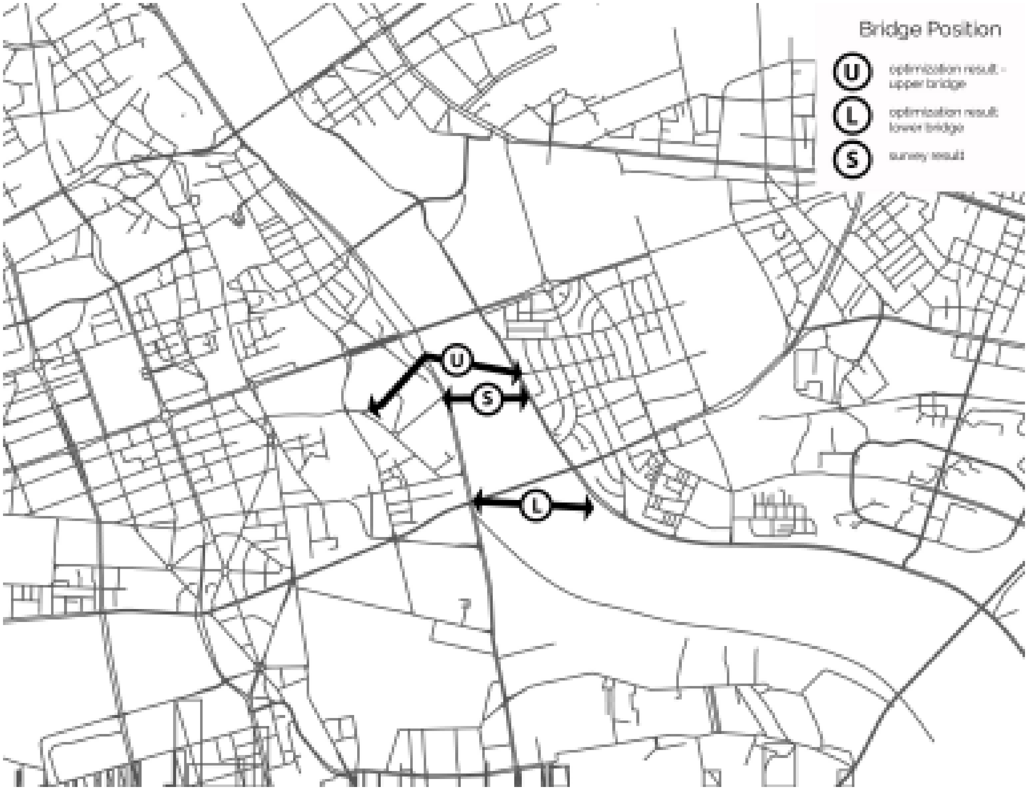


Figure 8
Schematic map with positions of new bridges

ations in which computational capabilities are essential, especially when solutions require responding to big data, that we as humans are simply unable to process. "As the amount of data goes up, the importance of human judgment should go down." (McAfee 2013 after Press 2014; [4]; [5]) Computer decisions may be free of human-specific biases and personal interests and as such may provide solutions that - even if not perfect and lacking moral validation - are better.

In fact, when asking the second question, we often assume that human effort is required to issue a command to a program or to write an algorithm. However, such assumption may be erroneous, as with the development of artificial intelligence computer programming may also be outsourced to computers. Will then the priorities of problem-solving be compatible with ours or will the artificial intelligence set new rules for potential solutions? Some think it is safer to always have a possibility for human-override of algorithm's decisions, (Davenport 2013; [6]) assuming it is possible. And "then again, humans can be even more wrong". (Kobielus 2015; [7])

Judging only by the voices among the participants and our personal opinions, we think that it may be beneficial to follow investigating two scenarios: human-centered and machine-centered. As of today, we cannot know what role for the architect will the future bring. In fact, from a deeper investigation of potential scenarios new ideas will surely emerge. We find it urgent to raise all these questions and arguments, especially among the students of architecture. Not doing so will lead us - architects - to a situation where the decisions about the future of our job, including its replacement by fully automated processes, will be taken without our involvement.

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# Visual Programming meets Tangible Interfaces

## *Generating city simulations for decision support in early design stages*

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*The utilization of visual programming languages (VPL) as tools for generating complex simulations has seen a constant increase in application in architect planning phases. The major advantage of such languages is, that they enable the user to create programs without needing traditional software development skills. In the last few years the CDP // Collaborative Design Platform was developed that seamlessly connects physical models with analyses and simulations in real-time. To facilitate an easier creation, modification and user interaction with the individual simulations, a VPL and an accompanying IDE were conceptualized and developed. In the context of this paper the core requirements, the concept and prototypical implementation of these new components are described in detail.*

**Keywords:** *visual programming language, tangible interface, simulation, urban planning*

## INTRODUCTION

Increasing requirements for architectural tasks, combined with a rapidly growing project size, lead to more complex conditions and connections in the planning and decision-making process. This applies to both, the conceptual urban planning phases, as well as to subsequent decision-making processes at the building scale. This rapidly changing situation requires totally new approaches and answers with regard to the design, planning and communication process. These changes do not only have an impact on the processes that are taking place, but also directly on the design and communication tools used.

The focus here is on the question how the effects of architectural and planning decisions can be made clear during the conceptual design phases, while at the same time an individual adaptation of the tools to the different design- problems is possible.

In addition to the consideration of established working methods and the tools used for design-thinking and design-working, the focus is primarily on the investigation of the digital methods that can be transferred to the conceptual planning context - the keyword is: Design Decision Support. A solution approach can therefore be found in the direct integration of decision-support tools like analyses and simulations into the early, creative planning- and design-process. In this way it is possible to visualize the effects of planning decisions directly and in early phases - both for decision-makers, as well as affected citizens or other stakeholders.

In order to meet the individual requirements of architectural design questions as well as solution approaches, in addition to the direct integration into the work process, a simple, flexible creation and adaptation of the analytical methods to the particular application is a prerequisite for such a system.

## CONCEPT

Taking into account the situation just described, the proposed method / prototype provides an intuitive, collaborative design platform coupled with advanced, real time computer analyses and simulations - easy to create and adjust. Starting from the requirements in the architectural planning process and in the context of decision-support tools, two relevant requirements for decision support systems within the scope of architectural design tools for the exploration of ideas in a creative context can be identified:

- Direct embedding in the creative thinking process: The use of simulations and analyzes nowadays occurs almost exclusively in later planning phases - usually only for the verification of one or several already made decisions. This creates a linear process of "generating ideas", "detailing ideas" and final "evaluation" of these, without a direct feedback into the design process and thus without impact on the planning decision. In order to provide a direct feedback of analyzes and simulations into the thinking process, a seamless embedding of these in the design process is required, in order to bridge the existing gap between established design tools and digitally supporting tools (simulations + analyzes). In that way, an integrated decision support can be implemented directly in the planning process and the existing linear sequence can be replaced by a circular, decision-supported thinking process.
- Easily creation and customization of the tools: Each design task, design approach or concept is characterized by different requirements and premises. This means that the parameters to be checked by the analyses and simulations can not be determined absolutely universally. Rather, an individual system has to be used, which allows both: the simple creation and the easy adaptation of the necessary analysis tools. In this way, a flexible response to the most diverse requirements in the architectural design processes is made possible. One approach can be seen here in the application of a VPL (Visual Programming Language) as a simple, code-free method of implementing different user-specific analyzes and simulations.

## RELATED WORK

The concept of utilizing visual languages for programming purposes is not a new phenomenon. A few VPLs and their environments where selected, based on their already commercial use in the field of architecture or their theoretical potential. They were observed and analyzed how they solve issues during the different types of validation.

Grasshopper (1) is one such tool, which is widely utilized for parametric modelling, lighting performance analysis and other similar evaluations that architects traditionally utilize during the design stages. Grasshopper offers a very intuitive way to utilize even the most complex features that it offers. By the integration of individual plugins the functionality is easily extendable. (see Figure 1)

A similar tool is Revit's Dynamo (2). It focuses on utilizing not just geometry objects, but applying the building information modeling (BIM) on top of the shapes. With the rise in popularity of the tool it started integrating cross-platform features to work directly with Grasshopper or to directly use the same third party tools its counterpart does (Kensek 2015). (see Figure 1)

VCCL (Preidel and Bormann 2015) is a VPL used to define building codes and guidelines for construction projects. It then uses it's development environment to continuously validate the current construction project if it fulfills these requirements in real time. The language offers also the possibility to visualize intermediate results of the validation process, which enables the user to highlight the parts of the project that directly violate said rules.

The USP (Seifert and Mühlhaus 2014) focuses on building regulations as well. Its primary goals is to observer how changes to those regulation would affect potential existing buildings. This is achieved through a two mode environment, the first part consisting of a VPL that allows users to define any regulations that they want to observe and the ways they want to modify them. The second mode interprets the context of the programmed regulations and visualizes them. These rule sets can be then applied to any concrete model that the environment supports.

One issue that all of the above mentioned VPLs and their development environment share, is that they utilize only the traditional ways of receiving input from the user. All construction projects and buildings are defined digitally either through preexisting files or through the tools themselves. This is in stark contrast to the way architects work during the early design stages, where physical objects are used to represent buildings and concepts. The proposed VPL attempts to bridge this gap between the physical models and digital real-time interactive simulations.

## SYSTEM SETUP

Based on the presented requirements a two-part system architecture was conceptualised and developed as a part of a research project.

### *CDP / Design Platform*

The basis of the project is an interactive design and communication platform for early urban development phases (e.g. scale 1:500 / 1:1000) that was conceived and implemented in the past few years (Schubert 2014). The focus is on the direct coupling of physical work models with interactive simulations

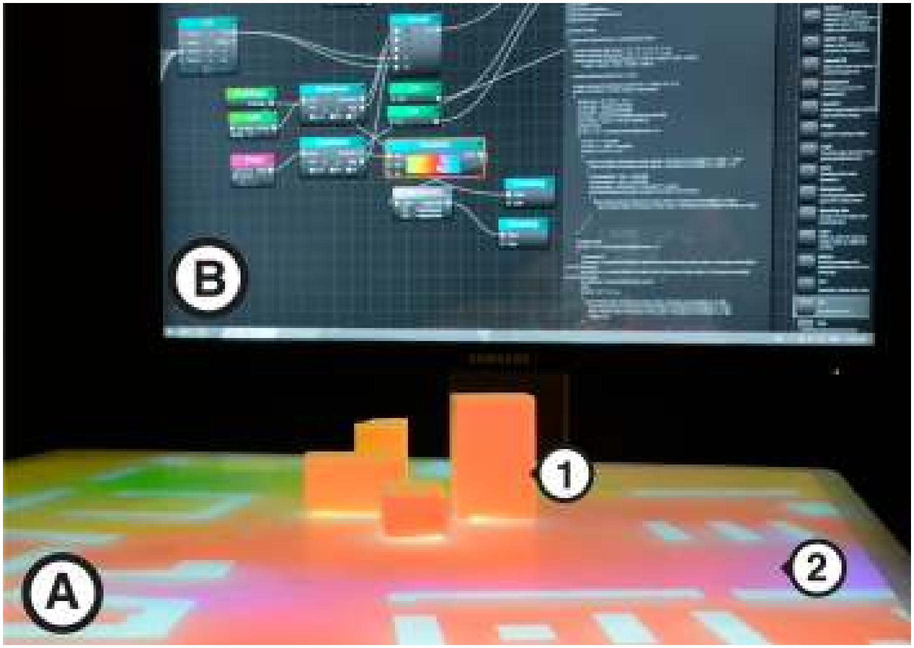


Figure 1
System setup: CDP // Collaborative Design Platform (A) - Physical models (1) on a multi touch table (2) are digitally reconstructed in 3D and realtime and serve as the simulation-base. Visual Programming Interface (B) - Easy setup and adjustment of analyses and simulations (e.g. noise) via nodes. The output of the calculations is displayed on the table-surface (2) and thus within the physical model (1).

based on a tangible interface. The physical model becomes the basis for the simulation: changes of the model (repositioning, cutting, rotating) have a direct influence on the analyses and simulations in real time. The calculation results are displayed in real-time in the physical model, adding additional layers of information to the model. Details of the physical - digital coupling and the framework of the CDP can be read in the following publications: Schubert et al. 2011b, Schubert et al. 2013, Schubert 2014.

### *VPL / Visual Programming Language*

In order to meet the changing requirements of different building tasks and, to enable the different user groups to make individual adaptations, a visual programming language (VPL) and an accompanying integrated development environment (IDE) have been conceptualised and implemented. The choice to create a new VPL is based on the traditional user-friendly interface and the minimal technical knowledge required to program with such languages (Hils 1992). To fulfill the requirement of real-time interactability with the simulations the IDE uses the VPL as an interpreted language, which trades the compilation and the associated performance gain for a fluid, uninterrupted user interaction. This also offers an easier reusability of simulations and higher productivity from the user (Ousterhout 1998). This solution serves as an add-on to the main framework (see Figure 2). The language and IDE have as a primary goal to circumvent the existing development process of simulations for the CDP (Schubert et al. 2011a), which requires not only in-depth knowledge of the implementation of the framework but also has to be recompiled every time a modification is made to the code.

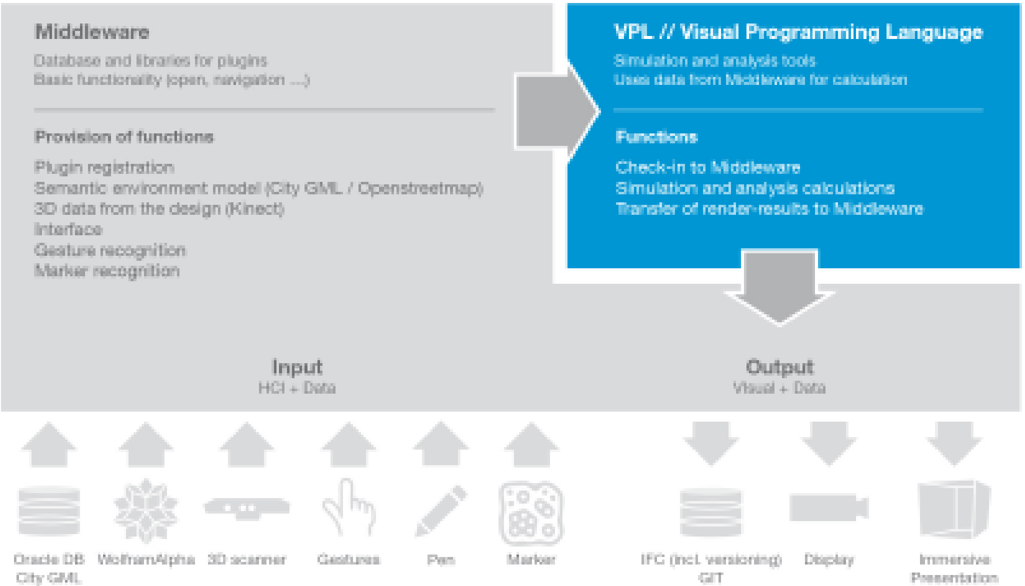


Figure 2
Software Framework: Build up on a Plugin Framework, the VPL is directly included in the main-application

To fulfil the preconditions of the creative design phases and the limitations of the framework, the following requirements were determined:

- programming operations are represented by nodes (see Figure 3), which have different inputs, outputs and control values.
- every change in the input of nodes, or the provided context of the CDP, is processed and visualised in real-time, without having to interrupt the design process.
- the interface is designed to offer architects, familiar with Grasshopper or similar applications, a recognisable layout
- the VPL and IDE are extensible, the development of further nodes or features requires minimal extra effort.

## TECHNICAL REALISATION

The IDE implements an Interface of the CDP. This offers an easier integration of the IDE as a pseudo simulation plugin for the framework. Through the interface, the IDE has direct access to all events, information and interactions on the main framework. For the visualization of the environment the Windows Presentation Foundation (WPF) is used.

Each syntax component of the VPL utilizes a main Interface that enables the easier interpretation and interaction between each other. These syntax components are then visualised by so-called Node visual elements in the IDE. Each Node contains a Grid Element in which all further syntax specification are placed. These specifications can be easily represented through traditional User Interface (UI) Elements like buttons, sliders, check boxes, etc. To exchange information between each Node we use a set of input/output connectors that exchange information. How that information is interpreted, utilized and stored is left to the implementation of each Node.

If we want a syntax component to react to a change or interaction in the framework or have access to some information, e.g. building information, then they implement one or more of the six available sub-interfaces. Each node implementing them will be called from the IDE when a specific event is sent through the Framework Pipeline.


Figure 3
Sample node layout: (I) Input connection, (O) Output connection, (L) Loop Trigger, (V) visibility. The node itself can be used for static input e.g. via Buttons, Checkboxes or Input-fields.

Although the environment mimics functionalities of similar programs, it also offers a variety of features that are unique for the needs of the project. Five of the currently 35 implemented components are described in detail. (see Figure 4)

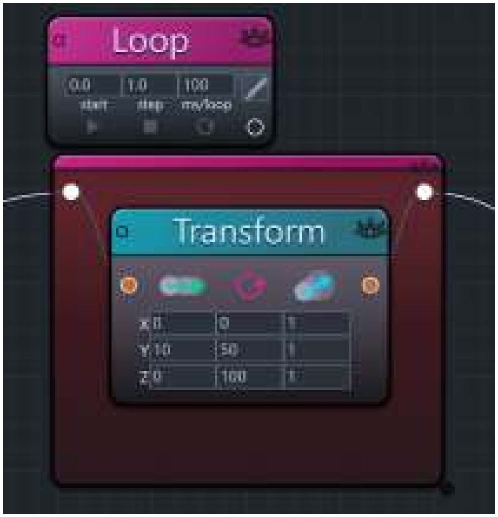


Figure 4
Loop Node: Increments a counter that has a start and step value each time cycle. Alternative executes nodes in the Loop box each time cycle.


Figure 5
Sun Node: Computes the shadows and the sun light for a given latitude and longitude position and the day of the year.

### *Loop Node*
The node starts a timer that increments a counter each loop cycle. By defining the step value, a user can define the increments with which the counter will increase. The ms/loop value specifies how often this will happen in milliseconds. The current value of the counter is then given as an output. Alternatively, it is possible to bind other nodes, that will be executed every cycle of the loop.

### *Sun Node*
This node is an example of how a whole simulation can be represented as a single node. It uses all geo-objects sent to this project from the core framework. The user can specify the geographical position of the objects and the time and date for which it should compute the shadows. (see Figure 5)

Additionally if the user wants to see how the shadows change throughout the day in real-time, they can add an input that represents how many minutes have passed since the specified point. To visualise the simulation the node provides two outputs, one for the shadows and one for light colour. (see Figure 6)

### *Rasteriser and Grid Node*
The grid node takes any geo-object and generates 2D points that are inside of the surface of the object. The spacing value defines the exact distance between two points.


Figure 6
Grid Node: Represents each object through points with defined spacing between them. Rasterizer Node: Discretizes space in X*Y Cells.

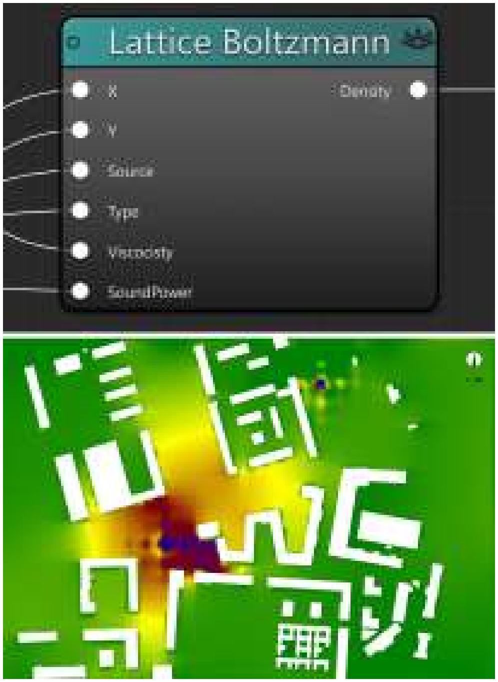


Figure 7
Lattice Boltzmann Node: Simulates one step of the LBM using a D2Q9 model with BGK for collision operation. A full simulation can be ran with extra utilization of the Loop Node.

The rasteriser node performs two sets of operations. First it discretises the screen space based on the x and y value. Then it takes the provided set of 2D points and marks each cell that contains at least one point as full. Because most types of simulation that use a discretisation of space have boundary conditions, the user can request, that all cells lying on the border of the screen domain are marked as such and override the previous check. It provides an output of two equally sized sets that contain the screen coordinates for the top left corner of each cell and what type of cell it is. The rasteriser node also provides a set of visualisation options. The grid option shows the size of each cell, while the fill function shows which cells would be marked as empty/full. (see Figure 7)

### *Lattice Boltzmann Node*

The Lattice Boltzmann Node implements the identically titled method from the computational fluid dynamics field. It uses a D2Q9 model for the discretization of the velocity and space (He and Zou 1997) and the Bhantnagar-Gross-Krook model (Bhatnagar et al. 1954) for its collision operator. It assumes that all sources of disturbance are based on increased pressure, and can be defined by the SoundPower input value. The Viscocisty input can control the type of substance that are simulated. The Source and Type inputs are bitmasks that define for each cell if it is a solid, fluid or border and independent of that if the cell is a source of disturbance to the simulation. The two bitmasks should have the same size as the product of the X and Y inputs, that define the discretization in 2D. The output is the result of one iteration of the simulation represented through the density of each cell.

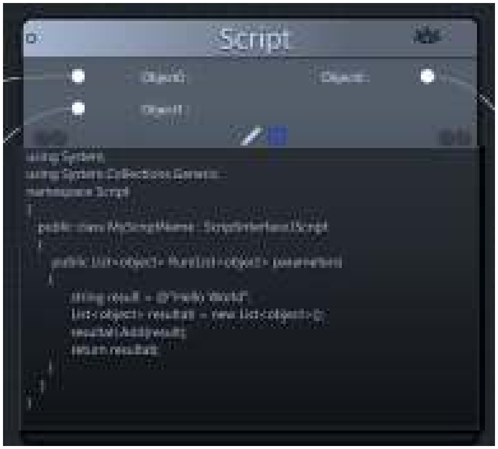


Figure 8
Script Node: Compiles and executes C# code with user defined amount of inputs and outputs

### *Script Node*

The script node provides the user with an option to create their own "mini-programs" that they can execute as part of their simulation. The node takes the input, output and source code, written in C#, and compiles a small library that it then executes with the parameters provided by the user. With this node, the user can define complex mathematical operations and simulations without having to extend the core framework or the project. Continues real-time use can be achieved by linking it with a Loop Node. (see Figure 8)

## SUMMARY

Within the framework of the project shown here, an interactive, visual programming interface was designed and implemented on top of the existing CDP // Collaborative Design Platform. The implemented prototype clearly demonstrates the potential of an iconic, visual programming interface for the creation and also for the adaptation of digital analyses and simulations. The implementation as a reactive computing software is of particular importance here and allows direct feedback from the visual programming interface. The direct coupling to a tangible interface expands the use of the CDP // Collaborative Design Platform enormously and enables laymen (such as stakeholders, authorities, etc.) to be directly involved in the planning process, taking into account objective criteria. First applications e.g. noise simulations, and shading analyses show the potentials as well as new fields of application.

## ACKNOWLEDGEMENTS

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[2] http://dynamobim.org/

# The city as an element of architecture

## *Discrete automata as an outlook beyond bureaucratic means*

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*This paper contributes to investigations in the field of aggregative architecture, discrete material assemblies, combinatorial ontologies and their possible up-scaling and implications on urban design. It argues that the digital definition of being discrete is not compatible with earlier, semantic definitions and their connotations on larger scales. Comparable to the breakthroughs in additive assembly by the use of discrete computation this paper demonstrates that the upscaling of discrete notions leads to considerations on the nesting and grouping of parts, here referred to as mereology. Via the means of an exemplary study it introduces the vocabulary of mereology and shows how complex compositions can be articulated with a collection of part-to-whole relations.*

**Keywords:** *mereology, discrete automata , aggregative architecture, part-to-whole relations, urban design*

## THE CITY AND ITS ARCHITECTURE

The notion of to be urban, or in other words of being situated in a city becomes rather interesting with the digital forms of cities designed by pure quantities: data. Strangely, today's abundant information inverses the foresight of an immaterialist city. The completed anthropomorphic scenography of our environment reverses as one looks to its main driving ingredient. Data becomes the missing link between the human and inhuman parts of the city as it makes things talk by pointing to its origin and author: the technical being. Here the role of architecture becomes crucial, as digital cities are always localized in their quantities, their parts, and their architecture.

In urban planning, one can observe an increasing tendency to describe, plan and share cities via logistic protocols and statistical means of big data. (Rossiter 2016) In the realm of digital logistics, buildings are here no longer singularly crafted enclosures, but reproducible products set within similar urban arrangements. (Easterling 2015) At the scale of the city, we face the vacillation of architectural entities purely as commodities. More and more cities are discussed with representations of occupation, ownership, and partitioning. Such representations are fundamentally different from the typical city-representations of the last century. In those former models, like the New York's zoning law, the city was established through the contour of its mode of production. The law manifested the city as a limit of buildable mass in relation to its plot. Thereby, city planning was seen as the regulation of that what has to be produced. Opposed to those former models, today cities are not discussed via methods of projective planning, but via logistic protocols and bureaucratic means on speculative beings.

## DATA ZOMBIES

First coined by Jonny Aspen as Zombie Urbanism, there is a dark side to such representations, especially in combination with big data. (Aspen 2004). In such models, a city is discussed mainly via general, mathematical factors, like interest rates. Here, the generalization of buildings to commodity plays a crucial point in their model making. These models are driven by economic abstractions turning cities into a giant, speculative warehouses of capital. Like any form of abstraction, such models have an enormous negative impact on live qualities in cities, merely through an increasing ratio between mortgage loan and average incomes. Comparable to other fields of big data applications, (Cathy O'Neil 2016) it seems as the adaptation of algorithms in urban planning and their exponential influence with the means of big-data increases inequality. Simply by one reason: The digital applications driving the data economy are based on choices made by (fallible) human beings. Many of these models encoded human bias into algorithms and therefore prejudice into software.

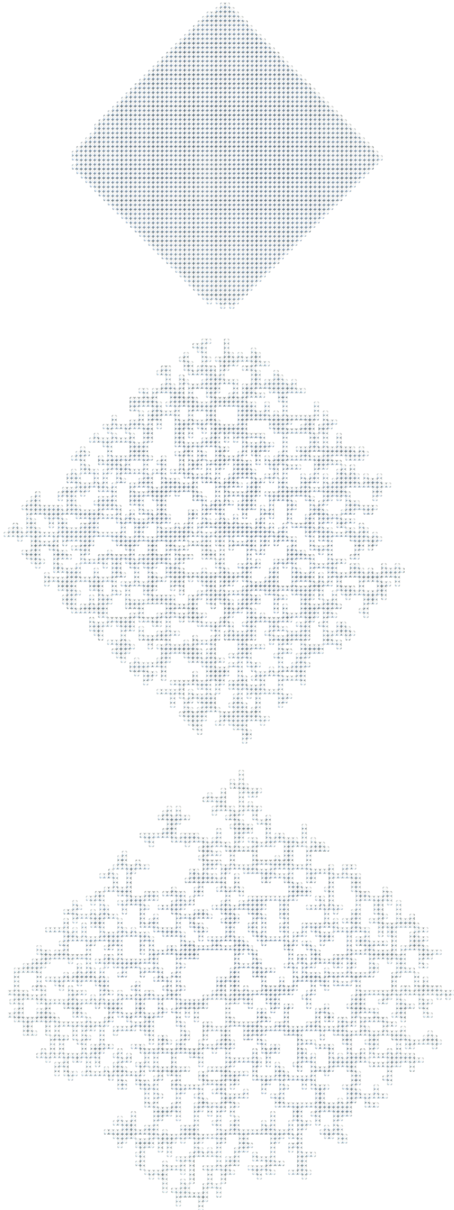
## THE DISCRETE

Such an insight on algorithms can be traced back to the work of Gilbert Simondon, who already pointed out in his analysis of technical objects that "what is inherent in the machine, is human reality, human gesture, which is fixed and crystallized in functioning structures. The modern machines are not mere automata; there are technical beings." (Simondon 1958) Such a notion of a technical being offers as well an opportunity, as it shows that every commodity is thought first as human institution before it becomes a part of an architectural object itself. At this point, we can connect to a renewed tendency towards discrete assemblies in architecture. Key is here a new notion of the discrete derived from the representation of an entity in object oriented programming. In reference to the programming paradigm - not to be confused with philosophical approaches (Leach 2016) - the term discrete leans on the concept of encapsulation, which in its consequence defines an object as an interface between an internal description and its external access. Internally, an entity is described as a pattern existing in a stable relation to its properties, abilities, and methods. On the other hand, externally an entity is defined by the kind of access to its resources and abilities through other objects. (Gamma 1995) Concluded from an external point of view, the possibility of a limited access means that descriptions of discrete objects might be incomplete. Externally seen parts of a system might be malfunctioning, yet from an internal point of view, it implies that discrete objects resist, behave, and interact. Res verse, considering the internal structure of an encapsulated object, discrete objects comprehend other forms, artifacts, and assets as its commodities.

Figure 1
The twist-lock, part of an intermodal container, one of the first physical products of digital logistics; source: https://upload.wikimedia.org/wikipedia/commons/e/e5/Containerverriegelung.JPG.

What was originally established as an efficient handling of complexity to write software, offers an attractive opportunity as this paradigm manifests itself in the physical forms of our digital culture. Architecturally, the set-up of their interfacing builds digital objects. Interfaces are formulated not by their specific content, but via a protocol, which filters, groups and nests: no matter what. (Garcia 2014) The protocol differs from the form of the shadowed volume marked by the zoning law mentioned earlier and similar descriptions of the last century. The zoning law conceptualizes an entity semantically through the marking of a territory. Here, a shape or contour

Figure 2
Arrangements of 2.500 four-sided cells each with different ratios of connectivity. From top to bottom: 4.4.4.4.4 sides, 4.4.4.3.2 sides, 4.4.3.3.2 sides.



carves out and separates shadow from air. However, to be able to separate, a general objective of cutting voids from mass has to be assumed in the first place. More computational speaking: a notionally standard scale is established to compare raw data derived originally from different scales. Using the concept of normalization, a carved territory is calculated and dependent on the set-up of the scale in the first place: it is a functional whole. (Rescher 1955) A territory, even if it separates areas from each other, is not discrete. Even the void becomes a part and is dependent on its initial conception.

In the recent past, computational performance amplified such functional dependencies simply by down-shrinking of parts to particles. Increased resolution led to more fine-grained determinisms, like in the case of a zoning law: the grain deflated from the building mass about the plot area, to the window panel allied with the sun-insolated floor area. Here a big-data approach adjusted the raw data of the façade-panels to the scale of the building envelope. Though, the new resolution has an uncanny side-effect: attributes of the window panel influence directly the program and thereby controls the interiority of the building itself. However, the calculus of the normalization is based on a measure relating to urban considerations between buildings and their contours only. The down-shrinking of semantic calculi creates a fallible transparency from building to building parts. Normalization simplifies complex relationships of the built environment to ratios, and in the most extreme case to an abstract ration like interest-rate alone. Here the digital version of the discrete offers an alluring alternative, as it is by default non-semantical and described as the pure act of partial sampling and nesting. Therefore, the discrete is inseparable from its compositional aspects, regarding its assembly or aggregative consistency.

## MEREOLOGIES

Not defined by reference to content or form, the new discrete expresses the resonance of its parts.

Built on partial access, discrete objects are always in one or another way parts. In conclusion, architectural form turns into an aggregational stasis of intervals between part-to-wholes, part-to-parts, and whole-to-wholes. Strangely, part-to-whole relations were neither explicit articulated as a framework, but they were always part of architectural descriptions. Already Leon Battista Alberti rendered in his treatise architecture as a circular, compositional tension between the city-as-a-house and the house-as-a-city. (Alberti 1451) Comparable to the useful terminology of topology or morphology, considerations on parts can be discussed with the term mereology. Formulated in mathematics and formal logics, (Varzi 2015), mereology should be seen here as a collection of strategies dealing with part-to-whole relations in architecture. As a theory of part relations, mereology takes compositions as its ontological primitives. Opposed to set-theory, mereology does not start with null sets, axioms, or any predefined structures. Mereology presupposes the individual, the automaton. It begins with the description of overlaps between discrete entities, considered as parts. In this lies the disciplinary contribution as terminology in architecture, as it can describe architectural form purely as its composition.

Subsequently, in this view, the smallest bits of architecture are poietic objects: human-made compositions, and indeed, made for specific purposes. But here opposed to semantics, purpose, and more technically the functional dependency is an internal aspect of the design of the entity itself. As an illustration, one can review the perhaps first physical product of digital logistics: the intermodal container. The development of the standardized shipping container went hand in hand with the digitalization of trade and the algorithmic optimization of traffic routes, beginning in the late 1960ties onwards. To calculate the flow of goods, a smallest bit had to be established, which supports at any location the similar method of stacking and handling. For this reason, freight containers share a number of key features, globally specified in the standard ISO/TC 104. Worth noting is that the stackability is not determined by an expected rule set, but by the detailed description of two specific design aspects: the corner casting and twist lock. (Figure 1) Finally, the design of the twist-lock allows the global coordination, stacking, and alignment of shipping containers. Digital protocols mold here a distinct part, which did not exist in the first place. In short: Form manifests data.

Digital disposition differs radically from dispositional diagrams of the last century. Such forms of organization, most famously the Domino-House imposed a datum, beginning with a Cartesian space to disposition columns, slab and subsequent building parts to an architectural object. Contrary, digital logistics rely on discrete entities, like the twist-lock, where the form of assembly is an intentional part of the part considered as the whole in the first place. In digital logistics, one can assume that the whole is subordinated to the part. Concluding at large scale: the city becomes an element of its architecture.

Figure 3
A mereological sampling of parts, here a catalog of courtyards extracted from existing buildings.

First computational precedents can be found in the model of space-syntax and its investigations on the relation between local morphological relations and global patterns. (Hillier, Hanson.1984) Whereas, in contrast to space syntax, this research intentionally does not link spatial patterning to social information and content. Figure 2 shows a comparable study to Hillier and Hanson's interest local linkages and their large scale figurations.

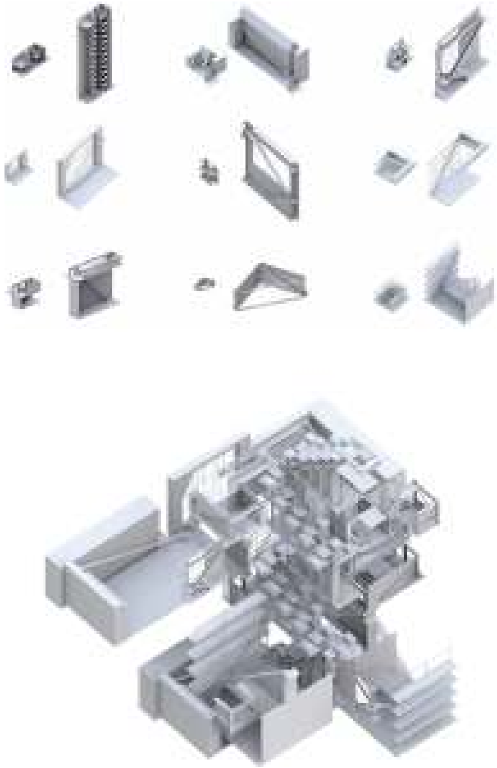


Figure 4
Left: asymmetrical part assemblies, right: generated massing with procedural bindings.

The mereological relationship evolved by digital logistics turns previous architectural considerations on parts upside down, especially structuralism. In structuralism, compositional defined by Roland Barthes, parts "have no significant existence except by their frontiers: those which separate them from other actual units. (...) what characterizes the paradigmatic object is that it is, vis-a-vis other objects of its class, in a certain relation of affinity and of dissimilarity." (Barthes 1972) In the architectural version of structuralism, the vis-à-vis of cells formulated a third object: the support structure. (Habraken 1972) Designed as vertical streets and courtyards subordinated the apartments as parts to the collected arrangement.

## THE RESONANCE OF PARTS

Both forms, digital logistics, and structuralism have in common that they design with the dependencies of group relationships. The one internally, the other externally. Both open the possibility to design with the access to parts, their comprehension, their incompleteness, in short: the resonance of parts.

Above all, in the field of material systems, a renewed interest in aggregational part-to-whole compositions can be observed. For example, research into Jamming-Based-Architectures (Zhao 2016) demonstrates that aggregated material systems can achieve stiffness and structural dimensions comparable to solid materials through the design of geometrical properties of a part even without structural considerations concerning the whole. In the field of architecture as precedents can be named the Self-Assembly-Lab at the MIT exploring information-rich materials containing assembly logic, (Tibbits 2012) and the combinatorial design studies by Jose Sanchez. (Sanchez 2016)

Complementary, to those ongoing investigations, this research deals with mereological model building. Specifically, this research explores possibilities of up-scaling and implications on urban design. Technically, a large proportion of the studies was carried out in simulation environments, using Processing and the game engine Unity. The modular architecture of these frameworks allowed the crossing of several software packages combining CAD-geometry, physics-simulation, graph analysis, classification, and clustering algorithms. Most of the following design studies were elaborated in a research-led teaching environment at the Bartlett School of Architecture, UCL London. The illustrations show an excerpt from the work of the Research Cluster 8, which is part of the post-professional architectural design program BPro-AD. The software framework developed by the author provided here a platform for the individual design studies. For a clearer understanding, studies from only one design project: “Wa/onderYards” by Chen Chen, Li Genmao, and Zixuan Wang are exemplary shown (see Figures 3, 4, 5, 6 and 7).

## SAMPLING PARTS

Framing the research to urban design, the smallest parts operate at the intersection between urban and architectural scale. One aspect of the research deals with the sampling of architectural parts from existing buildings. How can an architectural object be described as a composition of protocols, interfacing urban and architecture? Corresponding to the “composition over inheritance principle” in object-oriented programming, (Norvig 1998) architectural parts are here sampled in such a way that they express semantically polymorphic behavior. Borrowed from OOP, polymorphism allows the digital description of an architectural sample to assume different performances depending on its part-condition. Take for example the catalog of parts in Figure 3. The samples are mutually considered as courtyards and as compositions of i.e. stairs, windows, and floors. In the following, the polymorphic set-up supports the combination of several part-conditions in one arrangement.

Mereological sampling does not constrain a part to its relative proportions. As a bundle of partial, discrete statements, like the perpendicularity between a wall and a floor, mereological descriptions do not bind all dimensions equally. By default, such declarations are absolute and therefore asymmetrical. At first glance, absolute links seem to have a limiting effect due to their rigidity. But the resultant, partial directionality allows for greater flexibility in larger arrangements. Figure 4 shows a collection of samples rendered at the thresholds of certain part-conditions. For this, a custom software package was developed together with Christoph Zimmel enabling procedural bindings similar to BIM descriptions in a rigid-body-simulation-environment.

## ARRANGING PARTS

In a further step, common attributes of buildings, like access, privacy, and floor connectivity were formally described as a mereological condition between two samples. These formal descriptions were tested and visualized via the implementation into a digital simulation environment. The goal was to visualize the design implication of specific part conditions. Therefore, the arrangements should be seen purely as “mereologies,” not as buildings but as arrangements and the multiplicity of one part-condition.

For assembling, this experiments explicitly do not lean on voxel-space-models. Voxel space as a discrete simulation model is highly efficient with little computational power. Especially in additive assembly voxels are highly practically organizing material with binary decisions, like glue or no glue. However, the excessive research of the last century into grids showed that spatial continuity at larger scales is mostly contextual disrupted starting with asymmetric thermal expansion coefficients of material composites to issues of ownership, territory, etc. Therefore, it would be misleading to assume a Cartesian space at the intersection of architectural and urban scale. The example of the twist-lock shows that

Figure 5
Accumulations of similar parts have congruent characteristics. Left: figure-figuration comparisons; right: linear-branching type leads to courtyard condition in large-scale arrangements.

at larger scales spatial continuity is dependent on specific interfaces. Properties, like stackability, are achieved by the particular design of parts. Here, discreteness as a compressed form of information ensures shareability. Not to be confused with aggregative packs such models establish order by sharing specific, not random data. Therefore, for first research sequences methods of assembly with point-to-point connections were chosen.

For the conduction of these experiments a software library was developed in CSharp, compatible with Unity's API. The library allows the integration of physic simulation, protocols of assembly, custom data structures for storing and sharing data on part relations. To begin with the translation of formal discreteness into a digital design context, all studies build on rigid bodies simulation, which ensures a basic, geometrical boundary of each element. Rigid-body simulations have several advantages. First, the use of collision detection can extend a typical modeling environment. The resistance between geometrical shapes encourages physical awareness, which allows a more intuitive modeling similar to traditional design practices with physical models. Second, simulating physical geometry reduces conceptual dependencies. Comparable to the twist-lock, strategies of disposition, the arrangement and consequently the overall form are dependent on specific design aspects of one entity.

Modes of assembly build on the following procedure: a part is accessible through the provision of a list of vectors, indicating connection points. These vectors are extensible to store additional information, such as facing directions, type of preferred connection, or state of a connection. Such information is then used to move and orient one part to another part. In a trial and error placement, the cases of geometric overlap are checked. By overlap, a further place-and-check sequence will be carried out. With this procedures, dense packs can be achieved, simply by beginning the placing at the first element and continuing the place-and-check sequence with spatial close and available connection points. A spatial nearest neighbor search is not necessary as the placement can jump from the points belonging to one part to the points of connected parts. Collision checks using a standard physics-engine, are today performative reasonable. The author tested here two libraries, the open source Bullet library, and the commercial Nvidia-PhysicsX engine. With both libraries the author reached up to 2.000 sequential collision calls with a pile of 2.500 objects per second on a standard laptop, using box colliders. Decomposition and combination strategies can be used to describe more complex shapes. Performative studies showed here that explicitly designed compound collision shapes are mostly much more efficient than generated mesh shapes using fracture algorithms or concave collision shapes.

Interestingly, figurations resulting from the assembly of the same type and number of parts are congruent in their characteristics. The form and sequence of distribution have less influence on the consistency of the overall arrangement than the design of the figure itself. The design of the figure can be considered on multiple levels dependent on the compositional depth of nested objects.

## MEREOLOGICAL PARTHOODS

A compositional classification of samples into parts and wholes is digitally defined through the form of access. A digital part offers access to its internal composition. A digital whole is disclosed from any access to internal modes of compositions. However, since each sample is also a part of an arrangement, a whole strictly seen cannot exist. Therefore, a classification of a whole refers practically to a certain threshold of "wholeness." The classification into parts and wholes describes foremost a directionality of access. The kind of access can be quantitatively measured trough the mereological density of a part. Mereological density refers to the depth and access to nested objects. A high mereological density describes a low compression of information resulting in the accessibility to nested objects in the depth of its density. A low mereological density represents a high compres-

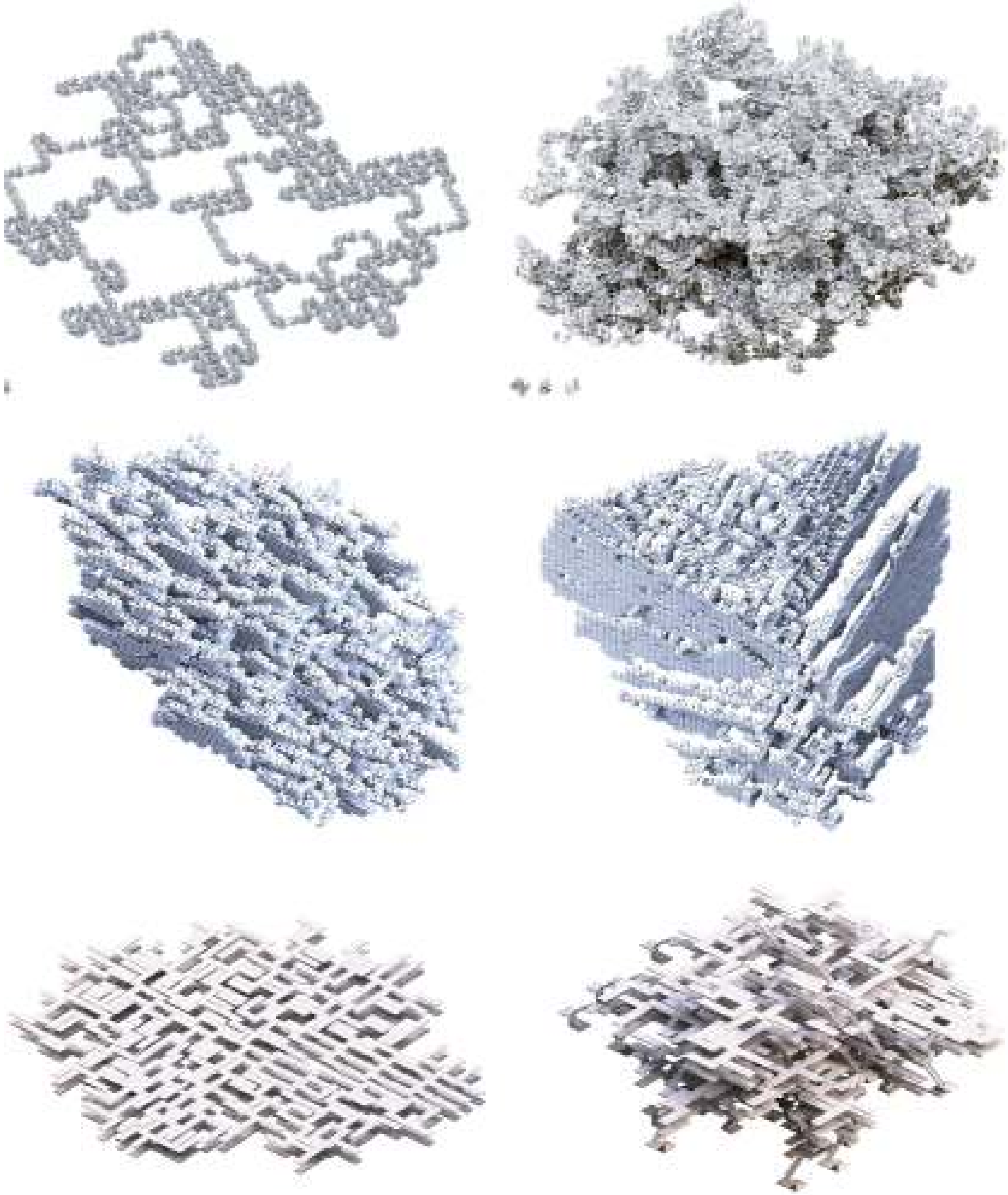
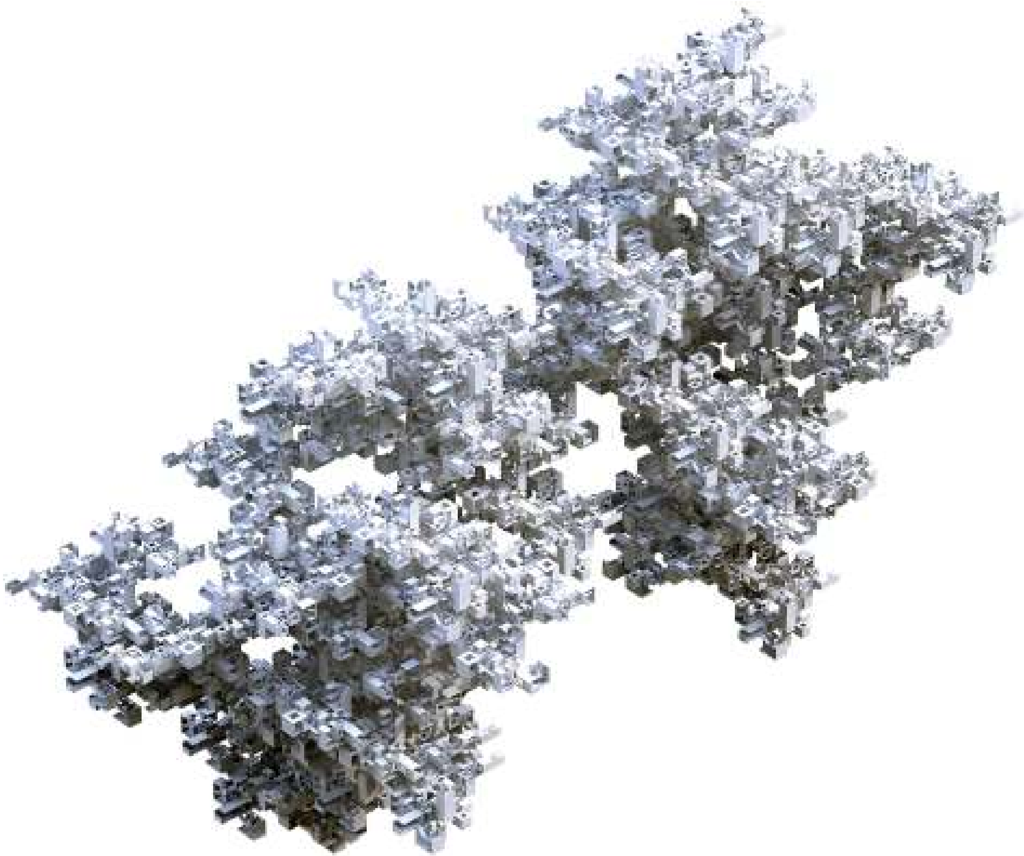


Figure 6
Figure 6: Top: Whole-to-whole relation. Aggregational figuration based on the outlines and mixture of different wholes only, left: arrangement of 2.500 samples with one type; right: arrangement from three different types of samples. Middle: Whole-to-part relation, relating sun-insolation to part-orientation; rendered with floor plates only. Left: sun position Berlin, March 21st, 10.00 am, right: Berlin, March 21st, 3 pm. Bottom: Part-to-Part relation; left: horizontal arrangement on one sample connecting two-floor plates; right: multi-level arrangement with three different samples, and a dominant ratio of sample one, rendered as floor plate connectivity.

Figure 7
Generated massing: mereological parthood condition: courtyard as a stair.



sion of information meaning flat access. Here, in the shown examples, a density of zero refers to the design of the part itself, a density of one refers to the position and orientation of their connection points.

With the means of mereological density, one can articulate decisive forms of compositions based on the depth of part relationships and their directionality. Aggregational settlements are coming closest to a whole-to-whole condition, developed by highly limited decisions between local entities. Figure 6, top renderings give a visual example. Here specific figurations were developed using the outlines and mixture of different wholes only. Whole-to-part conditions relate to urban fields, where elements are defined by a ground like the zoning law discussed constraints the height of a building in relation to a plot. The compositions in the middle of Figure 6 show arrangements, which relate sun-insolation to part-orientation. The samples were arranged using ray-casting, according to specific sun orientations. Since directionality matters, contrary, a part-to-whole condition describes how the consideration of a part that forms a whole. The vertical street of the structuralist movement is here a good example, where the apartment is subordinated to the collected arrangement. Part-to-part conditions refer to parts in different wholes which influence each other and their dependencies. In the two compositions at the bottom of Figure 6 polymorphic considerations of one sample partially as floor or stair alters the patterning of the arrangement. By shifting the access to parts as stairs increases the vertical orientation of the figuration. Such a list can be extended extensively by considering the depth of parts and would be unfortunately beyond the scope of this paper.

Mereological design begins with the sampling of parts, the translation, and the extension of part conditions. In a careful mixing of several mereological terms accurate and diverse arrangements can be achieved. Naturally, any building consists of an uncountable number of part-conditions. It is not the aim of this research to represent the complexity of a building just through part-descriptions. Rather it offers a strategic possibility to navigate as a designer with and beyond bureaucratic means.

The research presented here can be seen as a transdisciplinary study introducing mereological aspects into urban design. Therefore, the research shows and measures itself on compositional qualities and their potential at an urban scale only. It shows how complex compositions can be articulated by a collection of part-to-whole relations. However, this also limits the current state of the work. To assess the value of this research, it is necessary for a further step to apply these considerations in an existing environment.

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# Visualizing and Analising Urban Leisure Runs by Using Sports Tracking Data

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*Recently there has been a significant growth on the usage of personal fitness applications running on smart phones or fitness devices. These applications record millions of GPS points generated from the paths of runners. This data can be analyzed to comprehend behavior of runners within a specific location. In this study, using data generated from several sources such as Endomondo and Strava and other complementary data such as climate data, population data etc., we aim to find out the factors affecting running behavior in urban settings. For this purpose, visualizations of running activities are plotted with different variables by using BIG-DID, a software tool we developed as part of this study. Additionally, an evaluation of the tools used or can be used for data analysis and visualizations discussed. Finally, a linear regression model is introduced, which will be further developed in later stages of this study.*

**Keywords:** *Big Data, Urban Visualization, Fitness Applications, Leisure Runs*

## INTRODUCTION

Urban planners benefit from understanding how public spaces are utilized for certain activities, in order to create more lively public spaces. However, relating the activities undertaken in spaces to certain design actions or intent can be a complex task with dozens, if not hundreds, of different factors affecting behavior of people utilizing these spaces. For a better understanding of this behavior urban planners need data of factors affecting it. Until now data required for this task was coming from traditional sources such as questionnaires or interviews (Reades et al. 2007). Planning to promote healthy active city residents is becoming a priority for most of the cities. As the most available sports activity to public is running/walking, it is becoming crucial that we make our cities more running friendly. Various measures are taken by different organizations to motivate people for running, for example, Singapore HealthHub is organizing national steps challenge where users obtain points as they walk/run more (Healthhub 2017). In addition, the current boom in personal fitness applications that track users' movement with GPS and record them provides a way for users to track their achievements. This data, originally intended for personal use, can be collected massively, and used to help urban planners understand how streets are used for leisure runs. Although there are certain concerns such as the data having selective bias, its huge availability outweighs this disadvantage.

In this study, personal fitness application data is used along with other data such as climate, street topology, sociodemographic attributes, etc., to create visualizations and statistical analysis to be used for understanding factors affecting running behavior in urban settings. Additionally, an evaluation of the tools used or can be used for data analysis and visualizations discussed. Finally, a linear regression model is introduced, which will be further developed in later stages of this study.

## LITERATURE REVIEW

Running/walking is the focus of this study and there are various reasons for this. First, running as an exercise is easy to start, it does not require a special technique, equipment or field. Also, unlike team sports, it can be done solo, which makes it easier to incorporate in a busy life schedule of a modern urban dweller. There is plenty of research about running being helpful in maintaining a healthy life (Hardman et al. 2009). This fact is generally accepted by governmental agencies and municipalities, but even though these want to increase running activity, it is not easy to achieve this as most of the activity is performed in random locations and the spatial needs of running are not fully known (Scheerder and Breedveld 2015).

The effect of perceived built environment on physical activity has been widely studied mainly by using various data sources such as surveys, interviews, governmental data, and more recently by using crowd-sourced data. In a review study, Harris et al. (2013) collected 318 articles in the field (PABE Physical Activity and Built Environment), out of this 191 were about the relationship of built environment and physical activity, 79 were reviews on the past work in the field, 38 were about methodology, 6 were about interventions to increase physical activity and 4 were about other issues. The low number of papers that are about interventions show that there is still not enough knowledge for the urban planners to plan to increase physical activities happening in the urban space. In one such study, Troped et al. (2011) has demonstrated levels of sprawl in US and women's involvement in physical activity by using a questionnaire. In the same study, they found out access to recreational facilities increases physical activity levels. On the other hand, there was not any statistically significant change with perceived crime and sidewalk presence. Although there is significant amount of research done in the field, there is still not clear how to interpret the findings of these research.

Using personal fitness applications for visualizations and analysis is not new. Almost every personal fitness company that publishes visualizations of certain cities derived from their applications, but these are not meant to be used for analysis as they are not controllable with certain parameters, thus not very useful for urban planners (Strava 2017) Better examples come from transportation planning studies for bicycles. Oksanen et al. (2015) used personal fitness application data for bicyclers for plotting various heatmaps showing the number of cyclers at certain times. Hochmair et al. (2017) used similar data from Strava for estimating the bicycle kilometers travelled per block by using various parameters.

## SETUP

Understanding when and where runners are running is crucial to learn about the spatial requirements of running activity. This study takes place in Singapore, and the aim is to understand the behavior of runners in Singapore. Running data is obtained from fitness applications Endomondo and Strava. The technique to retrieve this data by web scraping methods are discussed in a previous study (Balaban and Tunçer 2016). For this study five hundred thousand users and their workouts are scraped from web. From 500000 users, there are 2436 users registered from Singapore and these have completed 44056 workouts of which 38073 are marked as runs by the users.

In addition to the running data, other supplementary data are used in the analysis part, these are: climate data taken from an online weather site that publishes archive of weather data, street topology data retrieved from OpenStreetMaps, census data such as population count, traffic data, and crime data. Every run is divided into certain time intervals (around 5 seconds) and for every time interval a GPS point is created. From the coordinates of the points, the location of the run is obtained such as the street, district or post code of a nearby location. These are stored in an online MySQL database to be used in the later stage of visualizations and analysis.

After the database is set with the required data, initial step was to decide on the software to make analysis and visualizations to understand spatial requirements of runners. GIS (Geographical Information System) software was a logical choice and QGIS and ARCGIS are tried. ArcGIS comes with an initial challenge as it does not have MySQL connection capability, therefore the data is converted to csv files and imported to ArcGIS, however, this step is time consuming as the data is more than 10M entries and it should be divided into chunks. Both ArcGIS and QGIS have extensive capabilities of displaying geographical data and they provide Python programming options. The second step is statistical analysis, and R and Tableau have been deployed as software options. R is an open source statistical software and it is widely used by the research community whereas Tableau is proprietary software and it is more popular in business analytics. They both provide many options for data analysis, and as their purpose is data analytics, it is easy to connect to different data sources. After experimentation with GIS software and statistical software, the decision was to have a tool that combines both capabilities in one interface which is called BIG-DID see table 1. The reasons for this decision were because he aim is to create a tool for urban designers/planners who will not necessarily have the skills to use either GIS or statistical software. Also, in this way, use of expensive software such as ArcGIS and Tableau is avoided.

BIG-DID runs on a PHP server and it is built by using Laravel framework. It is connected to the MySQL database that holds all the data. When the client starts the system and selects the required parameters, the result of the query is passed to the client. At this stage, certain JavaScript tools are used for creating visualizations, D3 for statistical graphs and Leaflet for map based visualizations. Similarly, overall static heatmaps showing runs per kilometer per street are created. This visualization has the same filtering capability so that planners can select certain time frames, climate conditions, etc. Heatmap capability is introduced with the help of Leaflet plugin Leaflet/heatmap.

Table 1
Software used in this research

| Tools | Type | Advantages | Disadvantages |
|---|---|---|---|
| ArcGIS | GIS | Easy to create<br>Easy to create geographic visualizations<br>Web based capability | No MySQL support<br>Hard to include functionality<br>Expensive |
| QGIS | GIS | MySQL support<br>Fast<br>Easy to create geographic visualizations<br>Comes up with tools<br>No web based capability | Hard to include functionality<br>Certain things are buggy/hard to work |
| BIG-DID | Software | Allows to develop web based interface is shaped by the programmer<br>Web based | Hard to setup initially, needs programming skills to setup |
| Tableau | Statistical | Easy to create statistical graphs<br>No web based capability | Very slow working with database (10M data points) |
| R | Statistical | Easy to create statistical graphs<br>Web based capability (R Shiny) | Requires programming<br>Can be hard to setup (R Shiny) |

Figure 1
Weekday - weekend run statistics

## OBSERVATIONS

For urban planners, it is crucial to know when and where do people run, to better understand the spatial requirements of running.  Running behavior changes with various conditions; working individuals tend to run either after work hours or during weekends. However, for every city this situation can change, in some parts of the world it might be unsafe when it is dark or it might be too cold in the winter. Therefore, spatial requirements of running also change from city to city. This research focuses on Singapore.

Singapore is a country/city with a tropical climate with a warm temperature throughout the year. There are two periods of rains which occur from mid-November to early March and June to September. During these months, there are heavy rains occurring daily. Also, it is one of the safest cities in the world. Therefore, we expect more runs happening after the sun sets and during weekends.

First analysis is about weekday and weekend runs see figures 1, 2 and 3. As expected, it is observed that on weekends the average running time and distance increases along with the times of runs that are performed. Also, throughout the weekdays after Monday, the number of runs decline until Saturday. Observations of figure 2 and figure 3 reveal the locations of runs that happen weekdays and weekends, respectively. Although these look similar, there are still some differences to observe. In both periods, parks such as East Coast Park (ECP), Bedok Reservoir, etc., are used extensively along with the streets near public housing estates. However, during weekdays, there are more differences in running locations then in weekends, and as the average running time and distance are longer, it is thought that more people go to parks to do longer runs during weekends.

Second analysis is about the time of the day when people run. As Singapore is a tropical city that is warm throughout the year, it is not surprising to see in Figure 4 that people avoid times with strong sunlight, and the most preferred time of the day for runs are before and just after sunset and during sunrise. A significant number of runs performed in Singapore are done without sunlight, hence lighting streets becomes crucial for safety of runners. Figure 5 shows that the situation does not change within the year. Figures 6 and 7 show the runs that are performed during day time and night time. The difference can be observed around public housing estates. There are more sprawling runs whereas night runs are generally concentrated in certain areas, which can be ex-

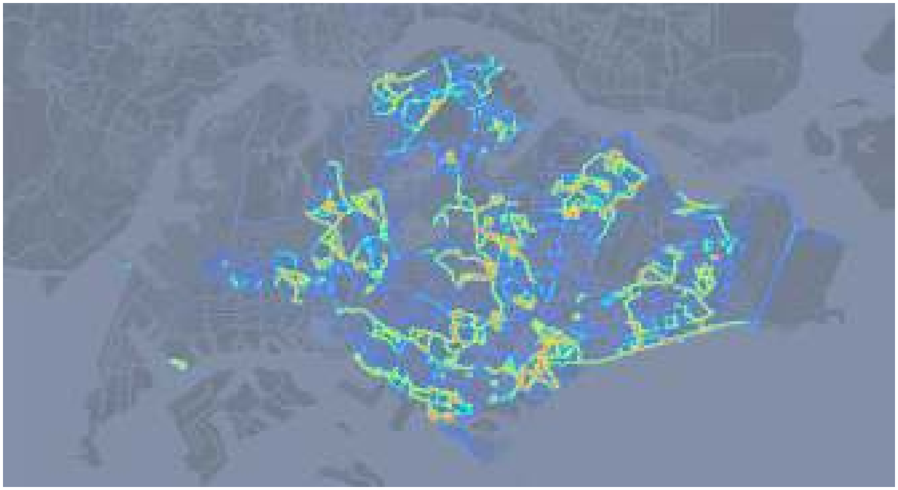
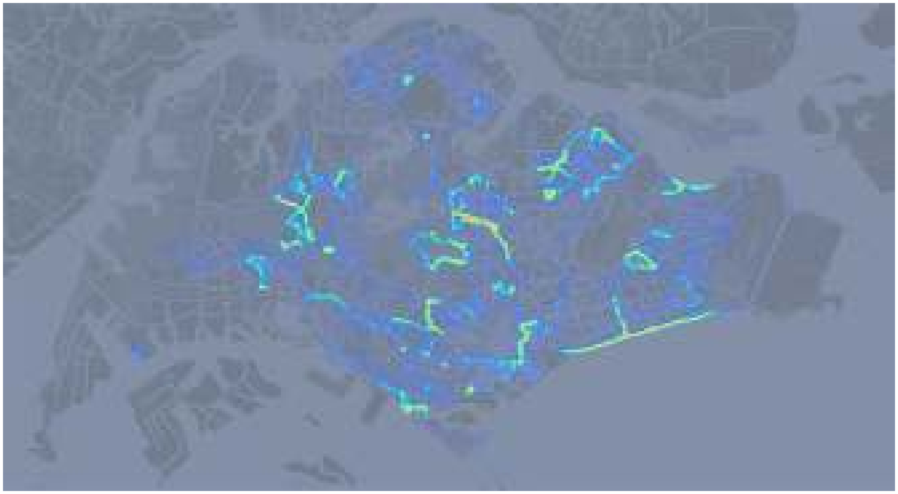


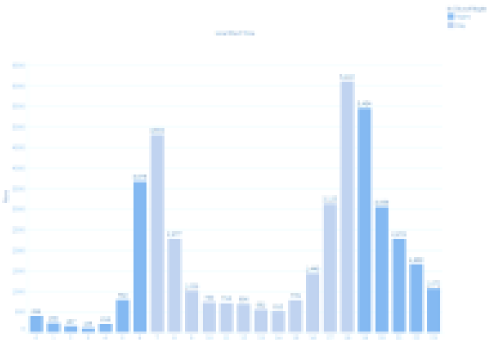
Figure 2
Weekday runs

Figure 3
Weekend runs



plained as people running in the daylight can change their routes whereas people running at night prefer routine.

Figure 4
Time when runs are performed



Singapore, having a tropical climate, has a steady number of runners throughout the year, but this can change in extreme weather conditions. In certain years, forest fires in neighboring Indonesia brings particles to Singapore which is called haze. During those periods, it is difficult to breathe and the government advises people to stay indoors. One example of this occurred in September-October 2015 with maximum PSI level reaching 302 (very unhealthy). During that period, runners avoided days with high particle levels but they run in the days just after haze dissipates. Similarly, during rainy season at certain days Singapore receives more than 100mm of rain. During those periods running patterns change, runners avoid paths that can be slippery or that puddles can form on.

For enabling urban planners to see patterns of running behavior at some parts of city, a dynamic visualization interface is created that shows users running within the selected part of the city on top of a map in a dynamic timeframe. Users can select the time frame: certain parts of the day, day or night, weekdays and weekends, etc. Users can also select certain demographics such as male, female, or certain age groups, junior, adult, senior, etc. With this capability, planners can see good performing streets which are running friendly and compare these with less running friendly streets.

Last visualization is for street catchment. This shows a catchment visualization for any street in the city that is listed. For this purpose, every point of all runs that use a certain street is drawn on a map, points that have more runs are colored differently denoting the intensity. The aim of this visualization is to show a street's ability to attract runners, and from what distance. Also, it shows the connectivity of that location with the rest of the surrounding. In Figure 8, we can observe Bedok Reservoir, which is a lake/park around a residential area, and is used for running frequently. In this plot, the entry points of runners, and where they start and end their runs can be observed.

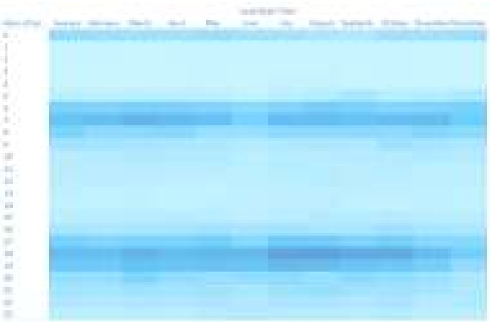


Figure 5
Time when runs are performed throughout a year

These visualizations are great for giving an overview of a street's situation in accommodating runs. While an expert planner might be able to guess why a certain street is not running friendly, these tools do not provide reasons for why they are less running friendly. To be able to understand the reasons, statistical analysis of the streets is described in the next section.

## ANALYTICS

Visual presentation of data regarding a phenomenon to planners/designers is a powerful way of displaying how that phenomenon happens. However, although visualizations are good for showing what is happening overall, it is difficult to isolate a parameter's influence on the overall behavior. For this purpose, planners need to include analytics of the data to determine a parameter's effect on the behavior.

For runs happening in the urban environment, there are four categories of variables, these are: street networks(N), location(L), sociodemographic(S), and climatic (C) variables. The representation can be given as:

$$R = f(N, L, S, C) \tag{1}$$

In this equation, R is runs in a street, N is network characteristic of a street (such as typology), L is location characteristics (such as pedestrian walk width), S is sociodemographic characteristics (such as crime rate), C is climate characteristics (such as raining or not).

Network variables include topology, hierarchy, morphology and scale (Hochmair 2017). Topology is the connectivity of the streets to each other, hierarchy is measure of importance of a street such as a main road, morphology shows the "shape and fragmentation", and scale is the supply.

Location variables include location specific variables such as pedestrian walk width, presence of a covered walkway, presence of a main road, etc.

Climatic variables affect users' participation in leisure runs. Seasons create peak months for running which are generally summer months in European countries, whereas tropical countries are bounded by rainy seasons such as monsoon. Therefore, the variables affecting the regression model are: temperature, uv, wind speed, rain fall and air pollution.

Social variables include crime rate, gender, age, etc.

With this model at hand, we tried several variables such as weekdays, weather and time. As discussed in the previous section, weekdays affect the count of runs. It was possible to derive a linear regression model for the days of the week with a certainty of around 80 percent. Also, haze and rain have certain effects on the number of runs happening. These variables are added to the linear regression model. However, the model discussed here needs more data and development, and will be described in the later stages of the research. The final model will be important for an urban planner for creating guidelines for running friendly streets.

## CONCLUSION

This study uses personal fitness data for creating a toolbox for an urban planner in making streets more running friendly. For this purpose, several visualization and analysis tools are created. This toolbox will

Figure 6
Runs with daylight
7am-7pm

Figure 7
Runs in the dark
7pm-7am

Figure 8
Catchment area of Bedok Reservoir, a popular running site

help urban planners in making analysis of streets for leisure runs more easy. Although personal fitness data carries a selective bias, it should be noted that it is getting more and more popular, so the bias is getting less erroneous. Also, the number of valid observations these tools give to the urban designer makes it very useful. Therefore, a careful usage of these tools will be very valuable in urban planning process.

## ACKNOWLEDGEMENTS

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[1] http://metro.strava.com/

[2] https://www.healthhub.sg/programmes/37/nsc

# COLLABORATIVE AND PARTICIPATIVE DESIGN

# On-site participation linking idea sketches and information technologies

## *User-driven Customised Environments*

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*The paper introduces the methodology related to the topic of citizen-driven urban design and revises the idea of on-site participation of end-users, which could prospectively lead to customisation of architectural and urban space in a full-scale. The research in the first phase addresses the engagement of information technologies used for idea sketching in participatory design workshop related to local urban issues in the city of Chur in Switzerland by means of the Skity tool, the sketching on-line platform running on all devices. Skity allows user, which can be individual citizens or a community, to sketch, build, and adapt their ideas for the improvement of an urban locality. The participant is the expert of the locality because he or she lives in this place every day. The content of this paper is focused on the participatory design research project conducted as a study at the ETH Zürich and the Hochschule für Technik und Wirtschaft HTW in Chur in collaboration with Future Cities Laboratory in Singapore, mainly concentrated on the first step of the methodological approach introduced here.*

**Keywords:** *responsive cities, urban mass-customisation, idea sketching, ideation, on-site participation, citizen design science*

## SCOPE OF THE PAPER

The research project introduced in this paper consists of the three phases i) idea sketching, ideation [1] as a supportive method for urban planning processes to deliver citizens' visuals and ideas to inform experts and stakeholders, ii) prototype development of a preferred solution using fabrication technologies and techniques, and iii) a direct participation of citizens in a building process on-site and in a full scale. The paper content is mainly dedicated to the first phase of the participatory design research project related to engaging and activating citizens in the design and governance of their city with new-developed online sketching platform **Skity** *(Sketching the City)* [3][4][5], explained in the *Skity-the Sketching Tool* section. By means of the sketching activity, the citizen as the user produces ideas, simple sketches and drafts, for example as the proposal for a drone port in Africa by Foster and Partners (Deffner et al. 2016).

The paper outlines the methodological approach how it is possible to activate citizens for the discussion and to make them to be aware of their environments they live in. The methodology of the first research phase has been tested in a case study related to the selected problematic urban area of the city of Chur in Switzerland engaging local young people, the students of the Department of Architecture at the HTW Chur. The main focus of the study was to find a way how to improve the livability in a city considering the knowledge and proposals taken directly from local citizens by means of current information technologies and in that way to inform other citizens, experts and stakeholders via publicly accessible platform.

## INTRODUCTION, HYPOTHESIS AND RESEARCH QUESTIONS

The paper revises the idea of on-site participation of end-users, which could prospectively lead to customisation of architectural and urban space in a full-scale. The idea is based on bottom-up requirements and tailored preferences of people in rapidly changing societies, climate and broader cultural conditions. The strategy refers to the social and environmental needs and the ability of the cities to adapt according to users' necessities. On the other hand, it presents an usage of a ICT as an advantage which allows collaboration and participation off-site and in asynchronous way. More people can benefit and participate whenever and wherever, and that also allows for people to follow up ideas, post and respond to other's posts.

The hypothesis of this research is built up on the assumption that on-site participation with lean tools like pen and paper in combination of current advancement in the field of information technologies will yield appropriate results which can contribute to livability of environments in various scales (a building, a neighbourhood, a public space, a district, even an entire city). In order to activate the community to be more engaged with its environments, this particular research will be focused on a neighbourhood scale.

By developing this strategy, we might find answers on the questions already addressed by Verebes (2015, 2016) in regard the problem of mass-customised and adaptive cities and their prototyping: *How, at the start of the 21st century, do we heighten the materialisation of unique spaces and systems? What is the potential of computational prototyping methods for creating diverse and differentiated cities articulated as a "Distinctive Urbanism"?* And other research questions arise subsequently: How can participants directly influence their environments towards better livability in respect to their desires and preferences? What kind of an adaptive or building system allows users to do it? How can an urban neighbourhood be directly influenced by its occupants in a full scale? What is the exact role of digital technologies in this regard?

## PROBLEM STATEMENT

Our cities, neighbourhoods, buildings, and urban spaces suffer from the problem of standardized production, repetition, uniformity, monotony and similitude. There is a gap between industrially fabricated elements of small scale prototypes (such as cars) to extra-large architectures, urban environments, and cities in general (Verebes 2015). The ubiquitous standards, common production in a building industry and fixed permanent solutions that are no longer actual, can lead to anonymous and estranged life and societies in cities (apart from other social issues e.g. migration, poverty, broader cultural or political crises).

However, a city often changes and is activated from bottom-up and this characteristic of its fluidity and state of continuous flux strongly seeks for a feature of its adaptability. More specifically, it appeals for such systems that can adapt to local specificities with the impact on their spatial and geometrical qualities and with a consideration to urban density, interstitial space, connectivity, diversity and in respect to differentiated local climate zones (Weinstock 2013).

Architectural and urban planning is nowadays a highly specialised process, which does not actively engage the users of these spaces in the design process and in consequence to some extent neglects their needs, preferences, and also does not take advantage of their local and living knowledge of a place, which could benefit the design of more diverse, adapted and adaptive environments. However, although participatory processes exist and have occasionally been successfully implemented, generally applicable frameworks or process models are scarce or non existent as well as the tools to support these.

## AIM OF THE RESEARCH

Following these questions, the goal is to gain new ideas directly from the citizens and to develop a customised urban environment which is built, modified and adapted on-site in a full scale directly by the end-users. This way of influence for the liveable environment is key to innovation. The results are ready to discuss, to explore, to share and to conduct: digitally, using the application by means of personal digital devices and manually, i.e. physically, haptically, interactively on-site and fully bottom-up in order to empower and activate a local community life, its social character, capacities to participate and its values (Bullivant 2017) with an impact to the environment's livability.

In so doing, the research in a long term will propose a building system, a prototype, consisting of a set of simple parts leading to a diverse number of more complex architectural and spatial variants which can be achievable and built on-site by the end-users. The prototype will be introduced in a separate article.

## STATE-OF-THE-ART

The idea of the on-site participation is actually quite old. Apart from built vernacular structures and urban systems all around the world already explicated by Rudofsky (1964), built favelas in South America with their sheer beauty of architectural spaces (Kerez 2016) or informal settlements in Africa or Asia, there is a plenty of architectural and urban design proposals, sketches and models for systems dedicated to direct on-site participation conducted by architect Yona Friedman (Friedman et al. 2010) starting from late 40-ies in the last century till today (Seraj 2015). Although Friedman's solutions can be considered as utopian and radical in a way, they show a proper base for a spectrum of possibilities how the combinatoric strategy can be used in an architectural and urban design, concentrating on an adaptability of space, following the simple rules for an assembly and characteristics of improvisation and transformation condensed into simple comic-like explanatory manuals for non-specialists. Taking into account current research in the field of adaptive environments in combination with information technology, the agenda at the AA DRL explores new ways of materiality, responsiveness and prototyping methods using digital technologies in systems that actively seek to engage and participate in their environment (Spyropoulos 2016), started in early 80-ies by Walter Segal and later by Frazer et al. (1995). He continued in Segal's idea of a self-built housing system, developing the *Self-builder design Kit* where self-designers were allow to design the building layout before it is built in an interactive electronic way.

It is necessary to combine a direct active role of users together with these abilities of systems to adapt. The users could directly modify the spatial character of the environment which can be stored and learnt by the system itself and which can be offered in different scenarios or modifications.

## METHODOLOGY

The research project aims to engage users on three levels: in the design, prototyping, and testing. De-

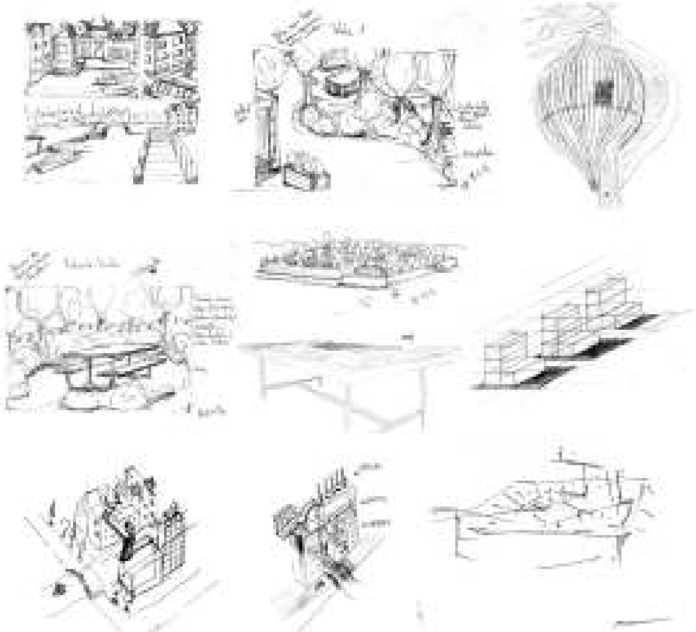

Figure 1
Idea sketches made by hand without any digital techniques [3].

pending on what the actual design problem is, it could also include ‘making’ (Greenfield 2017). In a long term, it is conducted as follows:

1.) Engaging analogue and digital techniques allowing sketching and custom-based generative models dealing with combinatory techniques (Bohnacker et al. 2012) to provide spectrum of possible solutions how to assemble and configure the spatial configurations of the architectural or urban space. The spatial system consists of pre-defined shapes, objects, modules and models which users, participants, citizens can interact with. They can model and explore the spatial possibilities according to their preferences using:

- analogue sketching techniques with pen and paper (Figure 1)
- digital techniques by means of using devices (tablets, digital pens, cellphones, computers)
- a physical models in a small scale (3D printed or fabricated models) manipulated and explored during on-site workshops
- building pre-prototypes (small-scaled prototypes) in a full scale

The proposed content, sketches and digital models can be accessible on-line, as an integrated part in already developed Citizen Science on-line applications such as the **Skity** tool [4], the web-based geometry editor **QUA-KIT** [2] (Chirkin et al. 2016) or as a standalone generative modelling system available for citizens as an application.

The first methodological step introduced in this paper is focused on a local community-based empowerment and includes a development of a workshop framework where a selected local community can meet, sketch, collect, discuss and model the ideas for any improvement of their environment according to their preferences, requirements and knowledge. The research also discusses the relation and differences between digital and analogue approach and compares these two ways of collecting the information and creating possible design and improvement solutions.

2.) Based on the results from the previous step, the prototype of a preferred solution in a case study will be made in a full scale using fabrication technologies and digital techniques. This methodological step will be technically the most difficult and will take the most of the effort to develop such a system.

3.) On-site participation and assembling the system in a full scale with participants in a selected urban area in a case study: using the system in a selected space on a community-based scale (e.g. social habitation units, refugee camp study, ephemeral urban solutions, floating units on the water). These assembled systems will be final outcomes of this research.

The detailed explanation of the 2nd and the 3rd methodological steps will be introduced and explained in separate articles.

## *A Workshop Framework: Case Study in the City of Chur*

Following the above mentioned methodological steps towards reaching overall aim of the research, we conducted the first part of our research intention condensed into a workshop with local citizens in the City of Chur. During the workshop, the participants selected and identified problematic urban area in Chur and proposed several ideas how the particular area can be improved, activated or empowered. By means of analogue and digital idea sketching, as a form of off-line and on-line communication, the participants collected ideas as an input data for further discussions, tests and decision-making processes.

The citizens, local university students as a community of engaged participants used the web-based tool **Skity** [4] for idea sketching. The tool allowed to collect sketches and draft proposals that can be stored as images in a database. Each participant can be aware in what sense other participant contributed to the area as the tool allows the user to observe other proposals directly on the screen of his or her computer or a mobile device. Workshop tested the efficiency of the digital sketching related to urban environments taking into account individual desires of the participants and their ideas. Furthermore, the technological aspects and current limitations of the developed on-line sketching tool **Skity** was tested and observed as it was used for the first time among the participants.

## *Skity: A Web-based Sketching Tool for Citizens*

The Skity tool, as a digital sketching platform used in this study, is a web-based application developed for visual participatory design and communication purposes. The tool is based on the java-script libraries: Mapbox , jquery and a modified version of sketch.js with the graphical interface displayed in any web browser. Mapbox provides tiled map service so it can be used in any case studies across the globe and in any urban scale, from the wider relations in strategic planning of territories to small-scale urban details, like streets, squares or public zones (Figure 2).

The user interface consists of navigation buttons related to three spatial scales. There is a switcher between two modes of the digital participation: sketching itself and marking the environment based on various qualitative or quantitative criteria that can be observed by the citizens. Citizens can contribute in ranking and providing the information about public and private traffic, noise level, temperature, pollution, social exchange, vitality, walkability and affordability by marking the issue of the urban space on the scale from 0 to 10 (0 means no issue, 10 means very big issue). This would bring another level of understanding and assessment of the urban areas by engaged citizens that can be taken into account.

The sketching mode allows the user to sketch directly on the displayed map as on the sketching paper into a separate layer and save the image separately. Each user can create his or her own sketch or is allowed to participate on other users' sketches. The digital pen with a free hand, mouse or even a finger can be used for the digital drawing using any mobile devices or a computer (Figure 3). As the tool is a newly developed prototype, a proper user administration of the collected data or secure login management for invited participants has not been implemented yet.

### *Observations and Results*

The sketches provided by the participants have been stored in the database for further observations and discussion (Figure 4). In that way the group of local participants with their ideas can contribute to the overall discussion and they can share the ideas visually. The visual results are accessible online [4]. Each citizens' design proposal outlines an individual strategy how to improve the area, e. g. proposing more open public spaces areas in the blocks, better connectivity and accessibility of these public spaces, elimination of parking cars in the area, putting the main traffic flows underground, etc. The variety of proposal can be considered during decision making processes by the municipality and discussed among citizens.

Figure 2
The graphical user interface of the Skity tool - the marking mode. The users are allowed to mark various urban issues [4].

Figure 3
The Skity tool - the sketching mode.The user can sketch directly on the map on a separate layer with various colours of outlines and fills [4].

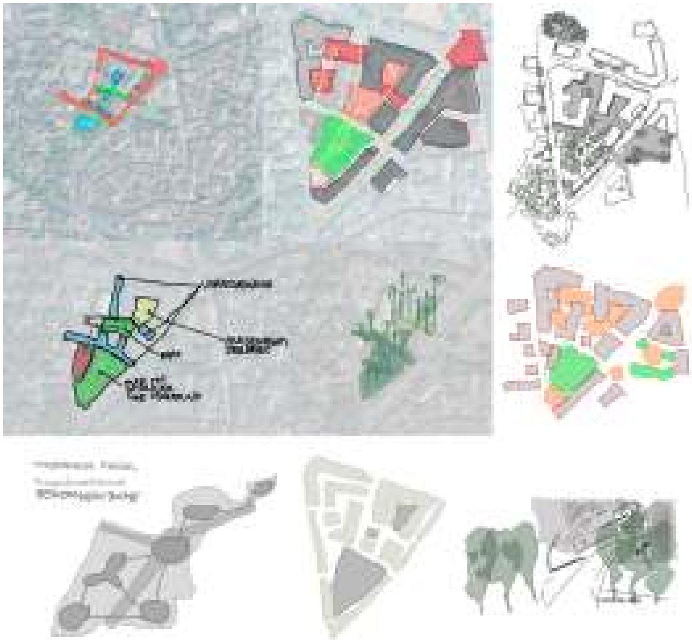

Figure 4
The sketches accessible online for further discussions and a closer cooperation [4].

Furthermore, the tool also contributed and initiated discussion among participants, during the workshop. As it has been observed, the digital tool does not take away from or inhibit analogue interaction and discussion.

## CONCLUSION AND DISCUSSION

The paper introduces the research initiative of user-driven customised environments and outlines the first methodological step in this regard. This include analogue and digital idea sketching. The sketches serve as a first input to activate the discussion among citizens and experts and can inform the authorities about observed issues of the particular urban area. To have an on-line sketching and communication tool accessible for everyone within the process, the **Skity** software has been developed for a direct participation.

Skity can serve as a basic and first platform for citizens to contribute with their own ideas about the city they live in. The tool allows the users to input 2D sketches on a map into separate layer that can be switched between sketching mode and the marking mode. As the background map is geo-referenced, it is possible to locate the sketches according to precise geographical reference of the area.

As the observed workshop results show, digital tools if applied and embedded correctly in a workshop context could support and facilitate on-site as well as off-site, synchronous as well as asynchronous interaction and discussion.

### *Future work*

As the study has been conducted with 10 participants only and also the group of participants chosen, i.e. students, is not representative of the local population, it is necessary to test such a participatory tool with higher number of local citizens that can be involved in the design process. This will lead to the question how to observe and evaluate the results efficiently. High number of sketches, data collected and stored could be explored using machine learning methods and image processing procedures prospectively with a crowd-sourcing implementation based on preferred evaluation criteria (connectivity between public spaces, spatial and temporal accessibility, preservation of valuable spaces, spatial conditions - visibility, openness, closeness, compactness, etc) and any qualitative aspects of the environment based on the principles taken from urban theories with combination of current advancement in the ICT. Furthermore, a proper application of the methodology into a real world scenario would be beneficial in order to inform urban governmental bodies, municipalities and stakeholders. This will prospectively contribute to the urban governance strategies of the near future in the era of *responsive cities* (Schmitt 2016).

The direct implementation of the on-site participation design strategy can follow after the first methodological implementation in a real case. However, pre-studies and small-scale prototypes are needed to be done to test the possibilities of adaptability, transformations and reactivity engaging digital techniques and preferred technologies together with analogue studies. The proposed full-scale adaptive prototype for a particular urban area expects to reach more diverse unconventional spatial solutions based on citizen's preferences.


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# Learning Participatory Urban Research

## *Towards a Network of Collective Ingenuity (OURB)*

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*This research was put together by four Master's students from KU Leuven Faculty of Architecture, who are self-motivated to investigate the possibilities of collective methods for designing within the Urban context. This paper is divided into two parts, the first being a scholarly investigation into learning from the collective mentality shift, and movements; discovering the added values of operating immersion/eversion from the virtual worlds to the physical one and analyzing key factors for engaging the public on online communities. Following, the paper brings to light the challenges the future of urban planning faces during today's digital shift and the solutions possible through the introduction of digital platforms as support to urban planning structures. The second part is the complementation of the first, as the research team showcases the findings by testing out the learned concepts and conducting on-field social experiments. The paper concludes with an analysis of the results, and future directions to the research project.*

**Keywords:** *collaboration, co-creation, collective ingenuity, digital platforms, social engagement*

### INTRODUCTION

Over the past decades, the basic capacities of information and communication technologies (ICTs) have shown exponential increases in performance relative to costs (EEA, 2016). Even though ICTs can be powerful tools to build communities and enable cooperation, we will only reach meaningful results when technology begins to be accompanied by political and citizen's will to reinvent the way we cooperate, live together and build our future. Whereas technology is essential, true collaboration is cultural and behavioral: it requires 'to care', caring for others, caring for shared purposes (Rossetti di Valdabero, 2016). The key to success lies in a hybrid collaboration of the physical and digital, where challenges can be collected in the physical and virtual, and bring inclusive wise solutions for all.The sharing of knowledge and ideas creates exchanges. The world is full of untapped intellectual resources that can now be mobilized. By coming together, it is possible to tackle the current challenges and find solutions more effectively (Lévy, 1994). Our cities are currently facing tremendous economic, social and environmental challenges; but we can provide solutions that exist by doing more with less.

### *The currents from collective ingenuity*

The internet allows for different systems that gather, combine and distribute real-time data information, made available during every moment of our daily life to have a more efficient and connected city for smart developments. This powerful source of information gives way to the emerging socio-economic currents of crowdsourcing, like the makers movement, the circular economy, the inclusive economy, and the economy of sharing and "Smart city" approach which integrates many of these concepts. These currents explore smarter ways of living together with the support of digital tools and platforms of that have recently been created.

Co-creating makes it possible to find solutions that nobody can achieve alone (Hesseldahl, 2017). The world is full of great ideas, valuable information and helpful hands that can be leveraged - as long as they are open to them. Embracing this attitude of inclusiveness allows for the outsiders to become a part of the solutions to their own problems, giving power to the powerless. Emergent paradigms as the one of circular economy show how many people have special skills or knowledge that others can benefit from - if those who need them, know where to find them. In the past, it was difficult to connect people interested in sharing, today social media makes things easier. Thanks to new currents platforms are created in which needs and resources correspond, and trust can be built (Hesseldahl, 2017). This is why online platforms emphasize the importance of user transparency, recommendations and evaluations by previous users.

### *Possibilities of using collective ingenuity's power in the urban context*

Recently, in the context of urban design, planning and development, there is a sense of a more equal contribution of ideas and solutions, with a co-creative attitude. Governments are recognizing the value of opening up to external contributions, even if this means losing some control over the results. In a future prospect, leaders will be forced to abandon top-down management because contributors to a project may be from other organizations - even clients or volunteers, and good governance will consist in motivating others by the insight of their constituents. Intellectual property will need to be rethought: to encourage co-creation within an open ecosystem, IP must stop being an intellectual protection to become an intellectual partnership. And finally, citizens will understand that co-creation is an opportunity but also a requirement.

There are plenty of good citizen engagement practices out there but they are underused within the planning system. Citizen engagement follows the traditional ask/respond consultation model and is largely dictated by legislative requirements, repeatedly reaching similar demographics. Often occurring too late in the process, citizens input often has little influence on decision making. Engagement usually takes the form of 'objections' and citizens lack a positive way to influence plan making and local development in a meaningful way.

### *Solutions from a digital platform which harvests collective ingenuity*

In this paper we suggest that a possible way to harvest collective ingenuity might be by establishing a "one stop source", a digital platform with the support of local initiatives. A co-creation format where we can merge diverse data sources; physical site and environmental assessments from experts, with citizens' valuable local wisdom. The idea is to facilitate the communication of all city actors simultaneously in order to find connections and patterns in order to build a strong evolutionary analysis of the urban fabric. To be able to detect problems to turn into possibilities and open up opportunities for smart design proposals to arrive. Within this context and believes we are currently working on building our own digital platform called OURB and physical platform called OURB on Wheels and Heels. The aim of this project is to support the communication and collaboration between stakeholders of a city, by providing tools, that will bring them together to discuss information, share expertise, and create connections that will inspire a collective development of a city.

The platform will be based on a user intuitive map where the information can be visually organized via GIS location, storing multiple layers of information. As a digital crowdsourcing platform, it will constantly be evolving and therefore displaying the most current information about the city. Users will be able to share their needs, desires, proposals and oppositions, which will be tracked and displayed. Therefore creating the most updated overview analysis of the local knowledge for urban development. The platform aims to have the capability to collect data for analysis in order for city experts to contribute knowledge. It will also bring social input for investors and municipalities who look to have a greater understanding on citizen relation with proposed architectural and urban projects. The overall goal is for a more efficient and democratic way of communicating and discussing projects to take place. On which the public and local experts have a louder voice in order to reduce the risk of investment and merge top down and bottom up strategies.

### *Local issues within the planning systems and societal challenge*

The initial inspiration for this project is also stating the issue of why it is important to do this project. While attending a workshop in Belgrade about creating livable cities, the research team had the chance to learn about the city's future development projects and personally observe what are the conflicts that arise from the way the decision process is held. Big protests against this projects with around 150.000 people participating were not enough to fight the absence of democracy and transparency. Talking with Arnstein's (1969) words, the level of participation of citizens in this case was absent and reduced to a mere manipulation of the civic will.

During next four to five months the research group have been researching the application of a possible platform for social engagement taking it into the Belgian context, looking deep into the planning system in Belgium in order understand the transparency and democratic level in the country in which the research was held.

Brussels can be taken as a particular case in which the government is trying its best for increasing the participation with city projects through neighborhood contracts. This system organizes small scale projects which are developed with a "roundtable" style discussion on the possibilities and have those small scale projects developed. Neighborhood contracts are an example in Europe for the methodology that is behind them, but this system still seems to be not hundred percent efficient and there are still evident obstacles in engaging population in a consistent way. This issue reinforces the research group's theory of whether an interactive online platform could be a support to the planning systems, and enable discussions online and help to share information and expertise at all times.

## METHODOLOGY

In order to test the affordability of the theory and strategy of a project for a sustainable online platform, our research team decided to conduct empirical tests in which some potential feature to enhance engagement of the public users on digital platforms are tested through physical interfaces, that already represent what we called OURB on Wheels and OURB on heels. The aim of these experiments was to make the physical system to collaborate with the virtual one, to crowdsource the problems and dreams of a community and foster the emergent horizontal and inclusive design attitude.

The experiments on the physical field are part of a research on users' engagement methods that works through to the comparison of two realities: the one of physical interfaces and the digital ones. Our literature review revealed that. Online platforms support bottom-up collaborative ontology building and allow user-based interpretation of heterogeneous information (Pak and Verbeke, 2010). Virtual environments can foster critical thinking and innovative thinking, re-discussing also the role of experts. Virtual realms have a potential to extensively redefine the existing realities and relationships, and to facilitate collaborative knowledge construction. However, assuming the positive potential that comes from the use and interaction with these systems, some negative aspects has to be considered: certain characteristics of human commitment in the physical environment are not replaceable with the opportunities offered by the confrontation with a virtual world. There is a fundamental asymmetry between physical and the virtual spaces: aware of the potential of both one and the other as well as their limits, the research team decided to merge the positive factors of the two contexts transferring them from one environment to the other and vice-versa, through the so called practices of immersion and eversion (Newton and Pak, 2015). In this way, practices that are recognized to be sustainable in one setting are transposed and tested into the other, and eventually brought back in a developed version. Thus, the field experiments represent the second step of the investigative process; after a research about the potential features that foster the participation of public users in online platforms, the team applied the relevant findings to test the physical field research. According to the methodology, the results of the second step of the research could then support a further study on the applicability of certain features to strength both online and on field engagement.

## ICT A TOOL TO ENGAGE AND FOSTER PARTICIPATION

The idea of the internet of things (IoT) have allowed almost anything to be connected. This connectedness makes us aware of what is happening around the world, and is now shifting to a more proactive stage. Not only harvesting and sharing but also allowing for it to develop into a wider discussion and start tackling problems we are currently facing; from urban challenges to economical, political and cultural ones.

Users of online communities are becoming more and more proactive, they stop being spectators and start acting as participants. They are not longer part of a silent audience but instead are become active contributors. Meaning they contribute knowledge and information to online platforms, but also formulate an opinion. Opportunities for civic engagement can be expanded in urban design through collective intelligence.

ICT tools can be introduced in participatory urban design strategies as a tool to engage and foster participation. The strength of online communities lies in the engagement of its users defined by the users profiles/personas.

Through the analysis of different case studies on the behavior of online platforms' users, it's possible to identify factors that define people's engagement; Engagement of the users' persona is based on three critical factors: *trust, control, and motivation*. The status of a user's' persona is one of the main factors that determine how users interact on online platforms, and how they cope with trust and control. *Anonymity* and *identification* are also different factors to take into account.

Anonymity allows users to feel a sense of security and privacy; it allows all members to participate equally, since the physical interaction is missing, discrimination is harder to form and all users are able to voice their opinion equally. Anonymity grants people the ability of speaking their mind, leading to better discussions, better content. However, anonymity can translate into de-individualization, turning into poor, false or malicious content. With de-individualization there is also the danger of group behavior, called 'bystanders apathy'. When opting for anonymous profiles, the platform needs to set rules on how users should behave.The private nature of verification enables mutual trust between the users of a platform. The more users trust in their peers and in the platform, the higher their engagement level will be. However, identification could inhibit free expression. When the basic critical factor is established; trust and control, motivation is a way to increase the engagement of the users of a platform.

Another great tool that has shown to increase the level of motivation leading to engagement is *Gamification*, because of the following reasons: it motivates users, playing triggers positive emotions, and the achievement of something makes us feel better. By playing we learn to develop strategies, specific knowledge according to contents and by playfulness, moreover, anxiety is reduced, creativity boosted, social relationships established. Those activities that are properly gamificated, derive into a greater participation level. The most successful kinds of gamification are simple; they are about one kind of action leading towards one kind of outcome. *Validation, completion and prizes* are the most common gamification methods on online social media.

### *Introducing ICT tools in Civic engagement*

ICTs can promote better informed decision-making by providing city stakeholders with appropriate, up to- date and actionable intelligence. ICTs offer new and improved ways of ensuring citizen participation in planning decisions, for example through the use of e-consultations, gamification and engaging virtual communities.

Civic engagement can be expanded in urban design through introducing ICT tools as tool to engage and foster participation. Community members play a more active role than just 'likers' on a regular online platform, the participants spontaneously assume responsibility for the community and uphold its spirit and culture. People tend to be more productive in a community, because they already have a place within this community. The users will act as co-innovators in this co-learning context and produce knowledge together with researcher.

This inter-sectoral thinking will lead to the development of innovative methods and novel design concepts which will be implemented, tested and evaluated with the continuous participation of these actors. In this way, research will go beyond disciplinary boundaries and integrate non-academic knowledge, enabling learning from real-world practices. The position of the researcher will be of an active nature, and the research will be structured through cycles of action research. In these cycles, the researcher will work in close contact with local and governmental organizations for facilitating the continuous negotiations of sense-making and scope refinement among the contributors. Participatory collection of information and analysis will be organized in the form of co-creative participatory sessions with the users on-site.

For now, using online tools in urban development, hasn't reached the decision making stage yet. Decisions are always made within these organized physical workshops. This means that the platforms, as well as Facebook and blogs, don't provide the right type of communication to make decision making happening.

## EXPERIMENTS: OURB ON WHEELS AND HEELS

The diversity of the exercises carried out in the physical environment challenged the way we communicate different kinds of information. Experimenting diverse communication approaches is relevant to stimulate people's critical creativity and using alternative research tools can bring up unexpected output; developing different exercises had been a way to test the suitability of different tools that could be inserted in a virtual interface as well. For this research, two different experiments have been performed: the first one, called *"OURB on wheels"*, has been tested twice in two different environments and has been carried out with the help of a van, which acted as a physical supporting interface and an attractor enabler, representing an inclusive space to gather people. The second experiment, called *"OURB on heels"*,was based on a one to one investigation process, in which one surveyor tested the possibilities in engaging people with a direct and personal approach, recording information through the help of a digital application. Since the first experiment's purpose is oriented to test the possibilities to engage people through physical devices, the second is testing the affordability and the advantage of using certain media recording application to facilitate the collection of information through different media with the support of technological devices.

### *OURB on Wheels*

During the two sessions of OURB on wheels, the research team was able to involve people in the making of different kind of exercises; in consideration of the findings obtained from the previous research on the ways online platform enhance the participation of public users, the research team tried to transplant some of these findings to shape the method on which the physical engagement exercises were based on, testing certain influencing elements that foster participation, as the trust, the gamification, the anonymity.

The first on field session of OURB on wheels was organized in Brussels, carried out with a van working as a venue to host the practice of the little workshop. While analyzing the results of the experiment it was important to take into account the context in which the work has been carried on: the place picked for the first OURB on wheels' experiment is in a neighborhood in which the diversity of identities and uses of it does not facilitate its definition; its structure, the profile of the inhabitants and the users is very much diverse and the area is known to be a pretty much complex one and rather problematic. Facing a non-easy audience anyways gave us the possibility to get better awareness about certain issues concerning the direct involvement of people and the strength of certain communication approaches.The team invited people to go through 3 different exercises;

- Hands-on mapping
- Collages
- Videotapes

In the first exercise people were asked to approach a big map showing Brussel's central area and some adjacent zones and to indicate their ordinary daily route with a string, indicating their home as a starting point. A distinction of two colors marked a gender identification. This representation method allowed us to both mark crucial points and paths, creating a sort of rhythm-analysis map of the users of the area. This exercise's aim was to understand what is people's acquaintance with space representation on maps, and to test their capability to orient themselves in the map, reporting data on it.

Second aim of the exercise was to test the potential in the way of gathering information; it's relevant to notice how just a first glimpse on the finalized map gives an impression of how the space is used by the group of people that participated to the exercise. Translating this info into numbers or categorized data, would allow to make an easy study on the average social rhythm of the area, with the possibility to repeat the exercise in order to refer to different periods or space contexts.

The second exercise involved people in making an actual object, producing a collage which could answer the question "what's your ideal place?". Each element given to compose the collage had its own meaning and belonged to a certain category. The participant were free to compose these different pre-settled elements and use them according to their own wills, with addition of personal drawings / writings. The importance of giving pre-set elements is given by two factors: first, for practical reason of feasibility and rapidity; second, having the collages as different outputs based on the same elements, allow to make an accurate analysis of the results .

All the collages are a mix between pre-given elements and additional personal sketches or writings, easy to compare thanks to their monochromatic features and graphic similarities; it's relevant to consider as well the importance of the time that people gave to develop the exercise, as a proof of commitment and engagement.

As mentioned a positive factor of using given element to compose the object allow an easier and more accurate comparison between the outputs produced, but on the other hand it can lead to a lack of contextualization to the studied context and limit the way of expression (even though we notice that people were able to see different things in the same element). An interesting aspect that we noticed was the tendency of taking inspiration from other's work, like a sort of unconscious influence that tends to happen between participants.

Collages and similar creative experiments were simple yet really evocative output, they can be a way to understand people's values and thought process, surfacing unexpected themes and needs. With the belief that making things is a way to think thing things through, the exercise is unlocking creativity and making the participants going through a critical thinking process.

Creating amusement while practicing the exercise is recognized to be a way to facilitate the involvement of people, so the playful aspect of the exercise helped to attract more participants. The exercise was easily doable in order to gather the attention of a consistent number of people. This type of exercises were a success thanks to the gamification aspect that has been given to it. Playfulness and fun were two key elements for people engagement. All these practical considerations are important to define what's relevant in the design of an interface, whether digital or physical.

The third exercise developed involved people being videotaped for 30 seconds, time frame they could use to express with their own words what they liked about the area and/or what they would like to change. This type of exercise is a way to collect more direct data from the source, recording them without interfering with the researcher personal filters. It allowed for information to be captured straight from the source. Moreover, giving a time restriction put pressure to the interviewed to give concrete answers and narrow down to the most important information they could provide. Exercises as such were very demanding and can less easily get response from the public. Many participants were not willing to commit enough time to sit and be recorded, even though mentioning the very short length of the exercise is still a way to stimulate the engagement.Through the exercise the issue of trust was explored. Few people allow to be recorded, since the idea of letting personal images to be recorded can be seen as interference with personal rights.

In consideration of these findings, the research team partially reviewed the way of developing the exercises for the second event of OURB on Wheels. Overall, the goal of this second experiment was to test out how our exercises could work in a different context in order to support the idea that the exercises could be reproduce at different locations and settings.

The experiment was set out in another hyper diverse area, this time in Antwerp, but since embedded in an event organized by the municipality a lot of the crowd that showed up had already interested in participating. This time we didn't have to surprisingly invite people from the street but instead the participants that came were already interested in the event. The majority of these people are mostly highly motivated community members, that can be referred as the "believers" , people that will be the first to help and make something happen in the neighborhood. We could say that gender equality was better represented however diversity was less evident. After a count, we could establish we had 21 participants in our experiments.

This time, participants were again asked to explain their daily path, and with this exercise we were able to again start a conversation and find out a generic how inhabitants transit through the neighborhoods. This time people had an easier time figuring out their path, and so it was an easy exercise for them to partake. We would establish that everyone could find their way within half a minute. Overall we established as well that this already gave a good conversation starter that could lead to a second experiment. This exercises were accompanied with a newly introduced part which consisted of a chart giving to people the possibility to pick ,through a small critical process, possible architectural development solution for the future of the neighborhood. Four spots with high potential for development were selected and the participants were asked to make considerations on space, safety, health or livability, to then select one of the site in which they would propose a project.

It can be argued that the exercises could have been visually organized in a more simple manner and could have given more options. Although most of the participants were understanding the point and the visuals. It was also very interesting to see how the inhabitants learned about their environment from the exercise.

It's important to acknowledge the context in which the experiment was conducted, and how it affected the kind of people that took part and the amount of time they spent engaged. The fact the experiment was part of an organized public event meant that the citizens that chose to come were already motivated to participate and therefore the downside from this was that only people who wanted participate in community events were reached,which left a lot of people out of the conversation.

### *OURB on Heels*

The goal of the experiment called OURB on heels was to explore the usage of an ICT platform on the field in order understand how online media collection improves the efficiency of a surveyor to collect data about an area, and support the idea that the combination of virtual mapping facilitates the analysis of the urban fabric.

The tool is a mobile data collection platform that allows you to easily build mobile forms & collect data anywhere, at anytime. The most interesting aspect of this platform for Ourb on heels is the location-based data collection. This feature allowed the surveyor to automatically map out the collected information easily and efficiently in one place while exploring the area. Main features tested were: Digital location based mapping, Audio interviews, Photo capturing, Sound capturing, Video capturing.

Loose conversational interviews were conducted and in order to engage the different subjects into conversation, the surveyor had to identify himself and ask for permission to record the conversation, proceeding then to record on phone, asking questions and turning it into a casual conversation. When the conversation was done, some comments have been written down and saved on the digital cloud together with the location where the interviews were held.

Audio recording interviews were very welcomed by the interviewees and easy to perform on field. The location-based mapping of the information was also very useful and easy to navigate and locate our interview. The recording allowed to gather first source info, as it is not filtered through the researcher understanding of the conversation. The researchers were able to prove that the location based data storing allowed easy organization of data and is useful to navigate through the study area.

### *Conclusion on the experiments*

When comparing how we established participation in our 'physical' experiments, and how it is established on online platforms we can state that the critical factors remain the same. **Trust** is the first critical factor we need to establish. When asking people to answer anonymous to the questions no one hesitates, but when asking if we could film them, not many were eager to respond. With the people who were willing to be filmed, we had a preliminary interview to built up trust. Explaining them we are students translated in an active attitude, willing to participate in our experiments. Another determining factor was the **number of people** who were participating in our experiment. We showed the outcome of other participants by making their answers visible on the street. It drew passerby's' attention and made them curious. Seeing how many people responded to our questions lowered the participate barrier. We can argue the same for online platforms, the quantity of members of a platform reassures other non member that the platform is trustworthy. The Trust-profiles used on online platforms is a variant of the preliminary interviews we had to built up trust. However online this can happen more efficient, trust profiles are built by accumulating feedback from multiple interaction with different users. We gamified our experiment to motivate the citizens to participate. Important is that these tasks were simple, clear and generated fast answers. We noticed that **participants seek validation** the same way they do online, they compare their collages and answers to other participants, and saw this leading towards discussions, soon they started to address other issues, this shows that gamified experiments are a good trigger to discuss urban issues.

## CONCLUSIONS

The research group concluded that this paper attests only for the beginning of a comprehensive research, one where we dive even deeper in studying how we can harvest collective ingenuity through different ways of participation methods, physical and digital, to then facilitate the process of designing, increase engagement of all stakeholders and thus building a more democratic way of developing a city. This part of the research is a good starting point to set the next tone on which we will tackle the next phase for the developing of OURB, as we hope to further its development to the implementation of a digital platform and the continuance of the on-field experiments.

Having tested the theory through the experiments, the team strongly believes in the power of a combination between working through ICT tools and developing a work on field, acknowledging that the potentials of one approach can compensate the limitations of the other. As showed in the previous considerations, this collaboration has been helpful to enrich the research method as well; the analysis of several online platforms taught us the value of elements such trust and gamification, criteria that have built the shape of the experiments conducted. It can be concluded that **trust** depended on the amount of commitment the user had to give to each of the exercise, the feasibility of knowing what to expect, and the spatial context on which they stand. Then **gamification** was indeed one of our major key factors to achieve the participant's engagement. Through gamification of the inquired information became easy to extract, but it also gave way an alternative tool of communication. Gamifying means to make it fun for the user to give the data we needed to understand their point of view of each requested area, and indicated certain concerns, they could not communicate immediately. The exercises gave time for more critical opinions to be made as they needed to take some time to think.

Learning from our experiments and the theories for different forms of collective living, we conclude that there is a new mentality change that needs to take place in order to give way to the upcoming currents of collective ingenuity. The new currents, show how it is possible to do less with more and highlights the positive attributes of living through a connected world. The ideas of a world relying on collective ingenuity opens the doors for co-creation, expands on the possibilities of a more resilient city. We can now positively understand that our attitude of moving towards a more inclusive and collective planning system goes along with those of many innovative minds, even though the planning systems currently set, are inadequate and are not processing with this new mentality. We also learned that this new mentality is already taking force on the online communities and exhibiting some good results on harvesting the collective intelligence through different methods.

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# SenCity City Monitor as a platform for user involvement, innovation and service development

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*Urban dashboards visualize information about the measured performance, structure, patterns and trends of cities. This paper introduces a concept of urban dashboard as a platform for participation, research, and service development. We present and reflect the development process of the City Monitor, which is a test version of an urban dashboard for the pilot cities participating in the SenCity project. The paper describes and reflects on the concept, structure, and content of the City Monitor and its participatory and iterative development process, through a case study. The case study encompasses a pilot implementation of the dashboard concept in a context of a housing area in the Finnish city of Salo, where intelligent roadway lighting was tested.*

**Keywords:** *city dashboard, intelligent lighting, pilot, participation, simulation*

## INTRODUCTION

As the smart city ideology, initiatives, and developments are spreading worldwide, the familiar concept of a dashboard has been introduced in new interpretations as a core element of various smart city projects. In general, dashboards can be seen as instruments which display various measurements attempting to describe a system in real time. Thus, *city or urban dashboards, specifically, visualize information about the measured performance, structure, pattern and trends of cities*. Urban dashboards provide key information for delivering and improving services, formulating policy, and carrying out long-term planning. Dashboards provide data analytics in different forms to inform both citizens and authorities. Moreover, data can be made open for applications and employment by individuals or companies for creating services for citizens and new business. (Kitchin and McArdle 2016)

Before being introduced in an urban context, dashboards emerged at the turn of the 19th and 20th century in cars and airplanes. Over the first half of the 1900s, the dashboards found in cars rapidly grew from a singular instrument to include a speedometer, an oil gauge, and many others. Mattern (2015) has argued that the current amount of instruments in cars is mostly an aesthetic and customer-experience driven issue with little to do with the driver's functional needs. In airplanes, however, the dashboard, has become the de facto way of maneuvering a plane, and thus central to the survival of the plane and its passengers. (Mattern 2014, 2015)

In the 1970's, however, dashboard design made its first forays into the urban context. The government of Chile designed and implemented a cybernetics-inspired decision support system. Visually, this was a futuristic-looking operations room in a hexagonal layout, where walls were used to display data. However, this futuristic presentation of automated data was still an illusion, with a vast amount of behind-the-screens human labour required to deliver it (Mattern 2014, Medina 2011). Actual aggregation of automated data occurred in the 1980's, when stock brokerage firms began to use the now-iconic multi-screen stock data terminals by Bloomberg. In the 1990's, aggregating and mapping urban crime rate data became a central issue for many US cities. Begun by the then-crime-ridden New York in 1994, other US cities soon followed suit. Since then, various other cities around the world have created their own urban dashboards, many of which are publically available on the internet. These include, among others, the Dublin Dashboard (www.dublindashboard.ie), the eliko Kalaranna SmartStreet dashboard in Tallinn (www.eliko.ee/smartcity), and a massive intercity dashboard in Latin America and the Caribbean (www.urbandashboard.org).

The existing urban dashboard applications have lately been the subject of scholarly scrutiny, and as such, some criticisms have also been presented. Most of these criticisms seem to revolve around the issue of the nature of data itself. Specifically, urban dashboards inherently must operate under the assumption that the real world can be translated into rational, orderly forms of knowledge that can be neatly visualized and organised; thus, they keep the messiness of the real world out (Mattern 2014; Kitchin and McArdle 2016). Therefore, if they are used unreflexively and in isolation, they can remove cities from their wide-spanning historical, political, and social entanglements (Craglia et al. 2004; Mori and Christdoulou 2012).

Thus, due to the complexity of the real world, dashboards exclude much more data and unquantifiable knowledge than they include. Categorically, issues which are not somehow quantifiable must be left out. Furthermore, the indicators are not objective and value-neutral; they are produced, chosen and presented under certain assumptions. Therefore, dashboards are necessarily informed by their designers' normative understandings of what should be measured and examined (Drucker 2013). These underlying assumptions can be further obfuscated if data are utilized as composite indicators, which combine several individual indicators. Dashboards also produce meanings, generating novel understandings of what the city is (and what it ought to be). Therefore, the design decisions built into the dashboards have political consequences. Finally, the quality of the data naturally determines the quality of the information that users can receive from the dashboard. (Kitchin and McArdle 2016).

Overall, dashboards can provide and foster useful insights, allowing a one-glance access to critical information concerning cities; however, it is important for designers to openly reflect on the design decisions that have been made. Furthermore, it is important to highlight and explain the origins of the data that is visualized, so that users might judge for themselves the quality of the information. Also, as urban dashboards are such potentially powerful tools, the participation of citizens and various stakeholders in their design and use should be addressed and reflected upon.

Following these notions, the aim of this paper is to introduce an urban dashboard as a platform for participation, research, and service development. In the following sections, we present and reflect the development process of the *City Monitor* (Kaupunkimonitori), which is a test version of an urban dashboard for the pilot cities participating in the *SenCity* project.

The *SenCity* project is building a smart LED lighting and digital service platform in six cities in Finland. The project pilots smart outdoor lighting in different kinds of urban environments. The *SenCity* activities focus on three aspects: 1) to study users' needs and experiences of intelligent lighting, 2) to develop and test new technologies such as sensing, data analysis and communication needed for user-centric designs and services, and 3) to generate business opportunities for smart, data-based services. In the pilots, the aim is to employ lighting infrastructure as a service platform - an IoT backbone - in intelligent cities. Together, separate pilots in six cities around Finland create a living lab ecosystem for developing and testing innovative solutions in the future. The *SenCity* project group consists of collaborating research institutions, cities, and companies in lighting and ICT fields.

## OBJECTIVES AND METHODS

The paper describes and reflects on the concept, structure and content of the *City Monitor* (www.sencity.fi/fi/kaupunkimonitori) and its participatory and iterative development process, through the description of a case study. The case study encompasses a pilot implementation of the dashboard concept in a context of a housing area in the Finnish city of Salo, where the *SenCity* project has tested intelligent roadway lighting.

In the case study area, presence sensitive roadway lighting, adapting both to the motor vehicles using the road and to the measured traffic density along it, is being tested. Users' experiences of the lighting have been collected with the help of questionnaires from the community of about 1000 households using the road in their daily traffic as well as from other interested inhabitants of the city. The evaluation has been accomplished in three parts. These are connected with different phases in the development of the lighting system, the publicity of the project, and how much information is published about it. For information sharing needs we have designed and developed a test version of an urban dashboard - the *City Monitor* for Salo. Besides getting valuable feedback of the users' experiences about intelligent lighting, we can analyse the influence of the shared information on users' experiences, attitudes and values. Moreover, participants can evaluate the development of the dashboard and give us feedback concerning it, including their needs and wishes as potential users.

In the paper, the epistemological issues of dashboards are scrutinized especially in the context of this case study. The design challenges and development and participation process are explored and reflected upon. The relevance and applicability of different types of data, the suitable visualization and analytics methods of data, and the functional opportunities of the dashboard are discussed. The analysis of the questionnaire results concerning the feedback of intelligent lighting solution as well as of the test version of *City Monitor* will be published later in another articles. The test version of the dashboard will be opened in June 2017 and the feedback will be collected during three weeks.

Methodologically, the basis of our research can be found in traditions of research-by-design, qualitative and participatory research and technological research. In addition, our research can be defined as transdisciplinary research, referring to Gibbons et al. (1994). The research subject concerns various research disciplines such as research of lighting design and experience, architectural research, engineering and HCI (Human-Computer Interaction). Typical to all of these disciplines is that their research problems are not usually set within a one singular disciplinary framework. Additionnally, the research problem and knowledge production operates within a context of practice. In the research process, the framework of methods is being developed and modified throughout the process to respond to the needs of research and to the research questions.

## VISION OF A CITY DASHBOARD IN THE CONTEXT OF THE SENCITY PROJECT

In this section, the concept of *City Monitor* is described and related to the general aims of SenCity project.

Besides the three basic **functions of a city dashboard** - information sharing and analysis; control of systems; and development and business - we want to highlight two further functional levels of the *City Monitor*: participation and research. Thus, providing information is not seen only as a one-way process from city to citizens but as an interactive, bidirectional learning process where inhabitants - the users of the pilot areas - can give feedback and information concerning local conditions, services, plans, and development, and where city authorities can obtain valuable insights into contexts and users' experiences. This social and contextual user knowledge, however, can also be valuable for other users of the pilot areas and, moreover, for the companies involved in developing services. In the course of our ongoing project, as well as in other development platform projects in Finland, some challenges in generating truly useful smart city services and feasible business models on IoT have emerged; one critical factor seems to be the lack of understanding of users' needs and behavior and a missing link between technology hype and user experience (Pihlajaniemi et al. 2016). Thus, in the *City Monitor* and in the whole *SenCity* platform, research about users' experiences and needs occupies a central role. The dashboard is employed as a tool for gaining feedback of the pilot installations and experiments with them. In addition, the whole design and implementation process of the urban dashboard can be seen as an iterative research process where participatory methods are applied.

In our vision, the final city dashboard for the *SenCity* project **operates on many levels and has several aims**. It has a *public layer*, which provides information for citizens about the pilot areas including, for example, environmental data, on-going processes and activities. The *administrative* layer is meant for city authorities and for different organisations of the city, and it is intended to enable the control of systems' operation, to aid their decision making, and to develop, for example, maintenance processes and render environments more safe, sustainable and economic. The *third* layer is opened for third parties, for those companies that pilot cities invite to use the platform and give permission to analyse and apply generated and collected data in order to develop new services and applications for citizens and business ecosystems based on the data.

In contrast to many famous examples of realized urban dashboard projects, which present the city as a large scale entity which is benchmarked and branded globally, in the *City Monitor*, the focus is on scrutinizing and visualizing the **individual local contexts in depth**, in order to enable local development and community participation. We see this in-depth participatory, contextual, and research-oriented approach is, on the other hand, as the very value which would attract also international partners and companies to employ the generated development platforms and create international collaboration.

## DEVELOPING AND TESTING THE CITY MONITOR

The development of the *City Monitor* for Salo is an iterative, participatory process, where users' involvement and research analysis is employed in formulating the content, user interface and visual expression of the dashboard. It is still an on-going process, however, and at this point, we want to reflect on and share its status. We discuss the realized dashboard from the following viewpoints: 1) Information content: What kind of information is shared? 2) Presentation methods and technologies: How is the information visualized? 3) Participation and research: What methods are used in involving users and in research activities?

### *Sharing information with the City Monitor*

In the *SenCity* project, testing solutions of intelligent lighting in urban contexts is in a central role. In Salo, we carried out a ten weeks' testing period during the winter-spring season in 2017, where we involved a housing area community as participants in giving us feedback of their experiences. Thus, the core content of the *City Monitor* is a presentation of intelligent lighting in the Kalkkimäenrinne street that housed the *SenCity* project pilot. In this way, our participants, as well as other citizens of Salo, could learn how the newly installed LED lighting was operating, while they were taking part in our research and evaluated lighting. The *lighting and energy* section introduces, what kinds of control methods were used, what were the different kinds of lighting behaviors that were applied during the winter-spring months, and how much energy each of them was using. This is information, which was, for research purposes, kept in secret in user evaluation in order to not influence participant experiences.

Even though dashboards usually visualize real-time information, in this case, we have chosen to simulate historical data from a single chosen day (Feb 8 2017) in later winter. This is due to timing; if one wants to illustrate the behaviour of an intelligent lighting system, it is impossible to do so during summer months while outdoor lights are completely turned off except for a couple of hours in the dead of night, because of the vast amount of natural light at night in northern latitudes. Thus, we have chosen a date during which dark period extends to the active period of the day, and illustrate three different versions of tested lighting control methods using the passive infrared (PIR) sensor data collected from the luminaire poles.

This data, which indicates the presence of car traffic along the street, is used to simulate lighting behaviour and energy consumption of the test area. The tested control methods were: 1) *Daylight level based control*: The street lights were on at 100 % level when there was not enough daylight and turned off during the bright period of the day (from 8:20 - 17:30); 2) *Presence based dynamic control*: Lighting was controlled so that always around a moving car, lighting was brightened to 100 % and in the other parts of the street, lighting level was kept in 20 % (stand-by level). The lighting followed the same timing as in daylight based control being available during the dark period of the day; 3) *Presence and traffic-density based dynamic control*: Besides having the same functions as in daylight and presence based control, the system also analysed the amount of PIR sensor alarms during 10 minutes periods and with pre-defined reference values, decided whether the traffic was dense, moderate or low. This influenced lighting control so that with dense traffic, the stand-by level of light was highest (70 %), with moderate traffic 40 %, and with low traffic 20 %. However, always around the car, the lighting was brightened to maximum 100 % level.

In addition to lighting, we implemented presentations of other available data concerning the Salo area. *Street camera views* with street level temperatures indicates the driving conditions. This was not from the same street but from a similar type of road nearby. *Weather information* of Salo describes current weather type and temperature of the air. In one section of the dashboard, the *events and activities* that happen in each day in Salo area, were presented on a map. In addition, we wanted to include participatory and *social information* in the *City Monitor* to be available. This was realized in this pilot version simply with a live Twitter feed plug-in.

## *Presenting information: visualization methods and technological solutions*

As our emphasis in the pilot dashboard was in presenting information about lighting, we concentrate in this section mostly on describing how this information was visualized. Furthermore, intelligent lighting behaviour is an element which is seldom included in city dashboards and presenting it includes many interesting challenges. One challenge is related to the dynamic behaviour of light. How to present complex behaviour, which combines several types of logic, as in control version 3, and make it legible? In our case, the behaviour is related to a time range of 24 hours indicating the patterns of traffic density. However, the dynamic changes due to the presence of cars occur within seconds. In which way could the dashboard's user comprehend changes in lighting in both of these time scales? On the other hand, lighting is an immaterial element of environments, which is experienced as part of complex three-dimensional material contexts of the real world, by users of environments acting and moving in space.

We solved this challenge through our design, where we combined dynamic visualization of the lighting behaviour and scalable charts presenting the average lighting and energy consumption levels (see Figure 1). The visualization of adaptive light-

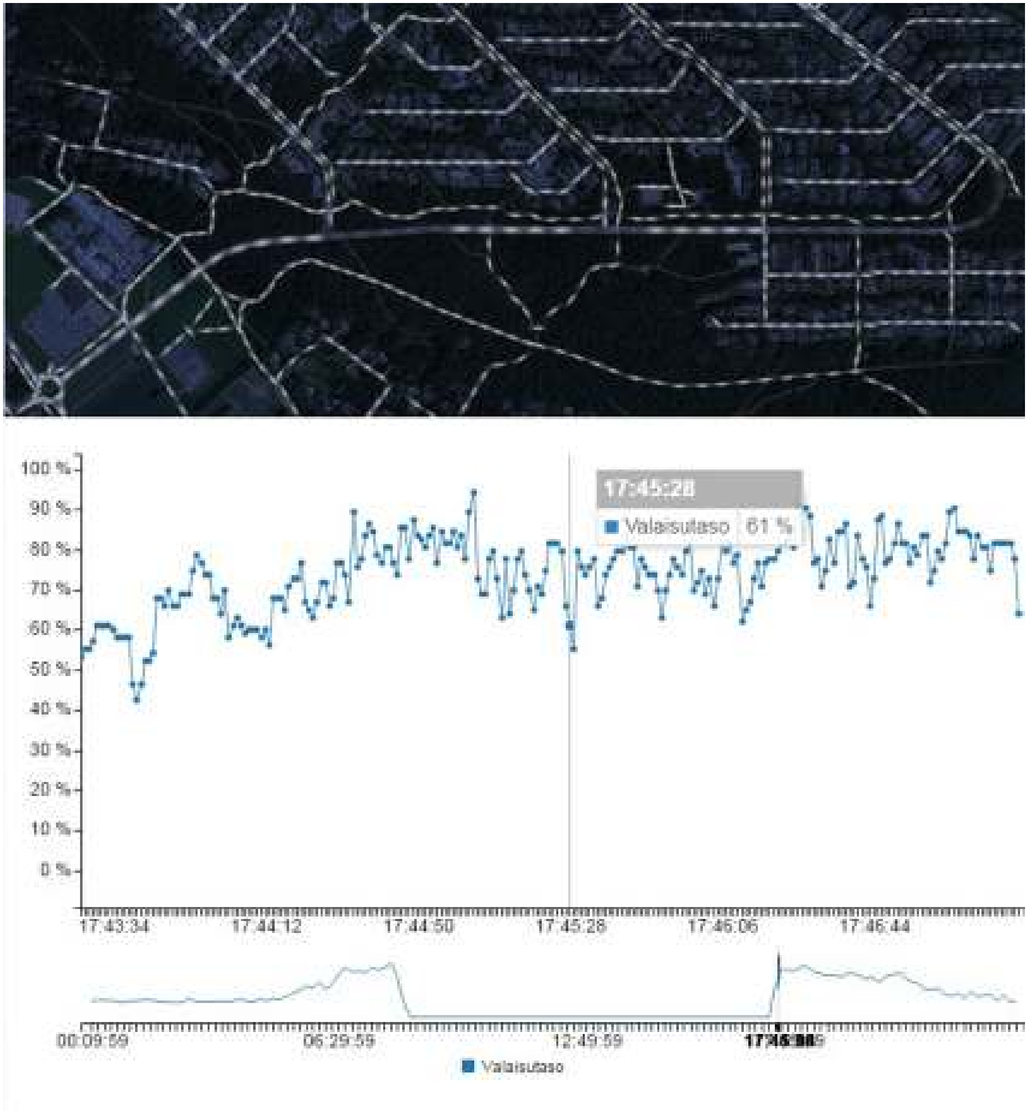


Figure 1
Screenprint of the simulation of intelligent lighting in Kalkkimäenrinne.

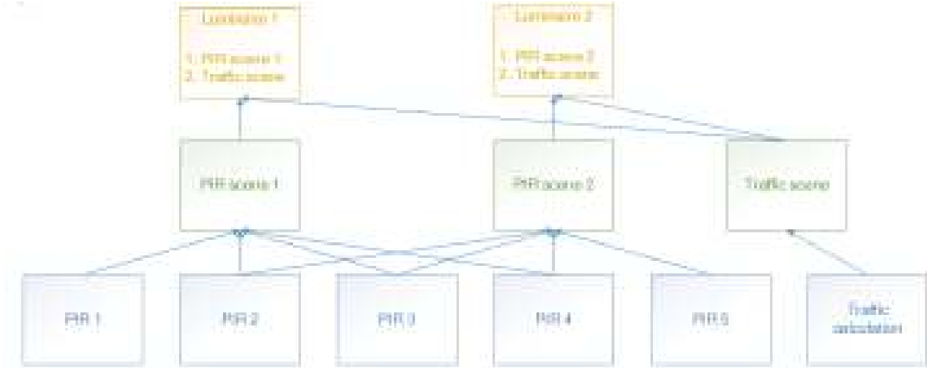


Figure 2
Relation between sensors, scenes and actuators (luminaires)

ing behaviour was realized in the form of a dynamic light map, presented on the aerial photograph of the housing area with dynamically altering illustrations of light distribution along the routes. A light map is a 2D drawing type used by lighting designers in describing the visual impression of lighting configurations in urban environments. In an earlier research project in University of Oulu (Adaptive Urban Lighting), the concept of a dynamic light map was developed for a design tool *VirtuAUL* for simulating the behaviour of adaptive lighting (Österlund & Pihlajaniemi, 2015). In the same project, a real time presentation of adaptive lighting behaviour in a park was realized with a similar kind of technique for a web-based mobile service describing urban information (Pihlajaniemi, Österlund and Herneoja, 2014). In the *City Monitor*, the aim was to create a dashboard interface, with which users could themselves change between different control types and zoom to different time spans of the chosen date. Besides dynamic light map simulations and lighting and energy consumption level charts, the dashboard included textual descriptions of each lighting control type and instructions how to use the simulator.

A lighting control ecosystem called *LightSense* was used to generate simulations of different lighting behaviors on the *City Monitor*. The *LightSense*, developed by VTT Technical Research Center of Finland, is capable of simulating lighting functionalities based on simulated time of day and sensor events.

The *LightSense* lighting controller manages the events based on publishing and subscribing to them. In the case of controlling Luminaire 1, as represented in Figure 2, the luminaire has subscribed two scenes: PIR scene 1 and the Traffic scene. Scenes subscribe events published by the sensor level. Luminaire configuration includes a list of subscribed scenes, their priority values, and all the settings relevant to that particular scene, for example, luminaire brightness and color temperature. When multiple scenes are active at the same time, the settings related to the one with highest priority, take place.

The scenes may be active at all times or be activated only when needed. The traffic calculation scene, which in this case is set as a low priority scene, runs all the time in accordance with the traffic levels based on traffic calculation events. PIR scenes are activated when a PIR event occurs. The scene stays active for a duration which has been set at the PIR scene configuration.

In the Salo pilot, a Finnish company Lumine Lighting Solutions Oy delivered the intelligent lighting control in Kalkkimäenrinne street. In the *City Monitor* simulations, all the passive infrared (PIR) data collected by the Lumine's system during the selected testing day (8.2.2017) was used. The sensor events were listed as comma separated values for each 41 luminaires. The sensor events were converted into a format interpretable by the LightSense lighting controller so that it could simulate the lighting situations as they were performed in real life by Lumine's system.

| | | |
|---|---|---|
| 555; | 8.2.2017 0:05:00; | 1 |
| 289; | 8.2.2017 0:05:23; | 0 |
| 287; | 8.2.2017 0:05:28; | 0 |
| 293; | 8.2.2017 0:05:33; | 0 |

Figure 3
Excerpt of the data fed to LightSense controller

Figure 3 represents an excerpt of the semicolon separated data fed to the *LightSense* controller. First value represents the node or event happening at the day, and time is seen as the second value. First row having the value of 555 has a special purpose. It represents a moving average of the total number of vehicles passed through the pilot area. The moving average has a range of 10 minutes. Other three rows represent PIR sensor events and the time they occurred.

The accuracy of the simulation depends on the speed it is run. For quick demonstrations, the simulation can be accelerated 1000 times, simulating a full day in 1.5 minutes. However, at this speed, simulation artefacts occur in individual luminaire levels, i.e., at some points, some luminaires may have been turned off when they should have been on. This generates approximately a 10% error to the total simulation. The simulations used in the City Monitor have been accelerated to double speed, which generates no errors at all, and a full day can be conveniently simulated during out of office hours.

Figure 1 represents the results of the simulation visualized as a dynamic interactive web page. The figure above visualizes the Kalkkimäenrinne pilot area and intelligent lighting on a map, the figures below show the average lighting level and energy consumption of all the luminaires in the test area during the day, as a percentage of the maximum level. In the upper chart, user can zoom to a desired time span. The image above the chart represents the state of all the luminaires at a time of day the user has selected by hovering a mouse cursor over the lower chart. When a user moves the cursor over the values on the chart, a tooltip shows an average lighting level, in this case 61 %.

The simulator generates data in JSON format, which represents the state of all individual luminaires at every second in the day. The data is inserted into a MongoDB database in four resolutions: raw data for every second, and averaged data by 10 seconds, a minute, and 10 minutes intervals. The data is served from the back-end so that the majority of the data is queried in 10 minutes resolution. The data selected by a user is retrieved from the database in the best resolution available. In the Figure 1, the selected area is so small, that in this case, the data is retrieved in 1 second resolution.

The other types of information were visualized with different techniques. The Finnish Transport Agency (Liikennevirasto) provides an open interface that can be used to access street camera images, traffic fluency information, automatic traffic measurement information and real time weather station data in JSON format. We have selected one camera in the Salo region that shows the visual road and weather condition as well as air and road temperatures at the same location. The weather data and the image is reloaded every five minutes.

The *City Monitor* also provides information on the current events in the city. The city of Salo provides many web pages and RSS feeds where the information can be harvested. The city monitor shows the events for each day on a map as well as in a list form. Each event has a link to the original event page on the web pages of city of Salo for further information.

The lighting simulation, street camera view and the city event map were created as separate web pages, which were imported on the dashboard page using HTML iframes. The iframes allow incorporating basically any other web page on another web page, as in this case, on the main Sencity *City Monitor* page running on WordPress. Because of the resolution constraints, the *City Monitor* shows a grid of smaller, but usable preview views, which the user can enlarge for better usability.

### *Participation and research*

In the *City Monitor*, participation and research are intertwined. In this pilot version, we encompassed two web-based questionnaires in order to involve users to develop both the future lighting design for the City of Salo and the city dashboard.

The user enters the *lighting related questionnaire* through that section of the dashboard, where the simulations are located and information about lighting solution is provided for the users. The questions were related to the general attitudes about lighting in urban environments and specifically to the three tested control methods of lighting. Additionally, we asked feedback of the simulations and the visualization methos of lighting and energy information in the dashboard: Were the simulations and graphics illustrative and clear? Did they help the user to understand the function and behaviour of lighting in Kalkkimäenrinne street? Did they help the user to understand the relation of lighting to energy consumption? How could the presenting of information be developed? As the participants for our research had already been evaluating the realised lighting control options in the real world, we were also interested in learning whether this given knowledge has an influence on their opinions about the solutions.

The other *questionnaire* was meant *for developing the City Monitor* itself with the feedback from the users. The questions were related to the participants' use of digital technology in everyday situations and to the idea of a city dashboard. What kind of information would the participant like to gain through the *City Monitor* and what kind of information should not be presented there? What kind of thoughts does this kind of presentation of real-time knowledge about the city raise in the participants? We were also interested to learn in what ways the participant would like to interact and communicate with the *City Monitor*. We also asked the participants to evaluate the pilot version's usability and presentation methods.

The questionnaires were realized with Google Forms tool. Besides these structured means of giving feedback, which was going only to the researchers at this point and not to be published as such, there was a possibility to publish comments visible for other users in the *City Monitor*, as tweets.

## DISCUSSION

At the moment of writing this paper, we are still in the process of launching the *City Monitor*. We are hoping to get a high participation rate and a good sample for our research to aid the development further.

In the pilot version, all the elements of the *City Monitor* vision were not yet realized. The dashboard was operating only on the citizen layer, which was meant for sharing information, participation and research. In addition to this, the complete city dashboard would have an administrative layer for city authorities and a third, business layer for companies. In this way, the same data could have three forms and three purposes within the city dashboard, which would operate as a development platform. For example, PIR sensor data of an area can be transformed to visualizations of flows of people, or, like in our case, to simulations of smart lighting behaviour. On the citizen layer this is shared as information. On the business layer, companies can gain or purchase the access to the generated and stored data, in order to analyse it and develop applications and services, both for city authorities and citizens. On administrative layer, the city authorities can benefit from the analysed data which aids the decision making and development of maintenance processes, for example.

New technological solutions, such as smart lighting, are often unfamiliar for users and city authorities and hard to comprehend as complicated systems. This may hinder testing and applying new solutions, and exploiting them commercially. New means of communication and visualization are needed, such as the simulator for smart lighting presented in this paper. We hope that it can in an interactive and illustrative way to help users to discover themselves the influence of different control methods on the illuminated urban environment and on energy consumption of lighting.

In addition to the highly research-oriented participation methods - the questionnaires - which we used in this pilot version, other more lightweight methods to involve users could be applied within the *City Monitor*. These could activate inhabitants to look after their own urban environments and to take responsibility of it, for example by adding feedback or notice of defects on the map, or by giving hints of nice spots or events in the neighbourhood. In our vision, the local-context-oriented nature of the *City Monitor* would encourage users to take possession of their own city, in the virtual and in the real.


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# DSA - Digital Support for Art

## *Process and Tools to Realize a Large Sculpture in a Heritage Urban Environment*

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*This paper reports on a research project oriented to support the communication for, and realization of a sculptural masterpiece within an urban context in the historic centre of Rome. The sculpture has been installed just a few months before the 2017 eCAADe, thus enabling conference participants to explore the final output in situ. While the whole process of creation of the art piece is outlined, our focus is on the description of implementing various technologies like laser scanning, Virtual Reality (VR) and Numerical Simulations that have been used to accomplish the relevant tasks. The general field of investigation is how digital tools and a VR approach to modelling, simulating and developing sculptural components of an artwork could facilitate the workflow between artist, client, designers, engineers, urbanists, archaeologists, art foundry fabricators and public authorities. Methodologically, an action research approach was adopted for this project, primarily for its ability to link between research and practice in order to solve a realistic multidisciplinary problem in its actual setting.*

**Keywords:** *Cross-disciplinary Collaboration; Virtual Reality; Integrated Design; CAVE; Digital Support for Art*

## INTRODUCTION

This paper reports on a research project oriented to support the communication for, and realization of a sculptural masterpiece within an urban context in the historic centre of Rome. In respect of the scheduled workplan, the sculpture has been installed at the end of May, just few months before the 2017 eCAADe, enabling conference participants to explore the final output in situ. While the whole process of creation of the art piece is outlined, our focus is on the description of implementing various technologies like laser scanning, Virtual Reality (VR) and Numerical Simulations that have been used to accomplish the relevant tasks.

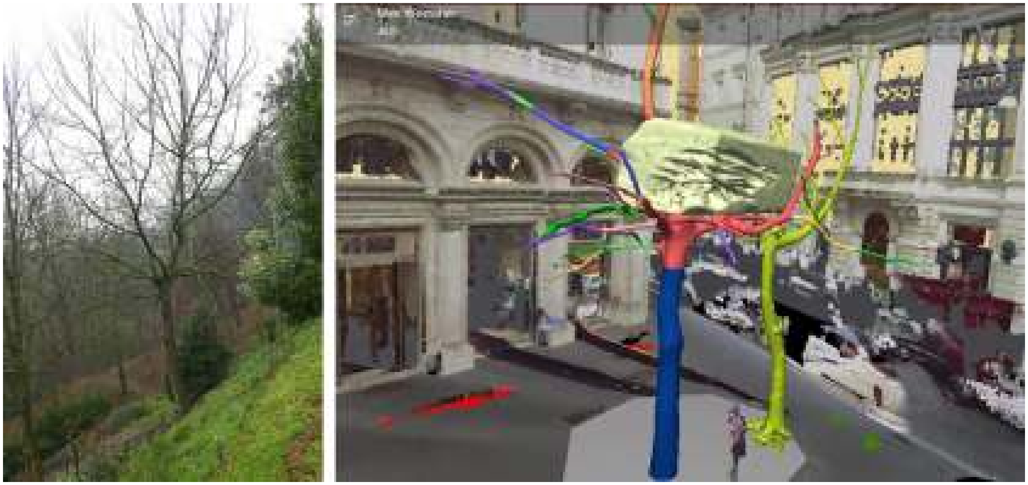

Figure 1
Real tree (left) to be transferred into artistic artpiece (right, VR-visualization with color coding)

The general field of investigation is how digital tools and a VR approach to modelling, simulating and developing sculptural components of an artwork could facilitate the workflow between artist, client, designers, engineers, urbanists, archaeologists, art foundry fabricators and public authorities. Methodologically, an action research approach was adopted for this project, primarily for its ability to link between research and practice in order to solve a realistic problem in its actual setting.

## SCULPTURE AND PROJECT PHASES

The artist, Giuseppe Penone, key exponent of '70 Poor Art movement, has been called by "Fendi", a fashion company, to produce a work of art for donating it to the City of Rome, to be installed in an urban public heritage space, "Largo Carlo Goldoni" square, close to the Spanish Steps. The work consists of the artistic transposition of two real trees, whose maximum height "above ground" amounts to 17.53 m, and their total weight to 8 tons. They support a large

Figure 2
Discretization of wood components (left), samples of cast bronze branches (right)

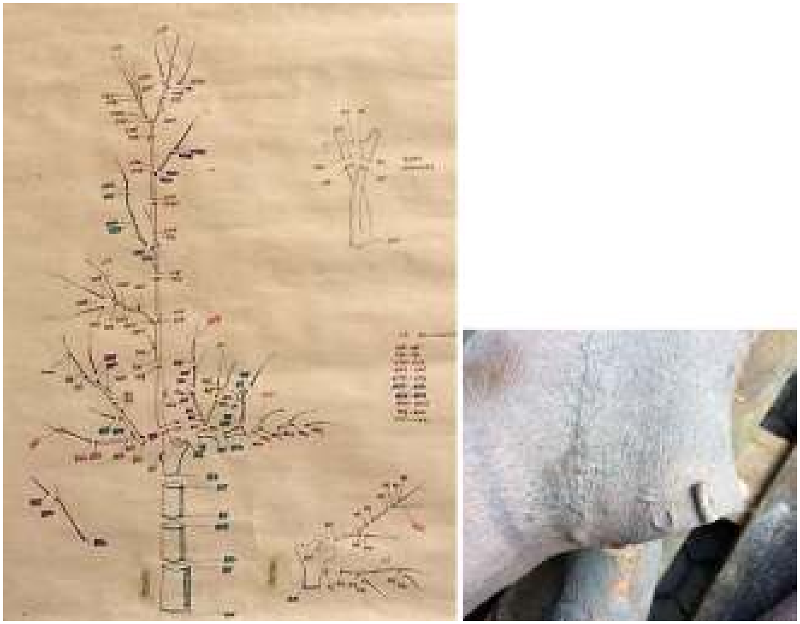

Figure 3
Sketch: Mapping tree elements (top), identification number and orientation mark in cast (bottom)

Figure 4
Bronze branches temporarily mounted on a board for scanning from different positions

block of stone approximately 3.5 x 1.5 x 1.5 m, weighing 11.4 tons. (see Figure 1)
The development pipeline can be summarised in the following phases:

1. Artist idea and rationale: Identification of real trees;
2. Finite components discretization and cataloguing;
3. Construction of the mold and casting of components;
4. Digital survey of both, the artworks' components and the installation context;
5. Digital reconstruction of three-dimensional model in the context;
6. Testing and remodelling of the artwork in an immersive virtual environment;
7. Manufacturing of a three-dimensional model for architectural/urban representation and evaluation;
8. Realization of a three dimensional CAE model for structural analysis.

While phases 1-3 were carried out in a conventional, analogue way, it turned out that due to numerous constraints the project could not be realized within the given time frame without a supportive digital workflow. It was both needed technically (e.g. for the structural analysis and for the assembly of parts) as well as for optimization and communication of the design.

## REVERSE ENGINEERING OF THE TREE CAST IN BRONZE

In similar projects, the artist optimized the design of the artistic trees directly in the foundry. The single cast bronze pieces as well as necessary interior static structure elements were adjusted to the artist's directions in the foundry at scale 1:1 by heavy lifting, welding and cutting in a cumbersome manual process. Compared to these projects, the boundary conditions of the discussed project are much more complex, just to name some constraints:

- seismic requirements in Rome
- distance from surrounding facades/buildings/car lane
- distance from lighting cables
- restrictions on visual impacts (max 80 m)
- foundation in a highly installed ground of archaeological importance
- tight timeframe
- branches have to maintain a clearance of 5 m to existing public lighting wires, traffic signs and two floor buses passing very frequently on the adjacent street.

As it turned out, a realization with the conventional approach was not possible within the given constraints. After phase 3 it was decided to switch to a different approach with digital tools supporting further realization. The authors proposed a digital workflow, which covered all following project phases up to the final installation of the art piece. The proposal was accepted by all participants and then carried out by the authors.

In phase 4, 61 different bronze cast branches had to be scanned, identified and re-assembled in 3D. Whereas it would have been much easier to scan the whole tree or at least main parts of it, the late decision to implement the digital method required us to reverse engineer the tree. An overview over the marked elements as well as a reference line on some cast elements helped to a certain degree but the procedure still caused substantially more work. (see Figures 2 and 3)

For the scanning process a FARO Focus 3D laser scanner (range: 0,6 m - 130 m, distance accuracy 2 mm) was used. Each branch needs to be scanned from at least 3 positions in order to have enough overlap for a seamless reconstruction of the cylindrical shape. In order to reduce the overall scan time (a high-resolution scan takes more than 5 minutes), several branches were mounted on two boards and scanned together from 4-5 different positions. The complete scanning procedure took about 12 hours. Each scan captures a spherical 360° area around the scanner, just excluding a 15° cone at the base. (see Figure 4)

Figure 5
3D scanning of the 11,4 tons block of marble carved in the workshop of stonemason

Figure 6
Scan sessions at night (less crowded) and during daytime (crowded)

For the next step, FARO “SCENE” was used to register the different scans to each other and crop out the area of the point cloud which contains the branches. A surface reconstruction was also carried out within Scene with a typical triangle size of 20 mm. At a branch diameter of 50 mm, these results in a surface approximation of 2 mm, which matches the distance resolution of the scanner. A higher resolution would not be more accurate but would only capture more noise.

The surface models were imported into Autodesk 3DS Max, where a hierarchical model was created which resembles the structure of the tree as it was sketched by the artist (not as grown). The coordinate axes were aligned to the branch directions of the lower end of each branch so that a rotation around the main axes of each piece would not result in a discontinuity of the overall branch.

In addition to the branches, the main marble block which was in the final stage of being carved by hand had to be scanned too. Tests with a Mantis Vision hand held scanner did not work out at all. Apparently, the marble surface did not provide enough visual structure to allow the scanning software to track the scanners position.

Thus, the same method - scanning with the Faro laser scanner - was used again. 11 different positions were chosen - from below and from above - to capture the whole stone except for the positions that the stone block was placed on. (see Figure 5)

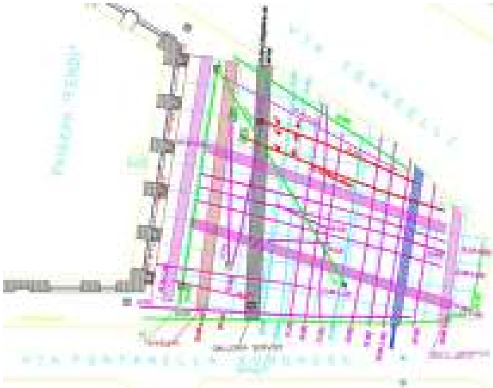

Figure 7
Results of GPR scan of underground infrastructure

## CAPTURING THE SQUARE AND ITS SURROUNDING

As the focus of the project is set on supporting the realization within the surrounding context, it had to be captured both above and below ground.

A first a volumetric model was generated from OpenStreetMap data, the outlines of the blocks and buildings were imported in Autodesk 3DS Max and extruded to an average height. However, for the visual representation for the planned CAVE (Cave Automatic Virtual Environment) VR working session, a more realistic and far more detailed capturing method was needed. Again, the previously mentioned FARO laser scanner was used to scan the street

Figure 8
Workshop in CAVE optimizing the project

space from the Spanish Steps to the Largo Goldoni Square.

This was 4 blocks along Via dei Condotti as well as the buildings surrounding the square. All together 21 scans were made. Four night-time test scans showed, that the spatial impression for the project is better done with daytime scans. And though the advantage of less people and traffic around night-time and thus in the scans, we decided to do 17 daytime scans, one at every street crossing and multiple scans on Largo Goldoni Square to compensate for shadowing by pedestrians and vehicles.

Further scans from the roof of a building at Largo Carlo Goldoni were taken to complete the square surrounding and having protrusions like balconies fully captured and not only from street level. However, the daytime scans (approx. 4-5 hours of scanning) required a lot of manual work to remove people and cars from the 3D point cloud. (see Figure 6)

The foundations of the artwork, namely the roots of the two shafts, can find a place only and exclusively in a position such as to be compatible with the interference constraints constituted by the numerous underground infrastructure lines which exist in the subsoil.

Because only rare and unreliable information is available, a survey by GPR Georadar instrumentation was undertaken. So the 3D model was further enriched with this mapping of the underground infrastructure. Due to the limited information density, it was only modelled as boxes and tubes in the 3D model based on the survey plan. (see Figure 7)

## COMBINING ACQUIRED DATA AND VISUALIZATION = VIRTUAL REALITY

After having acquired all relevant data, a full day workshop was held in the CAVE at High Performance Computing Center Stuttgart (HLRS). Participants were the artist, several involved engineers as well as the client. The focus of the workshop was to finalize the geometry of the artwork, find the optimal solution with the engineers and communicate it with the client to approve the design. (see Figure 8)

For this interactive workshop, the static point clouds of the surrounding as well as further geome-

Figure 9
Workshop narrative

try like underground piping were imported into the VR software COVISE/OpenCOVER[1][2]. A plugin was programmed to interact with the tree and with the fabricated tree parts/branches. The branches could be picked and freely moved with a 3D mouse.

To interact more precisely, rotation and position sub branches could also be changed numerically with sliders and number input fields on a tablet PC. The CAVE model was updated instantly. The whole tree, its foundation, individual branches, and also the stone leaves were moved through multiple iterations and therefore optimized for aesthetics and also functional parameters.

The decision-making process was facilitated and strengthened by means of a conceptual session of "digital sculpturing". The artist was able to get a preliminary view and also edit his work right in the virtual urban environment. At the same time, all

Figure 10
Output of the workshop: digital model approved by the artist and 3D printed model

other participants in the session could carry out their assessments in real time and thus could give feedback on the constructability of the artwork. They could also evaluate the impact of the artwork against the context-dependent constraints, including compliance of the foundations with underground services. (see Figures 9, 10 and 11)

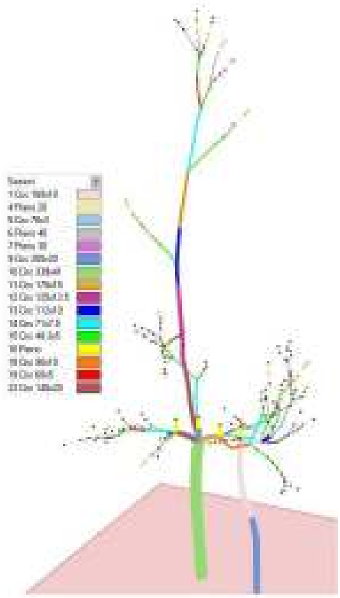

Figure 11
Reconstruction of the geometric model of tubular and structural nodes

## PROJECT IMPLEMENTATION

The installation working site for ”Leaves of stone”, which included the maturation time of the foundations’ castings, took place coherently with the planned schedule.

In less than a month the following phases have been respected: Archaeological excavation and digging of foundation (5x6x3m); Siting of plinth reinforcing steel bars; Plinth concrete casting; Hardening of concrete; Insertion of prefabricated iron bearing piles (depths of 12-15m); Covering and restoration of the paving; Unloading of the work of art components, discretized for transportation; Installation of steel and bronze pieces; Placing of the marble stone; Final finishes.

For the inauguration of the work of art, permanently installed in the public space, a ceremony was held on May 22nd 2017 with the presence of the highest institutional representative and international press: the image of the sculpture, its three-dimensional shape in Largo Goldoni’s space, after the unveiling, looks identical to the one prefigured by the simulation experiment.

3D rendering and printing output of the Stuttgart workshop, which was held seven months earlier, allowed the right procedural time for the authorisations by the competent authorities. As a result, the project implementation is compliant with all the existing regulations. The simulation has shown to be consistent with what has been phisically achieved:

Figure 12
Photo-simulation including 3D rendering of the artwork

Figure 13
Largo Goldoni today, after the installation of artwork.

this is a succesfull demonstration of this applied research work (see Figures 12 and 13).

## CONCLUSIONS

The discussed results explain the benefits and challenges observed using this method as well as provide avenues for further investigation.

For the overall project, these technologies and methodologies showed their effectiveness in speeding up the process and increasing its quality. For example, one of the two trees turned out to be about one meter shorter than previously envisioned in the conceptual phase and thus one of the trees had to be cut shorter in order to have its roots at the correct height. If this operative task were realised in the Foundry instead of in the CAVE, it would have implied at least 3 months of deadline postponing. Most of the branches were rotated and modified according esthetical issues and clashes with the stones and surrounding buildings. The "leaves of stone" have been revolved and redefined in order to create an axial variation according to global perception. Finally, the foundations have been defined.

Digital simulation has shown to be consistent with the masterpiece that has been phisically achieved, thus compliant with all contextual constraints: this is a succesfull demonstration of the multidisciplinary applied research work.

By means of structured interviews to the involved actors, an original contribution is that the research helps in clarifying some of the ambiguity relating to: digital modelling and traditional sculpture technologies working in tandem; Virtual Reality as simulation tool for managing complex urban context constraints; culture of art versus culture of technics. The result of structured interviews of all participants are currently ongoing and will be presented in next future.

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[1] https://github.com/hlrs-vis/covise

[2] https://www.hlrs.de/covise/

# Data-responsive Architectural Design Processes

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*Current advancements in information technology and mechanical components offer incredible new possibilities for innovation in architecture. Many aspects of our physical environment are becoming integrated with information systems, a phenomenon that has been referred to as the ``Internet of Things.'' The implications and applications of this technology are far-reaching, and students who are learning about design in today's environment have a bewildering array of new tools available for their exploration. This paper reviews some of the central concepts of contemporary data-driven design, and describes how these concepts can be used in a pedagogical framework to encourage student innovation. The authors provide details about their work with students in IDR Studios, and highlight some of the innovative design solutions created by students using information-based toolsets. This research provides a pedagogical framework for helping design students to engage with new technological resources as they work to develop the architectural intelligence.*

**Keywords:** *Adaptive Systems, Internet of Things, Big Data, Data Driven Design Process*

## INTRODUCTION

The Internet of Things (IoT) is the name frequently given to environments in which wireless sensor networks, transceivers, and physical actuators merge with information systems, allowing the physical devices to respond to one another and to human participants, either directly or remotely. In other words, many parts of our physical environment are on the verge of becoming extensions of the Internet (Atzori et al. 2010; Gubbi et al. 2013; Vermesan & Friess 2014). The emerging IoT can be seen in many places, including homes, industrial workplaces, hospitals, energy grids, and traffic management systems (Bellavista et al. 2013). Urban services are a particular focus of growth for the IoT, due to the complexity of city environments-and also, perhaps, due to a push by national governments to more fully monitor and control public affairs. While a variety of policy-related concerns remain to be addressed in this area, it is undeniable that the IoT has much to offer humanity, including great improvements in efficiency in the areas of energy consumption, traffic congestion, industrial monitoring, waste management, and all kinds of city infrastructure use and operations. Taken together, this application of the IoT in civic infrastructure has been referred to as the rise of "smart cities" (Schaffers et al. 2011; Zanella et al. 2014).

In an ever-changing social world, the most congenial built environment is one that does not limit us and impose itself on our aspirations, but rather has the capacity to change and respond to our needs in a fluid manner. Throughout its history architecture has evolved in this fashion, incorporating the latest technologies to better serve various social goals. In today's world the pace of innovation is accelerating exponentially, making new technologies and materials available to the field. The use of these new technologies in architecture can be an important tool for meeting contemporary social challenges, making our lives more amiable, and reducing resource consumption. Real-time data gathering and analysis, in particular, allows us to automate routine tasks at both the micro- and macro-levels, improving the ease and effectiveness of our daily activities. These "smart environments," when appropriately implemented, can make our lives more convenient. They also have the potential to be more flexible and responsive than traditional architecture, thereby expanding the range of our freedom and creativity (Batty et al. 2012).

This paper presents an overview of several areas in which architectural design can be usefully supplemented by contemporary data systems, building bridges between the world of information and the world of physical design. It also demonstrates the way in which such approaches to design are being integrated into pedagogical frameworks to help students explore their creative capacities within an ever-changing technological world. Everywhere around us today the informational and physical realms are becoming more interconnected. What is the role of the architect in this context?

## ARCHITECTURAL DESIGN AND THE BIG-DATA CLOUD

The big-data revolution has influenced every aspect of a city life over the past two decades. However, smart cities are not merely the result of data collection; the quality of the urban environment resides mostly in how the data is used. Civil servants can implement systems that analyze, synthesize, and react to data as a means of improving social and economic services. The primary methods of collecting this data involve linking GPS information with satellite remote-sensing, smart phone applications, online social media networks, and interactive data systems focused on crowd-sourcing. The result is a rich field of opportunities to better understand how cities function (Batty et al. 2012). New data-driven techniques can allow for a rational and objective design process that achieves high-performance, efficient architecture tailored to a specific geographic context. As a result, the built environment becomes an active participant in the life of smart cities, drawing on data to respond to the needs of the city inhabitants. When architecture and urban design are driven by ongoing data collection in this manner, the result is a more flexible design process that grows and adapts to residents, much in the same way that a biological organism adapts to its local environment.

Sensors and cameras, digitally-controlled utility services, telecommunication networks, transportation infrastructure, and building management systems can also provide sources of information that can be monitored, analyzed, and fed back into the system to improve city services. When combined with information volunteered by individual residents, this "every-ware" data offers a more cohesive understanding of the city across multiple scales (Hancke & Hancke 2012; Townsend 2013). It can be used to evaluate existing conditions, to predict future outcomes, and to facilitate design and planning. At the same time that it improves the delivery of public services, the "every-ware" approach can also support greater public access, participation, and transparency (Allwinkle & Cruickshank 2011; Schaffers et al. 2011; Batty et al. 2012; Kitchin 2014).

The field of architecture has much to gain by drawing from developments in computer science, and in particular from the IoT approach. By incorporating interconnected sensing and actuating components in urban architecture, our designs become more responsive and gain the ability to share information as part of a unified smart-city framework. Eventually, the connection of data to the built environment will change the architectural design process into a data-driven field that better responds to human needs both before and after occupancy. This approach will help to blur the hierarchical distinctions between owners, designers, and inhabitants, and it can empower ordinary people to have a greater say in the construction of their environments.

## A STUDIO FOCUSED ON ADAPTIVE SYSTEMS IN THE BIG-DATA ERA

The primary idea behind adaptive systems is to make architecture more responsive to the needs of its inhabitants in a day-to-day fashion. Adaptive systems have been used since the very beginnings of architecture; they can be as simple as doors and window-shutters, which allow the occupants to make adjustments to temperature and air-flow as needed. In the contemporary world architectural adaptability can also be incredibly sophisticated, as can be seen, for example, in the kinetic works of Santiago Calatrava (Millwake Art Museum 2001). The degree of adaptability in contemporary buildings varies widely according to the sophistication of the embedded machines. In general, however, recent years have seen an explosion in the prevalence of adaptive architectural systems, which has corresponded to the increasing practicality of artificial intelligence and active mechanical components.

Scholars have analyzed and categorized adaptive systems in a variety of ways. Fox and Yeh (1999), for example, classified kinetic architecture into “deployable,” “dynamic,” or “embedded” systems. These authors then also divided the means of adaptive manipulation into “internal control,” “direct control,” “indirect control,” “responsive indirect control,” “ubiquitous responsive indirect control,” and “heuristic responsive indirect control.” Ramzy and Fayed (2011) proposed an alternative categorization that organized adaptive systems based on the extent of their kineticism, their configuration, and the specific mechanical techniques used. What all of these commentators agree on is that adaptive systems are becoming increasingly important in today’s architecture, and that they have an important role to play in addressing social and ecological needs. Numerous scholars have called for research growth in developing new design methods and performance-based paradigms to support the spread of contemporary adaptive systems (Ramzy & Fayed 2011; Arenas & Falcón 2014; Kalantari 2016). The IoT and related computational technology merges seamlessly with the goals of adaptive architectural systems, providing tools that designers can use to enhance the environmental quality of buildings and promote more flexible, human-centered designs.

In a studio class that the authors have developed based around the use of adaptive systems, students explore methods of designing amid responsive environments in the era of big-data and informational-physical interconnectivity. Their journey starts with an immersion in scholarly literature and lectures about computational methods for information analysis. This instruction is combined with more traditional architectural education regarding the behavior of materials, fabrication, assembly, and so forth. In developing their projects, students make use of cutting-edge architectural software such as Grasshopper and Firefly, Python scripting, and a physical computing environment using Arduino microcontrollers. Students in the studio used these tools to design a new visitors’ center for their university, drawing strongly on the principles of adaptive systems and data-driven design. Examining the research process that these students went through demonstrates the exciting possibilities of designing amid the IoT.

### *Phase 1: Understanding the Internet of Things*

The first part of the design process for students was to conduct a literature review to better understand contemporary outlooks on the IoT. The students were assigned to convey their understanding of the literature in the form of info-graphics (Figure 1).

Students engaged in the university visitors’ center project were divided into four groups for the purpose of conducting the literature review, with each group focusing on a separate topic:

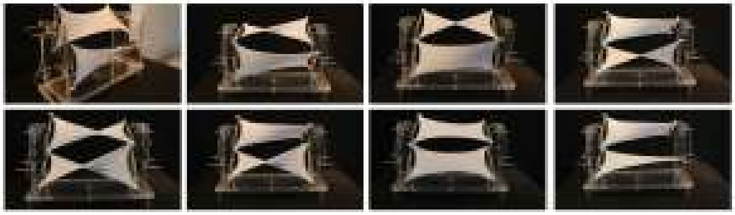
- IoT Smart City Applications. Students in this group researched the concept of the smart city and the ways in which smart cities optimize resource-use, planning, and services. They learned about information exchange protocols and the integration of informational analysis with the physical components of the city, including transportation systems, utilities, and other major city components.
- IoT Smart Building Envelope and Structural Applications. Students in this group researched adaptive structures in the building envelope, and how these structures are becoming connected to information systems as part of the IoT. They examined case studies focusing on kinetic systems and climate-responsive design through different mechanisms such as operable roof systems, movable building flooring, and kinetic apertures (Sherbini & Krawczyk 2004; Gelpi 2013).
- IoT Smart Space Applications. Students in this group researched the integration of the IoT within interior building spaces, as a means of creating greater spatial flexibility, functional plurality, and performance quality. The use of the IoT in interior spaces can promote human interactions with the built environment as well as improving the overall occupant experience. The data-driven aspects of design become very important in this context, and allow for a better understanding of human behaviors and needs in interior building spaces.
- IoT Building Automation Applications. Students in this group researched how the integration of IoT applications into building systems can allow facility managers to more effectively and proactively maintain buildings at peak operational efficiency. They learned about the use of sensors and automation that allow smart buildings to improve in energy efficiency even while providing more comfortable and productive conditions for occupants. The students examined the different needs and technological solutions that go into the operational management of smart buildings, and investigated how individual buildings are beginning to be seen as a part of a much larger city system through greater informational connectivity.


Figure 1
Info-graphic showing the potential relationships between Kinetic Design and the Internet of Things. This figure demonstrates the potential of real-time data to create higher-quality and more user-interactive architecture.

### *Phase 2: Exploring Adaptive Systems*

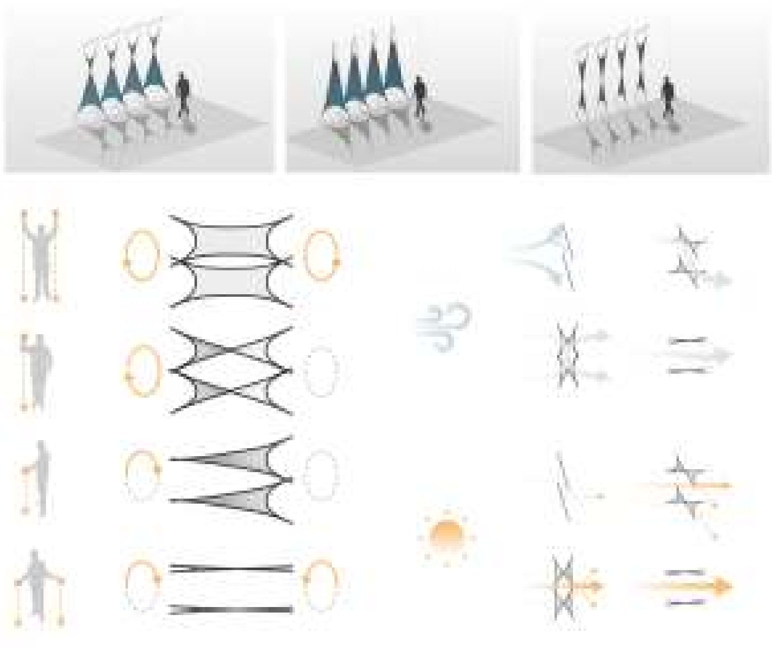
In the second part of the design process the students began to experiment with physical spaces, observing how built environments can be designed to gradually change based on various environmental and user inputs. They designed and fabricated a kinetic mechanism to explore the operation of adaptive sys-

Figure 2
Translating human movement into the form of the adaptive model.



tems, and they investigated how naturally occurring adaptive systems can serve as the inspiration for programmable built environments. A knowledge of material behavior and transformable, foldable, and deployable systems was vital in this exploration. The students were required to consider how their designs would change over time, and to incorporate activators such as heat, humidity, light, and motion. They made use of computational modeling in their explorations, as well as technologies such as 3D-printing, laser cutting, CNC routing, plasma cutting, and vacuum forming. During this phase the students also had the opportunity to collaborate with the members of the university's Robotics Club to learn more about the use of micro-controllers. Many of the students had no previous experience with these topics, which resulted in a wide variety of unique and creative innovations as they gained vital practical knowledge in the field (Figure 2 & 3).

Figure 3
The motion-tracking system allows users to interact intuitively with the built environment, adjusting factors such as light-opacity and the direction of air-flow through either intentional gestures or passive environmental responses to the human presence.



### *Phase 3: Creating Data-Based Scenarios*

Using the knowledge gained through their previous explorations, students in the studio went on to produce designs for a new university visitors' center. These designs drew strongly from data-based scenarios and made use of adaptive system concepts. The resulting solutions show a strong effort to integrate the informational and physical environments. Students were instructed to design the building as a component of a smart city, and to incorporate elements that can respond to a wide array of data (including individual information volunteered through Internet-based media, city data such as demographic information and transportation schedules, and "machine-to-machine" data derived from sensors and related devices). Participating in a data-driven design process allowed the students to develop scenarios through which their adaptive building designs would react to the environment and to human inputs. As can be seen in the following examples, the design solutions created by the students focused on very different aspects of data-driven design. They are indicative of the wide array of creative innovation that is possible through the use of information technology.

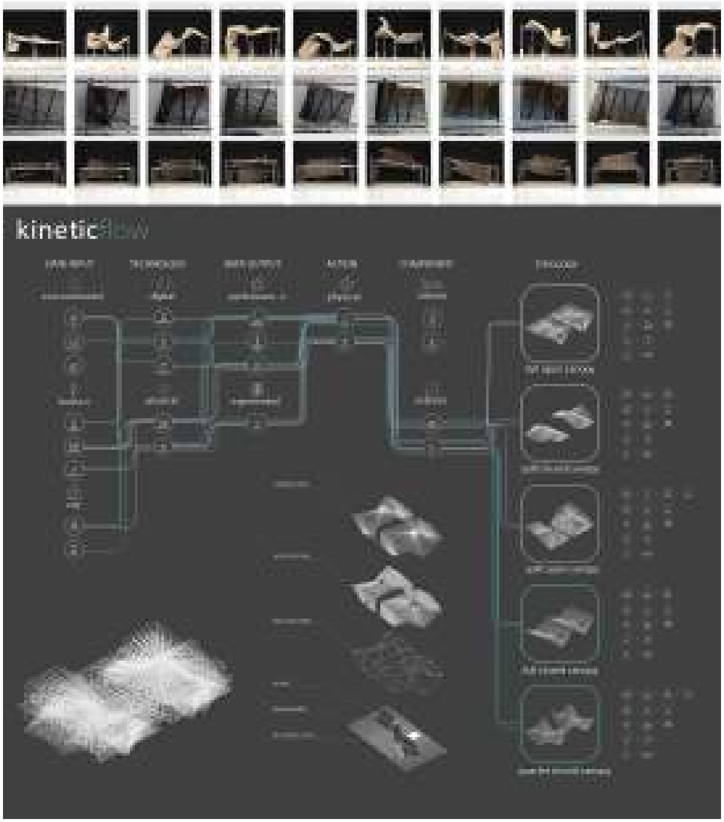
The KINETICANOPY Project. This building is aware of the constant fluctuation of population and climate. Using real-time data to inform and reshape the structure and skin of the building, this new addition to the university campus is able to accommodate a variety of event types and sizes, while also adapting to the ever-changing urban conditions of pedestrian circulation. Using a hydraulic piston system, the columns and beams of the building work as a cohesive network with the ability to move in multiple vectors, allowing for different possibilities of form and function. At the same time, a building facade composed of rotating panels has the ability to respond to ever-changing weather patterns and occupant circulation. The facade provides shade and shelter from the elements while also becoming a kind of interactive display as it adjusts to the environment and the movement of the building's occupants. Incorporating weather and population data into its calculations, the space continuously changes to suit the users' needs.

While much of contemporary architecture incorporates a biomimetic component in looking to nature for its form-making inspirations, the impact of this approach is often limited to formalism. Kineticanopy's exploration of bio-kinetics allow the architectural appreciation of nature to move beyond mimicry and to incorporate the changing natural environment in an ongoing, multi-directional interaction. The building also comes with its own app, a software program that can be downloaded to allow users to provide input into the lighting, shading, and spatial orientation to better suit their needs. The app includes a calendar and event-planning program that provides notifications about planned uses of the space, indicating any possible clashes. The app also incorporates information about nearby walking, biking, and driving routes and the features of the surrounding district and local businesses.

The new building will act as a gateway of expansion between the university district and the growing residential area surrounding it, allowing visitors, students, and the general populace to share ideas and create stronger connections with their environment. For the purposes of architectural development, Kineticanopy demonstrates a number of promising new concepts including transparency, large active deformation, and homogenous surfaces. The use of an electro-mechanical system connected to sensors allows for automated adaptation based on occupancy or predefined configurations. Interior spaces of the structure could also incorporate adaptive structures, including partitions, furniture, and other transformable elements that respond to user inputs (Figure 4).

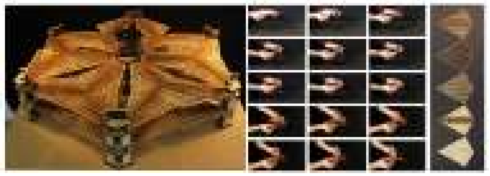
The TENSILBILITY Project. This building is an adaptive structure that adjusts to its users' needs based on real-time environmental and human data. The entire structure expands and contracts so that it is more energy-efficient when its full expanse is not needed. By processing information supplied by its

Figure 4
The Kineticanopy design proposal, showing the integration of machine-to-machine data in the project.




users and the surrounding environment, the building, as an active agent decides how to best adjust its walls, structure, openings, exteriors, and interiors. The design incorporates curvilinear-oval and curved-triangle patterns that are reflective of the surrounding environment and nearby river. These elements of the surroundings are also made visible through the generous use of glass construction. The furnishings are curvilinear as well, and are designed to be moveable to accommodate the changing form of the structure. The interior spaces respond primarily to human activities and input, whereas the exterior form responds primarily to environmental conditions, including the temperature, time of day, and weather. The structure creates a visually and intellectually compelling mixed-use space that meets all zoning requirements and encourages visitors to engage with students and the local community. While the ground floor is oriented according to the city grid, the upper floor's primary alignment is to local wind patterns, allowing for natural ventilation (Figure 5 & 6).

The GREEN VISITOR CENTER Project. This is an adaptive building that responds to solar radiation, human activity, and contemporary energy needs. It interactively connects the history of the site to a forward-looking and inspirational environmental ethic. The preservation of history is expressed through permanent gallery installations that help visitors learn about the natural and human setting that they are a part of, including the vision of the facility and its use of reclaimed materials. The environmental ethic is also expressed by incorporating an eco-space and natural light-well within the heart of the building, allowing students and visitors to interact and relax in contact with nature.



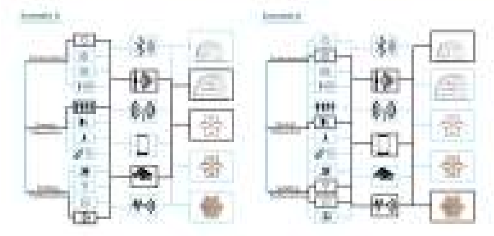


Figure 5
The Tensilbility design proposal, showing the integration of adaptive systems with real-time data.

Figure 6
The Tensilbility is a reconfigurable structure that interacts productively with both its occupants and its surrounding physical environment through sensors, microcontrollers, and actuators.

The green structure is remarkable in that it makes use of an adaptive system based around the benefits of algae, primarily as a source of renewable energy. The algae are incorporated into the building design as an organic mesh over the exterior surface of the building, as well in other locations, where they serve as energy producers, as a form of interactive sculpture, and as an interactive informational installation. The algae absorb sunlight and carbon dioxide, while producing energy, oxygen, fertilizer, and food. They even help to clean the nearby river, as its water is circulated through the building to support the algae ecology. This building looks to nature not only as an inspiration for a static ideal of beauty, but also an integral and continuing process in the built environment.

The building's form is made up of a hydraulic truss system that responds to solar data, curling downward and inward to create a cozier enclosure during poor weather, and curling upward and outward to provide more space and collect additional sunrays during pleasant weather. The truss will also respond to human input so as to create a more open or closed environment when necessary for programmatic reasons. The form of the building and the surrounding algae skin are purposely contrasting, as a symbol of the conflicted balance between humans and our environment. The algae skin appears to be engulfing the building, while the truss system pokes through the skin as though fighting back. In reality, however, the relationship is symbiotic in that the algae are providing power for the building, and the building gives structure and purpose to the algae cycle (Figure 7 & 8).

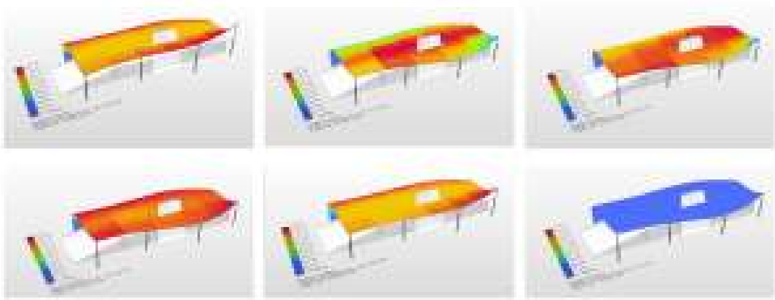
## CONCLUSION AND FUTURE WORK

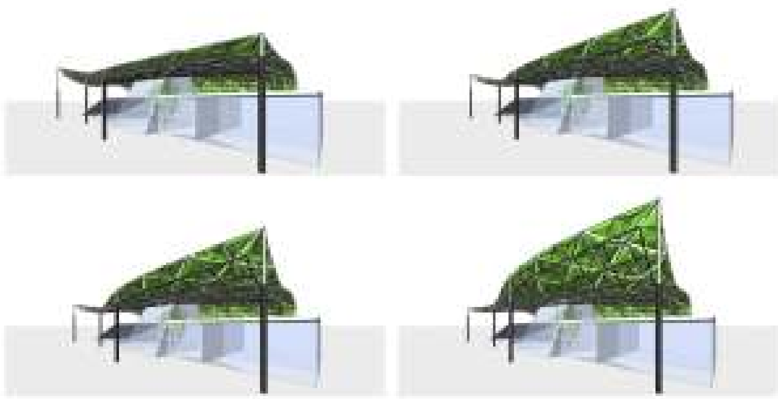
The Internet of Things can be understood as a seamless combination of data-driven design and adaptive systems. By showcasing the application of data-driven design strategies within a pedagogical context, this paper indicates some of the exciting innovations in architecture made possible by our current technological environment. The field of architecture has much to gain by drawing from developments in computer science and other related fields. As the interface between information systems and the physical environment continues to become more sophisticated, the prospects for innovation will only increase.

The educational approach described in this paper can be seen as a framework for integrating adaptive systems and data-driven approaches into a de-

Figure 7
The Green Visitor Center automatically adapts its configuration based on radiation analysis to absorb the maximum sunlight for algae growth.

Figure 8
The building's form is made up of a hydraulic truss system that responds to solar data.





sign studio and thereby unleashing students' creativity to innovate with cutting-edge technological tools. The framework starts by introducing students to the relevant ideas in computational design, fabrication, information analysis, and responsive systems operations, and then builds on this basis through practical experimentation and design. In taking this approach, students become part of a new paradigm in which "architectural design" is not limited to the physical environment, but is rather understood as an interaction between the informational and physical realms. This allows our design to more fully account for all aspects of the human experience and human needs.

The outcome of this ongoing research is a platform for designers to study and create amid the new possibilities of architecture in the current technological moment. Instead of suggesting an ultimate solution for kinetic architecture needs, this research provides a proposed method that serves as a stepping-stone to endless design discoveries. Our studio on contemporary adaptive design in the era of big data incorporates multiple disciplines in a collaborative goal-driven environment, encouraging designers and researchers to reinterpret architecture as a way of working amid the Internet of Things. Students are at the forefront of this process, as they learn to evaluate and analyze data-driven design potentials in order to create smarter environments for the future. The authors of this paper are excited to continue forward on this pedagogical path to see what our future holds.

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# DESIGN TOOLS - PROGRAMS

# Collective Construction Modeling and Machine Learning: Potential for Architectural Design

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*Recently, there are significant developments in artificial intelligence using advanced machine learning algorithms such as deep neural networks. These new methods can defeat human expert players in strategy-based board games such as Go and video games such as Breakout. This paper suggests a way to incorporate such advanced computing methods into architectural design through introducing a simple conceptual design project inspired by computational interpretations of wasps' collective constructions. At this stage, the paper's intent is not to introduce a practical and fully finished tool directly useful for architectural design. Instead, the paper proposes an example of a program that can potentially become a conceptual framework for incorporating such advanced methods into architectural design.*

**Keywords:** *Design tools, Stigmergy, Machine learning*

## INTRODUCTION: EMERGING TOOLS USING MACHINE LEARNING

What is intriguing for the author about recent progress in AI is the development of machine intelligence that can compete against and outplay humans in games such as strategy-based board games and video games. Recently, AlphaGo, a program developed by Google's AI company, DeepMind, defeated Lee Sedol, considered by many to be the world's strongest player in the game of Go, using algorithms such as deep reinforcement learning (Silver et al. 2016). AlphaGo was not initially preprogrammed by humans to play Go with any specific strategy, but its AI can learn to interpret the game's patterns and play against itself to improve its strategies over time. DeepMind also demonstrated that its AI can learn how to play early arcade games such as Breakout by Atari and surpassed human experts on some such games (Minh et al. 2015). Unlike other previous AIs that were developed for mostly pre-determined purposes using only functions to solve initially defined scopes, methods utilized by DeepMind are known to learn strategies for such games using data input based on raw pixels that represent states of games (Silver et al. 2016).

The methods by DeepMind use reinforcement learning as one of the core algorithms. Reinforcement learning is based on an important model of how humans and animals generally learn from an environment to find out strategies to collect rewards through experience (Sutton and Barto 1998). AI agents in such environments can choose to perform certain actions to increase their rewards and to improve their control of environments. This framework of reinforcement learning can be applied to environments of games such as Go or Breakout using deep

Q-learning network (DQN) algorithms. Using a digital tool more familiar to us such as the Unity3D game engine, Shimizu (2016) has presented an example that trains and teaches a character to catch more food pellets using DQN inside a gaming environment, and which uses pixel-based first-person views of the character as input data for its DQN. This open source example demonstrates that the character can gradually learn a better strategy for movements to collect more pellets within a limited duration and indicates that the toolkit can be applied to other games with different scopes and purposes.

Learning from these exciting advances in AIs that can compete inside gaming environments, the author has speculated about a hypothetical game-like format for a simulation environment that can work with computational methods such as deep reinforcement learning for applications relating to design activities. What if we were to create a computational environment where groups of AI agents could compete against each other to build habitable structures? What if we then used an advanced algorithm to train AI agents to build better structures that satisfy their needs? From these questions, the author proposes a simple conceptual project in this paper.

## COMPUTATIONAL INTERPRETATIONS OF COLLECTIVE CONSTRUCTIONS

One of the primary inspirations for such an approach is computer simulations of social insects' nest building behaviors, called collective constructions, conducted by biologists and computer scientists. Design processes in wasp and termite colonies are known to possess self-organizing processes, and their final formal configurations are the results of optimization by locally distributed multiple intelligences. In the notion of stimulus-response called "stigmergy" (Grassé 1959), information from the local environment under dynamic progressions stimulates and guides further activities in construction. A certain local state of the system becomes an incentive for the next construction for individual workers, and this process continues to feed new information to the builders. In this way, information is always provided from the dynamically changing environment rather than any source of information external to the ongoing construction activities. This is one of the reasons why social insects, such as termites, can undertake complex constructions without knowledge of the ultimate form of the structures. Consequently, the products resulting from these collective activities are often thought to possess emergent properties.

Theraulaz and Bonabeau (2000) are two of the pioneers who have provided the computational interpretations for the logics behind the collective constructions by wasps. Their interpretation of wasp behaviors was based on the notion of precedent stigmergy. In their conceptual experimentation using their computational simulations, the ultimate objective was to gain cohesive structure solely from locally assigned series of construction rules without providing any global information about the structure such as blueprints. The wasps in their model do not have any global sense of what they are constructing; instead, they have their local sensing as a stimulus to continue their constructions. The author previously had based some projects on applications of self-organizing aspects of collective constructions (Narahara 2008).

The generative methods of Theraulaz and Bonabeau were based on three-dimensional cellular automata with locally defined rules, and agents moving randomly inside the lattice to drop the building blocks according to the cellular neighborhood rules. The present author has adopted these ideas for the following proposed experiment, as this could potentially be a framework to apply aforementioned advanced approaches such as deep reinforcement learning.

## PROPOSED EXPERIMENT

The following is the overall picture of how the experiment works, with more details to follow. Groups of builder agents with different behaviors compete to construct building-like structures based on their actions inside a 3-D digital environment in a finite time sequence during one episode. After every episode, each group's performance is evaluated based on how well builders can construct structures under certain evaluation criteria. In principle, the evaluation criteria can be programmed in various ways (see later section for more details). The program for the experiment selects elite groups of builders which outperformed others from the previous episode in order to formulate new groups of builders by partially inheriting behaviors from previous elites. In theory, the program will develop more competitive builders that can construct better structures based on the applied evaluation criteria after many episodes-similar to the way programs using DQNs develop better AI players for games such as Go over time.

### *Actions of Builders*

The experiment starts with ten color-coded groups that consist of fifty builder agents in each group. The builder has four actions–*step, flock, attack, and build*–to execute in each finite time step of the running of the program and has the capability to sense and distinguish sixteen different local conditions that are detected through its cone of vision. The builder decides which action to take based on its detected condition in the current time step. The following is more detail about the four actions (Figure 1).

A builder can move through a three-dimensional environment randomly using the *step* action by updating its heading direction randomly and moving its position forward in each time step. This is the most generic and ambient action of a builder and adds a stochastic element for the program so that a builder has the possibility to reach all areas in the environment. *Flock* is the action to align its heading direction to the average heading direction of teammates within its cone of vision, and the builder starts to follow its teammate when this action is taken. This action adds the opportunity for builders to act together if such an action by a group increases rewards under certain conditions. For example, this action adds incentives for builders to gather at areas where there are more opportunities to build structures. The action *attack* will influence any others detected within its cone of vision. If the attacked one belongs to any opponent team, it will turn into a teammate of the builder by inheriting its team's behavioral profile and the color. If a builder attacks its own teammate, this action will eliminate the teammate. Results of these actions are determined using the success rate calculated based on heading directions of builders; the success rate is higher if the builder attacks others from behind.

The last action is the *build* action, which triggers a builder to place a unit building block at its current position. The environment has a discrete reference grid. The unit block is color-coded based on a team's color, which visually distinguishes the territories of

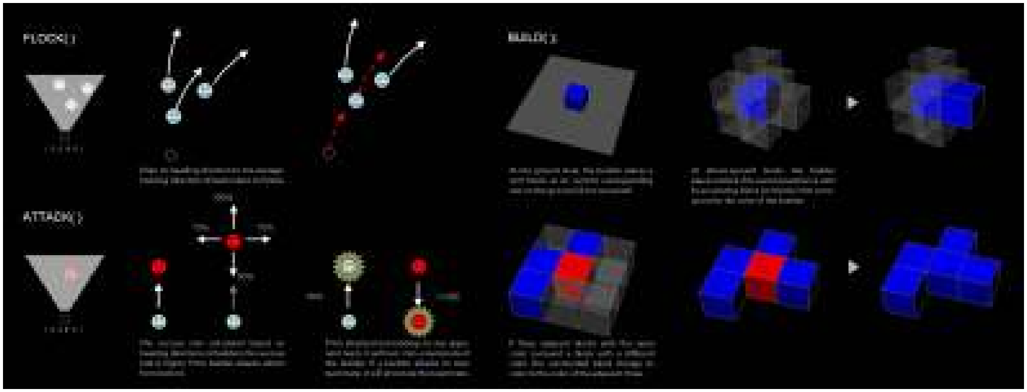

Figure 1
Diagrams explaining builder's actions: step, flock, attach, and build.

each team. When the *build* action is taken, at the ground level of the environment, the builder places a unit block at its current corresponding slot on the ground (if not occupied). At above-ground levels, the builder places a block if its current position is next to an existing block (or blocks) that correspond to the color of the builder. As a consequence of this action, if three adjacent blocks with the same color surround a block with a different color, the surrounded block has to change its color to the color of the adjacent three blocks. Unlike results from the previous three actions, these rules are influenced by the condition of the environment. Some of the agents' actions change a condition of the environment, and these changes can also influence agents' decisions for actions and rewards for the future in a reciprocal manner.

### *A builder's decision-making mechanism*

Each builder is designed to have different tendencies to take which action under which condition using an artificial neural network. In this experiment, all builders in the same group possess the same neural network setting for the sake of simplicity and calculation time, though it is a good consideration to have a group with different proportions of builders with different settings for more advanced future experiments. This neural network has four inputs based on the condition sensed by a builder, four hidden layers, and four outputs for a builder's next action, with thirty-two weights for interconnections of the network ($w_{ij}^{k}$: $1 \leq i \leq 4$, $1 \leq j \leq 4$, $1 \leq k \leq 2$) (Figure 2). At the outset, all weights are initialized with randomly defined values; thus all groups of builders have a random response for an action in a given condition. There are four criteria for a builder to check to find its condition based on what appears on its cone of vision, which include: *whether the builder is at the ground level, whether the builder is next to an existing building block, whether builder(s) from another group are near, and whether builder(s) from its group are near,* and these four criteria correspond to the four input values of the network. (Four binary results from the criteria provide the aforementioned sixteen different conditions (i.e., $2^4$=16).) Four output values are calculated using input values and weights and then compared. The most triggered output value among the four from the neural network will be selected, and the builder will execute the corresponding action to this output. Assigning different values for these weights produces a builder's neural network that triggers different actions under different conditions and creates a builder with a different behavioral tendency from the original builder. Improving the system for neural sensory outputs for a builder by updating the weights of the neural network will produce a builder that can perform better under certain evaluation criteria in this program.

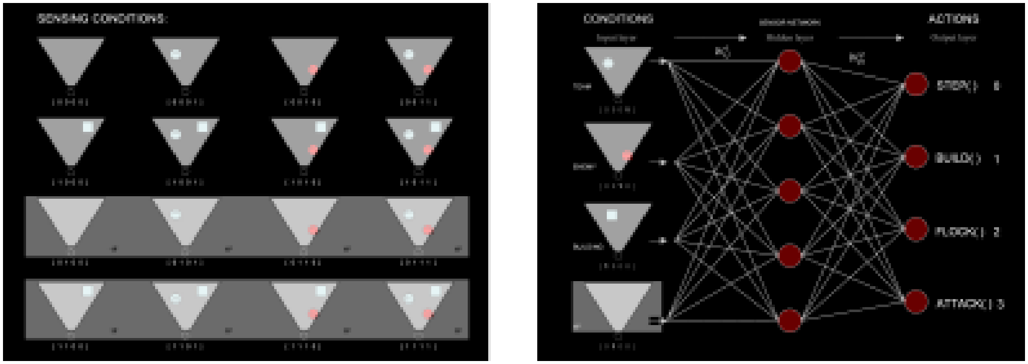


Figure 2
Builder's sensory conditions and a neural network.

### *Evaluation criteria and a formulation of a set of new groups*

At this stage of the experiment, the evaluation of the performance by each team was simply measured by the total number of unit blocks produced by the team multiplied by the number of the surviving team members. This evaluation implies that the team that produces a greater volume of structures and maintains or increases the higher number of team members - by executing the attack action in the right circumstances - obtains more rewards. For the sake of simplicity and time for calculation, this reasonable and simple evaluation was formulated at this time. However, in principle, criteria could include rewards for more complex results, for example, shapes of structures based on structural stability or lighting conditions. After each episode, weights of the neural network for four teams that scored higher among ten teams are selected to remain for the next episode. In order to increase diversity for builders' behaviors, some parts of weights from the four elite groups are randomly selected and are recombined among each other to create new neural networks that partially possess characteristics from existing elites but are not identical. Additionally, in order not to stagnate on the same behavioral patterns influenced by the previous generation, in a random chance of occurrences, some weights are mutated with randomly assigned values. These operations produce ten new groups inheriting behaviors from four elite groups but also not always identical to those from the previous episode. This setup for the program, commonly found in a genetic algorithm, is expected to improve builders' behaviors, generation by generation, producing better structures based on the evaluation criteria provided inside the environment.

## RESULTS AND OBSERVATIONS

Up through the first ten episodes, none of the groups demonstrated any particularly notable productivity compared to the others. Logs of their actions and sensing results printed on the console showed there were many inefficient actions by builders, such as attacking and thereby losing their own teammates, or omitting to build when they could and should have. Usually there were a few small piles of blocks evenly distributed with all (or nearly all) ten different team colors scattered on the environment at the end of every episode. Starting from around thirty and up to a few hundred episodes, three to five larger piles with dominant team colors gradually appeared. Numbers of survivors from teams also started to vary, and stronger teams ended with more members. Extinction of some teams was also observed. At this stage, counterproductive and meaningless behaviors, such as attacking when no one was around or eliminating one's own teammates, were much less present in the log. Beyond three hundred episodes, productivities among several dominant groups gradually declined and ceased to show any notable visual changes in the growth patterns of structures. By then all groups of builders had adapted competitive enough strategies without many counterproductive behaviors, other than some that were added by random mutations based on the rule of the program. The author speculates that expecting further improvement through competition among already sufficiently trained groups is inadvisable.

After the first experiment, one group of builders trained for four hundred episodes was inserted back into the initial episode of the program to compete against those that were not yet trained at all by the program, in order to observe how well the group had learned from the previous experiment. The trained group outperformed and dominated other groups both in its production of structures (number of blocks produced) and its ability to attack others to increase the number of its members.

Since the author has not yet added constraints mandating similarity to buildings in the real environment, some structures from this experiment resembled plants (Figure 3). At this stage, the experiment has not gotten far enough to explore emergent formal appearances of structures under realistic constraints for architecture based on agents' behaviors. Later, grid-like property lines that prohibit builders

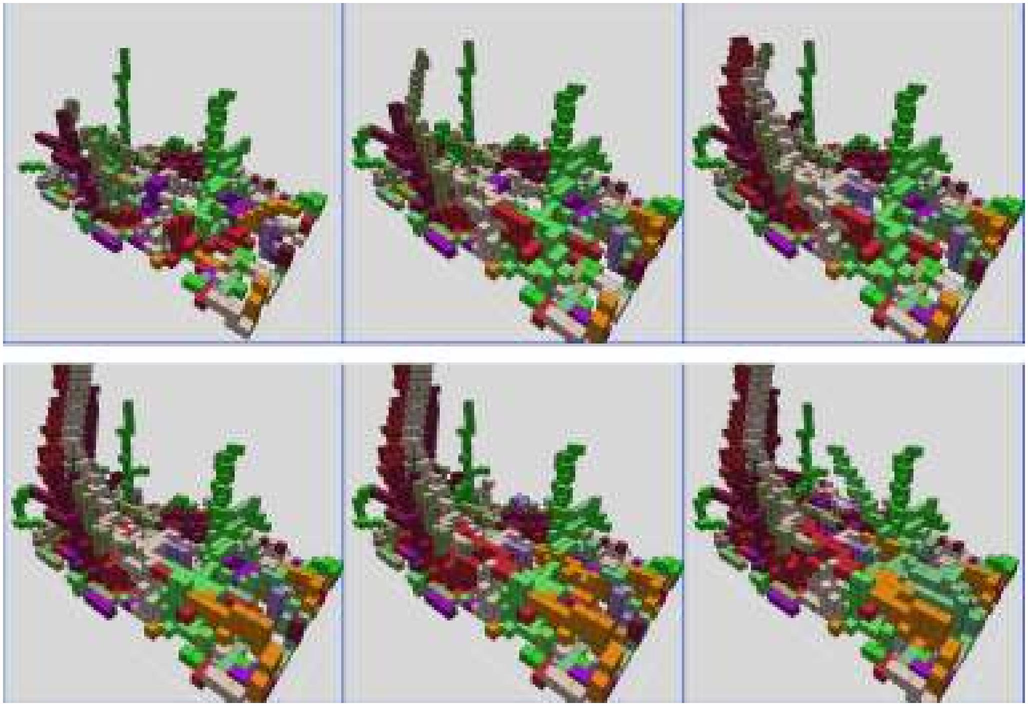

Figure 3
Results of
experiments

from building beyond those lines were added to serve as a starting point imposing more realistic constraints. After repeating the same experiment under this constraint, growth patterns showed blocks similar to the grid in Manhattan (Figures 4 and 5), and the result showed promise that the program's main flow can incorporate an additional evaluation criterion and still produce satisfactory results.

The experiment had extensive focus on the implementation of physical behaviors of builders and improvement of their behaviors inside the artificially defined environment. Although the experiment delivers unique results of building processes by builders in sequences and growth patterns over time, heavy focus on simulating the actions of builder agents may have counteracted another important objective - finding better forms of structures. The experiment has yet to reach the stage of fully exploring meaningful variations of formal structures that can be built based on further realistic evaluation criteria for buildings (such as structural stability, lighting conditions, or requirements based on codes).

As most human constructions rely on a blueprint for a final building design, it may be practical to dedicate all computational efforts to deriving final forms without seeking them through transitional growths by builders in steps. However, some building designs influence each other over time through negotiations within their physical neighborhoods-consider zoning regulations-and the proposed approach could be suitable for understanding growth patterns in dense urban conditions, settlements, and colonies.

In principle, adapting a DQN to the proposed program is possible. However, the overall complexity

Figure 4
Results of experiments

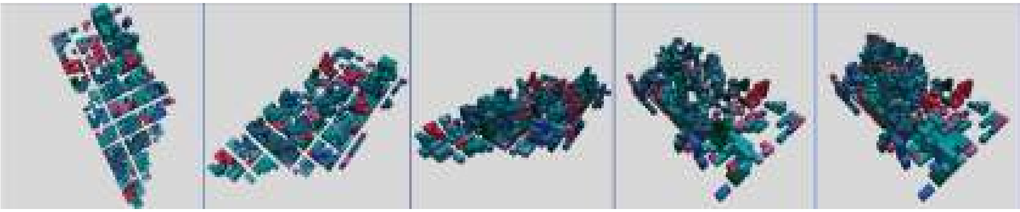

Figure 5
Results with the constraints of property lines

produced by the number of three-dimensional grids and applied rules is not as simple as many problems currently solved by methods using DQNs. Go has a grid size of 19 by 19, its state can be represented as simple 2-D pixel data, and, moreover, successful results by DeepMind were carried out by the use of state-of-the-art hardware and software (Silver et al. 2016).

## CONCLUSION AND FUTURE VISIONS FOR THE EXPERIMENT

As the proposed program has yet to incorporate a deep reinforcement learning method such as a DQN, the implementation based on mutations and recombination of a neural network's weights was used to improve the performance of builders generation by generation. However, the overall flow of a DQN program is similar to the iterative algorithm of the proposed one. Q-learning uses a lookup table that stores expected rewards of an agent taking actions in states, and DQN uses a deep neural network instead to approximate function in this table (Minh et al. 2015). The proposed program requires the author to preprogram specific discrete conditions to interpret the builder's vision-for example, whether a builder sees blocks or enemies in front. The program feeds forward the sensed condition as inputs of the neural network of the builder. By nature, this process imposes the programmer's interpretations of what agents see and how they influence the environment. However, the aforementioned DQN uses a raw pixel image directly from what an agent sees through its camera and uses it as a deep neural network's input without having a programmer define specific conditions before running the program. The precedent example by Shimizu (2016) using Unity3D also employs this approach.

Recently, programs using DQNs demonstrated that an AI agent could learn to play games by observing the screen without any prior information about those games. Those programs found strategies that were previously unknown to any human experts in games such as Shogi and Go. There is a premise that such programs can outperform humans in some areas where many unpredictable parameters are involved beyond common knowledge of humans. The online crowdsourcing puzzle game, Foldit, asks a player to find a shape that a protein folds into and attempts to predict the structure of a protein using human players' intuitions [1]. The game-like framework of Foldit is certainly applicable to the DQN's framework to allow machine intelligence to seek solutions for scientific problems.

Design is an extremely complex activity that involves many parameters and diverse value standards. Finding better formal solutions for possible built structures through computer applications is an extremely exciting topic for many designers. If we can formulate a design search into a game-like format to which advanced algorithms such as DQN can be applied, machine intelligence might find design solutions that have hitherto been unknown. One might think such an approach is only viable for a search under quantifiable criteria. However, computer vision programs using deep neural networks can already distinguish qualitative and abstract differences among art styles, and some programs can even create completely new images based on a selected style of an artist such as Van Gogh. Beyond quantifiable criteria, qualitative and abstract criteria such as aesthetics may possibly be incorporated into such a search in the near future.

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# Integration of CFD in Computational Design

## *An evaluation of the current state of the art*

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*The integration of building performance feedback in the design process is increasingly considered as a key aspect of the decision support framework that drives current high performance architecture, from early conception to fabrication. Although on other aspects of building performance there has been significant recent development on BPS integration in computational design, the integration of CFD is still largely unexplored, despite its significance in numerous design problems. This paper reviews the current state of advancement of integrated CFD simulation tools in computational design frameworks by evaluating three different integration approaches, each representing a different level of integration of CFD solvers within the commonly used computational design frameworks today. The objective of the study is neither to provide an extensive evaluation of all available CFD frameworks nor to assess the specific performance of the problem at hand, but rather to evaluate the potential and limitations of each integration approach from the perspective of the computational design user.*

**Keywords:** *Computational Fluid Dynamics, Simulation, Integration, Computational Design*

## INTRODUCTION

The integration of building performance feedback in the design process is increasingly considered as a key aspect of the decision support framework that drives current high performance architecture, from early conception to fabrication. The computational paradigm shift that leads the research in design methodology has been closely followed by an intensive development and integration of building performance simulation (BPS) tools that aim to support the performance goals of novel form-found and optimized architectures.

Despite this increasing significance of BPS tools and their consequent continuous development and integration in CAAD software, it is generally acknowledged (Clarke and Hensen 2015, Weytjens et al 2012) that currently available BPS tools are substantially deficient in providing optimized or even adequately informed design solutions. Their deficiencies relate not only to interoperability, modeling resolution, computational efficiency and lack of domain knowledge but also to the uncertainty of modern complex design problems (Hopfe and Hensen 2011, Hanna et al 2010). Furthermore, in the light of the evolving incorporation of computational design methodologies in mainstream architectural practice and subsequent research focus on more advanced, adaptive and real-time performing architectural solutions this complexity is inevitably due to increase. It follows that for these design spaces of higher complexity to achieve an adequately higher level of performance goals, a higher level of integration of BPS tools is needed, not only in mainstream CAD software but more importantly within the computational design frameworks that shape the forefront of performance-driven design processes.

This study contributes to the evaluation of BPS tools that are currently integrated in computational design, focusing on air-flow performance and consequently the integration of computational fluid dynamics (CFD) simulations. Although on other aspects of building performance, such as daylight, solar radiation and energy consumption, there has been significant recent development on BPS integration in computational design, the integration of CFD is still largely unexplored, despite its significance in numerous design problems, such as natural and cross ventilation, heating ventilation and air conditioning (HVAC), energy consumption, pedestrian comfort, structural performance and many more. Considering the performative potential that can be achieved through the geometrical complexity of the forthcoming additive manufacturing paradigm, this integration is a key step in enabling design solutions that will harness this potential.

The study aims to assess the current state of integration of CFD simulations in computational design through the case study of optimizing a 3D printed clay wall in terms of its natural ventilation potential. The scope of the study focuses purely on the potential of different simulation approaches that are currently available to architects and not on the design of the 3D printed wall per se. The objective of this approach is to evaluate both the accessibility and user-friendliness of available tools as well as their potential use in computational design and optimization processes.

## PROBLEM DEFINITION

Three different approaches were undertaken and evaluated, within this scope, that represent different levels of CFD integration within the computational design framework. Namely, a CAAD-CFD approach using the RhinoCFD plugin for McNeel Rhinoceros, a CFD integrated computational design approach using the Butterfly add-on that integrates OpenFOAM into the Grasshopper plugin for Rhinoceros as well as a fully integrated CFD approach using a Fast Fluid Dynamics solver developed in the Processing programming language (Chronis et al 2011).

### *The Case Study of a 3D Printed Clay Wall*

The case study undertaken is a part of an overarching study on the use of uncured clay 3D printing for the fabrication of a performative wall. The overarching study is the outcome of the Open Thesis Fabrication program, at the Institute for Advanced Architecture of Catalonia which is a research program within which a group of researchers are exploring the potential of digital fabrication technologies and in this case, additive manufacturing with uncured clay. The overall research objective of the study is to use the thermodynamic properties of clay and the potential of robotic 3D printing to create novel performative uses of an ancient building material. The development of the project involved thorough research of the climatic phenomena and the material behavior, physical tests using performance monitoring machines, such as a hygrothermal monitoring apparatus and a load bearing machine and digital simulations using solar radiation, daylight, thermal conductivity, thermal convection, thermal mass and structural analyses. The final outcome of the research program has been the design and fabrication of a real scale performative wall prototype that has been erected in the campus of the school (see Figure 1)..

Under the scope of this overarching study the objective of the part presented here is to optimize the wall's openings to achieve an optimum ventilation strategy for the wall. Taking advantage of the Bernoulli principle, the objective of the study is to optimize the inner wall geometry to achieve maximum cooling of the wall's compartments during the summer period. As stated above, this study does not focus on the design problems of the 3D printed wall or the overarching research questions of fabrication, performance and evaluation of the wall design itself, but rather on the integration and the usability of CFD simulations in the computational design framework that is used for the design of the wall.

The potential geometrical complexity that is allowed by the additive fabrication method opens a large solution space for experimentation which on one hand allows for greater performance gains but on the other makes insight of the performance of this solution space more tedious. It follows that a computational design approach is inevitable to explore this solution space and identify performance trends and consequent design strategies. However, the integration of a valuable performance feedback mechanism in terms of the ventilation performance of the wall has been proven problematic, hence the development of this study aims to tackle this integration and propose new approaches to make this integration more feasible.

## *Scope and Limitations*

Although the scope of this study is to assess the current state of the art of the integration of CFD simulations in computational design frameworks, the three different approaches taken are only a subset of the integrated CFD frameworks available today. This subset is however a good representation of the different approaches available for an architect or building engineer today. The selection of the tools that are used here was done based on certain criteria,

Figure 1
Final Full Scale
Prototype of the 3D
Printed Wall

such as the accessibility in terms of cost and expertise of the tools, the breadth of the user base of available tools and the integration of the CFD simulation frameworks with mainstream CAAD and computational design frameworks, such as the cases of Grasshopper and Processing. A different approach that has been considered, for example, is the mainstream CFD engineering package, ANSYS Fluent and its built-in optimization routines. The prohibiting cost of the license of the package though as well as the lack of its integration with a CAAD package have been fundamental in omitting it from this review. Other approaches, such as Autodesk Flow and its plugin for Revit, Solidworks Fluid Flow or RealFlow have also been deliberately omitted from this review, as they are either equivalent to the approaches taken here or, similarly to ANSYS, not integrated within the architecture-related design frameworks.

It should also be made clear that the aim of the comparison between the three different approaches is not an optimum integration method or the achievement of an optimum performance for the case study, but merely the assessment of the available tools and frameworks and their potential and limitations. Each of the different approaches achieves a different level of accuracy in the simulation, a different level of computational design integration and a different level of usability and accessibility for the architect, thus providing a range of levels for these objectives, each with its own merits depending on the problem at hand. Important issues such as domain knowledge of the users, open-source and free availability or documentation and community support are also important drivers in this comparison and any future use of it.

## EVALUATION OF CFD INTEGRATION AND OBJECTIVES

It is beyond the scope of this paper to describe the process of a CFD simulation workflow, however it is important to define the criteria upon which the integration is evaluated within the scope of this study. The first and most important aspect of this integration is the interface between the architectural and the simulation geometrical representations. As the focus of the integration is the potential of the CFD simulations within a computational design framework, a seamless link between the architectural geometry and the simulation model is essential. This first step involves the automated set-up of the domain, the meshing and the boundary conditions. Issues such as the adaptability of the mesh, the level of resolution and refinement and domain fitting to the architectural geometry are significant aspects of a seamless integration. The geometry of the 3d printed wall has been designed parametrically with Grasshopper for Rhino, which has served as the main platform for integration with all other simulation and analyses tools of the overarching study. Therefore, the geometry pipeline is assessed in relation to the main design platform, Rhino and Grasshopper. (see Figures 2 and 3)

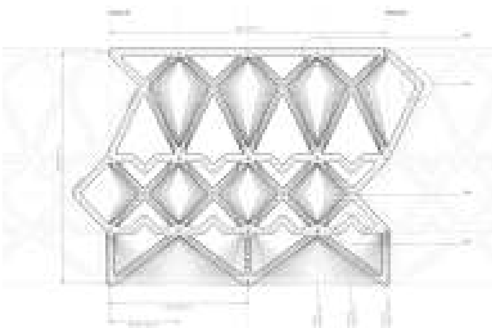

Figure 2
Parametrically Defined Module Infill Logic

The most important part of the simulation is of course the solver itself, therefore the speed, accuracy and stability of the solver are also crucial. Again, as the focus here is on the integration and not on the performance metrics of either the solver or the problem at hand, validations of the results are not performed and the accuracy of the solvers is derived from either their established status (PHOENICS and OpenFOAM) or based on previous research (FFD) and is considered as such. Furthermore, the accuracy of

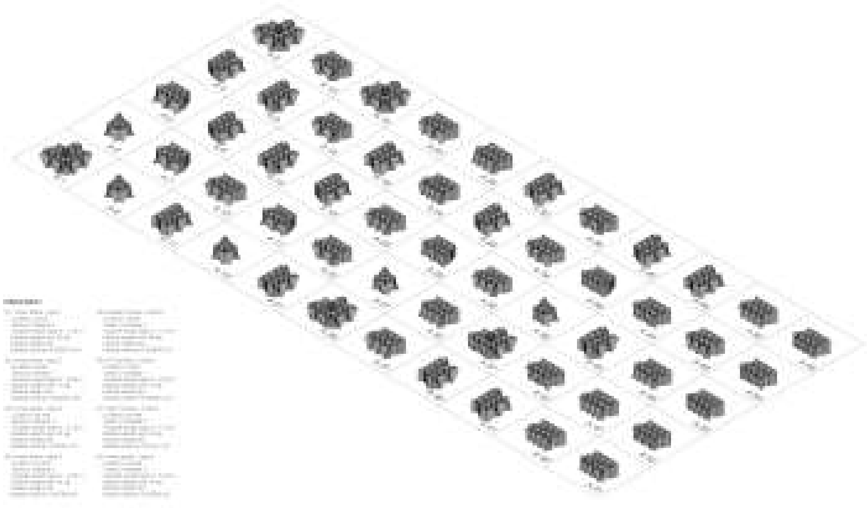

Figure 3
Parametrically Derived Catalog of Parts for Fabrication

each solver assessed is considered along with the potential scope of their integration and not as a means of comparison between the solvers.

### *Optimization and Iterative Solving*

Finally, an important aspect of the CFD integration is the post-processing of results, both for communicating the analysis to the user, but also for enabling iterative solving and thus integration of optimization routines within a computational design process. This latter objective of iterative solving and optimization, is key in harnessing the potential of integrating CFD in the computational design workflow, and the different approaches discussed here are achieving it at different levels, if at all. The aforementioned objectives of seamless integration, accessibility and user-friendliness are all prerequisites to this goal but, furthermore, to achieve a performance feedback mechanism for our overly complex computational design problems there is a need for dynamic representation simulation models. These entail advanced simulation concepts such as dynamic meshing, multi-physics solvers, dynamic resolution domains, customizable routines and high-performance computing, which although not discussed in detail here, are all considered as potential further steps on each evaluated approach.

## THREE INTEGRATION APPROACHES

### *RhinoCFD*

The first approach for CFD integration was done using the RhinoCFD plug-in for Rhinoceros (Rhino). RhinoCFD is a very recently developed integration framework for CHAM's PHOENICS and its special purpose variant, FLAIR which focuses on building air flow and thermal simulation. PHOENICS is well established in building physics research and practice and it has been a popular software solution among educators, engineers and integrated architectural practices. The integration of PHOENICS and FLAIR within the Rhino CAAD framework is in its infantry, nevertheless it has been very well received as a first integration step from the Rhino users' community. PHOENICS runs externally to Rhino, therefore the plug-in serves as an integration tool that, based on the native Rhino geometry, creates the mesh and simulation domain and model and then uses the PHOENICS solver to run the case externally. The results can be visualized within Rhino as well as exported and visualized in other platforms. Although RhinoCFD is fully capable of running advanced simulation scenarios, not all of PHOENICS' capabilities are exposed to RhinoCFD yet, which can be limiting its potential for use in a computational design framework. (see Figure 4)

RhinoCFD' s main benefit is its integration within Rhino and its native support of Rhino's geometry. The meshing and domain modeling are all done within Rhino and they are very straightforward. RhinoCFD uses an orthogonal mesh, which is adapted to different regions by detecting the geometry of the model. The regional control of the mesh is again straightforward although not necessarily very efficient in models with a large number of objects. The setting up of the domain is equally straightforward and with a few steps the user can quickly set up a basic wind-tunnel simulation, even with limited simulation expertise and no previous experience in CFD. The solver, which as mentioned runs externally and can run in parallel in the latest version of the plug-in, therefore the speed of the simulation is relatively fast. Results can be probed and visualized within the same file in the same straightforward way as well as exported and used to query any part of the domain, in order to progress a - manual - optimization process.

From a user perspective, RhinoCFD has a very quick learning curve and is very accessible to non-experts. In our case, the researchers were trained to use the software and could very quickly create and run simulation cases which helped them understand the effect of the openings of the wall in the internal channeling of the air. PHOENICS FLAIR, which is the core of the solver underneath RhinoCFD also has great potential in terms of its use in environmental engineering and, specifically in our case, its energy and radiation models are essential in progressing the study, as the thermodynamic effects of the

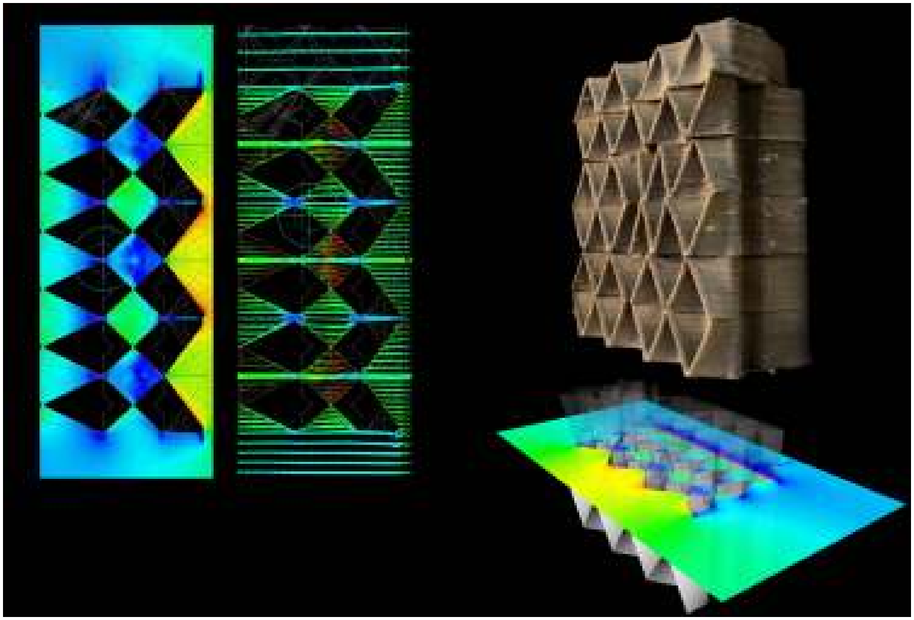

Figure 4
RhinoCFD
Simulations of the
3D Printed Wall

wall depend on them. The modeling and meshing parts using this CAAD-CFD integrated approach are quite straightforward. RhinoCFD uses an orthogonal mesh, which is on one hand easy to set up and manipulate but on the other not as efficient for complex geometries. A body-fitted mesh is available in the full version of PHOENICS, but not exposed to RhinoCFD.

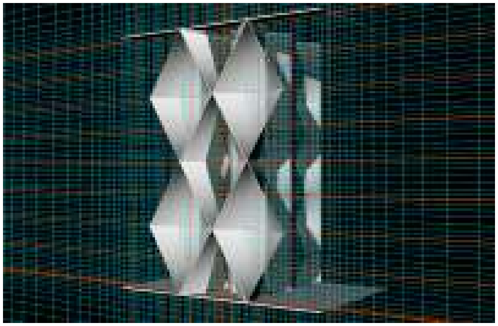

Figure 5
RhinoCFD
Orthogonal, Non
Body-Fitted Mesh

The most important limitation of RhinoCFD is that at its current stage it does not allow an iterative optimization routine to be based on it, as it is designed for single runs. PHOENICS has optimization routines which are though both limited and not yet implemented within RhinoCFD. A potential solution to this problem would be the integration of RhinoCFD within Grasshopper, a step that is currently being tested. Exposure of RhinoCFD to Grasshopper could allow the programmatic run of the solver from a Grasshopper component, thus allowing an iterative simulation, coupled with the many optimization capabilities of Grasshopper. This would still be a limited approach as the simulation domain needs to be revoked every time due to the lack of a dynamic domain and mesh but it would nevertheless allow for a valuable CFD integration in computational design. The solver is also parallelizable, something that could help more in enabling iterative optimization routines. (see Figure 5)

Overall, RhinoCFD is a great integration effort for CFD in CAAD. Its user friendliness and seamless integration make it a great introductory CFD simulation platform for architects with limited domain knowledge and its robustness, scalability and engineering capability give it great potential for more complex use cases. In our study, we have used RhinoCFD extensively in a trial and error optimization process and therefore we consider this approach as a very valuable first step for integration. As mentioned, exposure of the solver to Grasshopper would allow coupling with iterative optimization processes, thus this is considered as a next step for our study. On the downside, RhinoCFD is powered by PHOENICS, which although reasonably priced in comparison to other CFD platforms of the AEC it is nevertheless, proprietary software, thus its development and source are depending on CHAM.

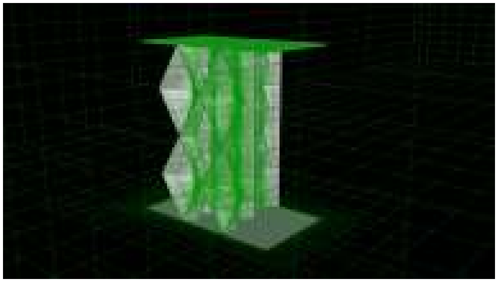

Figure 6
Meshing of the
Model with
Butterfly add-on in
Grasshoper

***Butterfly***

The second approach undertaken is the only currently available CFD integration for the Grasshopper computational design platform. The Butterfly add-on is connecting the most recognized open source CFD solver, OpenFOAM to the Grasshopper plugin and to Dynamo for Autodesk Revit. OpenFOAM is developed for Linux-based operating systems and thus it does not run natively on Windows, the main operating system supported by Rhino and most other CAAD software. It is however distributed for Windows encapsulated within a Docker container, which runs a Virtual Machine (VM) that runs Linux. The complexity of setting up the VM that runs OpenFOAM is currently the main limitation of this approach and the main reason that it has not been our main method of simulation in this study. Despite its difficulty to set up for Windows though, OpenFOAM is a very powerful and robust CFD solver that has endless capabilities. Butterfly is also relatively new as an integration effort and thus it exposes a small subset of OpenFOAM' s capabilities to Grasshopper, which is though not a limitation at this stage. The most important benefit of this integration is that both Butterfly and OpenFOAM are open-source and freely available and supported by large communities of users and developers who are constantly extending the capabilities of the solver and its integration, each evidently at a different scale. They are also both well documented, although Butterfly does require some background knowledge on CFD modeling and simulation to properly set up and run

Butterfly runs completely integrated within Grasshopper, although most of the preprocessing, the simulation and part of the postprocessing is happening externally. Butterfly is essentially wrapping all OpenFOAM commands and necessary files in a number of Grasshopper components that communicate the commands to the VM and write these files to a shared drive location. A great effort has been done to simplify this process as much as possible and provide default configurations whenever needed so that novice users can easily set up and run simulations, but due to the more advanced nature of the solver, the domain set up is not always straightforward. OpenFOAM' s meshing process runs in two steps, creating first a coarse mesh and then a finer, body-fitted one. There are many capabilities for mesh refinement and optimization which are exposed by Butterfly and many more that are provided by OpenFOAM. As the geometry is referenced directly from Grasshopper, the whole process can be parametrically controlled at every step. The integrated part of OpenFOAM currently allows for incompressible flow and heat transfer but again, there are endless possibilities for further development, based on the breadth and depth of OpenFOAM' s capabilities. The solver can also run parallelized, depending on the resources exposed to the virtual machine. The results of the simulation are probed externally but can be visualized and real-time queried. One significant aspect of the solver is that the simulation parameters can be altered while the simulation is running, allowing even more possibilities for optimization and control. (see Figure 6)

The open architecture of the solver, in combination with the full and open integration of the Butterfly add-on in Grasshopper make it an excellent base for coupling CFD with optimization and computational design. The geometry, domain, meshing and all other simulation parameters are open for customization, automation and iteration giving endless possibilities for CFD-informed performative design. The only limitation for iterative optimization methods is Grasshopper's linear architecture. On the other hand, the main limitation of the approach of Butterfly is, as mentioned, the very cumbersome process of setting up the OpenFOAM, which is the reason why our experimentation with it has been minimal during the initial parts of this study. The complexity process is related not only to the VM architecture but also to basic operating system limitations, such as administrative rights or differences in Windows versions which have been proven very difficult to overcome in a group of people working with different system setups. These issues could potentially be tackled in the future with batch setup processes, although this is also not straightforward to implement. Further to the software architecture issues, OpenFOAM and consequently Butterfly are considerably more complex in usage and not as accessible to novice users. OpenFOAM' s documentation is broad but not focused to non-experts. Overall, the potential of this approach is considered the most promising for the purpose of the study, although it has not been fully explored yet. At this initial experimentation, an iterative optimization routine has been performed as a proof of concept and the aim is to further study the limitations of the approach by involving more complex geometries and simulation problems. However, at its current stage, the approach has not been useful for the problem at hand, as it has been very difficult to set up both the solver and at a later stage the complex geometry and domain of the wall optimization problem.

### Processing FFD

The third approach taken is using a self-contained and fully integrated CFD solver with some built-in geometry optimization capabilities, developed in the Processing programming language. Previous studies (Chronis et al 2011, Athanailidi et al 2014) have demonstrated the potential of integrating a less computationally expensive CFD simulation engine not only in early design stages, to inform preliminary design decisions, but furthermore in form finding optimization processes using genetic algorithms. The Fast Fluid Dynamics (FFD) solver has been developed based on a numerical scheme initially developed for the computer graphics industry (Stam 1999) and it has been previously validated for limited design problems (Zuo and Chen 2007). The integration of the solver in Processing as well as the geometry meshing, results probing and visualization and optimization routines are all developed by one of the authors and thus there is full control over the entire preprocessing, simulation and postprocessing workflow.

The full integration of the solver code within problem-specific developed Processing applications has been proven to provide a great potential for iterating solving and customization in terms of the simulation and optimization processes but it has been very poor in terms of its geometrical capabilities as well as the performance and validity of results, due mainly to the limited accuracy of the solver as well as the lack of resolution and mesh refinement. The developed application uses an orthogonal square mesh, with no refinement regions and very limited boundary condition options, which makes it very hard to define a complex problem adequately. Moreover, the solver lacks proper turbulence modeling and although it has a basic buoyancy model, it is very inaccurate and thus not suitable for thermal modeling of the problem. Considering that the simulation part can be replaced in the future by a more accurate and capable CFD solver, either in the form of a library or another natively coded solver, the evaluation of the approach focuses on the potential of a fully integrated CFD simulation within a programming language that the user controls and not on the results of the solver.

One of the most important limitations of the approach, at its current stage, is that it requires a custom-made application for every given design problem, as the geometrical representation of the problem is hard coded within the application. To overcome this problem, after our initial experimentation, we integrated the solver in an experimental plugin for Grasshopper with an aim to provide full computational design flexibility of the solver by incorporating it within the Grasshopper plugin. Therefore, at its current stage, the solver runs externally, but the geometry and simulation parameters are streamed real time from Grasshopper. This integration would allow the user to design the solution space with ease, thus rendering the need for the development of a custom application per case unnecessary. (see Figure 7)

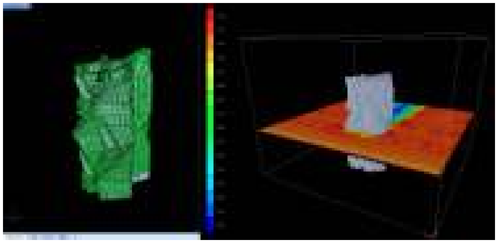

Figure 7
Grasshopper - FFD integration running in Real Time

Although the approach has in principle great potential as it allows full control by the user of the whole simulation engine, including the solver itself, and at a low level, it has generally considered as not appropriate at this stage due to the many problems of the solver. The inaccuracy of the solver, the meshing and flow modeling limitations and the lack of a parametric geometry module within Processing makes it very difficult to work with complex simulation problems. From a user perspective, this approach is also the most inaccessible as it requires programming knowledge as well as knowledge of the framework itself, thus making it impossible to distribute to a group of researchers, as was the case here. Despite all these limitations though, the potential of using a CFD solver completely incorporated in a computational design framework demonstrates significant customization potential. A further step, for example, could be the incorporation of a GPU based CFD solver with some thermal modeling capabilities, similar to the one used here, within Grasshopper, something that is part of the future work of this study.

## CONCLUSIONS

This study reviews the current state of advancement of integrated CFD simulation tools in computational design frameworks by evaluating three different integration approaches, each representing a different level of integration of CFD solvers within the commonly used computational design frameworks today. The objective of the study has not been to either provide an extensive evaluation of all available CFD frameworks or to assess the specific performance of the problem at hand, but rather to evaluate the potential and limitations of each integration approach from the perspective of the computational design user.

The study demonstrates the limited capabilities of all three approaches in achieving a seamless integration of CFD in computational design and supports the need for further development of such interfaces. Driven by this conclusion, our aim is to continue the development of an integrated CFD solver that would allow designers to get valuable performance insight on air-flow related problems within the computational design framework that they already use.

## ACKNOWLEDGMENTS

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# Performative Materiality

## *A DrawBot for Materializing Kinetic Human-Machine Interaction in Architectural Space*

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*This paper presents an exploration of movement as a design material to evidence human-machine interaction in an architectural space. An autonomous robotic vehicle with environmental sensory capabilities interacts kinetically with people by recognizing their emotional states from their body postures. A drawing device installed in the vehicle leaves a trace on the floor as a material testimony to the mutual dynamics. The complex yet surprisingly intuitive choreographic interaction of the machine and its social and physical environment blurs the boundaries between drawing, machine, and performance. In general, the project conceptualizes movement as a design material, drawing as a performative action, and social interaction as a physical force, all of which can be enhanced or mediated by digital technologies to produce results with aesthetic value.*

**Keywords:** *Human-Machine Interaction, Drawing Machine, Performance Design*

## INTRODUCTION

Automatic drawing machines are mechanical devices that produce drawings by moving pens or other drawing instruments along predefined paths or patterns. Their captivating appeal lies as much in the aesthetic qualities of the intricate outcomes as in the rhythmic and hypnotizing movements generated by the drawing process. While traditional drawing machines -such as the popular Spirograph toy- rely solely on harmonic movements driven by physical forces, contemporary drawing machines take full advantage of electronics and computer technologies to expand the range of movements, driving forces, and outcomes. Digital technologies allow drawing machines to be responsive and interactive with their surroundings, transforming the drawing process from being a predetermined fixed result to being a negotiated action between the machine and its interlocutors. As the interaction increases in complexity, the boundaries between artifact and performance become more blurred.

Inspired by the beauty of traditional drawing machines, and motivated by the opportunities of contemporary human-machine interaction technologies, this project starts with the aim of producing a machine that uses the complexity of human behavior and initial environmental conditions as driving forces to produce drawings in architectural spaces.

Particularly, we present an autonomous robotic vehicle capable of interacting kinetically with its social and physical environment in a mutually conditioned relationship. The vehicle, equipped with multiple sensing capabilities, can detect the physical and geometrical characteristics of its surrounding space, and also communicate with humans by recognizing their emotional states through their body postures. Based on these environmental and social conditions, the vehicle moves autonomously but responsively, leaving behind a mark on the floor produced with a drawing tool. Thus, there is a dialectic relationship between the vehicle and the human in which the movement of one affects the other, conditioning each other in an unintuitive way that forces both to explore space. While the movement is futile, the trace remains permanently imprinted on the architectural space as an aesthetic vestige of the choreographic dialectic of the performative experience. This project re-conceptualizes movement as a design material, drawing as a performative action, and social interaction as a physical force, that all may be enhanced or mediated by digital technologies to produce outcomes with aesthetic value.

## BACKGROUND

### *Re-thinking Drawing Machines*

Automated drawing machines most likely originated in the fifteenth century, motivated by the revolutionary advancements in mathematics, geometry, mechanics, and arts of the Renaissance. Examples range from the simple *ellipsographs* and *pantographs*, to the lesser known *helicographs* (for volutes and spirals), *antigraphs* (for mirrored drawings), and *cyclographs* (for arcs and circles). *Conchoidographs* and *cycloidotropes* (for roulettes) -the antecessors of the famous Spirograph toy- and *harmonographs* and *pendulographs* (for harmonic oscillatory movements) were more complex apparatuses developed soon after (Garcia, 2013). In general, these devices are based on stationary mechanisms that follow predefined cyclic movements determined by physical forces, such as harmonic pendulums. Their graphic outcome is highly determined by the mechanical behavior with little space for interaction with the human operator. In fact, the relationship between the machine and the operators is static and unidirectional, determined solely by the expert's control over the device.

Contemporary digital technologies offer an attractive opportunity to revisit these devices and explore other drawing driving forces that transcend the merely mechanistic. For example, Newswanger (2012), Howsare (2012), and Clarholm (2014) developed devices based on traditional drawing machines, but taking advantage of electric motors and computer numerical control (CNC) systems. A slightly more radical innovation can be observed in the hanging devices designed by Noble (2011) or Bynoe (2013), who utilized Arduino boards and the full range of contemporary electronics to create devices capable to draw with fine precision, but at the same time, to interact closely with their users.

A substantial different approach was taken by a number of artists who explored the potentials of wheeled robotic devices as drawing machines. The vehicles are typically built with two wheeled servomotors controlled by Raspberry Pi or Arduino boards and attached pens or brushes. Some of them move following a predefined scripted pattern (Pigford 2013) and others incorporate sensors to react to external conditions (Adenauer & Hass 2011). To us, this added capability -reacting to environmental conditions including people- is a revolutionary breakpoint that completely redefines the idea of drawing. By transforming the drawing machine into a responsive device, the value of the drawing lies no longer only in the aesthetic attributes of the outcome, but also in its representational meaning as physical record of an experience of interaction between the machine and its environment.

### *Kinetic Human-Machine Interaction*

The terms *Human-Machine Interaction* (HMI) and *Human-Computer Interaction* (HCI), were coined to describe the study of how people communicate and interact with machines and computers (Card et al. 1983). As an extension, *kinetic human-machine interaction* refers specifically to systems for which movement is the language of communication. In recent years, this approach has attracted the interest of architects, designers, and artists, who see an appealing opportunity for exploring the relationship between body, movement, and space in creative and expressive ways (Fogtmann et al. 2008, Jensen 2007, Larssen et al. 2007, Levisohn 2011, Loke and Robertson 2009, Moen 2007).

Current technology allows for a wide range of kinetic interaction, both gestural and full-body. A common approach is using optical technologies that capture light data (video, infrared, etc.), which is then analyzed for differences in time that may indicate movement. An archetypal example is the Kinect, a motion detection device originally intended as a peripheral for Microsoft Xbox 360, but which is widely used in interactive installations (Caon et al. 2011, Kang et al. 2011, Shiratuddin and Wong 2011, Cheng et al. 2012). A different approach is the use of position sensors (accelerometer, gyroscopes, tilt sensors, etc.) to capture spatial data which is then analyzed for patterns that may indicate movement. Depending on the level of precision and complexity required for the kinetic interaction, this approach can involve installing devices on the subject's body (Buechley and Eisenberg 2008).

In these projects, "machine" is not necessarily understood as an independent device that is separated from the human body, but more as a significant part of it, even if physically detached or remotely pulled through the agency of both. There is always a co-dependence between the two and a sense of confusion about the boundary. A number of art projects and installations exemplify this tension. The works of Rebecca Horn -such as *Unicorn* (1970-72) and *Finger Gloves* (1972)- could be examples of how body extensions and the environment relate to each other through movement, equilibrium and gravity. Michael Heizer with *Circular Surface Planar Displacement* (1969), instead, uses a motorcycle to produce large scale modifications on the surface of the desert. The human-machine interaction is still present when looking at the traces in his series of perfect-looking circles drawings: there is an embodied mastered knowledge on the speed and traction of the motorcycle and its turning radius through the use of his own anatomy in order to achieve such conditioned results.

## METHODS

The implementation of the project can be understood as the crossing between eighteenth century drawing mechanical apparatuses based on harmonic movements (Garcia 2013), Braitenberg's autonomous vehicles (1986), and wearable technologies for human-computer interaction based on gestural detection (Hartman 2014).

The vehicle was built based on a standard kit of a wheeled Arduino robot with two continuous-rotation servos and a pivot ball. The basic movements of the vehicle (forward, backward, and rotation) were controlled through the relative speed and rotational direction of the servos, previously calibrated to match microsecond values to actual RPMs. Four environmental sensors were installed on the vehicle: a photo-resistor on top, an infrared tracking sensor on the bottom, an ultrasonic distance sensor on front, and a magnetometer at its center. Additional turn on-off buttons and signaling LEDs were also incorporated to ease its operation. For detecting and tracking the movement of the human performer, we designed a simple wearable Arduino-based system with three tilt sensors (hands and head), a magnetometer, and a pressure sensor under a foot. This combination of sensors was proven to be sufficient to detect a wide range of position configurations and movement patterns (see Figure 1). To communicate the vehicle and the human, two radio-frequency (RF) modules were installed as transceivers. A mini XY joystick was also added as a safety measure to remotely drive the vehicle in case of need. Two servo motors installed on the back side of the vehicle were used to control the position, orientation, and pressure of (various) drawing tools, with a drawing precision of about 1% for linear movements and 2% for rotary movements.

The operation of the vehicle was determined by a series of predefined movements that were triggered by different combinations of values of the postural sensors in the human performer and of environmental sensors in the vehicle. Using psychological theories of body language, sixteen basic body postures were associated with presumed emotional states and consequent specific movements in the vehicle. For example, an aggressive posture in the human triggered a backward movement in the vehicle. The movements were not totally determined by the person, but altered by environmental conditions. For example, ambient light could act to indicate direction of movement, or floor color could indicate safe rest areas. Thus, the final movement of the vehicle was the result of a set of combinatorial rules. For example, if the human performer held an inactive posture for too long, the vehicle could change the movement rules in order to stimulate a new dynamic between them: perhaps the vehicle could escape from the light, forcing the human performer to approach, lean, and cast a shadow to keep it still. Programming the vehicle was straightforward, considering the relative simplicity of the movement rules. The code was implemented as a constant loop of two steps: first, collecting measurements from all sensors, and then, a series of mutually exclusive if clauses covering the full range of movements.

We performed a series of three progressive preliminary tests to evaluate and develop the functionality of the system (see Figure 2). Once operational, a final pilot performance was planned and conducted. A human performer provided with the body sensing system but no knowledge of the vehicle's behavior was asked to interact freely and spontaneously in a 400 sq.ft. area which included a bench, two spotlights, and a 100 sq.ft square of white powder on the floor. A sponge brush was attached to the vehicle as "drawing" device.

Figure 1
combination of sensors

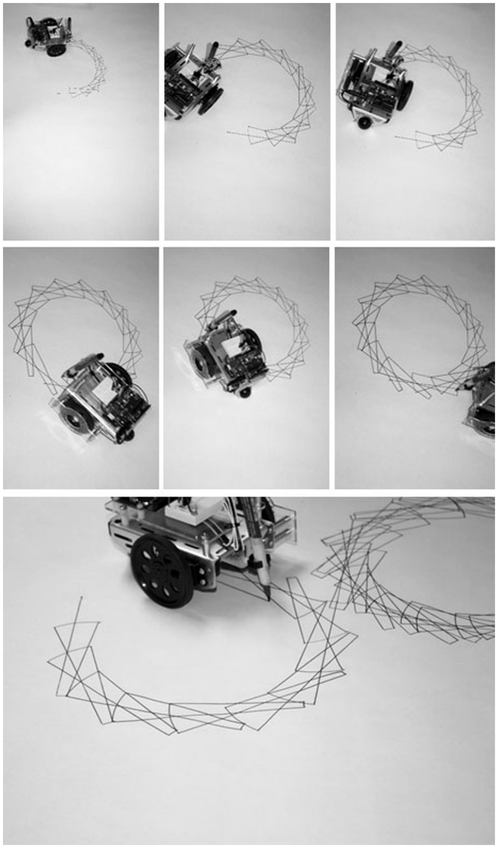


Figure 2
preliminary tests

Figure 3
performer at work

## RESULTS AND DISCUSSION

The final performance showed that the vehicle interacted dynamically with the human performer in an unpredictable, but not random manner. At least three "assumed emotional states" (surprise, fatigue and aggressiveness) were effectively activated during the exercise. The performer was able to decipher the relationship between light, shadow and movement affecting the drawing machine. She managed to use her own movement as a control variable to guide the robot to move towards her and/or over the powdered area. Thus, the final "drawing" corresponds to the traces and footprints on the floor left by both the vehicle and the performer, a proof of a mutually choreographed correlation between the machine, the human, and the environment.

The maturity of the final iteration of the drawing is evidenced by the accumulation of synergy between the two performers after a considerable period of time. The drawing left on the floor is more than just a consequence of the brush sweeping the white powder back and forth. It speaks for an aesthetically unexpected representation of the combined efforts between the person, the vehicle, and the contained space. The drawing becomes a testimony of the specific moods of the performers (human, machine), but also of the architectural environment they occupy. However, it is also not a simple choreographic notation that allows the reproduction of the performance -in the literal sense of *choreography* as the written form of a sequence of movements (as in dance, sport or military)- but is meant to evoke a sense of the mood of the performance. Jagged lines may indicate a stressful interaction, or circles may be sign of ecstatic happiness. The drawings convey not only movement, but also leave room for emotional interpretations.

During the exercise, a different material with a colored pigment was randomly added to alter the performance outcome through a less binary opposition between the ground black background/floor and the white powder. Although this decision did not alter the behavior of the vehicle, it added a different component that sustains a more provocative collection of results.

This project raises interesting conceptual questions that can be framed in a more general ongoing contemporary debate around the extensive limits and thresholds of design by/on the human and non-human (Colomina & Wigley 2016). Maybe the most evident disciplinary question is the redefinition of drawings as a performative action in space that challenges the traditional notions of representation. Drawings, in architecture, often mediate between what the philosopher Nelson Goodman categorizes as *autographic* -arts where the presence of the author is fundamental to the realization of the work, like painting- and *allographic* -arts where the works can be reproduced by different people multiple times without the presence of the author, like theater plays- (Allen, 2000). Architecture drawings are, in fact, far more speculative and puzzling tools than the plain result which becomes visible through different forms of media. In this project, the tension between the autographic and allographic is explicit: the drawing is the result of a complex interaction not only between the machine and the performer, but also between the vehicle's programmed movements and the uncontrollable environmental factors. It is impossible to clearly define whether the trace is more controlled by the human, the environment, or the machine.

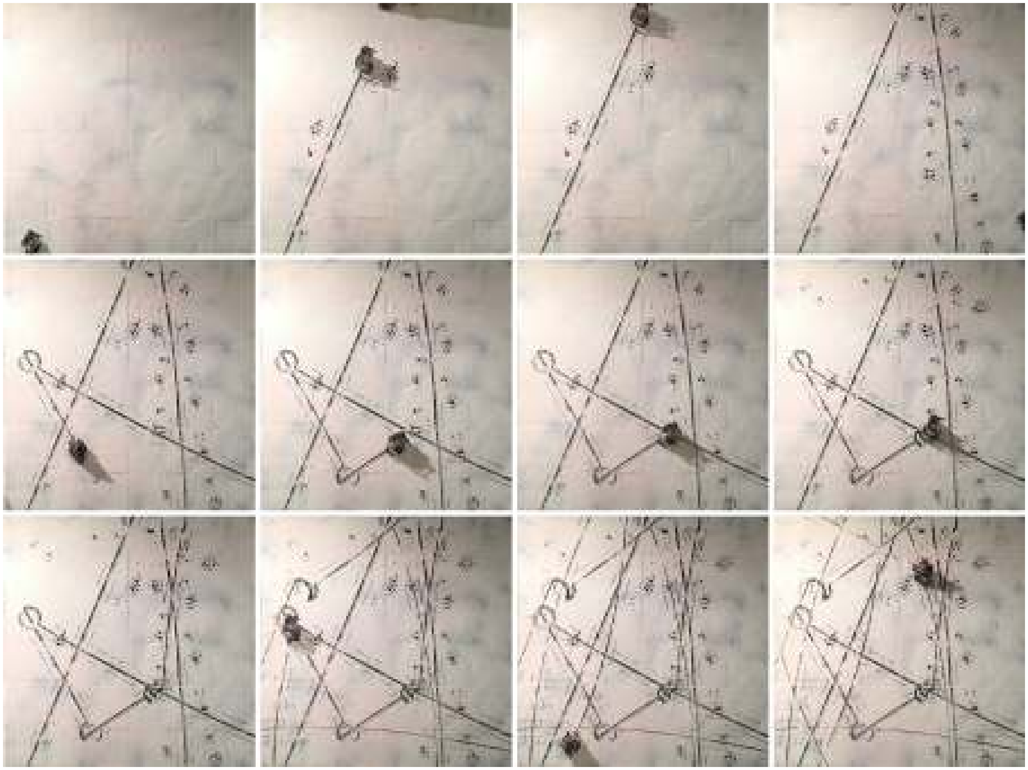
The project questions the aesthetic limitations and potentials embedded within the idea of (machine) control. Is the human performer who is guiding the vehicle by casting shadows over it? Or is the vehicle and the environment conditions (i.e. the position of the lights in the room) that are causing the user to move in a different way in order to get the vehicle underneath the shadow? At some times, it seemed that the vehicle governed all interaction, in the same way as a little boy crawling freely leads his mother behind him. Indirectly, the vehicle forces the human performer to interact actively with the environment, and consequently, to be aware of specific details of the architectural context: the direction of the lights, the color of the floor, the level changes. Indirectly, the work proposes an alternative form of art production which could position notions of authorship in a more environment sensitive paradigm.

The empathetic relationship developed between the performer and the machine -although both entangled in a socially awkward form of communication- was a remarkable discovery that we initially had not expected. It was not the individual human body or its psychological reactions what could explain variations in the line traces, but the person's empathy towards the machine's sensing capacity. This was clearly manifested through the coexistence of responsiveness and incomprehension between the performer and the machine. This is a remarkable clue which could be developed further in order to make the drawing and the perception over the experience much richer.

Finally, this work also brings up questions of how to position the outcome with regards to architecture and art as close fields. In our view, it could be read as mediating between an art and architecture project, since it discusses the possibility of describing the results only as an aesthetic product but also as an spatial intervention affecting human behavior. Yet, we argue that this idea of solely an 'aesthetic product' could be strong enough to become the driving force of an architectural investigation. Nevertheless, the system of values through which we could judge the experience is not the same that an art critic or architecture critic would adopt.

Figure 4
during the process

Figure 5
final drawing



## CONCLUSIONS

In this paper, we explored the use movement as a design material to evidence human-machine interaction in an architectural space. By using a drawing vehicle with environmental and social sensory capabilities, we produced abstract drawings on the floor that are a confirmation of how the immersive experience of basic emotional reactions and programmed sensing can transform a particular space, environment or setting into a relevant aesthetic material.

Our initial goal of building a drawing vehicle was successful in terms of functionality. Still, a more robust machine would be needed in further experiences with extreme environmental conditions (e.g. liquids or non-smooth surfaces), large-scale territorial contexts, or socially diverse environments.

The project lead us to re-think our own notions of materiality, which could also be intangible as we see it merely as movement. Indeed, we designed a flexible material with which to explore actuation, sensing and interface. Although at first it may seem that digital technologies play a central role in this type of architectural projects, we consider their position as essentially instrumental, only as a means to generate or mediate new spatial experiences, whose greater value relies in the phenomenological quality of the interactive experience. In this sense, the results of the indexed performative, social and physical aspects of the aesthetic product end up being almost entirely subjective.

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# Integrated Adaptive and Tangible Architecture Design Tool

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*In this paper, we identified two majority issues of current CAAD development situating from the standpoint of CAAD history and the nature of design. On one hand, current CAAD tools are not adaptive enough for early design stage, since most of CAAD tools are designed to be mathematical correct. as we conducted a detailed survey of CAAD development history, we find out that most of the techniques of Computer-Aided Design applied into architecture are always adopted from engineering track. On other hand, the interaction between Architects/Designer and CAAD tools needs to be enhanced. Design objects are operated by 2d based tools such as keyboard, mouse as well as monitors which are less capable of comprehensively representing physical 3D building objects. In addition, we proposed a working in progress potential solution with HCI approaches to fix these issues. We summarize that , the prototype proved that architects and designers could benefit from utilizing adaptive and tangible design tools, especially during massing studies in the early phases of architectural design.*

**Keywords:** *CAAD development,, Human Computer Interaction, Tangible User Interfaces, Design Tool development, Design Process*

## INTRODUCTION

As an ever evolving discipline, during the past few decades, the WIMP based CAAD tools have been redefining the foundation of architectural design and made extraordinary contribution to architectural practice. Meanwhile, it is also reshaping the typical workflow of architects and designers. Nowadays, with the further development of computer system and CAAD techniques, the expansion of building scale, the increasing complexity of architectural practice and collaboration, the existing CAAD exhibits a series of drawbacks while the new emerging technologies are changing the people's cognition of design activity. In this paper, we identified two majority issues of current CAAD development situating from the standpoint of CAAD history and the nature of design.

According to the recent cognitive neuroscience study, there are likely two ways that design idea usually occurs, one view is the instant inspiration like a lightning strikes, and another view is that the design idea is generated through continuing firmly attempts. It seems to be two opposite ways but both these two views are describing the same aspect of one process but on different levels. If considering design as an instant inspiration, it is actually the culmination of a series of intelligent process. As Pablo Picasso's quote "Inspiration exists, but it has to find you working" indicated that great ideas and eureka moments arise from everyday work. A designer have to at least be thinking about a topic or problem before he or she can find a creative solution. In addition, the goal of continuing attempts is for getting the best ideas which come out of the procedure itself. Design, as a continuous creative process, one of its main task is to capture and organize these insights and inspirations which accumulated through continuing attempts then expand the design idea to a larger scale and more practical level.

One challenge for architects and designers is that, architecture as the final result of design process is a complex and systematic product, and it requires long-term memory and significant information input. But human are more suited to short-term memory work and relatively less information input. Long-term memory work is not easy to carry out for human and it is not capable of being used for a dynamic process such as design. This is why nowadays architectural design process has always been break down into multiple steps such as concept design, schematic design, etc. In addition to the workload subdivision, people started using different kinds of external representation to divide problems into smaller conceptual element and different aspect of design, such as different levels of 2d drawings and 3d models which can be easily manipulated within the limits of short-term memory. At early design stage such as concept design, designer needs to offer an initial design concept to address the design problem. The concept is usually formed by establishing relationship between certain numbers of design elements. That requires that, while helping to record and organize designers' inspirations, the design tools to be used in the early design stage need to assist locating design elements and establishing relationship between these elements.

The emergence of computer and computer graphic system laid the foundation of computer-aided architecture design which has become the new tool and took over the dominant role in the architectural industry. Since the 1960s the first CAAD program which was liberated architects from blueprints by hand, architects have been employing the power of computer, more specifically, architecture-specific software into architectural design and practice. However, many of this software root in other industries, for example, Maya and 3Studio Max for computer animation industry and CATIA for aircraft manufacturing; while some are developed for the use across a wide range of industries, such as AutoCAD for mechanical engineering and architecture. In the following decades, CAAD has greatly changed the workflow in architectural industry and architects are benefited with higher drafting efficiency.

**Problem A.** Through the investigation of current CAAD tools we conducted, we found most of the CAAD tools are designed to be numerical driven and mathematical correct. It is not flexible enough for early design stage. The learning and memory costs, non-intuitive input method and unfriendly interface, all of them are responsible for architect's heavy workload and unnecessary repetitive work. They seem inevitable because of their industrial root. No existing approach can penetrate the core of designing, which is how designers work through creative processes to generate design solutions. It is awkward that almost all popular concepts about design tools have been established by people who do not personally design architecture but by software engineers.

The concept of CAD appeared the 1960s, but the definition of CAD keeps changing. During the earlier phase of CAD development, when Ivan Sutherland invented his Sketchpad at 1963 which integrated evolving design and analysis programs, CAD stood for Computer-aided Drawing (Drafting) instead of Computer-aided Design which were usually known by us. At that time the goal of CAD is drawing 2D document which continued until 1970s. Aleksander (1999) and Kalay (2004) illustrated that three generations of CAD tools have been invented in the history. The first generation CAD systems were designed to be intuitive and architectural. But the shortcoming of 1st generation CAD is that the system contains excess elements of architectural design procedural and lack of graphic interface, so that the solution is quite hard to popularize. It is worth mentioning that the geometric modeling route CAD system which was another first generation CAD route based on 2D wire frame model led by an industry giant had already been applied in engineering practicing while the architectural specific route CAD was still in pilot phase.With the growing demand of automotive and aerospace industry in 1970s, engineers desired to find new solution for defining complex geometry. The earlier CAD approach of geometric modeling system was a quite simple wire-frame system. It can only present basic geometry information, yet cannot effectively represent the topological relationships between geometric data. In 1962, a French engineer Pierre Bezier formed new surface and curve designing method, which let the problem of computer drawing curve became operable. Meanwhile, French aircraft manufacturer found a way to build free form surface in computer based on CADAM system. It is first time to completely describe the main information of 3D product's element. Thus, CAD technology has been broken through from 2D wireframe modeling to surface 3D modeling expression.

In 1980s, the demand of architectural company had changed. Not only drafting, architects started to use computer communicate with different project participants. The second generation of Architectural CAD system focused on drafting and modeling, rather than the first generation system which more focused on building design procedural. It was also defining different types of geometries rather than defining the building element properties. But comparing with previous context, we can summary that the second generation CAD of architectural design such as AutoCAD is quite similar with the CAD technology used in engineering industry in early 1970s. They all focused on 2D and 3D geometry such as line, polyline, surface and simple geometric relationships. Even though some companies started to develop rendering and modeling software for architects, it still just followed the action engineering industry. At the same time, engineering industry had already start their new experiment. Although the previous CAD technology of engineering has had the description for 2D and 3D geometry, but still hadn't find a way to present geometry's physical properties such as quality, the center of gravity, moment of inertia. Engineering researchers successfully achieved the solid modeling technology which can illustrate the topological relationships as well as the geometric properties. The first commercial solid modeling application was released at 1979, which was called I-DEAS. The solid modeling technology was based on unconstrained free-form model, users can directly modify geometry model, but the disadvantage is that cannot provide non-geometric information such as material, processing, etc.

But architectural design is a complex activity. The third generation of CAD system had become far more complex than the previous generations, architectural elements are interdependent, and the number of these elements is uncountable, if any of the data in the system goes wrong, it will have serious negative impact on entire project. Then, how should architects deal with the situation which has large number of associated data. Just like we've mentioned previously, engineering design tools are always adopted by architectural industry. In the current engineering industry, they've applied parametric and variable modeling techniques to solve these problems. Parametric technology is feature-based, full-size constraints; all data correlated each other, dimension-driven design, completely overcome modeling free form unconstrained state. Beyond the completing logical structure, parameters can be modified at all times. Variable modeling technique is developed based on parametric technique. Such as Grasshopper, Generative Component, Digital

Project are the best examples to illustrate how architectural professionals apply the engineering technology into architectural industry.

Because of the practicality, reliability of architecture are emphasized, it is almost impossible for any form of experimental reforms to firstly happen in architectural industry. Just like the invention of the elevator led to the rise of high-rise buildings, the practical needs of architectural technology will not exceed the needs of social productive forces. Hence, adopting technology from other areas is understandable. But the learning process that current CAAD tools required, dis-intuitive input and unfriendly interface, is leading to architect's heavy workload and unnecessary repetitive work.

The nature of architectural design is a materialization process reflecting the designer's creative thinking. The design process is imagination interacting with the assistance of all kinds of tool. The think pattern behind this process is from abstract transiting to concrete, from flexible to accurate. But the current CAAD tools which adopted from engineering track or developed by engineers are mostly numerical driven asking for an accurate numbers to be employed even the design is still situated in the early stage. But the mathematical approaches for design decision-making are not capable of handling uncertainty, multidimensional complexity, and flexible compromises. In addition, according to Simon's book: The Sciences of the Artificial, design as an iteration process, repetitive work is unavoidable. The optimized CAAD tools should provide sufficient adjustable space allowing designers to make changes to reduce the repetitive process. Designers and Architects are expecting to be provided with assistance of establishing relationship with flexibility from CAAD tools instead of emphasizing accuracy. (see Figure 1)

**Problem B.** On other hand, the interaction between Architects/Designer and CAAD tools needs to be enhanced. The currently CAAD tools are fundamentally limited within WIMP interface, which employ 2d based input manipulation and 2d based output display. Design objects are operated by 2d based tools such as keyboard, mouse as well as monitors which are less capable of comprehensively representing physical 3D building objects. Design is an act of seeing, thinking, and making. Which involving eyes, brain and hands. Architectural designers are responsible for designing the aesthetics and spatial details of a building - the building's size, shape, space utilization, and site requirements.

That requires that no matter which tool designer selected, pencil, mouse or something else, design aids should assistant the coordination of interacting among eyes, brain and hands . Through the association of brain, hands and eyes, architectural designers are aware of information; through the repetitive creation, architectural designers would have chance to re-define information and get feedback so that they can make the right decisions.

To any architect, the interaction process with computer for their work is not only using tools. It terms of a type of progressive skill-building, different way to interact with tool which engages different body parts, definitely has a great impact on the work efficiency And human cognition. To some extents, computer games have one thing in common with the work flow of contemporary architects- progressive skill-building. The biggest computer game on the world, Wii and Sony have bring various remote controllers to free players from limited There will never be a certain answer on which is the best to engage human brains to improve skills and make progress on the path to mastery. But obviously, it's wise to limit it on keyboard and mouse exclusive while any other industries are Seeking for wide variety of alternative and trying to keep their occupation engaged with work by innovative experience.

The CAAD tools provides architects/Designers a new way and means to explore the new idea, and introduces designer a new metaphor to see, to think and to make. But, if architectural designers didn't actively and critically consider that the changing of technology would impact on our ability to communicate and think, the CAAD technology will be crippling. A brand new CAAD tool needs to be cre-


Figure 1
a brief History of CAD

ated which will further inspire designers by weakening operation and providing more flexibility at early stage. In this paper, situating from the standpoint of new emerging techniques, we provided a survey of tangible and adaptive design tool and their potential of being applied in design space. In the past two decades, as computer science and human-computer interaction have risen to a popular topic over the world, traditional architectural digital tools have been reviewed from an interdisciplinary perspective. The efficiency of perception is associated with the interaction methods so as the influence of these tools' interface in architecture industry has been enlarged. Tools with tangible user interface is one of the good examples among the innovations of tools to help the translation between physical world and digital world and provides an open mind on architect-friendly and intuitive input and display methods.

## BACKGROUND AND RELATED WORK

We evaluated few innovative digital technologies such as Tangible User Interface and The shape-changing technology which can be potentially adopted into design space and help to optimized design tools.

A tangible user interface is one in which the user interacts with a digital system through the manipulation of physical objects linked to and directly representing a quality of said system. In 1997, MIT media lab presented a new vision of ”Tangible Bits” at the CHI '97 conference. The concept of Tangible User Interface (TUI) that is based on physical embodiment of digital information & computation, in order to go beyond the current dominant paradigm of ”Painted Bits” or Graphical User Interface (GUI). Humans have evolved a heightened ability to sense and manipulate the physical world, yet the GUI based on intangible pixels takes little advantage of this capacity. The TUI builds upon our dexterity by embodying digital information in physical space. TUIs expand the affordances of physical objects, surfaces, and spaces so they can support direct engagement with the digital world. The idea with Tangible User Interface is to have a direct link between the system and the way you control it through physical manipulations by having an underlying meaning or direct relationship which connects the physical manipulations to the behaviors which they trigger on the system.

This last statement is where the secret lies. It's not just a question of having a physical controller for your digital system for the sake of having one, but making sure that by implementing one, it's use makes sense to the user and has added value for a more natural and intuitive control of your design. In a sense, the interface becomes virtually invisible, as the user has an inherent knowledge of manipulations such as grasping and moving objects (after all, we've been practicing since we were toddlers) so user is able to concentrate more on the system and the triggered behaviors than on how to trigger them.

Coelho and Jamie (2007) provide a holistic approach about how to design a shape changeable human computer interface. One of the main ideas is finding the suitable material for building a shape changing interface. Since there are already several types of material are changeable, the authors explore the properties and limitation of the available materials. One of the main challenges of shape changing was its mechanical properties. But currently, the material can respond with a more adequate behavior to its changing environment. The authors point out that some alloy or dielectric will become dynamic under the influence of direct or indirect electrical stimuli. They provided several currently available materials which can change shape. Most of them are alloy and dielectric. The properties of these materials are different than regular material, such as deformation strength or power requirement. The authors cite shape memory alloys as a main material to descript in the paper. Once heated, shape memory alloys will form a specific shape and it will be able to indefinitely recover from large strains. After the temperature changing, the shape will return to the original form. But shape memory alloys is not suitable for all the applications, it needs to consider forces, displacements, and temperature.

Majken,etc.(2012) defined the endpoint of shape changing, and the mid-point which is called transformation. Transformation is defined into several aspects, such as Kinetic Parameters and Expressive Parameters. Kinetic parameters contain the some physical value like speed, frequency and description of spatially and geometrically values. Another key context in the paper is talking about the interaction, the authors found that in the aspect of shape changing area, there are three kinds of interaction, which is No interaction, indirect interaction, and direct interaction. Direct interaction takes advantage of this bi¬directional relationship, and in some cases indirect interaction also uses digital input to change the physical form.

PneUI is novel project developed by MIT Tangible Media Group. The project provides me a brand new cognition of human-material interaction. In the aspect of architecture, we found that people will always pay attention on the objects which could enhance humans some of the sense, but architecture is lacking of ability in this aspect. if the research purpose is combining traditional architecture and human's daily object to fully interact with users, the Soft Composite Materials could be a great solution. Like it mentioned in the paper: "Hard bodies with construction of rigid structural and electronic elements have limited the form, function and interaction of shape changing interfaces in HCI." (Vertegaal,2008) Soft bodies could change its shape in terms of users need. PneUI is an enabling technology to build shape-changing interfaces through pneumatically-actuated soft composite materials. The composite materials integrate the capabilities of both input sensing and active shape output. This is enabled by the composites' multilayer structures with different mechanical or electrical properties. The shape changing states are computationally controllable through pneumatic and predefined structure. PneUI is consist of multiple layers composite material including liquid, silicon electronics, air passage and an origami structure similar to graphite composites. The combination of these composite materials leads the device be extreme soft and flexible.While this advanced technology is still stay in lab, but it gives us a great vision in the future. Soft objects can be used in the aspect of architecture design process to provide designers some of flexibility bringing more possibilities.

Leithinger and Follmer(2014) introduced an eye-catching project from the MIT Media Lab: A table built with motors, linkages and pins, that can render a person physically in real time via a digital source. Some articles hailed the technology with potential to change the world and others were captivated by its strange, almost science fiction-type quality. The consensus was that this thing was really, really cool. But for a concept so complex, the initial idea came from a simple beginning. The idea is inspired by those pinscreen toys where you press your hand on one end, and it shows on the other side. However, the 15-by-15-inch table, known as inFORM, is much more complicated than a toy. The choice for the motors came down to function and how Leithinger and Follmer wanted the table to work. They knew they wanted inFORM to be an interactive and perceptive process, meaning they wanted users to physically shape the table as well. The duo decided on the kind of motors that power faders, which are commonly used on audio mixing boards and cost $20 to $30 each. These motors are pretty weak, though, so Leithinger and Follmer used linkages-long cables that reduce friction. Each motor is then controlled by a custom circuit board with a microcontroller, which is then connected to a computer. By moving these pins up and down with computer control, user can form a shape, the shape can be a three-dimensional model you load from a computer, it can be a user interface, or it can be a shape of a remote person. The most complex feat the inFORM can accomplish is the last one-rendering a person or object remotely. For this, the tangible media team decided to use a standard Xbox Kinect, a sensor typically used for motion-intensive gaming, to capture a person's movement. A mounted projector also displays color. When setting out to create the inFORM display, Leithinger and Follmer-along with Hiroshi Ishii, professor and associate director of the MIT Media Laboratory-had a clear goal. "We really see this as a research platform where we can just quickly prototype things," Instead of waiting a few minutes or hours for a 3D printer to create a design or using even slower traditional methods of prototyping, testing out different scenarios can happen instantaneously. They also envisioned practical application in urban planning and CAD modeling, though currently in a lower resolution, where designers could physically manipulate their creations and changes would be reflected on their digital compositions. But the prototype device could also be a boon for other industries and areas that the creators never intended.

The limitation of 2.5 D shape display is the geometry cannot be overhang, but another gourp of researchers at MIT have developed a prototype environment, named ZeroN, which can suspend a object in mid-air and use it to navigate both a virtual and physical environment in a three dimensional space. Using active electromagnets, the environment can be programmed to manipulate the path of the ball or allow it be guided by hand. An intriguing feature is that ZeroN can "remember" and play back the movement of the ball, whether programmed or hand-guided, within the three-dimensional space. models of "planets" within the environment with programmed orbital rings, guide the ball as it revolves around the model. Adding a second model immediately changes the orbit of the ball, as it begins to revolve around two "planets." The simulator uses infrared stereo cameras, taken from conventional webcams. The cameras sense the position of the ball and objects within the three dimensional space and plots three dimensional models of the newly introduced objects in the environment. A second instrument for measurement called the Hall Effect Sensor. The cameras can build a virtual model of physical objects position in the ZeroN, which can then allow users to navigate the virtual environment with respect to the ball. The ZeroN's applicability can range from architectural, gaming or even medical purposes, like virtually navigating the chest cavity of a patient. ZeroN however was built with the purpose of redefining what it means to interact with physical objects. "Our body and minds have developed great capacities for understand and manipulating physical environments. The long-term vision is to embed computation and physical materials that can directly interact with us. In this way, we seek to redefine the relationships humans have with materials, space and digital information," Lee said. The prototype is still a proof of concept and has its minor kinks to work out. audience may notice that the ball's movement is undoubtedly unstable. The electromagnet, in conjunction with the Hall sensor, which constantly calculates how much repulsion or attraction is necessary to maintain the ball's approximate position in the three dimensional space, may need to be programmed to for a gentler touch. But the video is evidence enough that Lee's concept works. In fact Lee has begun to build the ZeroN's second iteration. According to Fast Company, Lee is scaling the prototype to be capable of manipulating multiple objects within the ZeroN environment

## METHODOLOGY

The concept of direct manipulations to indirect is like driving a car by manipulating the steering wheel and pedals to giving a driver instructions.In the latter case, you don't necessarily feel the motion of the vehicle.

The same situation has been happening with designers for decades. People are always using the indirect manipulation input to approach the design intent. The limitation is from both hardware and software. For hardware side, the keyboard is utilizing typing to input command, but what's an architectural designer doing is communicating with object to develop the design idea but not giving command to control the object. What's designer need is a spatial platform to operate object wherein designers could have a multiple dimension reference. The mouse is seems to be a spatial platform due to its x and y operating space, but it just have two dimension. Using two dimension manipulations to operating 3d space is still missing the depth. For the software side, the WIMP interface is a combination of windows, icon, menus, and pointing. Each of these items is representing a command or a purpose. Sometimes calling one of the icons user will have to find another one. To use the WIMP interface, designers have to pay extra attention on software learning. Especially, some of the interface is not friendly enough for designer to learn and use.

We need to find better methods for designers to interact with their design, not only through mouse and monitor, but also through more intuitive and natural ways to sense and manipulate the project. The most intuitive tool should incorporate input manipulation through a natural language. Natural language in this context refers not only to a language like English, but also to human behaviors such as hand gestures. If the manipulation setting can be based on natural behaviors, it will be easy enough to be learned. The circular flow of information among thinking, observing, and making gives designers the opportunity to dynamically re-define the objects they sense. Body manipulation motivates designers evaluating object from multiple aspects so that inspire appropriate design intent. Grandhi (2011) explored people's natural gestures using "before" and "after" pictures and instructing participants to perform the gesture needed to get from before to after. The experiment suggested that user experience could be enhanced by developing the gesture vocabulary based on understanding that the actions are embodied.

Given the importance of visual feedback to designers, visual immersion incorporating both geometric and non-geometric feedback, is desirable but current hardware often interferes with UI interaction or communication. An augmented representation as output display has several approaches to enhance the experience of designers and achieve the desired results.We report here on one project that incorporate input using hand gestures and augmented output along with haptic interaction and visual abstraction.

In the physical world when people are manipulating a physical geometry, nobody will think about which gesture I should use to interact with the television. All the gesture come out spontaneously based on current condition. In the physical world, a physical object will provide people haptic reference but not only visual experience. For instance, when you need to open a bottle of wine, observing is obviously not a wise choice to do so, but you will have to touch the cork and hold to pull it up. Haptic feedback can allow user to judge how much force to be used to open the bottle.

As we discussed in the previous content, tangible user interface could be a possibility. Designers could directly work on a physical object to improve their design with more direct and intuitive interaction. Using a physical object to represent building geometry let designers better experience their design object and feel the proportion of the building shapes. For achieving the concept, we developed HYPERCUBE, which is tangible objects based massing study tool kits.

The general environment of HYPER CUBE contains a projector, an interactive desktop, and several sets of tangible objects based massing study tool kits. The interactive desktop is an ordinary desk covered by rare projection film. It needs to be associated with the projector on the top, and a regular web-cam from button. For the software, it mainly dependents on Processing UDP, reacTIVision and grasshopper. ReacTIVision senses the QR marker and transfer to processing then send the data though UDP to grasshopper.

Currently, we've developed three sets of tangible objects based massing study tool kits. The first set is static geometry containing a cube, a keystone, and a tapered. Each of the geometry represent a single building object. At the button of each geometry has a QR marker which can be captured by regular webcam, system also tracks the location and orient. I did several experiments and found that the regular lighting condition is not suite for the webcam to capture the QR marker. So we insert a 4 RGB LEDs at four corners behind the marker, when the 4 RGB LEDs are activated, webcam will clearly capture the QR marker. For the cube, keystone, and, tapered, each of these geom¬etry has a specific QR marker matching with. When user places any of these geometry above the desktop, the system will be activated. User could move or rotate the static geometries to do the massing study and evaluate what would be the best location and orientation of building. Using static geometry representing building geometry might be suf¬ficient for simply changing the location and orientation. But when massing study start getting involved form finding, the static geom¬etry is not a satisfied option. Beyond the static geometry, I develop the second set which is the transformable twisting block. For each transformable twisting block there is one potentiometer and one slide potentiometer inside the object. The regular potentiometer is mainly recording the rotating angle and the slide potentiometer is mainly recording the vertical height changing. Both of these potentiometer send real-time data into computer, thus the system could apply the data to generate a matched digital model automatically. The button of transformable twisting block is also covered by the QR marker, so the location and orientation information is also trackable.

The transformable twisting block is capable of affording more design tasks, such as evaluating the high raise building shadow situation or curtain wall reflection simulation. But the twisting block just have two dimension to be transformed, the rotating angle and the height. What designers need is more flexibility and less limitation. and all these transformation data need to be send to computer and generate the matched digital model. Based on our vision, we developed the third version of the tangible objects based massing study tool kits.

The third version of HYPERCUBE is made up of 10 transformable edges (two of them is diagonal)and 4 fixed edges. Each of the transformable edge is installed a slide potentiometer which connect to a central micro controller. A QR marker is also necessary for the tracking the location and orientation. Designer consider the CUBE as representation of a single room or a building geometry. He or she will just need to lengthen or shorten the transformable edges to change the shape, proportion, and scale of the cube. Once the central micro controller receive these resistance data, computer will convert them into length, and utilizing trigonometric function to reconstruct the shape of CUBE, all these transformation are remapping into a matched digital model with same geometric properties. The 3-dimensional physical CUBE provide direct manipulation and tangible representation of architecture geometry.

## SUMMARY AND FUTURE WORK

In our paper, we have introduced interactive 3D architectural design tool prototypes called Hyper Cube. The prototypes allow users to directly interact with physical 3D objects using nature or pre-set hands gestures. I described the system implementations, focusing on the workflow for developing gesture interactions (visualization and gesture recognition). We illustrated several interactions that the prototype support, and described application scenarios and possibility.

We summarize our contribution as follows: Developing several system allowing for 3D geometry being created and manipulated through interactions based on user gestures, while leveraging the affordances of enhancing the visual experience or providing haptic reference and good hand gesture to approach appropriate fully 3d working environment. This research highlights that it is possible and helpful for designers working in a total 3d environment.

The study space of designer oriented physical design tool remains partially unexplored. Our research is attempting to establish an understanding of the space as well as develop several system prototypes which could embody the vision we seek to explore. The invention of Integrated Adaptive and Tangible Architecture Design Tool will potentially completely change the traditional workflow of designers and bring them brand new working experience.

The research we've conducted thus far makes me realize that the study of adaptive and tangible architecture design tool will not be wholly accomplished, understood, and delivered within the domain of design study, or the domain of Human-Computer interaction research. Instead, the work I propose resides in the connection between multiple areas - an interdisciplinary environment which is necessary condition to support.

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# The Application of Daylighting Software for Case-study Design in Buildings

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*The application of different software, whether simple or complex, can each play a significant role in the design and decision-making on daylighting for a building. This paper, discusses the task to be accomplished, in real case studies, and how various lighting software programs are used to achieve the desired information. The message iterated throughout the paper is one that respects, and even suggests, the use of even the simplest software, that can guide and inform design decisions in daylighting. Daylighting can be complex since the position of the sun varies throughout the day and year as well as do the sky conditions for a particular location. Just because we now have the computing capacity to model every single minute of a day throughout a year, doesn't justify its task. Several projects; an architecture studio, a university office building, a school library and a gymnasium all present different tasks to be achieved. The daylighting problems, the objects and the software application and their outcomes are presented in this paper. Over a decade of projects has led to reflecting upon the importance of computing in daylighting, its staged approach and the result that it can achieve if properly applied.*

**Keywords:** *Daylighting Design, Daylighting Analysis, Radiosity, Ray-tracing*

## A GUIDE TO DAYLIGHTING

One of the objectives of International Energy Agency (IEA) Task 31 Daylighting Buildings in the 21st century was to construct a 'roadmap' towards guidance for better daylighting of buildings (Ruck, 2006). In doing so, three objective criteria; obtaining a desired illumination on the task, achieving overall lighting distribution and room definition and providing an optimised visual contrast and minimisation of glare, were established. Furthermore, several parameters to be considered for a space are its room characteristics inclusive of surface reflection and aperture (window) size, orientation, glass and shading type, as well as room geometry. Of course the ultimate consideration is the type of daylight (sky condition), its location and its availability.

There are specific programs (Daysim (Reinhart 2006, Yun and Kim 2013) or Perez's 16 different ISO sky types (CIE 2003, ISO 2004)) that provide for direct solar and sky light data to be produced for geometric computer models of buildings. Programs such as Lightscape®, 3d-StudioMax®, Desktop Radiance, Radiance, whether radiosity or ray-tracing (Greenberg et. al. 1986, Ward 1994)) based on calculation principle, can take advantage of this sky lighting information. It is the program type and its application, which needs to consider the task, required to be solved. So often programs are applied without any objective or understanding of why the program is used in the first place. What is the task we want solved? What are we analysing and with what software are we doing it?

In hindsight, several basic steps are considered in the re-construction of the processes used in several real projects as related to producing good and successful daylighting design. These have encountered some of the simplest CAD programs, such as Google Sketch Up, through to very computationally complex programs such as Desktop Radiance and 3D-Studio Max.

## STEP 1: BUILDING GEOMETRY, APERTURES & SUNLIT CONFIGURATIONS

Often there is no real option to external building geometry changes within a retrofitting project. About the only option is to consider where light has the possibility to enter the space, or not enter it. Sizes of window openings, glass type, their location and shading can all have an influence on the amount of lighting. However, this step, first and foremost, merely considers where and how light enters the space. An example in Figure 1 provides the sunlit configurations for extreme (Winter and Summer Solstice) periods for this project. Note that the extreme conditions, the maximum and minimum solar penetrations are considered here for a clear day. Furthermore, for the specific case, an afternoon time is simulated due to the considered West facing orientation.

For the design studio presented here, the light distribution across the work plane would most likely be disruptive. Therefore strong direct solar bands of light are most likely not desired in this situation and occupants would much more desire a diffuse light. In reality, if blinds are provided they get drawn down by the occupants and remain down for a very long time before they are retracted again (Reinhart et.al. 2006). Yet, 'green building' codes in Australia encourage this feature of solar penetration and such results receive a higher (star) rating.

The study of sunlit configurations however is a very important first step in daylighting. What needs to be recognised is where and how far light penetrates into a space. This initial stage of analysis is important because it offers possibilities in the design that could be controlled if required. In the example of Figure 1, there is an extreme amount of seasonal light entering directly at the lower perimeter level, more daylight is desired in the central part of the floor plan. A means of achieving this task is through the introduction of a monitor or clerestory aperture on the façade. This positioning of light entry into a space can have a substantial impact to successful lighting in deeper plan areas, if properly controlled, and the light is diffused. Here the addition of a 'strip' of open-

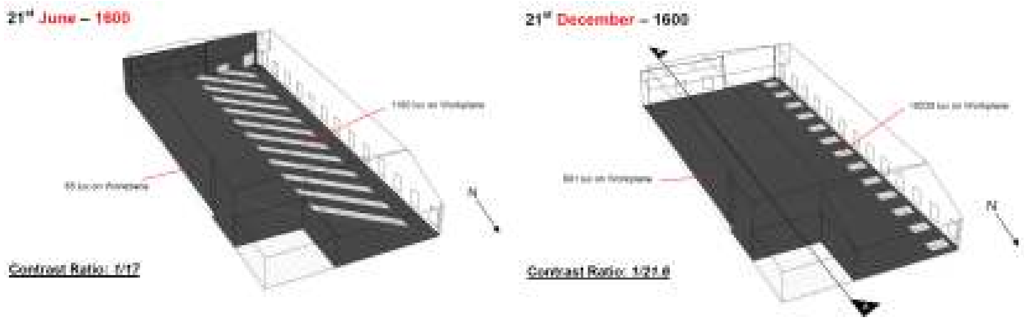



Figure 1
Winter and Summer Solstice - daylight penetration extremes

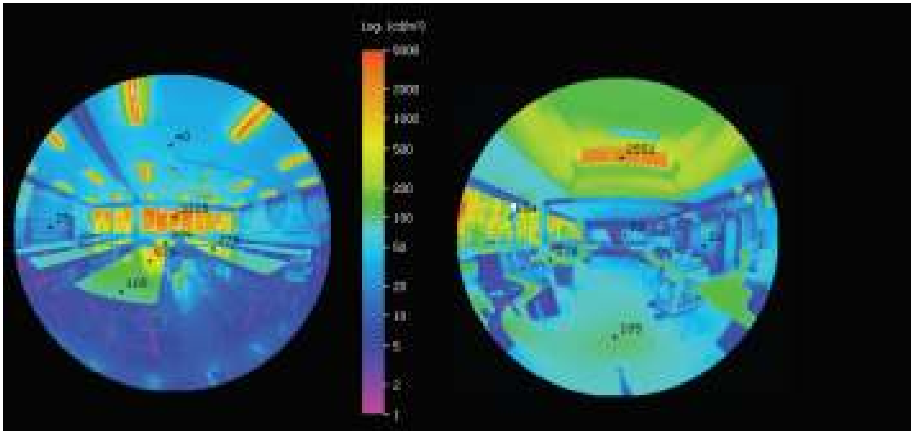


Figure 2
Before retrofit (left) with lights on and After (right) daylight only.

ings are positioned above the existing West facing windows (see Figure 6). It is most important to consider the glass opacity and transparency of solutions in this region of the façade to provide for a diffusion of daylight.

A real example of a successful design in relation to the concept of clerestory lighting is shown for a school classroom where before and after retrofitting results were measured. The measurement shown in Figure 2 utilises a CCD luminance camera, illustrating the surface cd/m2 results. Here the power of daylight is demonstrated, indicating better and more uniform results than an electric lit space. It should be noted that the daylight external conditions were practically identical for both cases.

Another example of utilising simple geometric computer simulation for studies of sunlit configurations throughout critical seasonal periods of a year is provided in Figure 3. In this particular case a library with an easterly facing façade is analysed. What is desired is the control of direct daylight into the space to avoid glare and contrast extremes. Here, again, seasonal extremes are selected for the analysis as well as time of day.

### *Step 2: Analysing Illuminance Levels:*

This next step is a significant jump from first. Now very generic interior surface reflectance's are applied to floor, walls and ceiling (20, 50, 70%). It is critical to consider the type of sky that is being applied to the simulation. Intermediate lighting programs basically consider 3 types of sky conditions: overcast, clear or intermediate (partially overcast). For an analysis that generally requires compliance with standards, an overcast sky must be selected so that a daylight factor can be calculated. It is unfortunate how much importance is given to this single based metric (Ward 1994, Reinhart et. al 2006). It is highly conceivable that for many of our global locations an overcast sky is not a typical daylight condition.

Our standards often focus on the end result, meaning that the quantity of light received at a specific area or working plane is of greatest importance. Again, and unfortunately, this metric often does not provide us with the means and methods of how light achieves its result. In other words, comparing the light we use to see (illuminance) vs. the light we see by (luminance).

For the space in Figure 1, a partial cloudy sky, represented the average sky condition and that solar extremes June and December 21st would be explored. Of these cases the 9:00a.m., 12:00 and 16:00 times were studied and considered. (see Figure 4).

Too often, we design for the 'worst case scenario'. What needs to be asked, 'Is the overcast sky condition

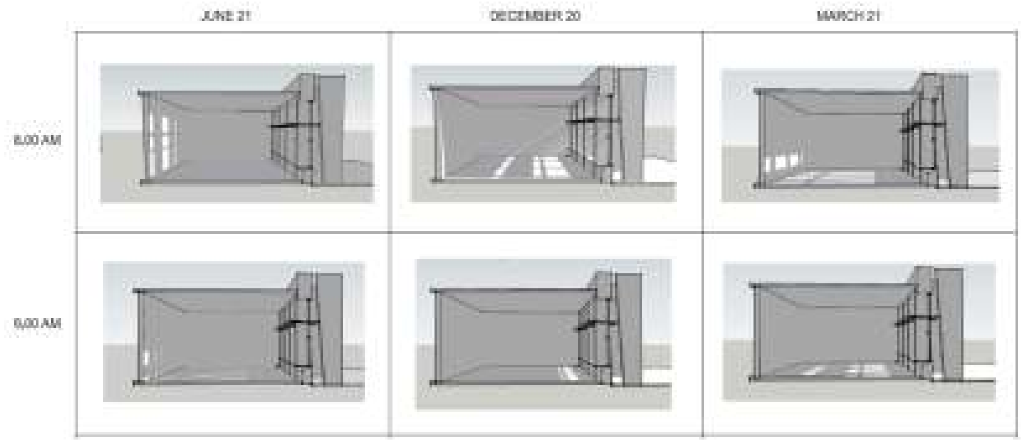



Figure 3
Cross-section of an East facing library with no vertical shading

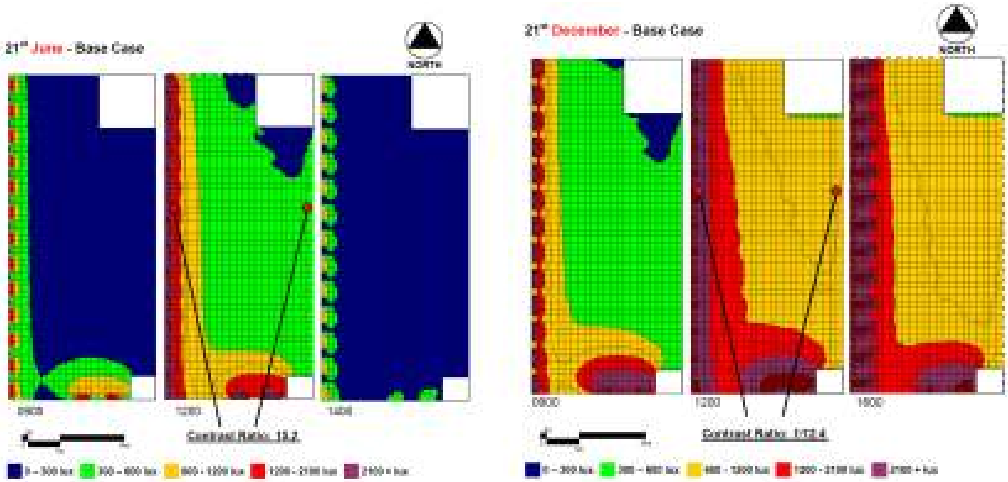



Figure 4
Illuminance modelling for Winter and Summer (extreme) cases

really the worst case?' Furthermore, it may be considered that diffuse sky light is more desired than direct light when considering the previous case in Figure 1. Another consideration might be to realise the particular type of sky that dominates climate and location for most of the year and to design for it. If we can solve the daylight condition for the type of sky that is 'typically' present then perhaps it is most likely that we have allowed for the use of daylight for most of the year. Further to this concept is that lesser light conditions can be supplemented by electrical lighting.

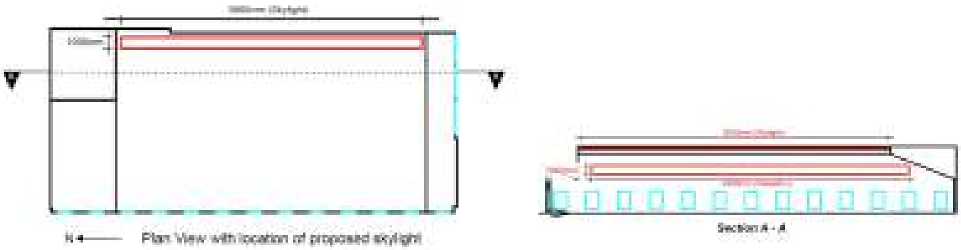



Figure 5
Additional window apertures considered for daylight retrofitting

## *Design Alterations*

From a first glance, considering the illuminance levels on a work plane, it can be asked and answered as to whether an overall 'balanced' lighting distribution has been achieved. The next step is one of design experimentation and perhaps this develops with experience. It asks where daylight would be most beneficial in entering the space. In an effort to balance the daylight throughout the space, a skylight strip is added to the East side (opposite the west wall). The results for illuminance consider the wall reflectance on the east interior wall to be 60%. As mentioned earlier a 'clerestory' light for the West wall is considered to allow for greater light penetration into the central area of the floor plan, the client however rejected this and therefore it was not applied (see Figure 5).

The results of the apertures as compared to the base-case (Figure 4) are shown in Figure 6. These clearly indicate a significant amount of more light entering the space at extreme periods, especially for the December case. Note that the clerestory light on the West side would have benefited the central work plane.

## *Refinements in the Design for Daylight*

For a particular design case, a gymnasium, a skylight was considered as the (only) option for bringing day light into the space (Figure 7). The refinements depended upon the size of the opening as well as the luminous (translucency and light transmission percentage) characteristics of the skylight. Furthermore, the design of the adjacent sloped surfaces (adjacent to the skylight) and their highly diffused reflectivity was a major contributor to a uniform daylighting result on the work plane (in this case the gym floor). The skylight aperture required quite some design attention and variable parametric studies. Two particular sky conditions were investigated; an overcast sky (15,000 lux) and a uniform sky (25,000 lux). While both these sky conditions are probably a far cry from a clear day of 100,000 lux, they help assist in providing a 'worst case' and average scenario of daylight availability. In hindsight, simulations should have included a clear day as well, because the aperture was even more shaded (translucency reduced) in its instalment than what was calculated.

The intention is to diffuse the incoming light at the skylight right from the start. However, a diffuse reflective area over a much larger surface, (3-4 times) that of the actual opening, (the sloped sides adjacent the skylight) are the key answer to glare elimination and effective daylight distribution. It provides the perception of expansive, dominant and uniform strips of lighting for this space. The modelling of this design in Desktop Radiance®, which operates under the ray-tracing principle (Greenberg et. al 1986, Ward 1994). This program yields the 'brightness' (luminance) candelas/m2 of the surfaces, which provides information on the amount of light emitted off each surface. The use of this metric is important in the study of contrast between surfaces and therefore the reduction of glare.

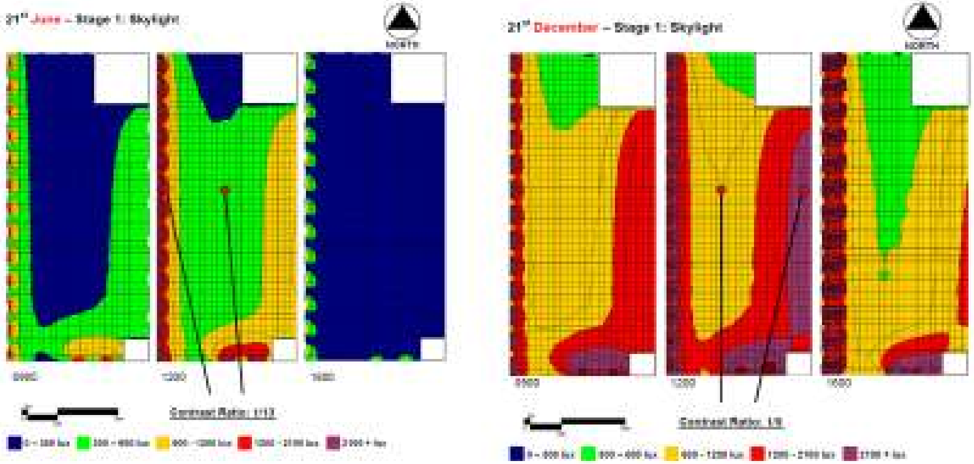



Figure 6
Illuminance levels after alterations from the basecase in Figure 4.

Another case in daylighting refinement considered dividing the equatorial facing façade into two regions; an upper clerestory region and a lower vision region (Figure 8). Again, the initial modelling began with a basic sunlight configuration analysis using a simple geometric software that also had GIS location and solar position capabilities. Here studies were performed again for extreme seasonal periods; Winter and Summer solstice as well as an equinox period (March 21st) to observe the sunlit configurations.

The façade division's main purpose is to reflect the unshaded direct light back onto the ceiling plane and to provide daylight deep into the space. The lower shading device assists with the control of sunlight and eliminates a direct solar penetration. Studies using a ray-tracing tool program provided for the design optimisation of an 'inverted' Venetian blind (Greenup et. al. 2001) (see Figure 9). The results of the final design without and with the clerestory light guiding blinds is simulated in Lightscape a pro-

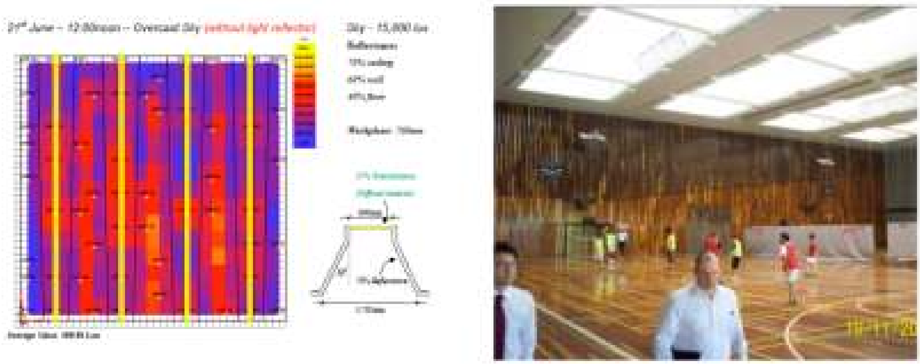


Figure 7
Daylighting distribution from skylight strips in a gymnasium

Figure 8
Cross-section of an office space indicating two regions in the façade.

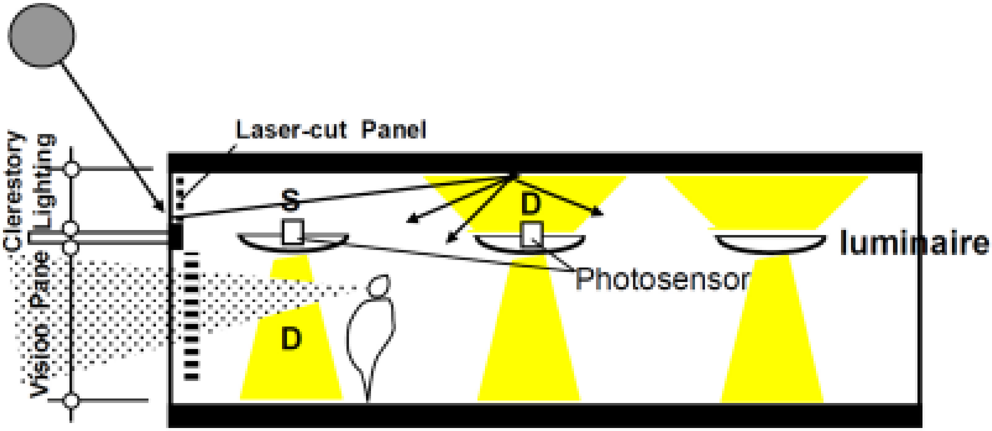
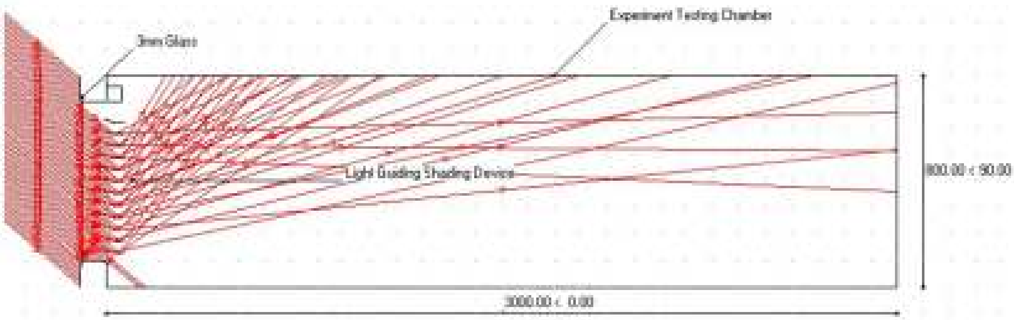



Figure 9
An 'inverted' blind in the clerestory region for directing light onto the ceiling plane.




gram based upon the principles of radiosity (Maamari and Fontoynont 2002, Tsanggrassoulis and Bourdakis 2003) (see Figure 10).

### *Selective Analysis*

Probably one of the most important aspects of daylighting simulation is to be selective in computation. Knowing to apply boundary conditions, such as the simulation of extreme cases - Winter and Summer are useful information in establishing the boundaries. Or in other cases, using the norm, a partially cloudy sky, to provide the definitive answer, is something that develops with experience. An iterative and parametric approach, in software, exists for the refinement to optimal daylighting design, where extreme sky conditions help to establish boundaries, alongside interior reflectance values, and window properties of

Figure 10
Room without clerestory light guiding blind (left) and with guiding blind (right).

variable size, transparency, or translucency, in providing a compromised result.

In the example of a school library, a light-shelf is applied to reduce the direct sunlight 'hotspots', while it also directs light onto the ceiling plane (see Figure 11). The light-shelf serves as a shading device to the lower window region and is effective at eliminating a substantial portion of the 'hotspots' (see Figure 3). The initial geometry is constructed in Google SketchUp. This allowed for the preliminary study of sunlit configurations on the library work plane. For the refined lighting study the surface reflectance and curvature design of the lightshelf was studied using 3D-Studio Max. This program has the capability to utilise the Perez - 16 different sky types (CIE 2003, ISO 2004) which yield the effectiveness of the daylight distribution onto the ceiling plane for various day types, seasons, and time.

Additional illuminance studies on the work plane are performed, without and with a screen in the visual section under the lightshelf (Figure 12). For the particular case (sky condition and period) it is noticed that the central part of the floor plan maintains a significant illuminance level in either case, with or without the screen. This indicates that the particular lighting program applied has the capability to simulate several reflectances of light off various surfaces.

## CONCLUSION

There are numerous procedures and tools in researching, designing and simulating for a successful daylighting outcome. While recent approaches currently seem to suggest that high powered multiple hourly simulation of multiple sky types with raytracing are the most accurate, the requirement as to whether these tools are necessary at the beginning and intermediate stages of a design analysis is questioned. The novice to daylighting design requires a systematic method rather than diving blindly into simulation. This paper is written in hindsight, considering numerous projects of the past and revisiting their approach to daylight design, simulation, and refinement and in some cases, post measurement. In doing this exercise, a process is discovered that could be viewed as a method of daylight design and investigation for a project.

Foremost are the basic investigations of 'where the sun goes' throughout the year for the room considered. After this, and perhaps even before any daylight simulation analysis, design alternations and concepts for window location, size and transparency, shading types, light-shelves and light guides are considered.

The next step is to consider the type of sky condition and the seasonal periods (extreme and middle seasons). Together with this, is the metric being sought from the simulation. If it is solely an 'end result', then illuminance is that parameter. However, if a more in depth understanding is sought on where the light is coming from, then luminance is the correct parameter. These two metrics, in particular luminance, need to consider the reflectance of the surfaces in the room.

In daylighting it is important to realise the criteria that controls the light. This begins on the exterior at the window opening size (aperture), its location,

Figure 11
A light shelf for a library: SketchUp geometry (left), modelled with 3D-StudioMax (right)

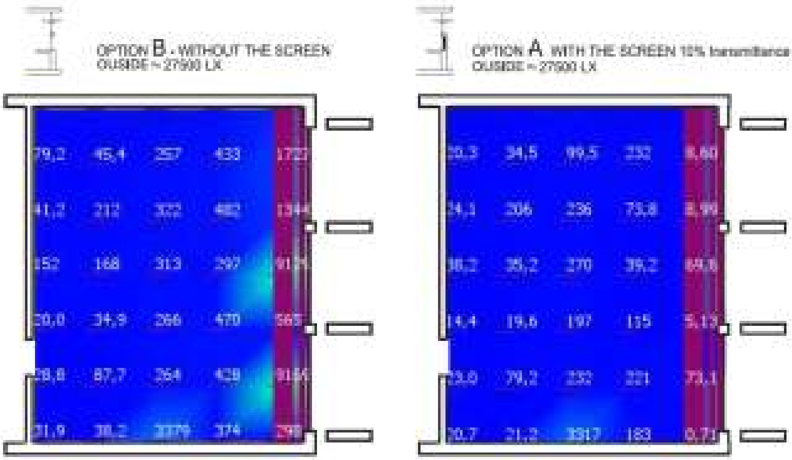



Figure 12
Illuminance result of light-shelf without (left) and with (right) screen: Dec. 21 - 10a.m.

translucency or transparency, shading or light guiding devices accompanying it. On the interior, it is the surface type; specular or diffuse, highly reflective or less reflective, horizontal or vertical, that determine how and where the light is distributed throughout the room.

It is also important to be selective with the time of day used for simulation, as with the first step (solar position and sunlit configuration) analysis to determine whether direct or diffuse sky lighting is incident upon the window apertures. Alongside the selection of sky condition; overcast, clear, or partially cloudy, is the importance in recognising what a typical average condition for the location might be. Instead of merely considering, what the standard requires (overscast sky), ask what the 'typical' sky condition for the location might be.

Finally, what might be most important is to consider the space function, and whether less daylighting supplemented by electrical lighting offers the best solution. It is better to be cautious and perhaps even a bit conservative with limits on daylight entering a space, since it often takes a long time before the blinds get pulled up again.

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# APART but TOGETHER

## *The Interplay of Geometric Relationships in Aggregated Interlocking Systems*

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*In this research, the authors discuss multiple design process criteria, fabrication methods, and assembly workflows for covering spaces using discrete pieces of material shorter than the space's span, otherwise known as topologically interlocking structures. To expand this line of research, the study challenges the interplay of geometric relationships in the assembly of unreinforced and mortar-less structures that work purely under compressive forces. This work opens with a review of studies concerning topological interlocking, a unique type of material and structural system. Then, through a description of two design projects - an interlocking footbridge and a vaulted structure - the authors demonstrate how they encouraged students to engage in a systematic exploration of the generative relationships among surface geometry, the configuration and formal variations of its subdividing cells, and the stability of the final interlocking assembly. In this fashion, the authors argue that there is hope for carrying the design criteria of topological interlocking systems into the production of precast concrete structures.*

**Keywords:** *Topological Interlocking Assembly, Digital Stereotomy, Compression-Only Vaulted Structures, Surface Tessellation, Digital Materiality.*

### A NEW CONSTRUCTIVE LANGUAGE

#### *An aggregated interlocking system*

An interlocking structure establishes equilibrium through compression forces; the weight of each heavy block is used against itself to maintain it in the air (Sakarovitch 2003). Being in a static state of equilibrium, the interlocking structure is carefully balanced under its own weight, without any additional binding materials (such as mortar joints) between the disparate blocks. In general, the stability of such a structural system depends on the location of its modules within the overall assembly and the adjacent contact faces of those modules. Specifically, the final module locks all of the other elements into position (see Figure 1).

### FROM STEREOTOMIC STRUCTURES TO INTERLOCKING SYSTEMS

In light of the relevant precedents for the geometrical complexity of topological interlocking systems, this section limits its scope to the historical development of stereotomy (Evans 1995). As an introduction to the nesting components of a volumetric block of material, this section not only targets certain historical approaches to digital fabrication, but also reviews recent state-of-the-art advances in this field.

Although history is rich with examples of interlocking stone structures, stonecutting is not the only way that geometrically complex building blocks can be created. Topological interlocking is rooted in stereotomy, but presumably stemmed from the field of reciprocal frames or nexorades (Baverel et al. 2000), such as in ancient Asian forms of timber construction (Brocato et al. 2015). Compressive strength and bilateral contact conditions are the threads that bind reciprocal frame and interlocking structures. The most remarkable example of a topological interlocking structure is the Abeille flat vault, in which identical truncated tetrahedron-shaped stones were assembled in a two-directional woven pattern that spans the curvature of the vault (Tessmann et al. 2013), providing an "all in one ceiling for the lower storey, and a pavement for the upper storey" (Fleury 2009). The rationale behind Abeille's system is similar to the principle of reciprocity employed by medieval building masters and found in Villard de Honnecout's fylfot grillage assemblies, Leonardo da Vinci's spatial structures, Sebastiano Serlio's planar floors, and John Wallis's scholarly work (Yeomans 1997). In such constructions, a discrete loadbearing element supports two neighboring components, and is mutually supported by two others to span distances longer than their length (Pugnale et al. 2011, Brocato et al. 2012). Patented at the end of the 17th century, Abeille's vault overcomes the structural instability of reciprocal frames when loads are not applied in a fashion perpendicular to their planes (Weizmann et al. 2016).

Based on a more complex version of a similar organizational pattern, Sébastien Truchet presented an improved variant of Abeille's design with the same cyclic distribution of loads. In Truchet's enterprise, similar to Abeille's, the entire bi-directional assembly is erected with identical blocks (Fallacara 2009) that lean on two adjacent blocks and endure two others. While Abeille's polyhedron-shaped blocks are composed of four intersecting flat surfaces in the shape of isosceles trapezia, Truchet's blocks have concave and convex surfaces made out of ruled sides. Along with the saddle-like joint surfaces of Truchet's vault blocks, their section profiles are different so as to be able to touch at all points.

In the projects put forth by Abeille and Truchet, the structural elements are combined to show the natural aesthetics of a stereotomic system. In both, each block is in contact with four others, and thus is a part of a squared homogeneous net reflecting its own inherent decorative pattern. As an improvement on Abeille's design, Truchet used no square

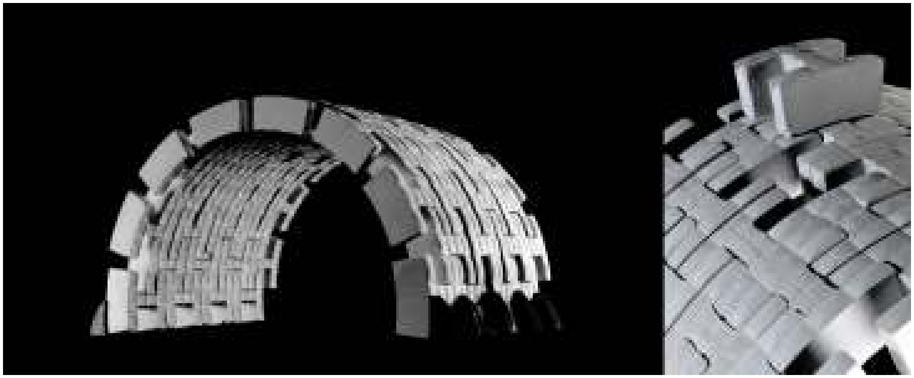

Figure 1
A stereotomic-like vaulted structure illustrating the division of a massive body into topologically interlocked elements. Freshman Design Studio, Texas A&M University, 2016.

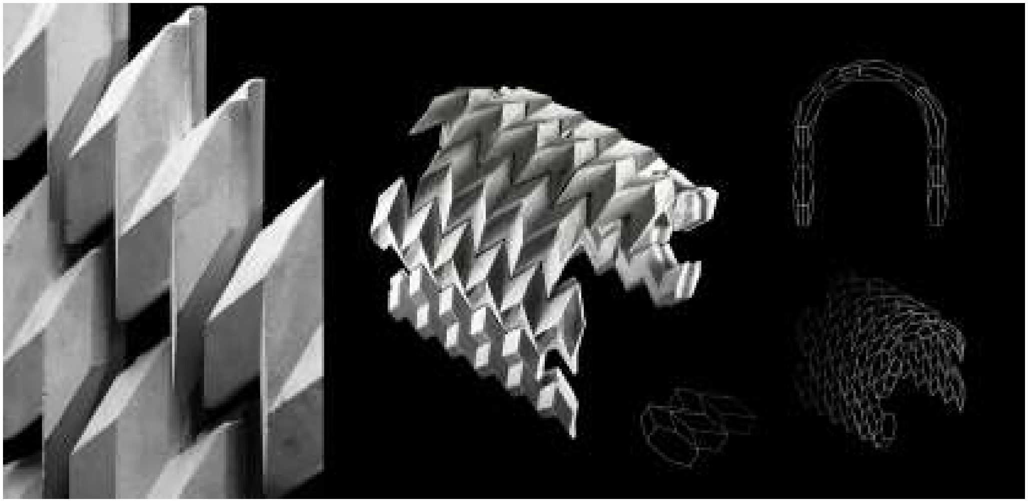

Figure 2
A vaulted interlocking structure using structural elements shorter than their span to cover a space. Freshman Design Studio, Texas A&M University, 2016.

voids on either the extrados or intrados sides of the ceiling, while Abeille left pyramidal holes on the underside of the vault to provide a coffered structure.

Although both of these flat, vaulted structures partake of the complex geometrical configurations of reciprocal frames in order to withstand their own weight, they behave differently from reciprocal frame structures (Miodragovic Vella et al. 2016). Contrary to reciprocal frames, one of the advantages of both Abeille's and Truchet's vaulted patents is their ability to sustain loads and control the displacement of their blocks. The loads cannot be discharged because the blocks are interwoven. After resolving their boundary constraints, both of these structural systems are capable of tolerating orthogonal and transverse forces (Brocato et al. 2014).

Unfortunately, the great geometry of these vaults only comes into play once the whole assembly process is completed. Additionally, the substantial horizontal thrust within the assembly requires a strong boundary condition to support the structure, such as buttresses or hefty walls (Miodragovic Vella et al. 2016). Thus, both of these flat vaults are not often applied in an architectural format as a successful construction method. Moreover, since Truchet's block has proven difficult to execute with an analogue tool, the vault does not offer many practical advantages.

From the 17th century onward, science and the art of stereotomy fell into general disfavor, due to issues of labor intensity, atypical craftsmanship, and geometrical complexity. After the first half of the eighteenth century, the industrial revolution and the introduction of new materials caused a sudden break away from stereotomy (Fallacara 2009, Rippmann et al. 2011, Miodragovic Vella 2016). A major shift in contemporary architecture, nearly two and half centuries after its demise the principles of stereotomy are now being revived. The applications of Abeille's stereotomic system have redirected attention to the development of new materials. Therefore, on a different scale, the potential for his system is being reexpored by materials scientists (Dyskin et al. 2001, Estrin et al. 2011, Khandelwal et al. 2012, Carlesso et al. 2012), and has become a research topic for academics and industry professionals alike. Syskin's team coined the term "topological interlocking assembly" in the course of their research on the stiffness, deformation, bearing capacity, and even sound absorption of planar configurations comparable to Abeille's core idea. There is now a great deal of speculation surrounding the concept of topological interlocking systems and their promise as a materials design principle.

As a basis for developing a paving system, Glickman (1984) proposed a set of interlocking tetrahedral units that could link together due to the inclination of their neighboring sides. In recent years, with so much attention being paid to assembling discrete components in complex loadbearing formations, many scholars (Tessmann et al. 2013, Miodragovic Vella et al. 2016, Weizmann et al. 2016) have attempted to incorporate stereotomy, at that point a vanishing building discipline, into their procedures for designing and fabricating freeform geometries (Andriaenssens et al. 2014). Additionally, due to technological advancements in digital design and fabrication, the associative rules of topological interlocking connections have motivated designers to test those rules on large, non-planar assemblies. The work of these researchers and designers is still in progress. It is worth mentioning that contemporary stereotomy-inspired studies have been developed to benefit contemporary architecture rather than to serve as a nostalgic replication of an isolated chapter in the history of construction and archaeology. For instance, the Brocato team's research has contributed to a better understanding of how Abeille's system could be adapted to designs for geodesic spherical assemblies (Brocato et al. 2010, Schwartz et al. 2014). These researchers also developed a prefabricated stone wall based on stereotomic designs (Brocato et al. 2014). The ever-consistent Fallacara has also transferred the geometric rules of Abeille's flat vault into geometrically expressive non-planar structures such as vaults and domes (Etlin et al. 2008, Fallacara 2009). Clifford and McGee updated stereotomic techniques through their translation of Inca stonework techniques into contemporary practice (Clifford et al. 2014, 2015). In the past few years, several academic institutions and research labs have investigated robotic approaches to self-supporting, compression-only, unreinforced, mortar-less structures; these include the Hyperbody Research Group at TU Delft University (McGee et al. 2013), and the Robotics Research Group at the University of Sydney (Fernando et al. 2017).

Fortunately, a continuous increase can be seen in the formal complexity of more varied stereotomic-like projects integrated with structural analysis (Fernando et al. 2015). By revisiting Ochsendorf's method (2010) and relearning means of erecting compressive vault structures, the Block research group at ETH Zurich was able to initiate computational modeling approaches such as Thrust Network Analysis (Block 2009) for form-finding and optimization in compression-only structures (Rippmann et al. 2011, Block et al. 2017). By applying equilibrium analysis to masonry structures and simulating their complex behaviors, they were able to find practical means of translating spatial masonry construction techniques into contemporary practice.

## AGGREGATED INTERLOCKING SYSTEMS IN PRACTICE

This research documented the incorporation of digital tools into a design pedagogy for simultaneously teaching the relationships among geometry, structural forces, and architectural form. By providing an opportunity to explore the construction-informed and structurally-aware design processes of two interlocking systems - including a vaulted structure (see Figure 2) and a footbridge (see Figure 3) - in the fall semester of 2016, freshman architecture students at Texas A&M University were able to identify certain challenges to realizing these structures and developing form-finding techniques. The mortar-free bridges and vaults were held together by the boundary constraints of their discrete elements.

Here, students attempted to incorporate precision, tolerance, and craftsmanship into their coupling of the design and construction processes for several interlocking assemblies, with all of their rich structural sophistication and aesthetics. Students' primary goal in these two projects was to take advantage of the potential of digital tools and their direct physical implications for the proposed interlocking systems by using geometry, especially if it could be implemented in a self-supporting structure.

Both projects were non-linear and exploratory, investigated with and through computations completed within a limited timeframe. By synthesizing both physical and digital form-finding techniques and simultaneously responding to assembly challenges, the instructors hoped to lead these beginning design students to develop their own integrated digital workflow, from design to fabrication and beyond simple digital modeling. To reach beyond digital representation, these projects asked freshman students to trace the relationships among materials processing, structure, and geometry, and explore the potential of topological interlocking assemblies within an architectural framework, as well as their related design methods and fabrication possibilities.

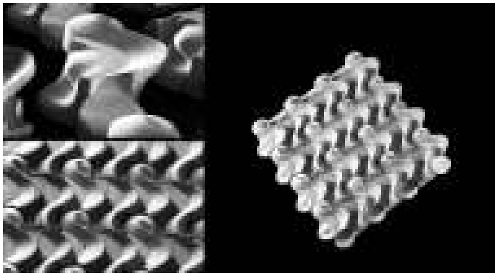

Figure 3
An interlocking footbridge, the macro-geometry of the entire assembly, and the micro-geometry of the joints. Freshman Design Studio, Texas A&M University, 2016.

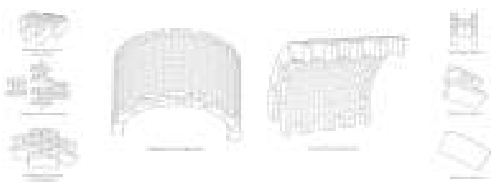

Figure 4
Obtaining just one type of block for the fabrication of the whole vaulted structure. Freshman Design Studio, Texas A&M University, 2016.

The key to designing an interlocking system is a comprehensive understanding of geometry in three-dimensional space. Since geometry plays an important role in stabilizing an interlocking assembly, both projects helped students investigate the reciprocal relationship between geometry and structure. In these projects, the bridge and vault and their respective structural characteristics emerged from the geometry of the blocks (see Figure 4). Since each block was a configurational condition based on its geometry, the whole interlocking system was highly constrained by geometry as well. Consequently, changing the geometry of each block such that the mutual surfaces were altered affected the overall stability of the structure. Students' prototypes were made and assembled from blocks that could be divided into several categories, depending on the forms of their interlocking joints, block interfaces, and seams, all of which were derived from the underlying geometry of their designs.

Topological interlocking assemblies have intrinsic vibration attenuation mechanisms. Thus, analyzing their principles can lead to a more profound knowledge of the behavior of seismic-resistant structures (Yong 2011) due to ground motion or soil failure. As a deep-rooted constructive solution to energy dissipation during seismic events, mortar-free interlocking structures with relative movability at their block interfaces can diffuse the energy of a dynamic load throughout. Under a dynamic load, the vault and bridge modules allowed for slight movements to dissipate significant shear forces without major failures, increasing the lateral force capacity of the entire structure. Students' proposed vault designs were for earthquake-resistant buildings that could withstand seismic waves in Southern California.

By handling movement, interlocking vaults are able to sway but not collapse. The proposed bridge and vault designs were tolerant to local failures. Failed blocks were held in their assembled positions by their neighbors, by virtue of the appropriate joint geometry between adjacent surfaces. Conceived to be an assembly of fragmented pieces, an interlocking structure, as an exceptional material system, does not let cracks propagate throughout. In the students' models, the chance of structural failure was decreased in cases of major damage because the structures could be broken down into smaller distinct components. By utilizing various analogue and digital tools, the projects offered a holistic understanding of the interplay of geometric relationships within different construction techniques and assembly configurations useful when designing forelocked systems. Both projects were initially developed with digital models.

By incorporating information, materials properties, construction knowledge, time, and space, this research clarifies how digital models can be a part of physical models. Although digital tools were used as a starting point, the final designs were developed somewhere between computational simulations and physical materials prototyping, while simultaneously transforming from one into the other. The translation of the virtual into the real provided confidence to freshman students witnessing how the possibilities of digital simulations enhance the potential of physical models.

## FIRST INVESTIGATION

### *An unreinforced interlocking footbridge*

In the first project, students were asked to envisage a relatively thin bridge system that could not be warped. Then, they examined principles key to the interlocking mechanism by applying a flat, small-span footbridge to a planar assembly. The goal was to create a structure that could traverse a small creek without requiring piers. By imposing kinematic constraints through the shape and mutual arrangement of its modules, students designed and fabricated several woven organizational patterns out of various networks of interacting elements (see Figure 5).

As mentioned above, no pillars were allowed in the middle of the students' bridges, so loads had to be transmitted to the two ends. The closely fitted elements in the bridges were capable of resisting static and dynamic loads, thus allowing foot traffic and bicycles to cross over. The students' bridge structures behaved as compression-active constructions to resist bending forces. The bridge elements that were assembled to mutually constrain the planar configurations were also easy to disassemble as demountable constructions. The design process for the interlocking assemblies was a systematic method of transferring loads at the interfaces between two neighboring elements that kinematically constrained each other, achieving stability through the interaction of neighboring elements and their geometrical and spatial configurations.

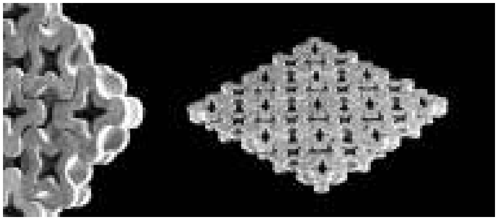

Figure 5
Organizational pattern of an interlocking footbridge that combines structural and ornamental building parts. Freshman Design Studio, Texas A&M University, 2016.

## SECOND INVESTIGATION

### *A self-supporting vaulted structure*

In the second project, students' models explored the nature and potential of applying appropriate geometries to compression-only interlocking structures with non-planar shapes made out of discrete components. Here, the vault's static components were subservient to the geometry of the joints, the respective shapes of the individual blocks, and their arrangement as a whole. The strength and equilibrium of the interlocking vaulted structures were achieved through their geometric configuration, as well as their spatial and formal characteristics.

Associating forces and form in a mortar-less structure once the interlocking blocks are completely assembled is a way of structurally defining space. As such, the second project helped students understand the dependence of an interlocking vaulted structure on its architectural spatial expression and connotations. The alliances among the structural, spatial, formal, and aesthetic qualities of the proposed vaulted architectural systems were employed to make a small structure called the Chapel of Silence. The resulting vaulted buildings required no additional side pressure or frame to hold the blocks together (see Figure 6).

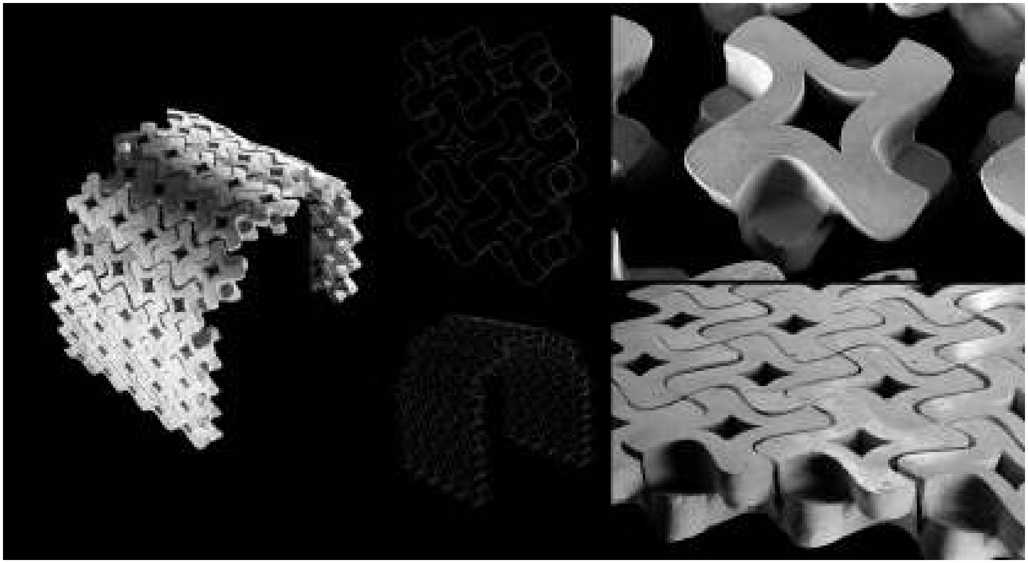

Figure 6
Complex architectural geometries for three different topological interlocking modules of a vaulted structure. Freshman Design Studio, Texas A&M University, 2016.

## PRINCIPLES OF THE MATERIALIZATION PROCESS

The design process for a compression-only interlocked structure uses an integral connection mechanism to deconstruct a continuous form into discrete blocks for fabrication and assembly (Griffith et al. 2006).

Since this design process meets a confluence of different formal, spatial, and structural concerns, it is cyclic and requires several feedback loops. Therefore, to coordinate the different constraints, any fabrication and assembly challenges should be brought forward early on.

Materialization involves several design and modification steps, including:

- Form-finding to determine the base surface geometry,
- Discretization of the base surface and application of a tessellated pattern,
- Generation of the geometry of the block modules based on the applicable profile geometries,
- Refinement of the structural form and tolerance design,
- Processing and replication of the fabrication of the modules, and
- Completion of the assembly sequences and required formwork.

These steps were carried out for both studio projects. The translation of the computed forms to constructible blocks was exemplified by making more than 34 complete physical scale models with interlocking assemblies built into their blocks.

**Surface Geometry.** In the design process, designing the appropriate surface geometry and dividing the surface into meaningful subdivided surfaces or cells can be challenging. For this research, the process began with a base surface geometry informed by structural concerns, as well as the means and methods of making. For instance, in a vaulted structure, the most important constraint that governs the stability of spatial assembly is its surface curvature radius. Therefore, the final form of the curvilinear base surfaces was geometrically defined as semi-cylindrical.

**Discretization.** The deconstruction of the base surface geometry into proper segments is a critical step in the design process. By using parametric geometric algorithms to divide the surface, it is possible to map regular, semi-regular, or non-regular surface tessellations onto the base, generating 2D or 3D grids (Rippmann et al. 2011, Weizmann et al. 2016). In both projects, the base surfaces of the bridges and vaulted structures were subdivided into almost evenly shaped cells along their initial isocurves. The ultimate goal was to achieve constructible blocks. Consequently, subdivision sizes were specified based on fabrication and assembly concerns, while retaining the designer's intent.

**Block Module Design.** The final bond of the assembly is closely related to the integral connections made between blocks. To create a continuous interlocking assembly, it was necessary to design a 3D puzzle-like configuration with particular tabs and slots. Although each cell emerged from the boundaries of the tessellated grid applied to the base's surface, it was not possible to translate the cell boundary to a solid; a simple extrusion command, based on the cell's normal service, can often generate the appropriate spatial geometry. However, in these structures, by using different types of surface commands and Boolean operations to subtract the desired parts of one block from another, the embedded connections could be modeled.

It can be laborious to model a block with an integral connection mechanism when it is part of a larger, complex geometry. To create the interlocking connections, the individual geometries of one or two axial sections are essential. The designers needed to progressively move closer and closer to find the desired profile geometry to drive the topological optimization process. In their projects, although the orientations of modules and geometries of the boundaries governed the material distribution of the force-locked structures, the contact faces of the mutual modules and their sections were critical to regulating the structural behavior of the assemblies. Both projects helped students to understand that the effectiveness of an interlocking system depends on the sections of its modules. In large part, the stability of these interlocking systems is not guaranteed simply by the natural compression between the blocks. However, the connections between each pair of mating joints makes it difficult to pull the entire structure apart.

In the students' projects, the vault blocks were held in place by the appropriate geometry of the surfaces in contact with neighboring blocks, and their mutual arrangement. In the interlocking systems, it was the geometry of the joints themselves that hindered the relative movements of the block pairs. Therefore, choosing the right corresponding geometry for the joints was key to the integrity of the structure. Through the use of geometrically-informed surfaces to connect blocks (rather than sophisticated mechanical joints or chemical connections), the discrete modules were able to form bonds. Depending on the shape of any two connecting joints, the students dealt primarily with geometric principles to design large sculpted concavo-convex matching surfaces for each joint. Besides the material properties of the blocks and the constraints that could arise during fabrication or assembly, the appropriate depth of the embedded connectors of each block followed the volumetric size and weight of the entire structure, the initial curvature of the final assembly, and the number, complexity, and direction of the blocks.

**Refinement of the Structural Form and Tolerance Design.** The behavior of an interlocking structure must be predicted before assembly, rather than after completion. Although the direction and magnitude of the forces have a significant impact on the stability of the assembled structure, to satisfy a thrust network within the structure's depth, structural concerns must be aligned with formal aspects. In this research, this step was accomplished via two substeps, resulting in an isomorphic structural condition on both large and small scales. On the large scale, to guarantee the structural integrity of the entire assembly, a global structural evaluation was considered; this maintained the structure's equilibrium in its final state. On the small scale, a local understanding of the forces applied during assembly was essential to satisfying intermediate equilibrium states (Ariza et al. 2017). Also during this phase, to obtain a minimum of gaps between blocks that result from tolerances in fabrication while also satisfying component strength, assembly tolerance had to be taken into account. The blocks had to have the capacity to be fitted in place during the assembly process when there were fabrication inaccuracies.

**Fabrication Process.** The fabrication workflow can vary from one project to another. In the studio projects, this process was divided into two main phases: rapid prototyping of the required modules, and the production of molds to replicate the modules through casting. Students employed cast concrete blocks to leverage the robustness, versatility, and appeal of concrete. Here, the prototypes were mainly built from uniform interlocking blocks. Although the projects took advantage of 3D printers to make individually unique blocks, it was obvious that uniformity made the mold-making processes less expensive. Since a wide array of blocks needed to be produced, most of the students' designs used only one shape of block.

**Assembly sequences.** The process of materialization provided an additional stimulus for thinking about the interdependent relationship between the surface geometry and structural behavior of a topological interlocking system at the time of assembly. In this research, the blocks were dry fit to one another and set in place at specific moments. Registering each block to its correct location relied on the other steps being accurately satisfied. Completion of the assembly sequence did, at times, require a temporary scaffolding system.

## DISCUSSION

In general, the main challenge with these types of structures is to maintain the structural integrity of the aggregated construction. This research allowed for a more holistic understanding of the geometric nature of interlocking structures. Through the discretization of flat or curvilinear tessellated surfaces into a limited number of cells with embedded, form-fitting connectors, the projects exhibited the potential of the structurally and mechanically responsive geometries informed by stereotomic principles.

This work reported on ways of mining the primary geometrical logic that expands topological interlocking principles towards the fabrication and assembly process. Examples of the applications discussed here were introduced through several scale prototypes. The two studio projects helped freshman students get acquainted with the challenges involved in designing and implementing this type of constructive practice by bringing into play the tangible geometric speculation of stereotomic systems. Students used hands-on experiments to unravel how the geometrical conformation of a part could guarantee the integrity of the whole. In their projects, the interlocking mutual support of the blocks in the prototypes captured the reciprocity principle upon which the topological interlocking premise was based.

The underlying organizational mechanism of interlocking systems provides the potential to streamline complex geometries. The lessons learned from these two topological interlocking projects, incorporated with digital computation and heightened by physical prototyping, reveals that their stereotomic nature could help designers investigate the potential of variations within the structure of the blocks. The fabrication of interlocking prototypes illustrates that there is a need to re-explore and improve upon the relationship between the working principles of stereotomy and their generative effect on the stability and form of a structure.

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# DESIGN TOOLS - ROBOTICS

# ROBOTRACK

## *Linking manual und robotic design processes by motion-tracking*

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*This study investigates design opportunities fostered by fabrication processes, ex-ploring manual and robotic forming. It links handcraft and digital fabrication techniques by implementing a motion capture system. It suggests physical prototyping as a novel form of design research, operating in the dynamic field between human capabilities, machine skills, and material behavior. This paper presents a series of experimental case studies created in a seminar taught by the author at Graz University of Technology. In this course, students con-duct tactile experiments, forming panels by hand and by robot, guided by the material behav-ior and reaction. Thereby, they explore the creation of architectural form in a dynamic inter-play between human, machine and material. Movement and speed of hand forming proce-dures are recorded into digital data, and then converted into machine code, driving a 6-axis industrial robotic arm. By using the same set-up for manual and robotic forming, both pro-cesses are relatable.*

**Keywords:** *design by making, digital fabrication, robotic fabrication, thermoforming, material behavior, motion tracking, craft, design education, design research, intuition, human machine interaction*

### INTRODUCTION

Following the age of digital design, nowadays the use of digital fabrication allows architects to reinstate materiality in design thinking. Menges expounds "A novel convergence of computa-tion and materialisation is about to emerge, bringing the virtual process of design and the physical realisation of architecture much closer together, more so than ever before" (2012). Gramazio and Kohler emphasize the importance of benefiting from the interplay between digital and physical properties: "Digital and material orders enter into a dialogue, in the course of which each is enriched by the other." (2008).

Within the last decade, architects have been appropriating industrial robots as a versatile and flexible tool for digital fabrication. They are "...re-using industrial robots as a well established basis and adapting them for architectural purposes by developing custom software interfaces and end-effectors" (Brell-Cokcan and Braumann 2012). Robotic fabrication is not just another way of digital fabrication, but it has the potential to change processes in the architectural de-sign and build practice into a dynamic design-to-build-process. "Designers have taken the flexible nature of industrial robotic technology as more than just an enabler of computationally derived formal complexity; instead they have leveraged it as an opportunity to reconsider the entire design-to-production chain." (McGee and Ponce de Leon 2014).

Figure 1
Case-study 1: Prototype made of laser-etched and painted panel, twisted around a special-designed forming tool. In this case study, the movements of the hand-forming procedure are motion-tracked and replicated on the robot.

Nowadays, robots are not just considered as a production tool of digitally defined models, but also as a design tool, fostering digital-physical design-by-making processes. This research intends to blur the technical precision of robots, directly integrating them into the design pro-cess, utilizing them as creative tools. Furthermore, robotics can help to establish a new kind of craftsmanship utilizing human capabilities. Along this research trajectory, this study aims to link the advantages of human skills to those of robotic processes, to create new ways of architectural design-thinking.

This study is based on previous research by the author, using idealized trajectories to thermo-form materials by a 6-axis robotic arm (see chapter "The development of the case studies"). Based on the findings in these explorations, the interest arose to investigate the movements of forming methods more closely. Therefore, these forming processes are reconsidered by manual experiments, benefitting from human capabilities. By precisely tracking and recording manual forming scenarios by a motion capture system, the hidden intricate, sensitive and responsive human actions can be analyzed.

The captured and stored data of manual forming allows us to draw further conclusions on the relation of forming movement and resulting geometry.

The benefits of human intuition, experience, sensibilities, and immediate reaction to material properties are appreciated and utilized to further inform robotic processes. Nevertheless, the advantages of digital and robotic techniques are capitalized, which enable us to store forming trajectories, modify them, or repeat them. Thereby, we can produce further numbers or varia-tions of prototypes with precision, little time and effort and independent of specific operators. (Figure 1)

## DESIGN BY MAKING

Architectural design is traditionally often based on "making", implementing materiality and physicality. In contemporary architecture, digital-pysical experiments play a significant role. The availability of digital fabrication tools enables us to investigate design-by-making process-es from a new point of view, linking digital and physical means.

Gramazio and Kohler define the term "digital materiality" in 2008: "Digital materiality evolves through the interplay between digital and material processes in design and construction" (2008).

This research examines the potential that arises, when production tools - manual or machinic - are used as key part of the design process, with a special benefit of linking these two ways of "making" by digital tools, i.e. a motion capture system.

In this study, geometries are not designed or simulated on the computer."...the material "computes" its form - it self-organizes for a given set of boundaries, forces, temperature or other constraints. Therefore, the resulting outcome my be unpredictable and highly depends on material behaviour. The tacit knowledge obtained in these experiments is a foundation for what Donald Schön defines as the designer's "reflection-in-action".

Donald Schön, professor of education and planning at MIT, expounds that we need to "re-flect" on our actions, on the spot, so we can still have an impact on the outcome. If we oper-ate outside our normal routines, outcomes are not as expected - surprises, uncertainty, or non-understanding occur.

Therefore, "Our spontaneous responses to the phenomena of everyday life do not always work. Sometimes our spontaneous knowing-in-action yields unexpected outcomes and we react to the surprise by a kind of thinking what we are doing while we are doing it, a process I call reflection-in-action." (Schön 1985). The case studies documented in this paper employ a hands-on approach, where choices and "spontaneous responses" of the designer highly depended on the material at hand.

"This is not a linear process- it could better be described as a feedback loop where experien-tial learning is combined with theory and practice in several iterations." (Symeonidou and Weissenböck 2016). This digitally extended design-by-making workflow fosters a new way of thinking about archi-tectural design and practice, based on exploration of materiality.

Figure 2
From left to right: Students exploring thermoforming by hand / Motion-tracking of a forming scenario / Robotic production of a prototype

## RELATING MANUAL AND ROBOTIC PROCESSES

Because of their versatility and their analogy to a human hand, robotic arms are especially interesting tools to explore the relation between human and machine processes. Gramazio and Kohler, one of the first architects to use robots at ETH Zurich, expound: A robot "... has not been optimized for one single task but is suitable for a wide spectrum of applications. Ra-ther than being forced to operate within the predefined parameters of a specialized machine, we are able to design the actual "manual skills" of the generic robot ourselves." (2008).

In this research, actual manual skills are related to and overlaid with robotic skills by a motion-capture system, investigating the tension field between manual making and digital fabrication (Figure 2). The goal is to view the robot not as an independent machine, but to make it a partner in the design process, and to augment its capabilities with human sensibilities. In his book "Abstracting Craft: The Practiced Digital Hand" Malcolm McCullough writes, "People have talents and intentions that technology may serve....For example, the computer industry now advertises not computers, but human-computer partnerships: it matters less what the technology can do alone than what you want to do with it. This is especially true in design." (1996). In order to benefit from the unique human capabilities, we can interact with a robot to create its own digital craft/robotic craft. Handcraft is altered digitally and a new kind of overlaid craft created.

## THE DEVELOPMENT OF THE CASE STUDIES

As mentioned before, the case studies presented in this paper are based on previous research. They are the third iteration in a series of design experiments which build upon each other, progressively increasing the complexity of the setup as well as the influence of human dexterity in the process.

The initial case studies are inspired by peers investigating the potential of robotic thermoform-ing, i.e. at ETH Zurich [1], at University of Innsbruck's REX LAB [2], as well as by the Asso-ciation of Robots in Architecture [3], creating a diversity of beautiful elements with individual geometries. In most of these explorations, a digitally simulated geometry was to be achieved.

The author's research considers robotic forming techniques not as a production process for predesigned geometries, but as a dynamic design-by-making process, aiming to explore a formal spectrum that is not simulated in the digital realm before.

In the first series of prototypes, flat sheets of acrylic glass are formed into 3-dimensionally shaped objects by a 6-axis robotic arm. A new fabrication technique is developed, by combin-ing robotic thermoforming with laser cutting, "By means of this combination, it is possible to achieve customized elements of different shapes and variable apertures, as well as transpar-encies and surface treatments." (Weissenböck 2015).

"The laser cutting process is applied to the material prior to the thermoforming process, creat-ing slots, openings or textures....After laser cutting, the panels are placed into a custom-made wood frame that is attached to the robots flange. The deformation of the flat surfaces is cre-ated by the robotic arm, moving the frame together with the panel along a pre-defined path and pushing it against a counterpart called "deformer". Depending on the point and depth of deformation in relation to the laser-cut pattern, different sizes and shapes of apertures are created." (Weissenböck 2014).

Learning from these explorations, the second series of case studies engages more complex cut-and-slot techniques, as well as more intricate forming trajectories (and deformer-tools). I.e., besides forming by pushing, combined operations of push, twist, tilt and shear are investi-gated. In these studies, it turned out that complex dynamic forming operations - like twisting - of thermoplastic sheets are very hard to manage on the robot. Either the material would slip through the tool, the panel would break, or the tool would be stuck after forming. Nevertheless, this seemed to be a very promising trajectory worth to investigate further, because of its potential to generate intricate geometries that cannot be conceived otherwise.

Therefore, the third series of case studies - which is described in this paper - engages hand forming to examine complex forming operations of twisting and rolling. As mentioned before, manual procedures are related to robotic processes implementing a motion-capture system. The advantage of the manual approach is the immediate feedback and instant material re-sponse, which is still somewhat hard to achieve by mechanical force-feedback. With your hands, you can feel the material's stiffness, its counter reaction, the force and precision needed, allowing you to adjust your movements accordingly and to build up a specific "craftsmanship" for these processes.

Motion and time of crafted processes are captured, making the complex manual movements visible, and informing robotic operations. The detailed process will be described in the following chapters.

## THE STUDENT SEMINAR

The case studies presented in this paper are the outcome of a one-week seminar at Graz University of technology, taught at the intersection of research and teaching.

The goal of the course was to address the rapid technological advances and paradigm shifts in design processes in education, to expose students to current technologies and involve them into the contemporary discourse. The seminar introduces a current design-research topic in the educational scene, investigating the interdisciplinary field between design, craft and machine.

In an experimental set-up, students employ manual and robotic processes for the exploration of architectural form. They investigate possible shapes and design outcomes by thermoform-ing flat sheets into 3-dimensional objects - manually or robotically.

"In this "Research by Making" process, students explore morphogenetic strategies through digital and manual design experiments, with the aim to develop different kinds of sensibilities, intuitions and skills". (Symeonidou, Weissenböck 2016).

In these studies, the final geometry emerges during the actual production process in the ten-sion field of manual, machine and material properties. A result is anticipated, but the expecta-tions are not always fulfilled: surprises and discoveries happen, as well as accidents. As men-tioned before, intricate craft skills are made visible and understandable by capturing the hand movements by a motion capture system. The same customized "end-effector" - the frame to hold the panel - is used for both forming operations. Therefore, the robot can replicate the same operations that are done manually, and conclusions of both techniques can be drawn.

During the course, students were exposed to manual techniques and digital tools, including fabrication machines. They were introduced to a laser cutter and a 6-axis industrial robotic arm - as well as to the motion capture system installed in the school lab. Being directly ex-posed to these technologies is essential for skill building and gaining tacit knowledge.

"Experimenting with a range of new tools, the students develop curiosity and learn by doing, getting directly involved in the design process by making." (Symeonidou, Weissenböck 2016).

Figure 3
Variety of used deformer tools, counter-frames, frames and produced prototypes.

## *Setting up the seminar*

In order to conduct this dense one-week workshop, a lot of technical issues needed to be tested and set-up beforehand, to make the most out of the short time frame and allow the students a fast start.

Before the seminar start, new materials were tested, as well as new deformer tools like wheels or gears. The motion capture system was calibrated and adjusted, a work table set up, and its positions measured to equal the robot station. To be able to import the tracking data into the software packages of Rhinoceros/Grasshopper [4] , a custom script was developed to receive and store the live data. Furthermore, the conversion of the tracking data to the robot procedure needed to be investigated. Robot sample scripts were prepared in HAL, a Grasshopper plug-in for robot programming [5], and tested on the robot.

This seminar consisted of 25 students, who were asked to arrange themselves into five groups. At the beginning of the course, each student group is equipped with a set of materials and tools: a number of plastic panels (Polystyrene or PET-G), a frame to hold the panel, a set of geometry tools ("deformer") to form the surface, sample "counter-frames" for forming only specific regions of their sheets, and a heat gun to make the material malleable (Figure 3).

To achieve diverse outcomes, each group was assigned a different starting point in terms of material to use and forming movement to explore: polystyrene or PET-G / forming move-ment: roll or twist. The Groups who explored PET-G later on switched to polystyrene, since it turned out to be much better malleable for employed forming procedures.

## *Hand forming*

On the first day of the seminar, students immediately started with hands-on experiments. By means of hand forming of the panels, the participants were introduced to the material and forming behavior of plastics (polystyrene, PET-G) when exposed to different temperatures. Thereby, possible shapes and design outcomes were explored. Forming was used as a dy-namic and quick shaping process, using motions and forces to create curved surfaces. Pla-nar sheets were heated and 3-dimesionally shaped by pushing, twisting, rolling or sliding them against/along a form-giving counterpart ("deformer"). These forming processes were guided by sensibilities, intuition, experience and material properties. Thereby, students acquired knowledge about thermoforming techniques, gaining insight about heating intensity, time, speed, distance and area, all of which influence the outcome.

The quick results and the experimental nature motivated the students to get very creative and curious, exploring numerous design options by experimenting with different materials, forming movements, forming tools and counter-frames. Additionally, the students investigated cutting and engraving of the surface, to get different stretching, transparency or texture effects. This was explored by hand cutting as well as by laser cutting.

After producing the manual prototypes, students were able to evaluate their experiments, to build up a design intuition and develop a clear design intent, which further informs the digital process.

### *Tracking*

One of the main research goals of this seminar was the understanding of the relation between manual and robotic forming. This was accomplished by capturing (and analyzing) the hand forming process with a motion tracking system. The students "choreographed" scenarios, which they developed in the manual forming test. Using camera-based technology, the most successful hand-forming outcomes were tracked. Movement and speed of the crafted processes were recorded and subsequently translated to robotic operations.

The institute's tracking system consists of six infrared cameras. Reflective markers were at-tached to the frame of the panel and tracked in 3D-space by the cameras. The data was read by the tracking system's own software in real time, and streamed to Rhinoceros/Grasshopper via an UDP-receiver (using the gHowl plug-in for Grasshopper [6]). The number of tracked points could be defined by distance or by time interval. Each point was tracked in x,y,z-coordinates, x,y,z-axis-rotation and equipped with a timestamp. As mentioned before, a cus-tom script was implemented in Grasshopper to record and store the captured data. Once the data was in Grasshopper, the tracked points were available as Rhinoceros geometry and fully editable.

In the tracking process, the students realized several problems of manual forming. It turned out to be very hard to provide smooth and precise movements when hand forming, in order to get useful tracking data. The students had problems to execute one continuous forming series for the whole panel, matching all points, heating times, movement speeds, orientations and forces. Naturally, the students hand movements were not that steady and therefore not able to exactly meet the desired heat and/or forming positions. This was made visible by analyzing the continuity of the motion-captured trajectory.

Most groups took several attempts until they were satisfied with their tracking results. Group 5 optimized their hand forming technique to the maximum, using multiple persons for forming: one was doing the actual movement, one was holding a help template to match the desired target points, one was monitoring the timing, and one was taking pictures. It turned out, that group work was the fitting set-up for this seminar.

### *Data manipulation*

After tracking, the students analyzed their data in the digital model. They compared the motion trail to the produced geometry. The motion-captured data was either considered as a design intent for further digital explorations, or directly converted to robotic operations. Furthermore, it was used to store, replicate, optimize or vary manual forming procedures and create additional prototypes.

In most cases, the tracked path needed to be slightly adjusted, so that each target is in the working range of the robot and can be reached by the kinematics of the 6-axis robotic arm.

Besides this technical issue, different ways of manipulating and translating the tracked data for robot forming were used, based on the students design goals. These strategies include direct translation, parametric modification, replication and optimization of the manual process. For example, one group selected the most successful pattern and distributed it differently the surface, one composed hand-formed trails in another order, and another one straightened wiggly lines.

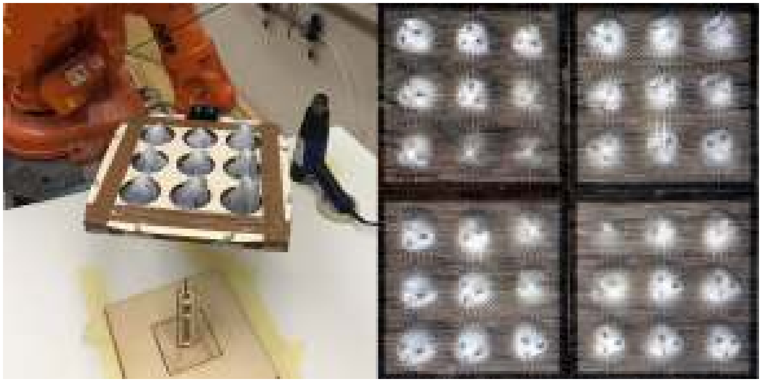

Figure 4
Case Study 1:
Prototypes made of laser-etched and painted panel, twisted around a special-designed form. Left: robotic forming / Right: clockwise: panels formed by hand/robot/hand/robot.

Figure 5
Case Study 2:
Prototypes made of laser-etched panel, twisted forming by a cube. Left: tracking of manual forming / Right: clockwise: panels formed by hand/hand/robot/-hand.

### *Robot forming*

During the last two days of the workshop, the student groups produced their robotic proto-types. After manipulating the tracking data, the defined points were attached to the robot as target points, their axes as target orientation and their timestamp directly fed into the speed component of the robot (using the HAL plug-in for Grasshopper [5]). Before execution, each code was double-checked on the robots own software, ABB RobotStudio [7].

Subsequently, the frame was attached to the robot's flange, the panel inserted in the frame, and the deformer tool and the heat gun positioned. After starting the robot code, the panel was shaped using the 6-axis robotic arm, an ABB IRB 140, moving it from heat gun to deformer tool multiple times.

Despite the execution of the code, it was still possible to interact with the robot via the teach-ing panel. This was especially useful in projects that rigorously changed the tracking data to new compilations. In this cases, students were aware that the robot forming outcome will probably not be as predicted, in favor of achieving emerging geometric results. Here, the ro-bot was driven in hand mode to be able to stop or interact via the teaching panel. In iterative steps, the set-up was optimized, often leading to new and unexpected results and deiscover-ing new design outcomes by the robot procedure.

In the following sections of this paper, three of case studies developed in the seminar will be described in detail, each using a different way of translating manual to robotic forming.

## CASE STUDY 1: DIRECT TRANSLATION (GROUP 5)

- Laser pattern: engraved lines
- Coloring: black pen
- Deformer shape: 3-pin
- Movement operation: push, twist
- Material: polystyrene, opaque, 1mm

In this case, the students aimed to replicate the exact manual procedure on the robot. This was made possible by the group's effort of optimizing their hand forming technique to the maximum, in order to get clean tracking data.

Translating the procedure directly to the robot, it was fascinating to watch the robot moving in shaky motions, resembling human hand movements. Thereby it got visible, how unprecise the apparent precision of manual forming actually was. However, it was no problem for the robot to execute all the tiny wiggly movements, and the produced prototypes turned out very well.

Despite the exact replication of timing and motion of the manual procedure (besides of course minimal imprecisions in the motion capture system), the result of the robotically replicated panels came out slightly different compared to the hand formed ones. Thus, we realized that in fact every tiny factor influences the material behavior. For example, the frame used for hand forming was made solely from wood, whereas the frame used for robot forming was made from steel and wood, the provide a stiff connection between robot and frame. Due to the different material properties of the frame, the temperature in the plastic sheet was slightly different, leading to minimal differences in the geometric outcome of the robotically produced panels.

Regardless, a series of three robotically shaped prototypes turned out virtually identical. Nevertheless, there is still one open influence factor, which is the slightly different material struc-ture of each plastic panel. In fact, out of three replicated panels, one got a hole at a peak point, where two others were perfectly fine. This demonstrates that the material is stretched to its limits. Making a minor adjustment in the parametric code of the Grasshopper/HAL set-up, i.e. reducing the deformation depth for half a millimeter, this problem could be fixed easily (Figure 4).

## CASE STUDY 2: MODIFICATION (GROUP 4)

- Laser pattern: engraved lines
- Deformer shape: cubical
- Movement operation: push, twist
- Material: polystyrene, opaque, 1mm

This group was interested in altering their hand forming trajectories for the robot phase, to investigate the emerging differences compared to the manually produced shapes.

The students took four local forming patterns of panels from different tracking sessions, al-tered them parametrically and distributed them on the panel in a new composition. As result of rigorously manipulating the hand-tracked data, the robotically deformed panels did not turn not out as expected and had noticeable different geometry than predicted.

In most cases, the surface slipped away from the deformer tool, diminishing the outcome of the twisted forming. Obviously, the amount and relation of push and rotate was not coherent anymore, as well as the relation of temperature and speed. Since there are so many influence factors like timing, speed, temperature, and relative position of each pattern on the panel, the results naturally come out differently. Despite losing the twist character of the hand formed panels, the robotically shaped panels provided valuable experience and insight in the co-dependency of the numerous defining aspects (Figure 5).

Figure 6
Case Study 3: Prototypes produced by rolling along a tilted, toothed wheel. Left: robotic production / Right: clockwise: panels formed by hand (PET-G) /hand/robot/robot.

## CASE STUDY 3: OPTIMIZATION (GROUP 3)

- Laser pattern: none
- Deformer shape: gear wheel
- Movement operation: push, roll
- Material: PET-G + polystyrene, opaque, 1mm

In this case study, the students appreciated the advantage of optimizing their hand forming procedures using the robot.

The group got the task to use a rolling deformer and to create linear deformations. Based on the explorations using a 3D-printed wheel for forming, and inspired by the creative hands-on experiments, the students developed a new forming tool: a tilted toothed wheel, which they designed, laser cut and assembled from wood. Due to the inclination of the wheel, when mov-ing and pushing the panel along the tool in a straight line, the deformed area resulted in a curve.

The geometries developed in the hand explorations and served as a design intent for the robot procedure, and led students to appreciate the advantages of the robot. By manual forming, it was not possible to achieve the desired precision of heating and forming along straight lines. Therefore, the group aimed to optimize their design using digital means. Based on the tracking data of the hand motion, straight paths were interpolated along the desired lines. However, in the robot tests it turned out, that due to the slight change of the path, speed and timing of the process had to be adjusted in several iterations to produce the desired outcome. Once these adjustments were made, identical prototypes of unlimited number could be produced (Figure 6).

## FINDINGS AND CONCLUSION

The study is adressing design-research-by-making in an educational realm, responding to new ways of architectural design and practice which are enabled by new technologies.

As described in the case studies, the outcome of this seminar provides a great insight on the relation between craft and machine, as well as on each's advantages and disadvantages. This digitally extended design-by-making workflow fosters a new way of thinking about architectural design and practice, based on exploration of materiality. In the documented case studies, form is the result of manual or robotic gestures of stretching and forming materials. Incorporating the advantages of human capabilities into robotic processes, machine abilities are augmented and a new kind of robotic craft is created.

The produced prototypes are appreciated as study objects, investigating the principle of "reflecting in action", as defined by Donald Schön (1983, 1985). As Schön states, we need to reflect on produced objects in order to fully understand "how professionals work". We "reflect-in-action", meaning we directly react, on the spot, to occurring situations and problems, and thereby increase our knowledge of the process and the results.

In order to engage the theory of reflection-in-action in design, this research augments robotic qualities by human properties. Linking manual and robotic processes allows for building up new sensibilities by experiencing and making. By hand forming, we can gain an intuitive un-derstanding of what the gestures and the forces we use will produce. Based on reflection-in-action, we build up skills and routines, which Schön defines as "knowing-in-action": This is "....the repertoire of routinized responses that skillful practitioners bring to their practice" (Schön 1985).

This new way of integrating machines into design, overlaying and augmenting them with human and material factors, provides an open field for experimentation. It allows for new ways of human-robot collaboration and design-to-production workflows. If properly employed, this methodology can unlock creativity and the discovery of new aesthetics and formal languages.

## ACKNOWLEDGEMENTS

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# Hydroassemblies

## *Unit-based system for the symbiosis of urban spaces and greeneries through hydraulic driven tectonics*

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*Hydroassemblies is a research thesis that investigates the architectural potential of a unit-based modular system that can recursively grow in space guided by hydrodynamic principles in order to generate intricate tectonic assemblies, integrating the roles of spatial articulator, water collector/distributor and plant cultivation substrate to foster a symbiotic relation with the urban environment. By implementing principles of circulatory systems in biology, the authors developed a system that grows through recursive formation of loops and articulates its tectonic via a continuous, interconnected branching network. The founding process improves upon a combinatorial algorithm of discrete parts, considering how iterative interactions at the local level have a feedback impact on the growth process at the whole system scale. The paper explores how features, spatial and perceptive qualities, affordances and opportunities emerge at the global scale of the formation from the interplay of local behavioral principles and environmental conditions. The provided implementation is a proof of concept of the production of complex qualities by means of massive quantities of simple elements and interactions.*

**Keywords:** *tectonics, combinatorics, unit-based system, branching network*

## INTRODUCTION

Having its roots in mereological studies (part to whole relationship) applied to architecture and combinatorial design experiments by Gilles Retsin and Jose Sanchez, the project tries to move beyond the static assemblage of discrete parts that follow an immutable set of rules, considering instead how local interactions and intensive properties can have a feedback relationship with the growth process of the whole system, interacting with its morphology during the aggregation. The aim is to investigate a process with combinatorial basis that, starting from a finite set of components, could generate a system that grows by recursive loops formation, and articulates its tectonic structured by an interconnected and continuous branching network. The network growth is guided by an algorithm that simulates the behaviour of fluids in the circulatory systems of living beings, while the assemblage is constructed out of pipes, in order to merge hydraulic and structural performances in a single element.

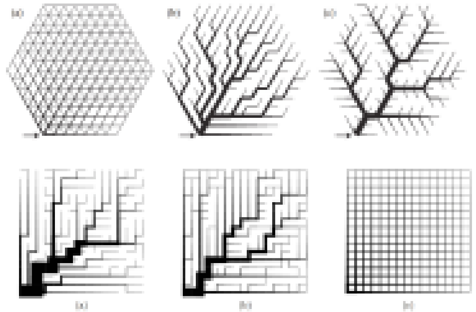


Figure 1
Examples of the conductivity distributions: tree-like network, hierarchical network with loops, network with loops and no hierarchical organization ([1] Bohn, S and Magnasco, MO)

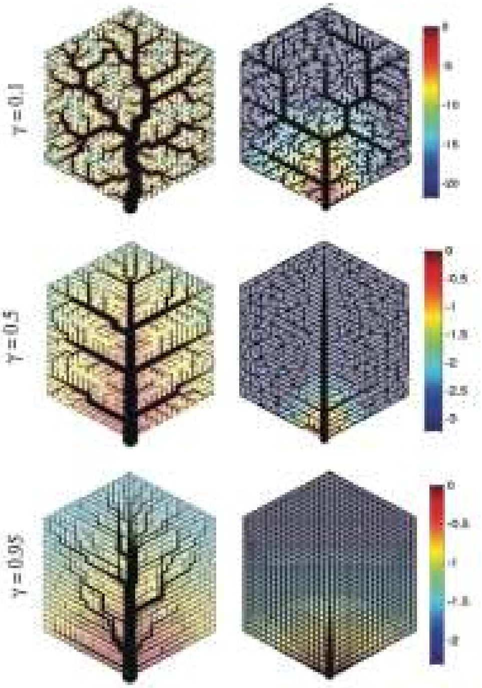



Figure 2
Loops as a result of optimizing under damage to links and under a fluctuating load ([2] Katifori, E, Szollosi, GJ and Magnasco, MO)

Wiscombe predicts that the impact of dense fluids in building design will soon peak for two main reasons: they have better thermal inertia and they are branching into system applicaitons for illumination, biofuel generation, cultivation and recycling/filtration; to channel this impact into a design sensibility, "it is useful to think of fluids in terms of vascular systems, integrated networks characterised by bundling and weaving, micro-capillary systems, and also secondary emergent effects such as structural performance and heliotropism in plant stalks" (Wiscombe, 2010). The project tries to enhance and emphasize this discourse towards a system for fluid transportation and management with architectural potential. For what concern the affordance of the system, a network of pipes can be used for fluid distribution and also for the treatment of wastewater that is compatible with specific species of plants and and needs a determined path length to chemically purify water from industrial sites, dockyard or artificial basins. Water distribution networks in cities could emerge from underground and could be implemented emphasizing design features of hydraulic systems (such as redundancy), extending their morphology and articulating them to create conditions to become devices for the city, involving water, plants and users.
Computation is the link between different phases of the project that allows the construction of the algorithm performing the system growth. In this sense it works as a bridge between the biological and the technological sphere, managing the complex, non-linear flow of information from simulation to fabrication, as well as allowing the extraction and reproduction of processes and behaviors from the biological world. In short, it enables the creation of processes governed by relations that define the project itself.

## BIOLOGICAL DISTRIBUTION SYSTEMS

The research takes as role-model biological circulatory systems, whose evolution has recently been of interest in biological physics and computational neuroscience. They can be represented as networks governed by physiological laws (such as the ones

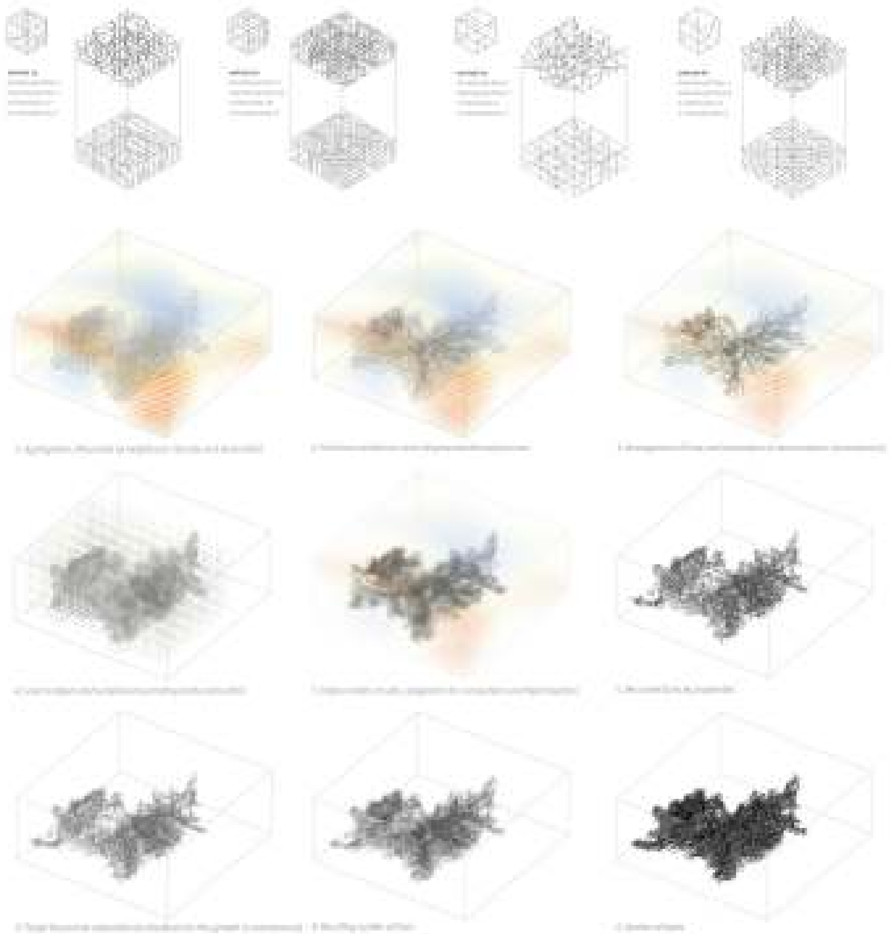


Figure 3
Some unit tests and scheme of the growth process

formulated by Moore, Poiseuille and Bernoulli) and metabolic principles and can be simulated to extract specific features. Bohn and Magnasco (2013) simulations on different kinds of organization and topologies of leaf venation show that the cheapest and most efficient network is a simple branching tree structure, which can be seen in the xylems of ancient plant species.

This kind of network structure, while showing high levels of distribution efficiency, performs poorly when facing damages in circuitry or fluctuation in fluid flows, and in adaptability to the change of external conditions. This is the reason why the evolution of biological distribution systems has developed hierarchically nested loops structures, not the most efficient configuration in terms of economy of means,

Figure 4
Growth samples changing initial parameters (density of neighbours, impact of the vector field in terms of directionality and angles in medial and marginal areas, and ratio of branching and anastomosis (in terms of distance between points)

but one that allows more resilience in the network, more efficient water pressure distribution in the circuit and adaptability to flow-rates variation (Figure 1). In this context the process of anastomosis, the continuous reconnection of branched veins, plays a key role in minimizing drops in water pressure and ensuring alternative paths for water and nutrients (Figure 2).

According to D'Arcy Thompson (1942) energy loss depends on basically two main factors in distribution branches: path length and channel radius. These factors are being evaluated every time in relation to the branching angle; while for similar radii the dissipation is lower and the flow tends to prefer the shortest path, for remarkable differences in radius the fluid tries to stay as long as possible in the larger vessel, changing direction later in the smaller branch. For this reason channels near the midrib (the central vein of the ramification) tend to be more directional with smaller angles, while in peripheral areas larger angles of ramifications can be found in order to avoid energy losses. These metabolic mutations are influenced not only by transport efficiency but also by local condition of stress, environment and quantity of light (heliotropism and gravitropism).

Branching system are usually modelled through fractal system, assuming that sub-parts are structurally self-similar to the whole. Murray's law ($d^3 = d1^3 + d2^3$ - which describes the cross section variation of branching pipes in fibrous systems according to the third power of their diameter), represents an extremely useful physical principle in the description of natural distribution networks, and it is as well helpful in the understanding of the variation of circulatory networks from the ideal fractal structures when dealing with diameters and local constraints.

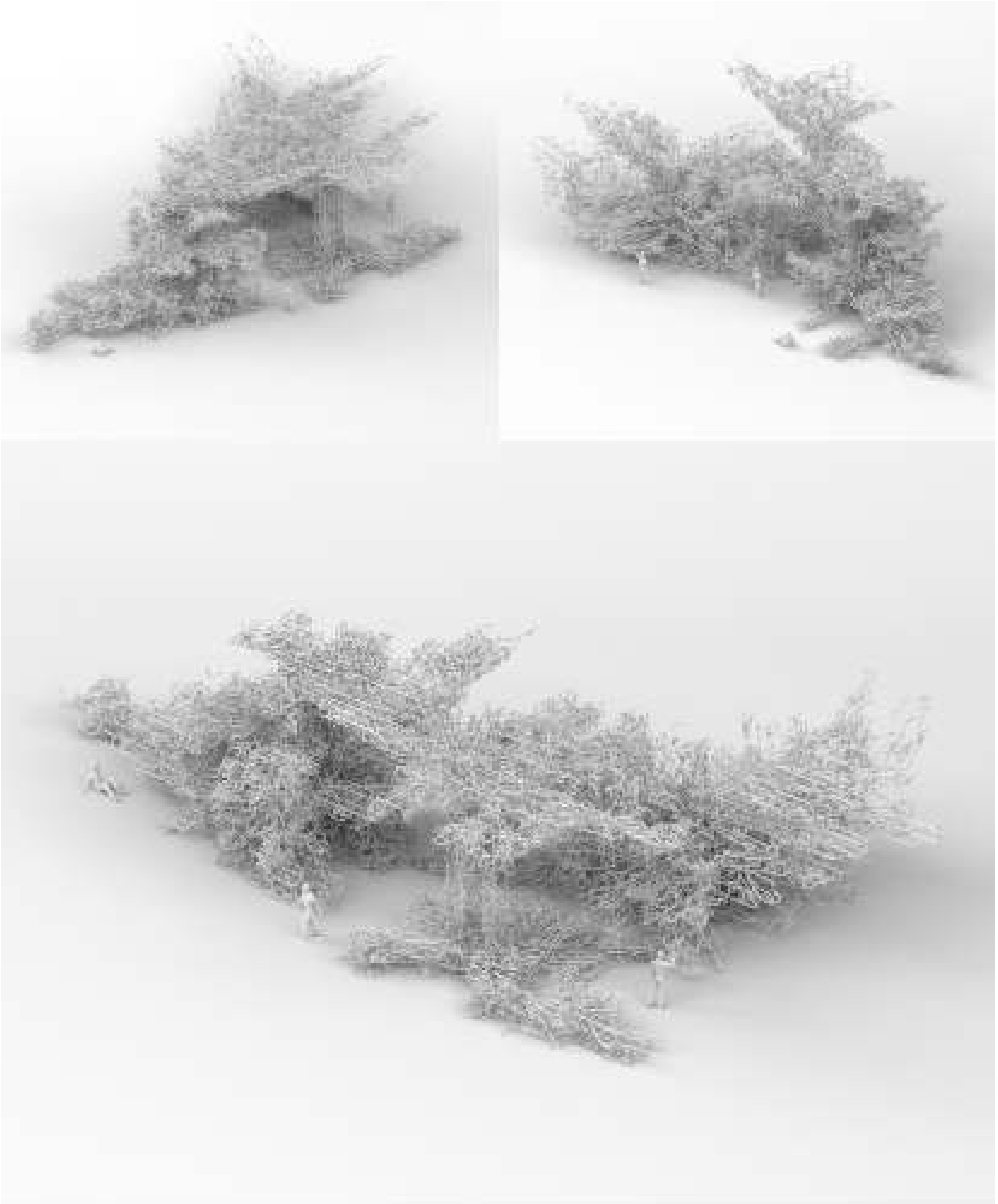


Figure 5
A full-grown example for the evaluation of its architectural impact

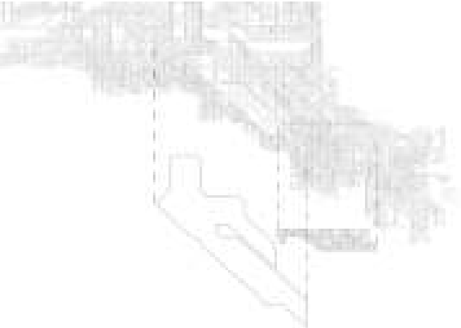


Figure 6
Vessels, tissues and surfaces

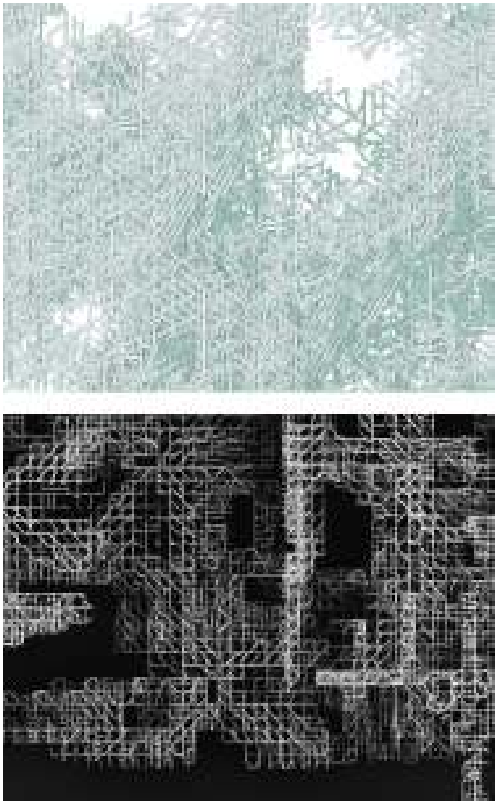


Figure 7
Emerging patterns

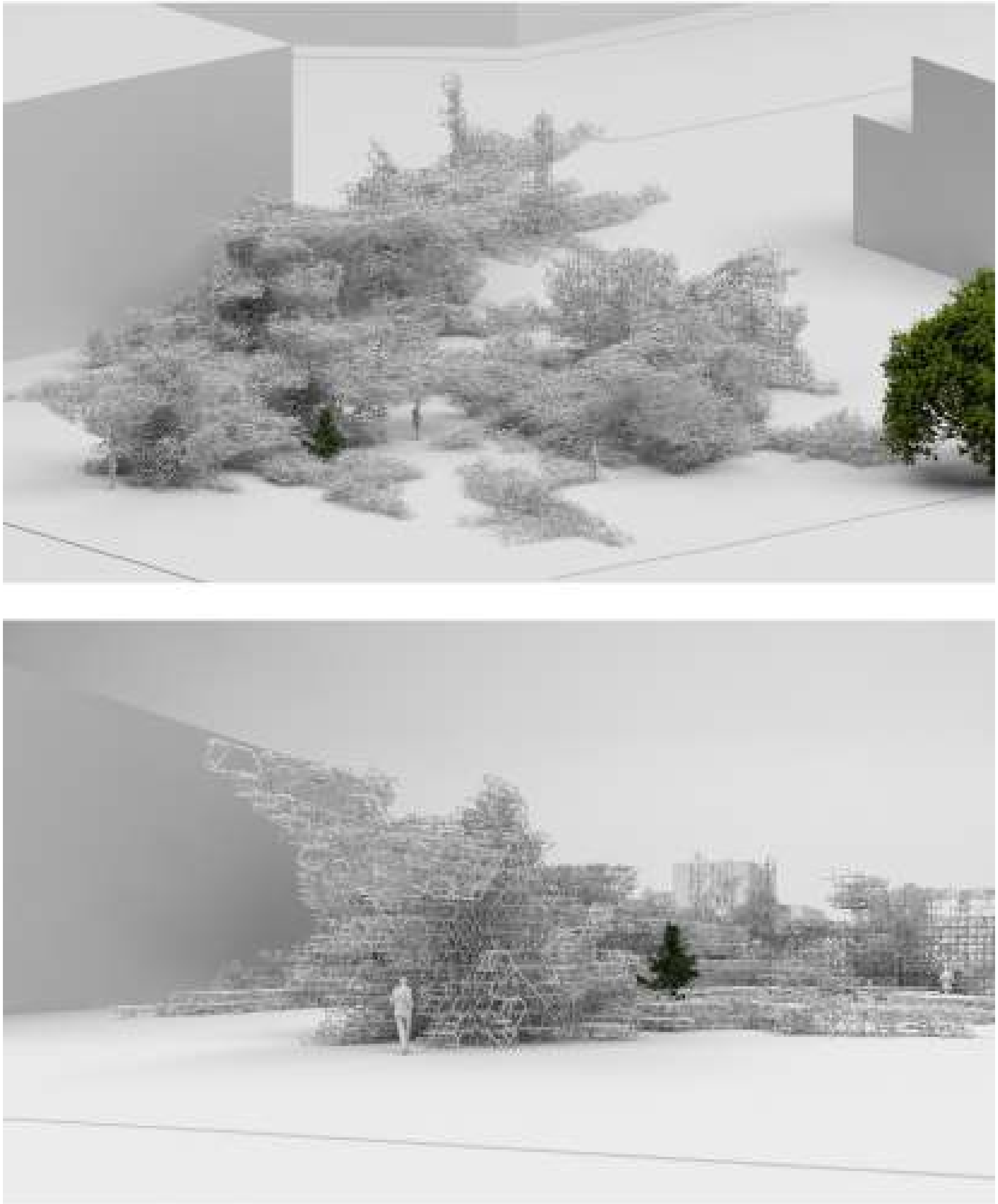
From a metabolic point of view, the 3/4 scaling law elaborated by West, Brown and Enquist (1997), describes the essential traits of biological transport systems, from mammalian blood vessels to bronchial ramifications to the vascular systems of the plants, and it is based on the assumption that a network that wants to supply nutrients the whole organism, must be constituted by a space-filling recursive system of branching patterns (sometimes fractal-type) in which final ramifications are of invariant dimensions. In the described network, the energy needed for distributing substances should be minimized, that is to say that the hydrodynamic resistance of the whole system must be minimized. The scale factor derives from the interdependence of geometric and physical factors bond by those assumptions. Although this law has recently been questioned, the discussion pertained the reliability of its results against real cases, not its intrinsic coherence. The concern of this research is the ability of a system to create, through iterative branching, a tectonic guided by metabolic principles and that relies on intensive properties. One that is capable of organizing itself in redundant and integrated structures that work as systems, both distributive and structural, creating spatial potentialities and vibrant heterogeneity by means of its morphology and articulation. The above concern is pursued by setting up a system that operates through a series of coherent morphogenetic rules but without the obligation to check against an existing example.

## DIGITAL PROCESS

These behaviours and principles are implemented as an algorithmic process, based on a voxel space that iteratively grows and subdivides in smaller parts and networks of lines intended as branches for fluids distribution.

The process starts with the definition of a set of units and their specific aggregation rules: each unit is considered as a branching component and it is modeled as a system of lines whose design parameters are related to their topology, varying the number of connections, branches and anastomosis, an-

Figure 8
The system is meant to colonizes urban leftover space, infusing rich and diversified qualities and affordances



gles between lines and paths length (Figure 3). The growth algorithm performs a recursive aggregation of units, influenced by a vector field affecting the voxels' growth direction and by endogenous unit-to-unit rules: direction and number of connections between each cell/unit and its neighbours are evaluated, bringing new units towards areas with suitable conditions and arranging them according to local circumstances. Units can align their main branch direction with the principal directions of the neighbours or differentiating their orientation from the prevalent one, thus creating a continuous path or forming locally closed reticular clusters.

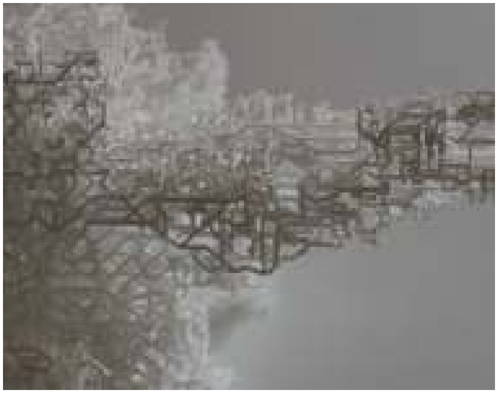
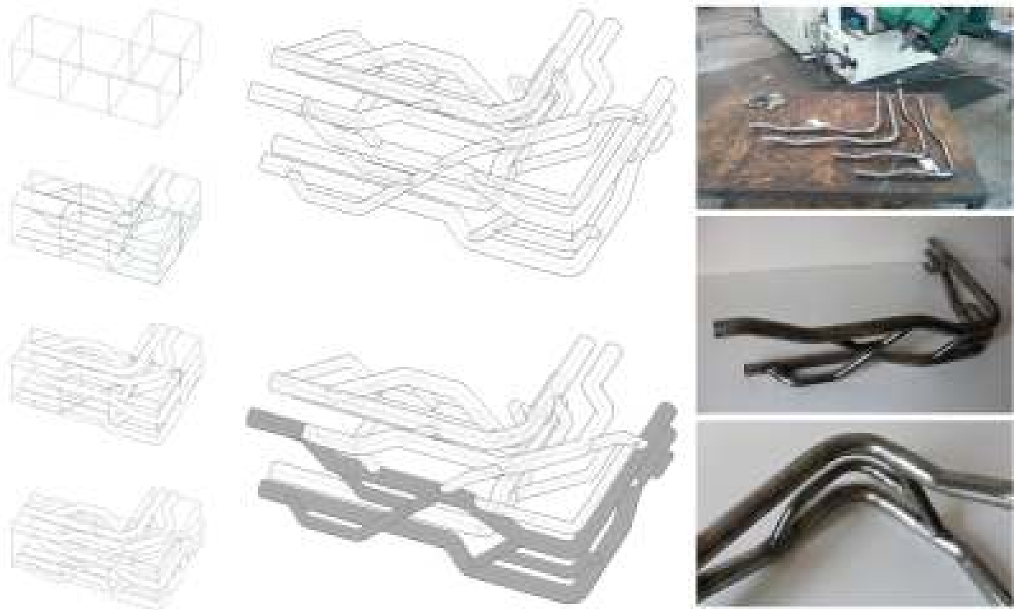


Figure 9
Close-up detail of 3D printed model (scale 1:100)

The number of neighbours considered in the iteration can change to achieve more directionality or to create clusters with heterogeneous behaviors. The units, although initially identical, might lose some branches or increase their resolution during the aggregation process, in order to increase the network redundancy and change the global growing framework. During the aggregation, point densities and free branches are evaluated, and units can grow increasing connections in certain areas or spread occupying unused portions of space. This behaviour changes according to the local conditions, with stronger alignment and smaller angles of branching in 'medial zones' (barycentric), in order to reduce load losses, and greater angles in peripheral areas, to minimize the time spent by the fluid in smaller sections where the friction is higher, as well as an increased level of anastomosis, following the role model's behaviour. Each unit can evaluate its neighbours' behaviours (the quantity of neighbours analyzed depends on different area and can be varied during the unfolding of the algorithm) in terms of direction, already connected points as well as points of possible connections. At each iteration, connection points between a voxel and its neighbours are counted, calculating the distance between the free points of the aggregating unit and the points of potential connection: if the distances are small enough, another order of local branches is created.

Different densities of connection levels or load circumstances can polarize the growth of the system or convey it to other portions of space, acting as a feedback system for the growth (Figure 4). Several tests were made varying the units' design and aggregation rules, evaluating the properties of the system during the aggregation in terms of increasing level of connectivity, redundancy, spatial articulation and complexity, avoiding inconsistencies (such as self intersections) and aiming for heterogeneous densities and distributions in order to elude congestion and allow pedestrian circulation and permeability. The resulting ramifications exhibit distributive and structural qualities, developed following topological and hydrodynamic principles: during the formation of clusters, at a fixed interval during the iterations, the density of the cells is differentiated according to stress patterns, changing again the resolution of the system. A second set of constraints (anisotropic environmental conditions - temperature and shadow patterns, site morphology and external obstacles) interacts in the process: the growth acts aware of field conditions and preexisting entities. The system is able to adapt to the environment and read external condition to form heterogeneous structures that subdivide and polarize the urban space by generating assemblies that can modify the microenvironment by emitting radiant heat or absorbing it through the pipes. They also form heterogeneous

Figure 10
Fabrication of functional prototype (scale 1:1)



shading patterns, due to the variety of growth shapes and densities. The set of micro-macro spaces and the related heterogeneous set of conditions created thus aims to a symbiotic relation with the urban space. To achieve those properties it is necessary to work with a large numbers of elements as the qualities of a system emerge within the quantity of its constituting elements. By increasing the number of iterations and the system resolution, the continuous ramification is enriched by an articulated spatial complexity and heterogeneity of performances, developing topologically connected voids that form accesses and routes through the system, but also enclaves, shelters and courts. The spatial organization emerges from the development of unit-based tectonics, and the whole is characterised by a series of conditions were structure, mass, surface and ornament can't be clearly separated but can be identified by a series of behaviours (i.e. column-like and truss-like)(Figure 5).

## ARCHITECTURE DEFINITION

A fundamental aspect of the process is to maximize the architectural impact of the system that it is not conceived to just transport water or treating it, but to extend principles of natural network to extend the features of water transport systems towards an extended set of affordances. Redundancy is a strategy grounded in abundance, in which every function is provided by multiple elements of the system and every element provides multiple functions. Higher order of vessel in higher parts are increased in density to have transitions to sort of tissues able to collect rainwater (Figure 6), in order to and convey it to storage systems to preserve and redistribute it based on needs. Networks of diffused tissues collect fluids also in case of damage of parts of the system, since the system of surfaces conducts water from higher parts to lower ones, providing the recovery of fluid losses and trasporting it to storages, while the excess of paths for each target point make possible to find alternative routes for the fluid. The entire assemblage is based on a composite pipe with aluminium core in a PVC glove and carbon fiber strata, similar to Splinetex(tm) technology, already tested as pipes with both hydraulic and structural properties, able to branch with standard connections and to differentiate their diameter.

The diameter of pipes can be parametrically managed, influenced by the climate conditions of the site, rainfall, humidity and they are woven to create a lightweight system that can be formed and assembled, expanded in its paths or disassembled. A functional prototype (representative of the geometry principles and distribution but not of the material) was developed using industry grade CNC pipe bending methods (Figure 10).

## CONCLUSION

Possible further developement of the project might be addressed both in the aggregation process (for instance developing feedback correlations with specific software for hydraulic simulations able to introduce further constraints) and fabrication phase (with a tighter file-to-fabrication pipeline and feedback interaction with a more comprehensive robotic fabrication and assemblage process to increase automation). The outcomes of the process, not predicted at the beginning but developed as results of a set of operations, show high levels of redundancy, and emergent properties, such as continuity, spatial articulation and heterogeneity, revealing interesting architectural properties.

A range of performances of the assembly tend to be dynamic, including the thermal regulation that can adapt to seasonal change managing the flows of water in the loops and differentiating time-cycles between underground water storage and vessels through areas with more or less sun exposition and shadows, creating a difference in temperature among the water and the environment and strategies of self-regulation, where the water management system is conceived as operating in relation to seasonal and daily cyclical needs. The system is conceived as a speculative model that allows to inhabit structures that are usually not inhabited in an artifact that aims to remap in a less trivial way the natural/synthetic threshold.

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# Elements | robotic interventions II

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*Reviewing the current research trends in robotic fabrication around the world, the trajectory promises new opportunities for innovation in Architecture and the possible redefinition of the role of the Architect in the industry itself. New entrepreneurial, innovative start-ups are popping up everywhere challenging the traditional model of the architect. However, it also poses new questions and challenges in the education of the architect today. What are the appropriate pedagogical methods to instill enthusiasm for new technologies, materials, and craft? How do we avoid the pure application of pre-set tools, such as the use of the laser cutter has become, which in many schools around the world has caused problems rather than solving problems? How do we teach students to invent their tools especially in a society that doesn't have a strong background in the making? The primary focus of this paper is on how architectural CAAD/ CAM education through the use of robotic fabrication can enhance student's understanding, passion and knowledge of materiality, technology, and craftsmanship. The paper is based on the pedagogical set-up and method of an M. Arch I studio that was taught by the author in fall 2016 with the focus on robotic fabrication, materiality, traditional timber construction systems, tool design and digital and physical craftsmanship.*

**Keywords:** *CAAD Education, Digital Technology, Craftsmanship, Material Studies, Tool Design, Parametric Modeling, Robotic Fabrication*

## INTRODUCTION

Ludwig Mies van der Rohe coined the sentence “Architecture starts when you carefully put two bricks together. There it begins.”(Mies van der Rohe) If we take him seriously, Architecture is, in essence, a material practice based on technology and craftsmanship. Mies didn’t receive any formal education as an architect, in fact before he learned how to draw in some of the most prestigious offices of that time, he started as a craftsman, learning the trade of stone carving from his father. One could argue that this education and knowledge of materiality, craft and technology set him apart from his peers. For Mies, the material was always the beginning, and his buildings that influenced a whole generation of architects persuaded through their painstaking craftsmanship and attention to detail (Whitman 1969). In parallel, the Bauhaus, where Mies was the third and last director also had a pedagogical system that believed heavily in experimental material studies and the study of different crafts. Today the Education of an Architect in many Universities around the world is very different. While students nowadays know how to map, model and mediate all kinds of big data, social aspects, and geometry, how to argue through critical thinking for or against a project intelligently, students seldom start from a material experimentation or craft to inform their design. In a profession that is heavily ruled by economic constraints and the concepts of mass production, the architect is very dependent on existing technologies and material systems, making it at times difficult to innovate. However, since approximately two decades we are witnessing a shift in architecture and its education that has the capacity to bring the profession again closer to materiality, craft, and technology. Computation, new software packages, and new CAAD/CAM construction methods have paved the way for architects, designers, educators and students alike to engage again much more in the innovation of building processes and the making of a building. With the advent of robotic fabrication in Architecture, we are now witnessing the next step in this evolution. Robots are now connecting technology and knowhow, as well as imagination and materialization, like never before, and have the potential to reveal a radically new way of thinking about materialising architecture (Gramazio & Kohler, 2014). While previously CAM systems were limited to a particular function, the robot starts to give the opportunity to open up an entirely new paradigm. Since the robotic arm in essence just represents precise numerically controlled movement in space, the architect him or herself can now invent and define the technology, craft and material system from scratch. Industrial robots are distinguished by their versatility. Like computers, they are suitable for a wide variety of tasks because they are "generic" and therefore not tailored to any particular application (Gramazio & Kohler, 2014). This offers not only ground-breaking trajectories for the education of Architecture students but also for the profession, challenging the predominant job description of specifying pre-existing building systems.

## OVERVIEW

However, every time a new technology was introduced there has also been a spirited discussion of their impact on architectural education (Senagala1999, Senagala, Vermillion 2009). Therefore this paper outlines a pedagogical strategy and method to instill new ways of thinking about architecture through the implementation of robotic fabrication into the academic education. The M.Arch I studio that was taught in Fall 2016 at the University of Hong Kong was, in essence, starting from first principles and searching for original methods that had the capacity to create architecture, space, and structure. It had two main objectives. On the one hand, it was a hands-on investigation on how to generate new technologies, material systems and craftsmanship with the aid of the robot, on the other hand, the studio looked in what way these new systems could be applied to develop full-scale performative architectural prototypes. As a point of departure, the studio looked into traditional architectural elements, such as the column, the wall, and the roof. Rem Koolhass stated in his 2014 Venice Biennale intro; Architecture is a strange mixture of persistence and flux, an amalgamation of elements - some that have been around for over 5,000 years and others that were (re)invented yesterday (Koolhass 2014). The research studio as well aimed towards the understanding in how we as designers can (re)invent the elements of architecture today through novel technologies at our hand.

## STUDIO | STRUCTURE, METHOD AND CONTEXT

The studio was structured into three segments, comprising of a research and exploration section on traditional Asian timber construction techniques, a module on tool design and fabrication, and a final segment that synthesized the two to design, fabricate and build an original 1:1 scale structure. The studio was divided into three groups of four students each and was supported throughout the semester by several workshops that introduced students to computational thinking, parametric modeling with Grasshopper, robotic programming through HAL, and the secure and safe handling of the robots.The first exercise started with an investigation of architectural elements based on timber construction systems within the Chinese context. In many cases today designers in the arena of digital architecture take the approach to look for systems or recognizable patterns in nature or the sciences, thus following concepts of bio-mimicry or mathematics. While this approach can produce fascinating results, over the years, I have witnessed that students have at times a problem with this methodology, since it lacks the direct link towards architectural applications, and thus students have difficulties to generate reasoning and establish ownership over their design. To avoid this phenomenon, this studio looked into existing architectural material systems that have been tested for various architectural elements throughout history. These elements were then meant as a basis to explore potential reinterpretations for contemporary solutions. Throughout most of China's architectural history, timber can be seen as the dominant construction material. The country is home to a diverse set of vernacular wooden architecture, highly specific to its context and rich in architectural expression. However, due to the standardized building industry of today that is mostly based on concrete, the construction of timber buildings in China has virtually ceased, hence in contemporary architecture, these traditional elements don't play a role anymore. One could argue that the extinction of the specific knowledge of craftsmanship involved is only a matter of time. Given this background, the studio sought to revitalize those through the aid of robotic fabrication. Through their research, the students eventually distilled three different systems that built the basis for their investigations. The first being the "Dou Gong" bracketing system, which usually is the structural network that joins columns to the frame of the roof. The second being the reciprocal frame structures that can be found in the timber woven-arch bridges in the Fujian and Zhejiang provinces. And the third being the "Luban Lock" or the so-called "Chidori system" a design concept derived from old Japanese and Chinese toys, and that elegantly produces a six-legged hidden joint (Fig.1). Based on unique structural principles and jointing techniques all three have in common that they follow very strict rules of construction, making them prone for computational explorations.

Figure 1
Woven Arch Bridge, Dou Gong Roof System, Luban Lock system

## COMPUTATIONAL SYSTEMS

One of the ultimate goals of the studio was to engage students in new ways of thinking about design processes and solutions.

While architecture is in most cases static, the process to arrive at an architectural solution is not. Computation allows the designer to produce many different versions of the same input system. With this approach, architecture can be thought as an adaptable system (Lange CJ, Rocker I 2013). Hence this method provides a framework for the designers to make viable decisions based on different parameters that can adapt to different needs and situations. A computational way of thinking is based on processes that start with elemental properties and generative rules to end with information, which derives form as a dynamic system (Menges and Ahlquist, 2011). Students, therefore, were asked to analyze the underlying principles behind each material system and to investigate their capacity to be codified and translated into possible algorithms. Utilizing Grasshopper for Rhino students explored the various possibilities embedded within their systems (Fig.2) with the focus to generate meaningful architectural elements. Part of the intention of this exercise was to make students understand that parametric thinking has nothing to do with a particular style, but rather with an approach to architectural design, hence any architectural system that follows certain rules could be parameterized.

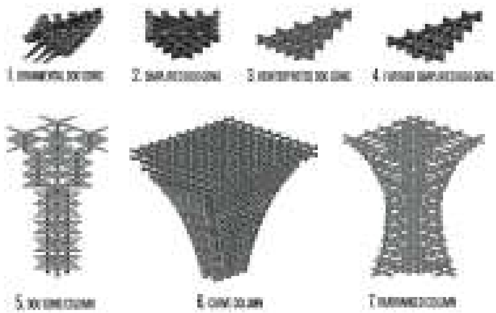

Figure 2
Dou Gong interpretations through computational methods

## FABRICATION & PROTOTYPING

The second segment directed the focus onto the making and craftsmanship and the translation of digital information into physical manifestation using the facilities in our lab. In our case the robotics lab is equipped with two industrial robots, a smaller one with no end- effectors to introduce students to the related concepts of robotic fabrication and a larger one that is equipped with a spindle. Since the lab has its limitations in woodworking, students were instructed to research the respective methods of traditional fabrication related to their material systems and to translate it into a set-up utilizing a router or spindle. When it comes to robotics in architecture students are confronted with a multifaceted array of problems ranging from code generation, tool design, fabrication techniques to procedures of assembly. In the past two decades, students in most architectural institutions had only the opportunity to use CNC fabrication tools such as the laser cutter or the milling machine. While those tools helped in the production of physical models, especially the laser cutter had an adverse impact on the student's understanding of tectonics and craft in architecture. Guided by the constraints of the machine, students avoided confronting themselves with the limitation of the pre-existing set-ups. Other than common CNC fabrication tools, the robot isn't limited to one fabrication method. Robots are therefore not used as a pure fabrication device, but rather as an open interface for architectural education (Brell-Çokcan, Braumann 2013).To avoid the mentality of becoming just a user of pre-existing set-ups of a specific tool, and to make the prototyping an integrated part of the design process the segment started with a challenge. Rather than using the robot with the mounted milling head for the testing of the fabrication process, students were confronted with the set-up that consisted of the smaller robot with no end-effector attached, and only a spindle with a 10mm cutter mounted on a table. This arrangement was not only challenging regarding tool design but also concerning programming the robot. The robotic arm is in many ways similar to the human arm and hand. To program a tool-path for a drawing executed on a sheet of paper mounted on a table with a pen that is attached to a robot via a penholder is relatively simple with recent software packages such as HAL. So to make students understand the complexities but also the opportunities within the various processes of robotic fabrication the set-up given to students was constructed the opposite way. In other words rather than working with a pen to canvas configuration, students had to deal with a canvas to pen arrangement, which makes the path design far more complex, but also more engaging into the creative process.

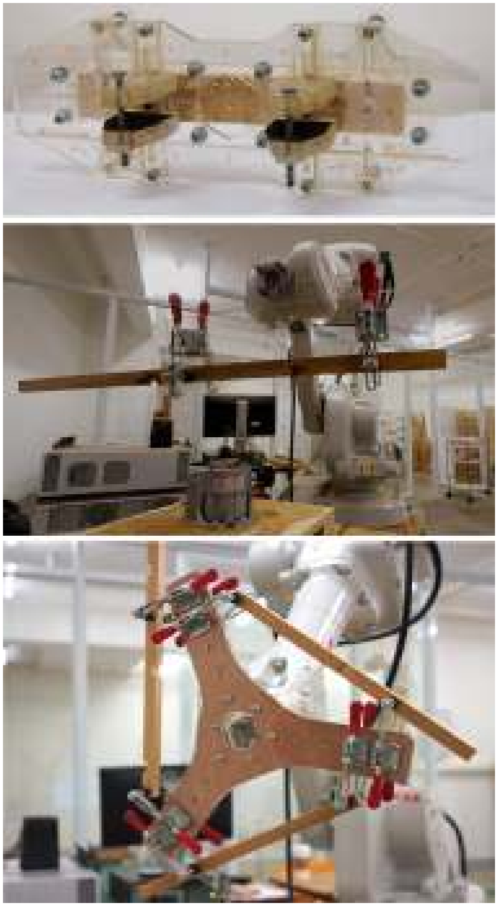

Figure 3
Various tool designs in set-up one.

As the constructive capabilities of the robotic fabrication process clearly define the design space and thus productively inform the computational design strategy. Its development can also be recognized as a creative act of design on its own (Budig, Lim, Petrovic, 2014).

## TOOL DESIGN

Usually, tool design is not part of the architect's education. In most cases, we rely on existing tools to produce a creative artifact. Here manifests the enormous potential and promise within the trajectory of robotic fabrication and assemblies. Craft as a form of mastery comes from the constant development and refinement of a set of skills to achieve an aesthetic result. Tools within this process are an important factor. The more sophisticated they become, the more precise a result can be. Tools can also shape an entire craft; therefore it is essential within the discourse of robotic fabrication to embed it into the pedagogical agenda. However, it is not just about the tool or the immediate outcome of the tool, but it is also about a learning process that prepares students for an architectural profession that continually relies on these tools and processes to evolve the field (Sweet 2015). Though the actual task of the tool was only to be a mounting device for timber stock attached to the robotic arm, it was quite fascinating to see the different approaches of the various student groups when it came to its design (Fig.3). While some fabricated already working prototypes at the start utilizing of the shelf clamps combined with laser-cut parts others produced clear failures that had no consideration for structural stability, precision or work efficiency. However, through the iterative learning process with trial and error, each group succeeded eventually to design and construct a device with unique properties performing to the needs of the individual design of their material system. Many of the traditional timber material systems were based on the use of multiple tools, such as chisel or saw. While those can be much more efficient to do the job, the idea in this segment was to focus only on one cutting device in order to understand the limitations and challenges. For example, due to costs students used mostly soft wood for their projects. The disadvantage of this type of material is that it easily disintegrates the moment the router hits the surface, leaving undesirable marks on the edge. To achieve clean cuts students, therefore, needed to think creatively how to overcome those through a smart generation of cutting paths.

## ROBOTIC PROGRAMMING

Students tacking the class didn't have any previous knowledge in programming or operating a robot. Therefore it is very important to introduce students to a system that was easy to learn and allowed for accurate simulation of the robotic movement. For the robotic programming, the studio utilized HAL, a plug-in for Rhino Grasshopper. As many plug-ins for grasshopper Hal offers the advantage of a brilliant documentation, that offers the opportunity for self-learning and puts students at ease with coding. Though most Master students nowadays have had previous interaction with parametric software packages, there is still a lot of respect and fear in the student body when it comes to special software and advanced technologies. Therefore the software became a key pedagogical tool and allowed students the precise simulation of the fabrication process.

## SYNTHESIS

To bring the knowledge forward accumulated over the first two modules and further advance the expertise within robotic fabrication and craftsmanship students switched in the final segment of the studio to the large robotic arm in the lab that is equipped with a large spindle. Students, therefore, had to develop new tools to fix the timber sections and a new system to generate tool paths for their final design. While the second module focused primarily on the replication of the existing precedent material system, the final design was meant to deviate from the original system and to push the capacities of 6-axis movement in space. Since the original systems were based on repetitive jointing mechanisms, any deviation from this would result in the dependency of many individual jigs if one would have to fabricate and construct it manually. The challenge for the students was, therefore, to depart from repetitive joints by introducing small changes that made the robot indispensable given the three-week timeframe allocated for the fabrication and construction of the final prototype (Fig.4).

## CRAFTSMANSHIP

Other than in the European or North American context where the majority of kids grow up in an environment where either their parents have a workshop in the garage, or they are exposed to artisanry through high school education, Hong Kong children rarely have the chance to work with tools or materials before they might enter a formal education of architecture or another design discipline. One reason is the pure absence of space within the city to allow for such culture; the other is the local educational system that is largely focused on mathematics and sciences. Liberal arts education in this setting is merely an extracurricular activity. While the students that were enrolled in the studio had already a previous degree in architecture, most of them were still new to large-scale prototyping. Exposing them to robotic fabrication in an iterative process, they learned through trial and error the craft involved to master their projects. Many mistakes had to be made to reach awareness for clearance dimension, surface finishes, edge conditions and precision. There is a tendency in students today to believe only because a machine has done something it is automatically good and doesn't need any further treatment. It takes this iterative process to stimulate the conscious and create a sensibility for the craft. Learning involves challenging preconceptions and assumptions that come under scrutiny when new worldviews are introduced. (Daas, Wit 2015)

## CONCLUSION

The outcome of the studio outlined above was successful regarding the architectural exploration, the design process but also in the overall debate with the students throughout the semester. However several aspects come to my mind that could deepen the


Figure 4
Large scale
Prototypes – three
explorations

pedagogical set-up on the one hand but also the student's learning experience on the other hand.Due to the lack of resources and expertise at the time of the academic year, the studio didn't allow for the development of tools that were electronically driven and controllable through I/O programming. Though I don't think that it is from a pedagogical point of view necessarily important for Architecture students to work on such devices, it is anticipated to integrate a module of such content into the course, since it offers a multitude of opportunities. On the one hand, it would allow for the collaboration between architecture and engineering students and therefore generate an opportunity to develop a cross-disciplinary platform for the robotics lab in both faculties. On the other hand, new software packages developed by people with an architectural background such as Firefly and HAL in conjunction with Arduino hardware would allow for new fields or trajectories within the architectural profession. Similar to the development of special modeling groups in the past two decades in large architecture firms such as SOM or Foster and Partners, the education of architects with robots and programming will allow future architects to diversify their knowledge and become innovators within the field. Hence it offers new opportunities to specialize as an architect after their formal education.An important aspect of the studio was to reflect on which role the robot will play in the future of the profession and how the role of the designer might change through this technology. Gramazio & Kohler's early Gantenbein vineyard façade is in this respect seminal, simultaneously exploring the approach of automated bricklaying an its architectural potential. It is precisely this simultaneity of craft, economics, and design that is so striking (Feringa 2014). Indeed this project gives an outlook in how the profession can emancipate itself from the constraints of the industry and change back to a more holistic approach in the future that might remind us of the profession of the Baumeister (Master builder).

## ACKNOWLEDGEMENT

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# tOpos

## *GPGPU Accelerated Structural Optimisation Utility for Architects*

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*The paper focuses on possibilities of already known engineering procedures such as Finite Element Method or Topology Optimisation for effective implementation in architectural design process. The existing attempts of complex engineering algorithms implementation, as a form finding approach will be discussed. By intersecting architectural form evaluation with engineering analysis complemented by optimisation algorithms, the new quality of contemporary architecture design process may appears.*

**Keywords:** *topology optimisation, design support tools, complex geometries, General Programming GPU*

## INTRODUCTION

Recently we have clearly observed immense changes taking place in architectural practice. A continuous development of Computer Aided Design tools complement by computational methods highly influence architectural design development. Fast spreading of generative and parametric techniques allows to extend existing design procedures including form finding process with additional aspects. Architects are looking for new approaches which may support that process with new and unique solutions for particular problem. Amalgamate of architects' design experience and precise engineering tools through generative design procedures, can bring new and undiscovered forms into contemporary architecture.

## BACKGROUND

It is observed that architects are developing new sets of tools which are changing the typical way of design procedure. As an extraordinary utility in the architectural design practice, topology optimisation methods might be pointed. On it bases, topology optimisation is a mathematical approach that optimises material layout within a given design space, for a given set of loads and boundary conditions, such that the resulting layout meets a prescribed set of performance targets. It could be implemented through the use of Finite Element Methods (FEM or FEA) for the analysis and a variety of optimization techniques such as the Method of Moving Asymptotes, Genetic Algorithms, the Optimality Criteria method, Level Sets or Topological Derivatives.
As a material distribution method, it can be divided on two main subfields: Layout Optimization (LO) and General Shape Optimisation (GSO) (Kutyłowski, 2004). The first approach concern grid-like or trust-like structures having very low volume fraction. Opposed to LO method, GSO is concerning higher volume fractions, optimising the topology and shape of material continuum. Topology optimisation al-

gorithm is very widely used in the industrial product design such as aerospace and automotive where mechanical parts efficiency and its material usage is crucial. Also Civil Engineering is not lagging in this field (Guest and Moen, 2010). Many scientific discourse and researches have been made, implementing Structural Optimisation for various purposes.

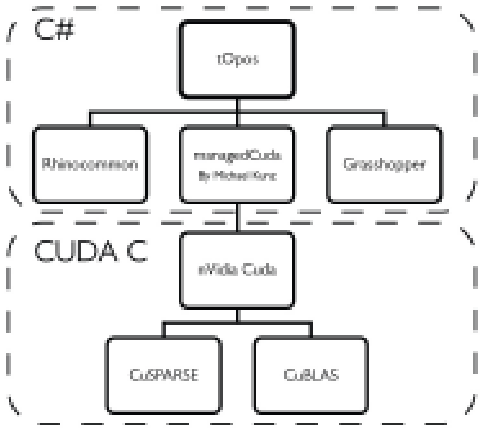


Figure 1
tOpos plugin library structure.

## Extending Architectural Tools

Nevertheless, topology optimisation as an engineering tool is rarely applied in the architectural design process. Commonly it is caused by a complex and time taking process to achieve results which would satisfy a designer. Qatar Convention Centre in Doha design by Arata Isozaki (2010) or design of wall through Extended ESO in Aktagawa River Side project (Ohmori, 2010) show the first attempt to combine architectural form finding process with engineering tools as a general design tool applied to real buildings. Except of compound form finding process, another obstacle to overcome might be the feasibility of the outcome structure, which is typically represented as a spatial boundary. Three dimensional versions of algorithm returns highly difficult geometries to manufacture by a common production process. Especially, when the result of optimisation is not intended for mass production, but is unique for particular problem. Some solutions for that problem is implementation of an additive manufacturing process named SLS for producing irregularly shaped structural elements developed by Arup (Block et al., 2015).

## Software Objectives

Existing architectural adaptation of topology optimisation are the result of deep research and time consuming experiments often aided by specialists in Civil Engineering. The tools applied for that projects are either highly specialised and expansive engineering software or individually developed toolsets for current problem. However, general purpose engineering programs available on the market containing Structural Optimisation algorithms, except of the cost, has many additional limitation which decrease a possibility of usage those methods by architects for enriching their design process. Their explicit user interface and moreover, plethora of options and decisions which user has to make, put it as a highly specified software dedicated to the limited range of users.

All presented arguments affirm the author about the need for developing a new tool for designers. It is highly intended to give the opportunity to variety of architects and designers to use the exceedingly complex and compound process to improve their designs without any specialised knowledge. In spite of all, it is necessary to stress that Finite Element Analysis (Zienkiewicz and Taylor, 2005), used extensively as a analysing process for Topology Optimisation, is highly time consuming as a resultant of finding a large number of unknowns. For a fast and effective design process and its evaluation, the new software needs to provide an immediate feedback. This objective compelled author to look for better, more effective solutions for FEA implementation. Complementary to described application of Structural Optimisation method in architecture, author will present a new approach concerning form finding tool based on Topology Optimisation algorithm accelerated with GPGPU technology.

## TOPOS - GPU ACCELERATED PLUGIN

Creation of new tools, adjusted to the nowadays performance requirements, enforces a software developer to use more sophisticated solutions. It is necessary to mention here, that by performance authors understand both, modern device computational capability which increases logarithmically and contemporary designers expectations towards applied tools. Especially, a designer's expectation for tools efficiency, immediate and real time reaction to changes are highly observed in other fields of the computer science, such as photorealistic rendering techniques, solar analysis, building information modelling. Topology optimization as a material distribution method based on numerical approach can be successfully enhanced by contemporary computing tools. Based on scientific researches (Schmidt and Schulz, 2011) authors came up with an idea of developing and implementing own topology optimization algorithm enhanced with the GPU acceleration which may speed up calculation process up to 160 times. The aim of the author research is to create a form finding real-time tool for architects based on the engineering Structural Optimisation Methods. As a main theorem, Simple Isotropic Microstructure with Penalisation (SIMP) method developed by Bendsoe and Sigmund (Bendsoe and Sigmund, 2004) was chosen.

### *Plugin Architecture*

The project, named "tOpos", unlike the complicated and expensive commercial tools for engineers is meant to be simpler, faster and more efficient. The basic environment for tOpos is Rhinoceros3D software with Rhinocommon libraries. McNeel software is used as 3D engine for data display and what is more, as a modelling environment necessary for the algorithm to create input data. tOpos also utilises Rhinocommon library to process meshes and vectors. The plugin core is based on the host code (performed on CPU) implemented on DotNet C# with acceleration kernels (performed on GPU) based on CUDA API (Sanders et al., 2012), the extension of C language. Interconnection between CUDA C and C# is managed by 1:1 wrapper named managedCUDA developed by Michael Kunz, which allows to use pure CUDA API without losing computational power and functionality. GPGPU (General Purpose computing on Graphics Processing Units) allows to exploit parallel architecture pipeline to bring a new approach to a real time application (see Figure 1). Implementation of GPGPU to accelerate algorithms per-

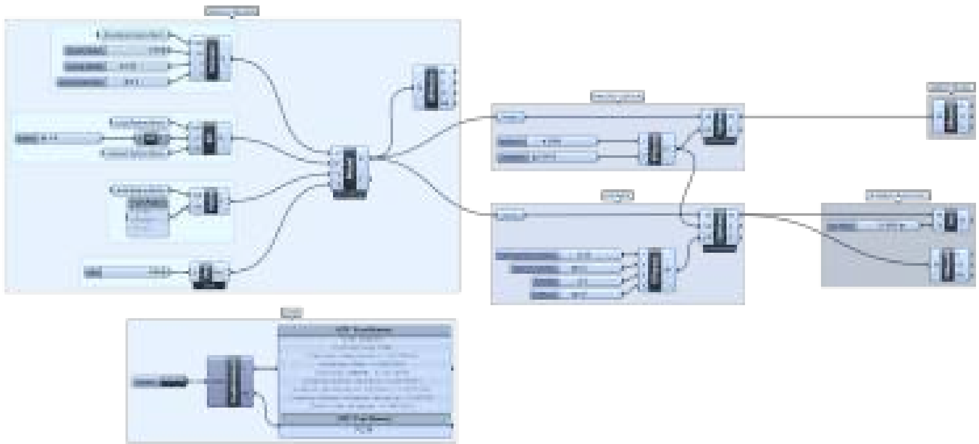

Figure 2
tOpos plugin structure (layout) represented in Grasshopper3D enviroment

formance, impose different computational pattern. CUDA technology, developed by nVidia, is based on SIMD computational approach, which is grounded on Flynn taxonomy and means: “Single Instruction Many Data”. This type of computational philosophy enforces user to use certain memory data pattern to speed up in-kernel data read-write operations. Therefore, data also has to be arranged in a specific, usually linear manner. In connection with different computational architecture, which enforce developer to redesign algorithms logic to fit GPU requirements, this platform has another disadvantage which need to be concern during algorithm design. Memory capacity embedded on Graphic Cards is smaller than amount of CPU memory installed in modern computer. This limitation has a big impact on data structure and it management.

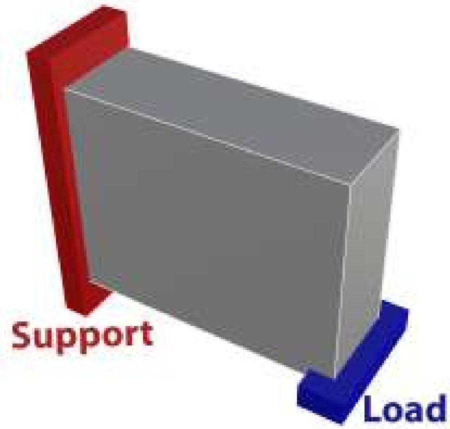


Figure 3
Initial condition for benchmark

### *Tools suited for demanding designers*

Contrary to current scientific implementation of topology optimisation presented by Schmidt and Schulz(2011) or Liu and Tovar (2014), tOpos has possibility to define irregularly shaped ground structure. User can shape initial conditions for the optimisation procedure without any limitations. The module responsible for creation of Finite Element model, creates elements only inside user defined boundary represents as a mesh. Its size determines the model resolution. This parameter has the greatest impact on both the final appearance and precision of the design and total time needed for computation. Although, the quality of resulting model can be chosen on the very beginning of the designing procedure or increased during optimisation process by utilize further adaptive subdivision procedure.

As was mention before, very crucial moment during optimisation process is analytical part of the algorithm. Based on (Martínez-Frutos and Herrero-Pérez, 2015) researches as a main FEA solver iterative Conjugate Gradient (CG) algorithm has been chosen. Opposed to direct solvers such a Cholesky or QR factorization, iterative solvers are highly adaptable for specific needs such a memory consumption or time reserved for solving particular problem. During plugin developing process, two CG solvers were design concerning memory usage on certain graphic card. The main difference is storage model of global stiffness matrix. The first solver, called Pre-Assembly(PA), creates stiffness matrix in CRS format before iterative process run. This approach reuse once computed matrix, therefore algorithms execute faster, but needs additional memory resources on GPU. The second solver, named MatrixFree(MF) calculate Matrix-Vector product in each iteration and never stores global stiffness matrix.

That cause slower code performance, but saves many resources on graphic card. To simplify whole optimisation process, tOpos FEA solver offers automated solver choice procedure. By estimating memory resources requirements for particular problem optimisation, plugin is choosing the best solution for designer. Except of all subroutines used for FEA solver such a BLAS or SPARSE operation on matrices and vectors, all intensively time consuming modules used for optimisation process are also implemented for GPU environment. As a result of CPU and GPU platform cooperation for numerical computations, high increase of performance has been observed. Optimisation time decreased from hours to minutes or even seconds for particular problems.

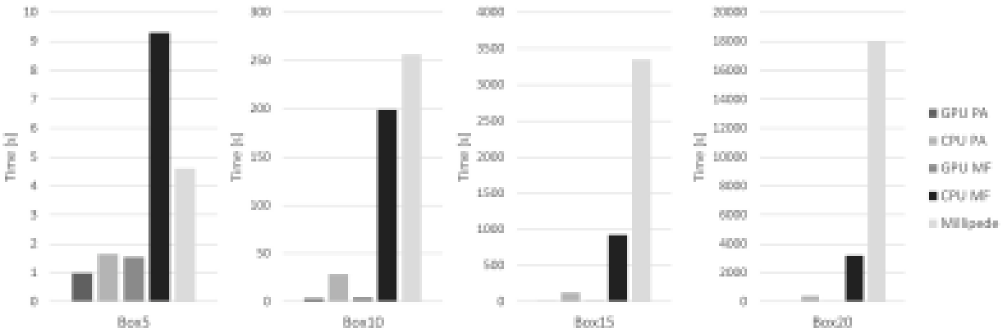


Figure 4
Numerical benchmark. Result for both tOpos (all solvers, all platfroms) and Millipede.

Table 1
Initial benchmark setups.

| Benchmark No. | Model Data | | Solver Type | Tested? |
|---|---|---|---|---|
| Box5 | Element Size | 0.91464362 | GPU PA | Yes |
| | System Resolution | X=5 Y=16 Z=12 | CPU PA | Yes |
| | Node Count | 1326 | GPU MF | Yes |
| | Dofs Count | 3978 | CPU MF | Yes |
| | Element Count | 960 | Millipede | Yes |
| Box10 | Element Size | 0.45732181 | GPU PA | Yes |
| | System Resolution | X=10 Y=32 Z=24 | CPU PA | Yes |
| | Node Count | 9075 | GPU MF | Yes |
| | Dofs Count | 27225 | CPU MF | Yes |
| | Element Count | 7680 | Millipede | Yes |
| Box15 | Element Size | 0.30488121 | GPU PA | Yes |
| | System Resolution | X=15 Y=48 Z=37 | CPU PA | Yes |
| | Node Count | 29792 | GPU MF | Yes |
| | Dofs Count | 89376 | CPU MF | Yes |
| | Element Count | 26640 | Millipede | Yes |
| Box20 | Element Size | 0.22866091 | GPU PA | Yes |
| | System Resolution | X=20 Y=64 Z=49 | CPU PA | Yes |
| | Node Count | 68250 | GPU MF | Yes |
| | Dofs Count | 204750 | CPU MF | Yes |
| | Element Count | 62720 | Millipede | Yes |
| Box25 | Element Size | 0.18292872 | GPU PA | Yes |
| | System Resolution | X=25 Y=80 Z=61 | CPU PA | No |
| | Node Count | 130572 | GPU MF | Yes |
| | Dofs Count | 391716 | CPU MF | No |
| | Element Count | 122000 | Millipede | No |

### *User Interface and functionality*

From the very beginning, tOpos was design to cooperate with Grasshopper visual programming environment (see Figure 2). Structure of the plug-in remain a general topology optimisation algorithm defined by Bendsøe and Sigmund which contains three phases: pre-processing, processing and post-processing.

**Pre-processing.** During the first stage, initial design variables are defined and the Finite Element model is build. To generate proper model for optimisation, adequate data need to be provided. Firstly, user has to define, as 3D mesh, general boundary domain for particular problem. Additionally, essential material properties for that region, such a Young module or Poisson factor has to be setup. All that data are collected in "Boundary Domain" component. Afterwards, based on discretisation principles defined by Finite Element theorem, size and number of elements has to be chosen. Depends on the user requirements, different resolution factors can be chosen inside "Resolution" component.

Last compulsory component required is "Boundary Condition", in which designer applies different loading and support conditions acting on the model. Both load and support constrains are visualised on model as a symbols, to allow user verification of applied conditions. Optional component named "Boundary Properties" can be used if supplementary openings or fixed region of material need to be provided in structure. All that data is gathered in "Model" component. Depend on the target computational platform, model can be created for GPU or CPU purpose. Is worth to mention that CPU implementation of the algorithm is performed on double-precision (64 bit double) variables unlike the GPU implementation which is single-precision (32 bit float) based.

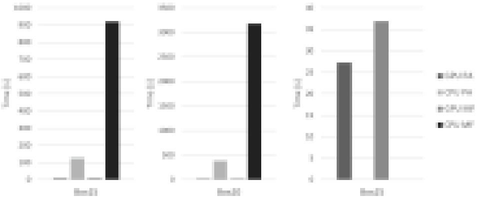

Figure 5
Numerical benchmark. tOpos results only. From the left: Box 15, Box20 and Box25 respectively.

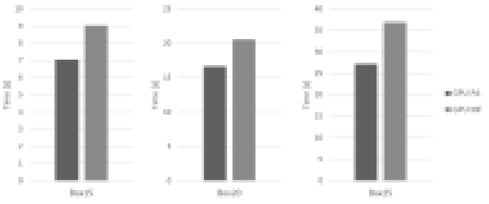

Figure 6
Numerical benchmark. tOpos GPU solvers results only. From the left: Box 15, Box20 and Box25 respectively.

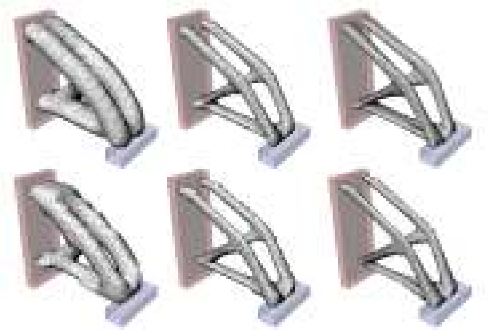

Figure 7
MMB beam optimisation result. Top row: tOpos results, bottom row: Millipede results. From the left: Box5, Box10 and Box15 respectively.

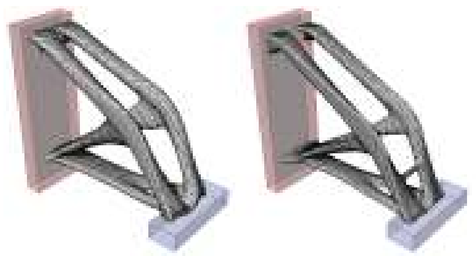

Figure 8
MMB beam optimisation tOpos result. From the left: Box20 and Box25

**Processing.** Second stage, the main part of the algorithm named processing, is the computational core of the algorithm. In this part, two basic components: "Solver" and "Optimus" can be distinguish. Both are designed to use multi-threaded CPU or GPU resources. First component perform only analytical part, returning only displacement field, op-posed to "Optimus", which perform iterative material distribution optimisation process return-ing optimal space material distribution. Both components can be precisely setup if needed by proper, extra "Parameter" block. As was mentioned in previous section, depend on the memory resources, user can adjust, just by one click, desirable solving algorithm: MatrixFree or PreAssembly or leave this decision for Auto mode. Additionally in "Optimus" component context menu, designer can select optimisation result preview methods. Two mode are provided: Iterative Preview, where result is generated after each iteration and Final Preview, where optimisation result is generated after last iteration. Depend on model resolution, Iterative preview can slow down whole process by computing new preview for each iteration. On the other hand, this approach allows user to supervise all design changes and respond faster for any errors or mistakes in design.

**Post-processing.** Last phase is post-processing, where the outcome material distribution data, represented as element densities, can be visualised as a 3D spatial model. Most accurate to represent boundary mesh out of variable (density) field space is marching cubes algorithm implemented inside "Iso" component. Additionally, based on deflection filed, extra data can be extracted from the model, such a principles stress, maximum deflection or structure compliance.

Utilising GPGPU inside Grasshopper environment is extraordinary solution. To manage CUDA context created for tOpos, extra component was designed. It allows to choose target card to perform computations, if more than one card is installed. Also, in case of any instability with graphic card, component allows to reset and clear GPU memory banks. Also it give user live information about consumption and availability of GPU memory. To use GPU computational power, graphic card has to be compatible with CUDA technology at least cc 3.0.

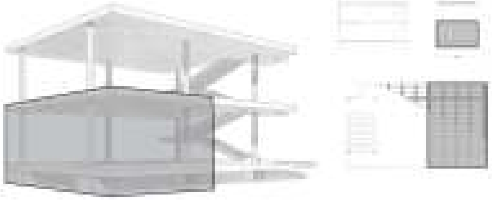

Figure 9
Domino - Experiment 01. Initial boundary domain.

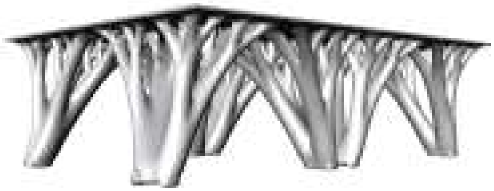

Figure 10
Domino Experiment 01. Results represented as IsoMeshes. Perspective view.

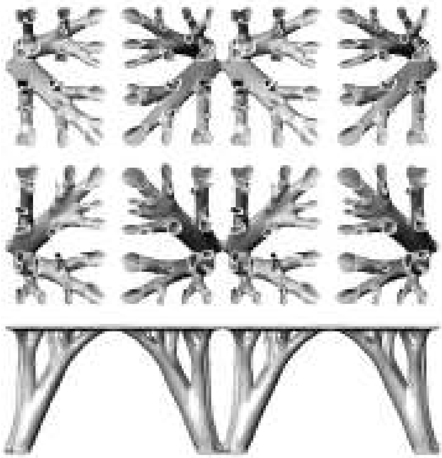

Figure 11
Domino Experiment 01. Results represented as IsoMeshes. On top: plan view, on bottom: side view

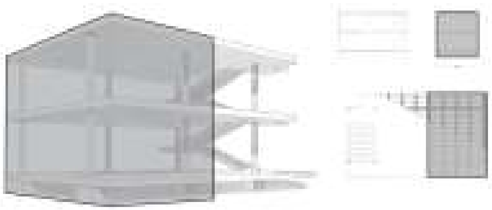

Figure 12
Domino Experiment 02. Initial boundary domain.

### *Numerical and Benchmark Results*

The numerical benchmark were performed to check general plugin efficiency, both on CPU and GPU. The benchmark was run on 4-core Intel i7-2600K 4.05 GHz CPU with 24 GB of RAM and nVidia GTX 970 as a GPU unit with 1664 CUDA cores and 4GB of memory. To verify algorithm correctness and measure performance, typical in literature, half Messerschmidt-Bölkow-Blohm (MMB) beam problem was chosen. The support and load condition are applied as shown on Figure 3. The performance evaluation was based on five benchmarks differ on mesh density and was per-formed for each solver separately.To compare and evaluate tOpos results both in performance and structure, Millipede plugin was utilised for additional benchmark. All setup data is presented in Table 1. It is worth to mention, that the same initial condition was applied on tOpos and Millipede plugin. Both plugins per-formed optimisation for 25 iterations.

The first graph presented on Figure 4 represents total execution time need to optimise MBB beam for particular FEA mesh density by both tOpos and Millipede plugin. During tOpos benchmarks CPU was fully overloaded and GPU kernels reported 95% of computational occupancy. It is caused by adaptation of FEM on irregular shapes. On graph it is clearly visible the huge divergence of the results for both approaches. Millipede reports low performance (high times) for semi and high dens meshes. The considerable disproportion in execution time between tOpos and Millipede, effected the graphs to be illegible.

For appropriate data representation, supplementary charts were generated only for tOpos results including all solvers and all platforms (see Figure 4). This set of graphs represents only semi and high dens problems as the most interesting for the author. Enlargement of mesh densities caused rapid decrease of CPU performance. But even rejecting Millipede optimisation data, charts are hard to read and evaluate because disproportion between CPU and GPU approach is to excessive. The third supplementary charts generated only for tOpos GPU results allows to perceive and analyse difference between MatrixFree and PreAssemble solver (see Figure 5). It has to be notice, that because of Millipede and tOpos CPU implementations reports more the 1 hour of computations, optimisation process for Box25 was per-formed only for tOpos GPU implementation. The detailed information about benchmarks components are presented on Table 2.

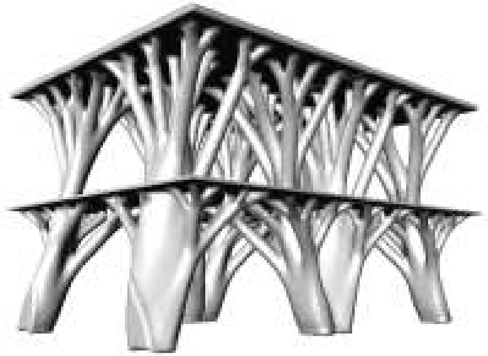

Figure 13
Domino - Experiment 02. Results represented as IsoMeshes. Perspective view.

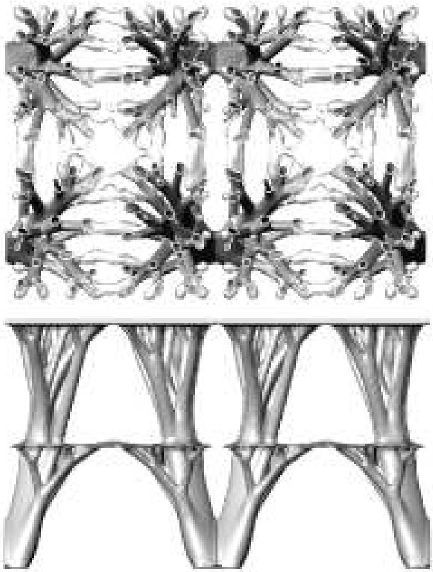

Figure 14
Domino Experiment 02. Results represented as IsoMeshes. On top: plan view, on bottom: side view

Spatial representation of optimisation result's for first 3 cases (Box5, Box10 and Box15) is presented on Figure 7 for both tOpos and Millipede plugin. It is visible, that spatial results are comparable. Minor difference in meshes can be caused by different implementation of filtering algorithms needed during optimisation to eliminate checkerboard problem. Case 4 and 5 (Box20 and Box25) were generated only by tOpos plugin and are showed on Figure 8.

Another important factor is memory consumption by the optimisation algorithm. Depends on GPU architecture and memory resources available for the computation, proper solver need to be chosen. In Table 2 the memory consumption regarding to the solver and platform in correlation to density of the FE model is presented. As visible, usage of MatrixFree mode require up to 7 times less GPU memory then PreAssemble.

## TOPOS INFLUENCE ON ARCHITECTURAL DESIGN

Numerical benchmark prove fast and reliable results of topological optimisation implemented as a tOpos toolset. This allows to perform the first sets of experiments and tests related to architecture. Basic series of researches were done based on architecture icon of XX century, the DomIno structure design by LeCorbusier in 1914-1915. Two case of structure will be presented. For both 50 iteration was be performed. The first case study focused only on the ground part of the Dom-Ino structure. Boundary domain for that problem is described on Figure 9. As a loading condition, 2kN/m2 load from top slab was chosen. Support blocks was place in exact position as is on original project.

Optimisation model resolution was high and contained almost 1.9M of degrees of freedom (629k nodes and 606k elements). Whole optimisation process took 8 minutes to be completed. Spatial results are shown on Figure 10 and 11.

The second case study focused on both levels of the DomInos structure. Boundary domain for that problem is described on Figure 12. As a loading

Table 2
Detailed numerical benchmark results.

| Benchmark No. | Solver Type | Time [s] | | | | | | Efficiency Y/X [%] | | | | Memory [MB] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Solved | Complianc | Reducton | Filtering | Updated | Total | | | | | |
| Box5 | GPU PA | 0.02804 | 0.00100 | 0.00007 | 0.00025 | 0.00962 | 0.97955 | X | X | X | X | 1.10 |
| | CPU PA | 0.06314 | 0.00130 | 0.00001 | 0.00009 | 0.00113 | 1.64445 | Y | | | | 2.01 |
| | GPU MF | 0.04908 | 0.00100 | 0.00008 | 0.00027 | 0.01091 | 1.53760 | | Y | | | 0.27 |
| | CPU MF | 0.36942 | 0.00133 | 0.00001 | 0.00010 | 0.00114 | 9.30312 | | | Y | | 0.34 |
| | Millipede | | | | | | 4.60079 | | | | Y | nd |
| | | | | | | | | 168% | 157% | 950% | 470% | |
| Box10 | GPU PA | 0.11597 | 0.00100 | 0.00011 | 0.00027 | 0.01256 | 3.27404 | X | X | X | X | 7.62 |
| | CPU PA | 1.12294 | 0.01013 | 0.00004 | 0.00044 | 0.00582 | 28.50582 | Y | | | | 13.83 |
| | GPU MF | 0.15977 | 0.00092 | 0.00011 | 0.00028 | 0.01229 | 4.35352 | | Y | | | 1.91 |
| | CPU MF | 7.93113 | 0.01023 | 0.00004 | 0.00042 | 0.00542 | 198.70558 | | | Y | | 2.41 |
| | Millipede | | | | | | 256.65726 | | | | Y | nd |
| | | | | | | | | 871% | 133% | 6069% | 7839% | |
| Box15 | GPU PA | 0.24451 | 0.00256 | 0.00023 | 0.00032 | 0.03033 | 7.02844 | X | X | X | X | 25.11 |
| | CPU PA | 5.01223 | 0.03532 | 0.00014 | 0.00142 | 0.01700 | 126.73508 | Y | | | | 45.54 |
| | GPU MF | 0.32874 | 0.00256 | 0.00024 | 0.00087 | 0.02611 | 9.04379 | | Y | | | 6.36 |
| | CPU MF | 36.73314 | 0.03524 | 0.00015 | 0.00152 | 0.01736 | 919.76577 | | | Y | | 8.03 |
| | Millipede | | | | | | 3348.48422 | | | | Y | nd |
| | | | | | | | | 1803% | 129% | 13086% | 47642% | |
| Box20 | GPU PA | 0.61947 | 0.00452 | 0.00024 | 0.00040 | 0.03340 | 16.64511 | X | X | X | X | 57.66 |
| | CPU PA | 15.51588 | 0.08197 | 0.00032 | 0.00320 | 0.03767 | 391.16612 | Y | | | | 104.46 |
| | GPU MF | 0.77951 | 0.00448 | 0.00021 | 0.00041 | 0.03067 | 20.56130 | | Y | | | 14.70 |
| | CPU MF | 126.88293 | 0.08338 | 0.00033 | 0.00326 | 0.03849 | 3175.39561 | | | Y | | 18.54 |
| | Millipede | | | | | | 18004.12845 | | | | Y | nd |
| | | | | | | | | 2350% | 124% | 19077% | 108165% | |
| Box25 | GPU PA | 1.00322 | 0.00804 | 0.00026 | 0.00054 | 0.06040 | 27.21107 | X | X | X | X | 110.45 |
| | CPU PA | | | | | | | Y | | | | est. 200.01 |
| | GPU MF | 1.40967 | 0.00812 | 0.00021 | 0.00107 | 0.05601 | 36.89091 | | Y | | | 28.27 |
| | CPU MF | | | | | | | | | Y | | est. 35.64 |
| | Millipede | | | | | | | | | | Y | nd |
| | | | | | | | | 0% | 136% | 0% | 0% | |

condition, 2kN/m2 load from both slabs was chosen. Support blocks was place in exact position as is on original project. FEA model resolution was also high and contained almost 3.8M of degrees of freedom (1.24M nodes and 1.21M elements).

Whole optimisation process took 25 minutes to be completed. Spatial results are shown on Figure 13 and 14.

As predicted, results in both cases are almost symmetrical and in form remind branched structures. Received structures and it appearance can by compared to structures design almost century ago by Antonio Gaudi. It resemblances is clearly noticeable. The results shouldn't be surprise, if a force based principles of the algorithm will be remembered. Material distribution algorithm locates material along force flow patterns by analysing structure compliance sensitivity. What is lacking in both case studies, is the fragility of the structure, desirable by the author. Further researches will be performed to fulfil this requirements.

From software engineer point of view, both case studies reviled a couple of minor bugs, reside in the tOpos core implementation. The most important was GPU memory leaking, unstable behaviour of fixed density component and proper units calculation. What is more, subdivision algorithm return invalid data, which precluded author to increase model resolution to gain finest structure. All this problems are during analysing process, and will be solved as soon as possible in connection to further algorithm performance optimisation.

From architectural point of view, results in both cases are almost symmetrical and it forms reminds multi branched structures. Received structures and it appearance can by compared to structures design almost century ago by Antonio Gaudi. It resemblances is clearly noticeable. The results shouldn't be surprise, if a force based principles of the algorithm will be reminded. Material distribution algorithm locates material along force flow patterns by analysing structure compliance sensitivity. What is lacking in both case studies, is the fragility of the structure, desirable by the author. Further researches will be performed to fulfil this requirements. Author predict, that still in development model subdivision procedure, could allow reaching more fragile and finer structures.

### *Further Work*

At the time the paper is written, an intensive work is proceed on next steps of application of topology optimisation algorithm on architectural purpose. Additional scenarios will be performed to evaluate usefulness of optimisation algorithm on form finding process. It is intended by the author to investigate what kind of buildings or architectural structures could be supported by topology optimisation based algorithms. It is predicted to achieve detailed research results before ECAADE 2017 conference will run.

## CONCLUSION

Fast spreading of generative design techniques allows to extend existing form finding processes with engineering solutions. Decrease of computa-tional time needed for form generation by appli-cation GPGPU technology, might encourage de-signer to apply previously unobtainable process into architectural design. Based on author's re-search potentiality to adhibit structural optimisa-tion methods towards architecture is noticeable. Spatial structures, as an outcome of those algo-rithms, brings new and unpredictable forms to contemporary architecture. Additionally, in col-laboration with additive manufacturing known as 3d printing, it moves a design process on the next level of freedom.

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# Fibrous Aerial Robotics

## *Study of spiderweb strategies for the design of architectural envelopes using swarms of drones and inflatable formworks*

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*This thesis research presents an integrated workflow for the design and fabrication of large-scale architectural envelopes using swarms of drones and inflatable structures as formworks. The work lies at the intersection of architecture, biology and robotics, incorporating generative design with digital fabrication techniques. The proposed approach aims to investigate the tectonic potential of computational systems which encode behavioral strategies inside an agent-based model. It is from local interactions taking place at the micro-scale of complex systems that a new set of architectural tendencies seem to emerge. The authors focused on the strategies developed by colonies of social spiders during the construction of three-dimensional webs. Their communication system and the characteristics of the material structure have been then modelled and translated in a digital environment. A physical fabrication process, in which the simulated agents become drones in a real world environment, was concurrently developed. The goal was to investigate the architectural possibilities given by an autonomous aerial machine depositing fibrous material over inflatable formworks and its potential usefulness in specific sites where overall conditions don't allow traditional construction techniques.*

**Keywords:** *tectonics, robotics, multi-agent systems, stigmergy, drones, inflatables*

## INTRODUCTION

The strategy underpinning the work is deeply connected with the logic of swarm intelligence, the collective behavior of decentralized, self-organized systems, natural or artificial (Beni and Wang 1993). Self-organization, intended "as a process in which pattern at the global level emerges solely from numerous interactions among lower-level components of the system" is a key element when it comes to design robust and decentralized systems (Camazine 2003). Swarm intelligence studies systems in which a complex action arises from a collectively intelligent group of individuals as it happens for many insects colonies, flock of birds, schools of fishes or mammalians groups. The design of simple rules and behaviors governing the individual agent actions at the local level can lead to the formation of swarms that cooperate in building complex yet reliable struc-

Figure 1
Colony of Anelosimus eximius, a species of social spider.[1][2][3]

tures. Collective species display decentralized self-organization, swarm behaviors and intelligence - intended as making an effective use of environmental resources through the construction of buildings and artifacts which sophistication (both in morphology and metabolism - i.e. the passive thermal regulation dynamics in termite mounds) greatly exceeds the intelligence potential of any single individual. Insects, in particular, exhibit great potential when it comes to share information and use them in a clever way. Ants, termites and spiders are common examples of societies capable of generating complex collective organization taking advantage of their elaborate communication system (Figure 1).

## BIOLOGICAL MODEL

**Social spiders.** Of all the spider species in the world, only about fifteen can qualify as social spiders. The individuals live together, share the same web and cooperate in a diverse set of activities such as brood care, web weaving and hunting (Bourjot et al. 2003). Spiders are gathered in small clusters throughout the web, under the vegetal sheets enclosed by the web itself and are distributed on the whole silky structure. Despite their apparent individual simplicity, these spiders are exhibiting interesting collective behavior during prey capture and web weaving.The authors focused on the architectures built by social spiders and the type of cooperation involved during the related construction task. These insects are able to collectively build silk structures bigger than 10 m3 consistently endowed with architectural qualities in different environments. Adversely from solitary spiders these colonies seemed to be aware of the global scheme of the structures they were to build or the task they were to realize. This hypothesis was nevertheless difficult to accept because of the intricacy and sometimes impressive size of the structures or complexities of actions compared to the apparently reduced cognitive abilities of the individuals involved. The theory of stigmergy developed by Grassé (1959) for termites lifted the veil on this mystery. Stigmergy is a mechanism where the structure created by an individual acquires stimulation properties that can control the behavior of a congener by reducing its degrees of freedom. A stimulating configuration acti-

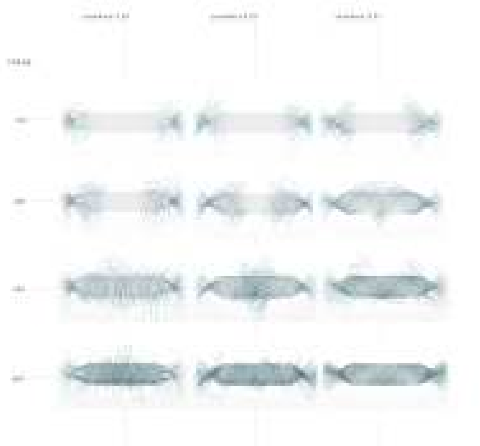

Figure 2
The diagram shows the influence of the stigmergic separation parameter over the final morphological result.

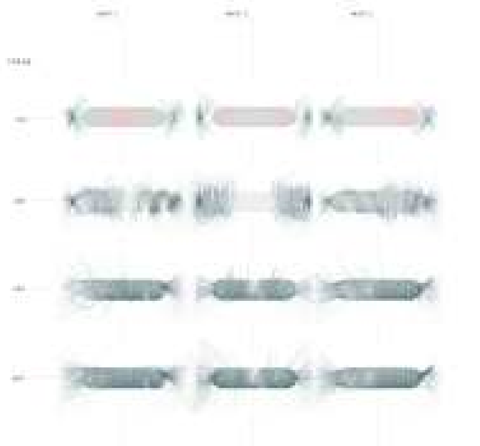

Figure 3
The diagram shows the influence of the surface mapping parameter over the final morphological result.

vates a response of another element of the system, transforming the original configuration into a different one that may trigger in turn another, possibly diverse, action performed by the same element or any other agent in the colony. Although each step in the sequence of interactions is based on rigorous stimulus/response dynamics involving only local information, this distributed system enables a broader plasticity at the global scale and the emergence of the phenomenon of self-organization, which unlocks the generations of higher forms of internally coherent complex organizations.

**Silk.** Like many other animals, spiders communicate through chemical signals or pheromones. This ability is often used to find prey but also functions in social and sexual communication. Silk plays an important role by influencing how the information travels along the elements of the colony. For example female specimens may deposit chemical traces on the ground or on the substrate by combining sex pheromones with the filament of the same thread in production. The male is then able to identify the silk thread produced by the adult female and monitor it using chemical and mechanical information. In a similar way spiders are able to perceive their local environment thanks to the specific nature of the silk they are depositing and existing structures play an important role as the spider is able to extrapolate useful information from preexistent silk. Stigmergy theory allowed the understanding of the cooperation mechanisms among social spiders, providing at the same time an operational model upon which the design exploration is based. Self-stigmergic processes (Krafft and Cookson 2012) suggest the involvement of a process similar to the stigmergy described by Grassé for explaining the construction of nests and termite mounds, except that the pheromone influence acts on the emitting specimen itself rather than its congeners. Preexistent structures guide the spider's subsequent behavior in the cases of both flat and three-dimensional cobwebs. The position and consistency of these pre existing pheromone-charged wires influence the construction of further fibrous elements.

## MULTI-AGENT SYSTEMS

The building strategies investigated in the biological role model were then encoded as rules of a custom written simulation program developed on the open source platform Processing [4]. Agents are modelled as constructors, with enough degrees of abstraction to allow the simultaneous interpretation of their role as both simulated colonial spiders and robotic units performing coordinated construction tasks in space.

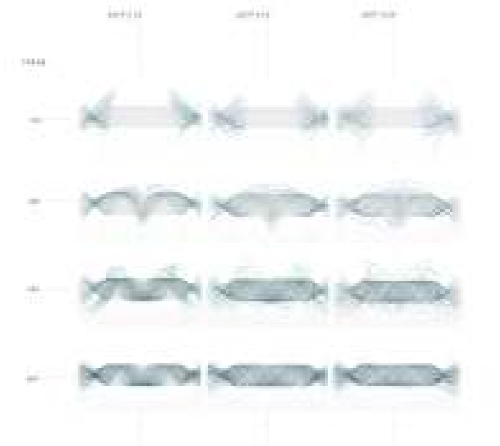

Figure 4
The diagram shows the influence of the stigmergic cohesion parameter over the final morphological result.

The explored behaviors can be outlined in three principal classes. The first one evaluates all the aspects related to distributed communication systems and swarm logics among the units, taking into account the stigmergic process. The second one examines constraints and opportunities of the robotic units chosen for the fabrication stage (i.e. quadcopters) so that each simulation can provide reliable data for further implementation. Finally, material features provided the basis to encode micro-scale behaviors into the system. The whole simulation is made up by a set of constructive units interacting with each other and the surrounding space depositing fibrous material on a previously modelled and analyzed reference surface. A series of input regarding the environment data and the initial surface geometry are provided at the beginning of the simulation, then the collaborative construction takes place. While the simulated entities don't carry a representation of the whole, they are able to share data with each other, the environment and the already built structure as well as manipulate the system by depositing new material. The constant stream of information is the key to build a feedback system in which every agent is constantly able to read the local state of the construction process and start/stop releasing material whenever certain conditions are fulfilled. When the global construction reaches stability (the surface is considered structurally sound and the expected fibrous density values are met) all the simulated units stop moving and the material behavior simulation begins: all the strands in direct contact with the surface undergo a stiffening process that simulates the "starching" procedure performed during material experimentations. The core behaviors underlying the setup of the simulation system can be outlined as follows.

## *BEHAVIORS*

**Separation.** Agents, conceived as robotic units, have physical dimensions and well-defined areas of action so that in the simulation builders can locally recognize the distance that separates them from other elements and avoid interfering with each other by respecting their influence area.

**Material deposition.** A key factor for the construction system is represented by the ability of the agents to modify the environment. During their movement they release a linear thread or filament formed by a chain of spring-particles blocks. These structures represent the spider silk and they are responsible for the main attraction forces for the agents. (Figure 2)

**Motion trajectories.** When developing windings, agents maintain a constant reference to the inflatable surface in order to develop helicoidal trajectories along the development axis of the surface. Therefore, the robot element is programmed to distinguish the main axes of the solid shape. The other fundamental component of motion is the tangential one. The agent extracts the value of the tangent to the surface for each position in the simulation space. By combining tangential and axial force, agents can determine the trajectory for the correct winding force. (Figure 3)

**Environmental conditions.** Each robotic element in the simulation interacts with the environment and specific elements within it. The reference surface plays a key role in the construction process: real world behavior of inflatables surfaces was achieved by using a mesh that binds the position of the particles released by the agents during the simulation. Agents are capable to detect the presence of the surface within a defined distance range. Once entered into the inflatable structure's influence area, they work out its principal axis and start a helicoidal motion. This type of movement coupled with the agent's ability to release material engenders to a series of windings that occur around the inflatable object. Simultaneously, the surface becomes also an attractor: data from geometric features and environmental analysis is mapped on its geometry for the agents to retrieve and process.

**Scalar field.** A volumetric scalar field was embedded in the environment, acting as an attractor towards the reference surface in order to limit any uncoordinated agent movement and avoid any construction happening far from the inflatable structure. While moving in space, the agent samples the field at each frame from its future location and calculates the average of the values found in its proximity at the center of gravity of the positions of the samples considered. Each selected value is stored in the voxel evaluation space. The agent then only considers values belonging to a specific optimal range for construction.

**Stigmergy.** The first force, called stigmergic separation, is represented by the interaction between the fibers already released (modelled as springs in the simulation) and the moving agent. The agent detects the fibers' particles in its cone of vision (oriented along its moving direction) and steers away from the calculated average position. Stigmergic separation avoids excessive fiber accumulation and overlapping, thus preferring a deposition that follows distinct trajectories. Stigmergic cohesion reverses the previous behavior, attracting the agent towards the fibers. Cohesion tends to create areas with abundance of material, highly redundant and sometimes chaotic. A proper modulation of these two behaviors can unlock extremely elegant and expressive solutions. (Figure 4)

**Material behavior.** As already mentioned, the system of particles and springs released by the agents mimics the behavior that fibers exhibit when impregnated in a liquid or viscous matrix. The term bundle refers to the strong forces that act on the scale of the material and manifest themselves through attractions and repulsions between adjacent material portions. In the present case the springs that came into contact with the inflatable surface are considered.. Once the apprehension (hardening of the fiber in the real case) begins, the particles start a proximity check, moving towards the average position of found neighbors if any are within a given threshold. In a real case scenario the spider web modifies its properties over time due to environmental exposition; likewise, a stretched wire impregnated in a matrix (resin, for example) undergoes a significant alteration of its mechanical characteristics. Accordingly, in the simulation the wires deposited over the inflatable lose their elasticity over time by increasing the springs stiffness value.

Figure 5
Process of preliminary analysis of the structure, extrapolation of one module and simulation of the construction system.

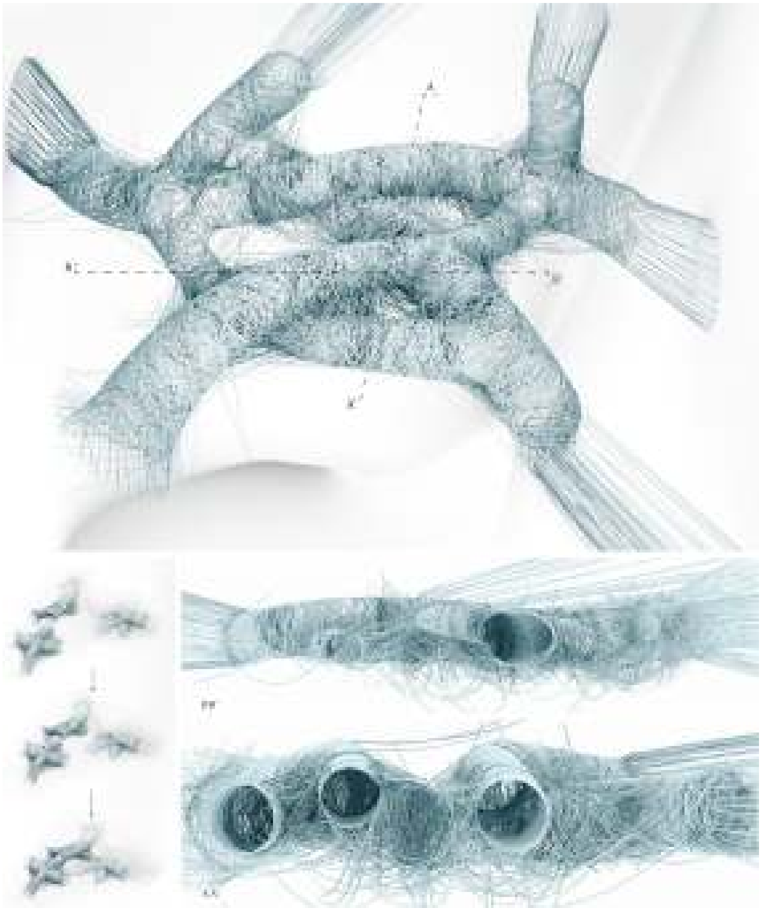

Figure 6
The resulting configuration is assembled on site thanks to the cooperation of a set of drones. On the bottom right. Side sectioned views of the structure.

## ARCHITECTURAL APPLICATION

The generative system under construction was then tested at the architectural scale to verify the potentialities previously noted. To exemplify one of the possible fields of application for the system an architectural proposal for a suspended structure in an alpine site was elaborated. The site characteristics do not allow the installation of a conventional construction site, therefore, to organize the circulation of material and people, the inflatable structure previously tested (cylinder, toroid, etc) has been modified and extended in order to achieve complex spatial organization and to accommodate connections between different part of the envelope. Taking into consideration the computational issues encountered in the simulation of structures with a large amount of elements and the opportunities offered by the use of drones, the process was split in parts. A first analysis and evaluation of the surrounding area is then followed by the generation of an inflatable surface. Subsequently, it was decided to divide the structure into seven parts and simulate the process on each module individually, preserving border conditions. At the end of the construction process all the artifacts produced are transported and mounted on site by the same flying robots. (Figure 5 and 6)

Figure 7
The image show a planned trajectory given to the drone in order to achieve a complete helicoidal motion around the inflatable formwork.

## MATERIAL STUDIES
To explore the possibilities of the constructive process and verify the physical behaviors of the system, a series of material experiments was developed from two basic components: the fibrous element (thread) and the supporting structure around which it is wrapped (an inflatable formwork). Cotton and wool threads (impregnated with a bonding resin) were employed mainly for their availability and cost over other kind of materials with equal properties at the testing scale. The inflatable elements were made with variable-sized latex balloons. The first models were needed to understand the limits and possibilities of the materials in question. At the same time the expressive characteristics of the obtained results were used to develop the most interesting features in subsequent experiments.

## FABRICATION PROCESS
Quadcopters represented a viable option to work with in order to translate the simulated construction system into the real world. The size of the space they can act upon is substantially larger than theirs. This feature, along with their unrestrained capacity to move in 3D space, is one that no other computer-controlled construction machine has nowadays and allows the construction size to transcend the one of its constructor. Flying machines perform construction tasks and build structure by releasing fibrous material on inflatable formworks; the developed pipeline codified the agent's trajectories and writing the code that was then fed to the robotic units. The quadcopter used in all the phases is a Parrot AR Drone 2.0 which, since its launch in 2012, has been vastly used in academic environments. It was chosen for its flexibility of use, the presence of a variety of built-in sensors and its affordable price. Despite its lack of payload capacity (an important issue for this research) it still represented the best option on the market thanks to a vast community of people already working on identical drones. The key challenges in this case were to locate the robot only through the data provided by its own sensors and then navigate in a robust manner even in the presence of temporary signal leakage. This required a solution to the simultaneous localization and mapping (SLAM) problem for estimating and controlling the robotic unit. These challenges are even more important considering issues such as low-cost actuators, noisy sensors, significant communications delays and limited computing resources on the robotic unit. To solve the SLAM problem on these aircraft, various types of sensors such as laser scanners, monocular cameras, stereo-cameras and RGB-D sensors have been explored in the past. The adopted system, developed by a research group at the Munich Technical University, determined a solution through a monocular system which enabled the robot to operate in small spatial environments as well as in open spaces. (Figure 7)

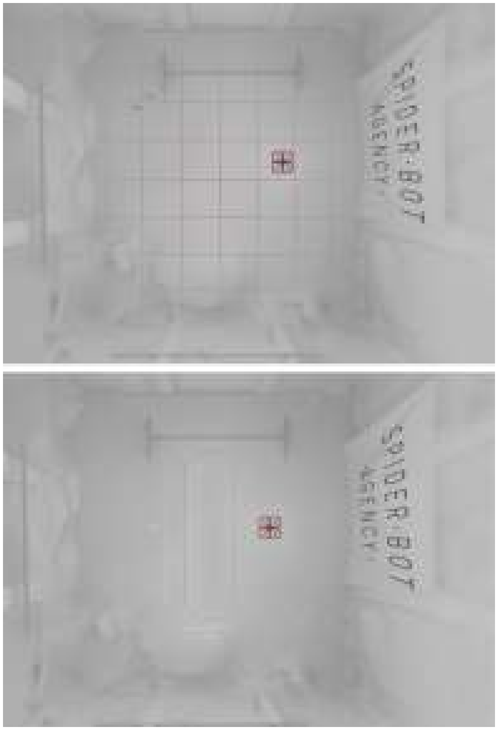


Figure 8
Digital environment for the simulated flight. The red dashed grid represent a useful reference which is then reproduced in the real space. The bottom image depicts the inflatable structure with its principal dimensions.

**Environment.** The drone dimensions and the monocular vision control system required the preparation of a suitable working area to work properly. A set of support structures was provided: a grid on the floor for constant tracking of the robot's motion trajectories, a textual map with black elements on a white background to create a visual reference and a system of three supports for the anchorage of the fibrous elements. The components layout was adequately traced for accurate reproduction in the simulator. (Figure 8)

**Movement.** The first test flights necessarily focused on the definition of the robotic unit trajectories. The drone was able to generate an effective localization map and, hence, an ad hoc reference system for space navigation. Once defined, the origin of the system can be provided with a series of spatial coordinates. The quadcopter waits at each point of the trajectory for the instructions transmission to complete. The control system therefore allows the definition of a unique trajectory once the origin of the reference system is identified. The trajectory execution is accurate and customizable through initial control parameters. In fact, it is possible to set the minimum distances between the position of the drone and the spatial coordinate to reach as well as the minimum amount of parking time around the desired point.The same type of experiment was then made by hooking the end of a wool coil to the quadcopter. The turbulence created by the drone propeller moves the wire during the flight. Although the effect was visibly significant, it did not show a worrying intensity for the continuation of the experiments.

Figure 9
Main environment of the fabrication process. The bottom image shows the anchoring phase of the threads to the supporting system.

**Inflatable construction.** In order to build a feasible pneumatic surface a plastic sheet (made by several pieces seal-taped together) was used, while a

Figure 10
Final structure.

connected fan ensured a constant pressure within the surface. The system proved to be flexible to small damage and suitable for the intended purpose. A support structure was also prepared to hold the inflatable structure in place while the drones performed their tasks. The support wires position was changed several times to prevent them from becoming obstacles in the drone's trajectories.

**Winding technique.** After the preliminary tests, the constructive process started. First, a specific simulation for the system was performed by extrapolating the agents' trajectories coordinates; these were then inserted into the drone control operating system. The communication with the drone happened via text files in which, in addition to the coordinates, safety parameters were set in case the drone entered emergency mode. The first results of the winding process are visible in figure 9. Initially, problems due to the friction force generated by the strands on the inflatable surface showed up; for this reason in some cases manual assistance to the drone in certain winding steps around the inflatable was necessary. In most cases, however, the robot was able to realize the structure independently based on the information provided by the digital process. Once the construction task ended the stiffening procedure started. A mixture of glue and starch was then applied on top of the strands on the pneumatic surface. At the end of the strengthening process (when the strands dried out), the inflatable formwork was pulled out and the fibrous structure reached its final state. (Figure 9 and 10)

## CONCLUSION

The construction system fully exploits the ability of flying machines to reach any point in space, allowing robots to move fibrous elements to location otherwise not accessible by conventional construction machines, manoeuvre in or around existing objects and interact with the already built elements. The outcomes are the result of a mediated approach capable of mixing top down strategies, necessary to intuitively steer the system towards articulated functions, and bottom up tendencies which, on the other hand, foster a variety of generative tectonic solutions while maintaining reliability and robustness. These assemblages are structurally non-linear: hierarchies emerge through transformative variations in intensity, capacity and density. They resist categorization as either pure surfaces or strands only, since the fibrous elements bundle and weave to form surfaces, while surfaces split into strands losing the traditional distinction between skin and structure, as the system operates structurally within a redundant, highly intricate assemblage endowed with intrinsic ornamental patterns. The fabrication method introduced addresses the potential offered by quadcopters in the field of architectural construction through the deposition of fibers on inflatable elements: this process can be advantageous in scenarios where traditional building systems and techniques cannot operate (e.g. Mountain gorges, forests, etc.). Experimental results provide a proof of concept and feasibility of the construction system, providing a useful reality check on economic and technical constraints for future developments.From the architectural as well as from the robotic perspective, various aspects of the approach deserve further experimentation: during the development of the work, critical elements of the inflatable system and fibrous assemblages emerged; specifically, the fabrication method for the inflatable formworks greatly limits the final morphological and typological result. A refined method would provide more reliable and complex structures able to address a wider range of needs. At the same time, the fibers and the stiffening solution have shown significant limitation in strength and robustness that require additional attention for large scale models. Further developments could also involve the robotics manufacturing system, implementing the possibility to engage multiple robotic units inside the constructive process. The exchange of information between the units and the ability to read data from the structure being created could significantly improve the tectonic results and the construction technique.

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# A cloud recycling light

## *(human) feedback matters*

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*The paper focuses on the question ``How does our built environment, urban culture and architectural production change through humans feeding back into digital systems of pre-fabrication and systems fostering industry 4.0?'' It discusses some risks and possibilities of digitisation and the city in an era of sustainability, networked design methods, production processes and digital communication tools in the midst of The Internet of Things. Glimpses into the case studies `a cloud recycling light', `dynamic field feedback' and `urban rigid origami switch' discuss the impact of material behaviour, human and machine feedback into digital systems - their behaviour, their ways of communication, the possibility of optimising future design iterations and their form. All of which may result in new architectural and urban typologies, driven by increasingly agile ways of weaving together complex systems.*

**Keywords:** *Industry 4.0, industrial production, Internet of Things, cybernetics, collective intelligence, feedback*

### CONTEXT - BEFORE THE FIRST DIGITAL TURN

In 1969, the first message was sent through the APRANET, a network connecting four computers. Three years later the First International Computer Communication Conference took place between 24th - 26th October 1972, in Washington DC. Bob Kahn organised a "computer communication network demonstration (connecting 40 computers) to run in parallel with the sessions." He announced his presentation as follows: "This demonstration will provide attendees with the opportunity to gain first hand experience in the use of a computer network. The theme of the demonstration will be on the value of computer communication networks, emphasising topics such as data base retrieval, combined use of several machines, real-time data access, interactive cooperation, simulation systems, simplified hard copy techniques, and so forth." (Kahn, 1972). Kahn's statement that "The social implications of this field are a matter of widespread interest that reaches society in almost all walks of life; education, medicine, research, business and government" is certainly valid today. A crucial difference, however, may be the rising communication with physical machines as well as increasing complexity and blurring boundaries between observing and learning systems (2nd order Cybernetics) and controlled systems limited to a repetitive input-processing-output linearity disregarding feedback (1st order Cybernetics). Vint Cerf joined

Bob Kahn in 1973 to developed the fundamental structural components "Transmission Control Protocol" (TCP) and "Internet Protocol" (IP) that enabled the flourishing of the Internet as a globally accessibly network for matter-less information transfer. With the advent of its successor the "Internet" - between approximately 1985 and 1995, when, on September 20th, the Federal Network Council (FNC) defined the term "Internet" a new global information system triggered the growth of an inter-connected world (Evans & Hooper, 2017). Since then networked digitisation of communication-, production- and construction-techniques and -technologies have increasingly replaced analogue processes on all levels. As previous industrial revolutions did, the information age is triggering change - through the development of artificial intelligence and "autonomously" acting systems and soon objects of all kinds. Following the industrial age starting around 1760, the machine-age (1880-1940) and electronic-age mainly characterized through its physical geographical fixed location, our contemporary digital network age challenges us humans with a globally, tightly networked and communicating world. A phenomenon that influences the possibilities for personal communication methods, such as hotspots for free usage of the Internet, access to digitally networked objects for e.g., transportation, transformations in industry, research, society, governance, economy and our built environment. The "personal" within the global communication has reached a level where mass-customisation is as possible as direct digital manufacturing in every household. Manufacturing process are hitting batch-size one production lines, which is certainly attractive on a large scale when applied for performance optimisation of modular building components.

## CONTEXT - IN THE SECOND DIGITAL TURN

The following three observations initiated the cross-disciplinary subject: a) The paradigm shift from analogue to digital architecture and development of cities is shaped by the accessibility of digital tools and ubiquitous computing. b) Merging of known top-down and bottom-up design processes (from data-mining to urban design). c) The requirement of re-thinking towards industrial processes in the construction industry - towards individualized pre-fabrication, due to global climatic development and demographic change with rapid population growth.

Figure 1
abstract networked map of Berlin

a) The first observation questions the idea of "the digital" as purely technical interface and encourages the extension of the digital towards, or rather back, to the material world. The query includes the topic of digital-theory (Carpo, 2011) and material making as part of education and research in computer aided architecture and design. The paper, however, introduces technical solutions fostering feedback into architectonic culture, an evolution of the human-machine interface, ubiquitous computing and machine learning, computer sciences, big data, information technology, governance. The technological ecology (L. Werner, Rossi A., PanahiKazemi, L., 2014) circumferences us in a second digital turn. It is offering design tools that can combine self-regulating data generation, systemic thinking, augmented reality, material intelligence, the industrial deployment of industrial robots in the construction industry, and socio-ecological developments. Big data, being implemented in land transformations (LTM) (Pijanowski et al., 2014) urban growth simulations and studies for the future, research in material technology is starting to be implemented in the curricula of architecture

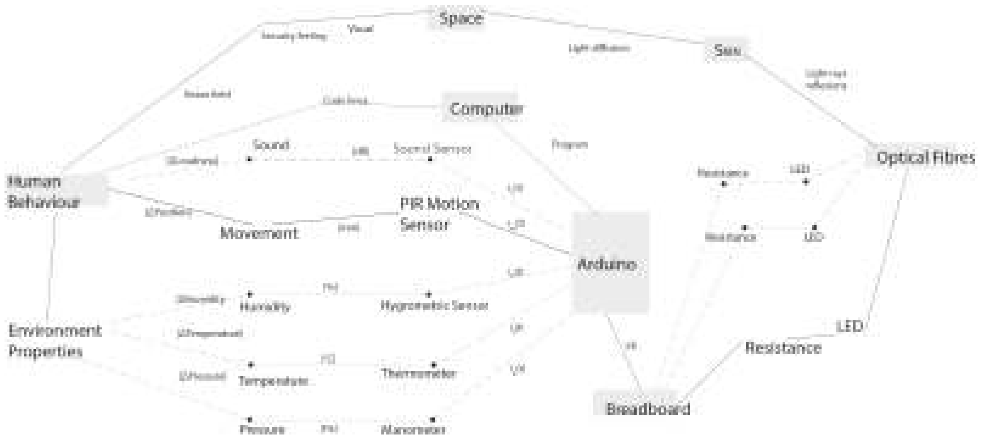


Figure 2
Component and Data Structure Diagram

schools. The global network has - in many cases - succeeded in local communication; it implies ubiquitous computing, augmented reality and material intelligence, but to mention a few. Feedback-based design strategies overwhelm our traditional understanding of the discipline of architecture, encouraging a rethinking of architecture, the architect's role and responsibility and a general understanding of what the architectural craft is (Kleemann, 2010).b) The second observation, a key topic running throughout the research is the impact of the advent and future perpetuation of intelligent materials, mass-customisation and the use of industrial robots on culture, society, human ecologies and their extension towards a robotic world influenced by artificial intelligence. Present technical changes trigger a reaction within the culture of architecture and urban design, which results in a merging of known top-down design processes and still novel bottom-up design processes. In this circumstance, digital data plays a key role in the learning system 'human-machine-material' - as information carrier and cybernetic feed-back-agents. The existence of interactive digital design laboratories increases continuously (Senseable Lab - MIT, Future Cities Laboratory - ETH Zurich/Singapore, CHORA Conscious City Lab - TU Berlin, Art + Design department - Northeastern University). The potential of digitisation lies in its ability to create and foster social and professional networks. Participation within the urban and local design process is possible. Intelligent pre-fabrication systems allow for the integration and immediate feedback of citizens', future owners' or tenants' desires in the design process in combination with external design requirements such as climate, sustainability, economics or biodiversity.

Figure 3
Sheet of bioplastic membrane

The question this technical development raises is: If industrialised and digitised mass-customisation democratises design and planning? A further question to project is, if this is a desired state and if so, what is the impact globally on a long run. The paper discusses if intelligent digital technologies - merging human and machine feedback - can improve the efficiency and flexibility of production through the customization of production?c) The third observation refers to the topic of human and machine feedback as crucial part for holistic systems integration in order to pre-fabricate, digitally manufacture smart building components for a growing world population in a changing world climate. Firstly, global demographic change (age) with an anticipated rapid population growth from 7,44Mrd. In 2016 to 11,2Mrd. humans in 2100 (source: Deutsche Stiftung Weltbevölkerung, 2016) is a challenge for architects, planners, politicians and the industry. Secondly, our buildings are responsible for more than 40 percent of global energy used, and as much as one third of global greenhouse gas emissions, both in developed and developing countries. This development in conjunction with climate change requires novel design strategies for the realization of human habitats and living-spaces. Hence, this article suggests a shift of the construction industry - following suit the automotive industry -, digital industrial pre-manufacturing and pre-production processes as well as building components with embedded intelligence for performance (internal) and environment (external) data collection - to be used for future decision-making (Chang & Chen, 2017). Modular building components and housing typologies are open to be redesigned innovatively in order to allow for swift construction and resilient sustainability. Projects presented are starting to develop possible models and reinvention of living typologies in a networked 'Conscious City' (Figure 1).

## A CLOUD RECYCLING LIGHT RESEARCH CASE STUDIES

Three projects, 'a cloud recycling light', 'dynamic field feedback' and 'urban rigid origami switch' aim at utilizing material behavior in order to developing architectural and urban typologies as well as the development of more flexible and versatile building components with embedded intelligence, resource efficiency and the potential of circular economy.

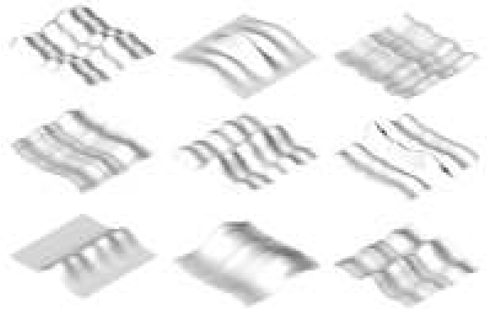

Figure 4
Variety of topography applying Perlin noise.

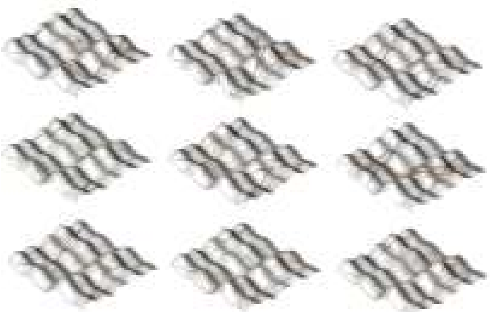

Figure 5
Variety of branch-types.

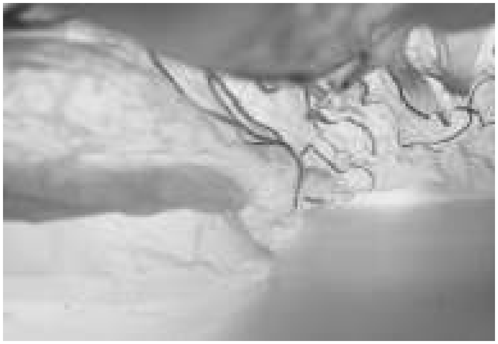

Figure 6
Cloud un-lit

Research is informed by the above thoughts and correlating global debate. 'A cloud recycling light' investigates in a customized component structuring a composite of fibrous bioplastic-material through the integration of structuring fibers (in the prototype made of Sisal) and optical fiber strands. The strands feed on existing light-sources in order to illuminate darker areas in the urban and rural environment. Activation is triggered through movement lighting dark paths for safe trespassing. It is a sustainable low cost material lightening system. This new component of the intervention is mainly made of an organic membrane - potato bio plastic and paper, two low-cost and common materials, and allows for large scale production (Figure 3).

Figure 7
Composite with lit-up optical fibre inside

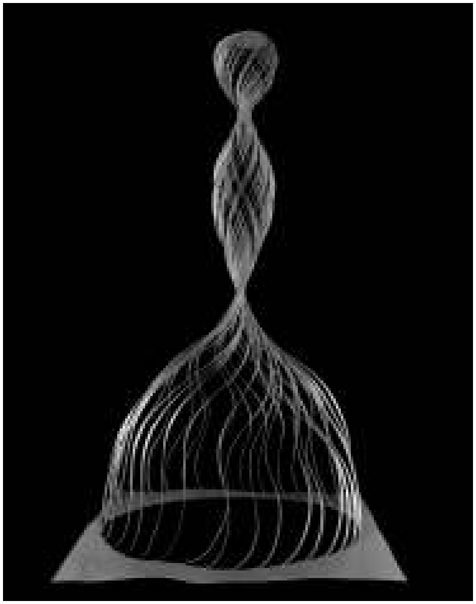

Figure 8
Activated spiral pattern on metallic coated paper

It uses the existing light and leads it through an apparently random network of fiber optics. First hand made, the final prototype aims to be CNC produced while using a pattern recognition process for placing the structuring fibers. Integrating even slight differences on the site leads to an infinite variety of final form. The process enables this element to inhabit the city on an urban scale offering high performance.

The topography of the surfaces is based on pseudo random numbers. Generation through 2-dimensional Perlin noise mappers. The final result of the topography is multiplication of two independent Perlin noise distribution in X and Y direction. The amplitude of Perlin noise (in our case the high of the composite panels) is a value between 0 and 50cm (Figures 4, 5). The original purpose the Perlin noise, developed by Ken Perlin in 1983, was to allow visual artists better represent the complexity of natural phenomena in visual effects. The prototype shows increased interactivity by introducing external parameters as well as a motion sensor.
The 'Component Data Structure Diagram' describes the relationship between visual field, environmental components and computational hard-ware once the component is activated Figure 2). An Arduino Microprocessor is used to measure motion as a variation of distance in millimeters, is transformed into an electrical signal in Amps and finally light (Figure 6, 7).

## DYNAMIC FIELD FEEDBACK

'Dynamic field feedback' is a structure developed through the application of processing and grasshopper aiming at an intriguing change of the micro environment based on human, climatic and noise behavior in the city. It suggests a "learning tool for perception".Dynamic Field Feedback is the prototype for a cybernetic kinetic structure. The project's aim was determined Louis Kauffmann's definition of cybernetics as "the study of systems and processes that interact with themselves and produce themselves from themselves" (Kauffmann, 2007 cited in Targowski, 2011). The work is nourished by a rich groundwork, partially provided through Gordon Pask's (Pask, 1969). In 1968, the ICA in London held the "Cybernetic Serendipity", where Pask's "Colloquy of Mobiles" was presented for the first time - an interactive, educatable, computer-based system composed of five mobiles. Representing a social system, the colloquy supported the aesthetic potential environment. By way of light and sound, the rotating elements suspended from the ceiling communicated with each other, independent of external influences. With the help of flashlights and mirrors, the exhibition visitors could assume the roles of the mobiles and influence the learning process (Pask, 1968). Through communication the mobiles learned to optimize their behavior to the point where they could interact with the least possible use of energy.

**Pattern and Form.** This technique used for the Project was "Kirigami" which literally means (Kiru) cut (Kami) paper and is an actual a Japanese art form. It differentiates with the traditional Origami or Kirie (cut drawing) because of the lack of folding. The project started with simple geometrical forms such as: circle, square, triangle, voronoi cell and hexagon (Figure 8). This limitation enabled us to understand the basic phenomenon before engaging in more diverse and complex designs approaches. Experimentation showed, that the distance between the cut lines affects the flexibility and fragility of the three dimensional form. That lead us to testing the combination of thicker and thinner distances between the cut lines and observed how that affected the form.

The shape illustrated in Figure 10 is generated by applying the pattern on the metallic coated paper. The same pattern was applied on a sheet of 2mm MDF (Figure 9). The thickness between the cut lines and the dimension of the pattern are the same. Due to differences in the material behavior the formal and performative results vary.

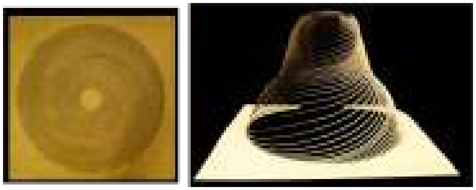

Figure 9
Activated spiral pattern on timber

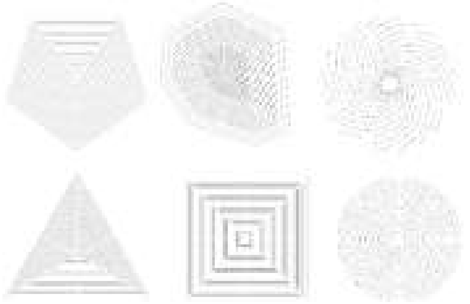

Figure 10
First tested patterns. Respectively rectangular, triangular, hexagonal, voronoi cell, circle, and spiral

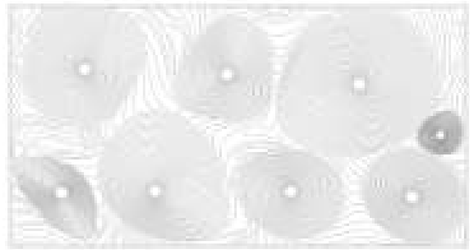

Figure 11
Final complex spiral combination pattern

Figure 12
Cut out pattern

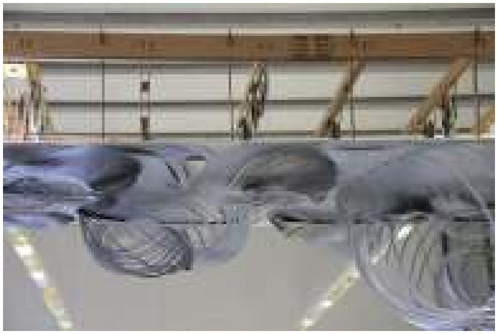

Figure 13
Final prototype

Figure 14
View of the pulley system. A motor activates the first wheel, setting in motion the rest of the system


Figure 15
Diagram of Inter dependencies

The form, which emerged on the metallic coated paper was found more aesthetically interesting and hence it was decided to continued working with this material.

### *Parametric Pattern generation*

The mathematical equations of a variety of spiral patterns were tested and simulated using Processing. By changing the parameters of the equation different configurations of the spiral pattern could be generated. This principle was used to create a pattern of multiple interconnected spirals. Apart from that attractor points at the center of each spiral was attracting all the lines. The further the line was from the attractor point the weaker the attraction force was. As a result, a pattern of eight interconnected spiral patterns was decided upon (Figures 11, 12).

Interaction activated motion. While working on a suitable structure able to set in motion our complex spiral pattern, we simultaneously studied a way to activate the mechanical components that would drive the motion. The most efficient way to proceed was to implement a motor device. This is why we decided to work with Arduino: an open-source device using a micro-controllers, and a long list of material that came with the kit we obtained. The communication/coding interface allowed to design the interactive object of desire. We further elaborated a coding file allowing us to control a small DC-type motor. As illustrated in the Figure 16, the DC-motor activates the first wheel of a large pulley system, indirectly setting in motion the complete structure (Figure 13).

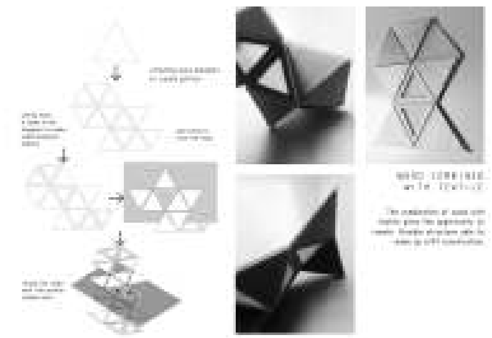

Figure 16
composite panel

As a result, a prototype of a single module of an interactive structure - that if placed in the urban context would create a continuous feedback loop with the passer-by - was built (Figure 14). The user would bring the structure into motion with the touch or movement, while the structure modifies the space, that effects the user. This would be potentially applicable in different scales making use of the same logic.

Figure 17
Triangular Origami pattern

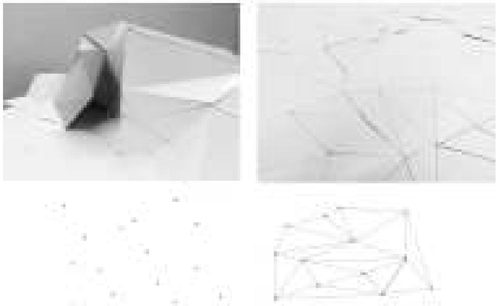

Figure 18
structural folding

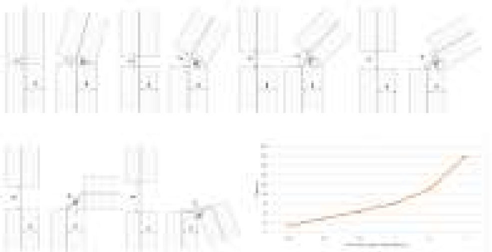

Figure 19
Dependencies between material thickness, panel distance and folding angle

In a building, it could simply act as an interactive ceiling changing in function of certain characteristics for example: noise volume, number of people, the weather also. For a town, it could become some sort of urban telephone where different neighborhoods could connect with each other through the apparition of these structures. It becomes somehow a device that could help a conscious city regulate itself and interact with its inhabitants (Figure 15).

## URBAN RIGID ORIGAMI SWITCH'

The project suggests a composite wall based on digital origami development. It investigates modular components for greenery, solar energy collection in conjunction with place-making. A prototype is designed to interact and communicate with its environment. This project describes a prototypical process for a flexible geometrical structure to be applied at an urban scale. The process involved experimenting with common material as paper and wood where the aim is proposing a method to create a composite material able to find application in constructing urban sheltering pavilions, noise and pollution absorbing screens or generally in facade engineering.

The technique of origami folding and rigid Origami was used for its plasticity and facility to create complex movements, forms and shapes using a simple material for example a paper sheet (Figure 19, structural folding - folding lines using a Delaunay pattern on a 2mm thick sheet material) (Tachi, 2009) (Resch, 1960s [1]). The complexity of the membrane increased with the addition of other components. Timber was chosen as the main material for the external panels, with added textile sandwiched it in order to allow greater flexibility in the folding angle. With this a dichotomy between a hard and soft material was achieved.

The contemporary approach to urban and architectural design often does not consider either its impact on future city structure or the rapid climate changes.

Figure 20
Making of rigid origami panel

Current lifestyle and amenities of the 21. Century lead to deteriorating quality of air and water. To maintain the best living conditions while preserving and protecting the quality of life, measures have to be taken. new built architecture should meet the expectations of sustainability and durability.

Figure 21
analogue prototype

Figure 22
elevation of possible ecology origami wall

According to this principle another idea about producing energy came to our minds. In order to cater for sustainability, the folding membrane is designed with bendable joints, that would move according to the sun direction. Combined with a CO2 filter we envisage an efficient membrane for energy collection. Conceptually designed to an urban space it can also be adapted to an interior space according to its conditions. This means that the size of the membrane should be adapted in relation to it - folding and adapting themselves to the environment.

## CONCLUSION

The entry question of the article "How does our built environment, urban culture and architectural production change through humans feeding back into digital systems of pre-fabrication and systems fostering industry 4.0?" may have partly been answered with the projects presented. The "wicked problem" (Rittel & Webber, 1973) of designing the built environment is additionally convoluted with the constant definition changes of all components the question entails - may it be "urban", "culture", "digital systems" or "industry" are constantly morphing, establishing novel relationships, levels of relevance and subcategories. The network-age encompasses a technological parametric ecology nourished by noise and perturbations, resulting in a system of increasing complexity and decreasing controllability. The shaping of the built environment is less subject to the above discussed evolution, it is rather a question of political decision-making powers and economic force. Computational Architecture as a field of research integrated in the field of the practical erection of buildings and construction of cities plays an indispensable and vital role in suggesting change, form and content. Thus, the question cannot have one answer, but an answer that evolutes or interacts according and with to the changes of the questions components. What may sound rather philosophical here is, in fact, an example of isomorphism between technology, semantic, action, analysis, optimisation and design. As architects we are designing systems with multi-layered complex relationships rather than discrete objects (L. C. Werner, 2014). The systemic and cybernetic approach described in the introduction and the projects mirrors a "radical constructivist" (von Glasersfeld, 1995) computational approach, which I believe is relevant to handle projects on a rational level of operation. “A cloud recycling light” therefore, acts as starting point, as a step towards solutions and innovation.

Figure 23
urban impression

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# DESIGN TOOLS - THEORY

# ARch4models

## *A tool to augment physical scale models*

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*This paper focus on the development and evaluation of a computer tool that enriches physical scale models of buildings, which are commonly used during architecture and civil engineering design processes. The main goal of this work is to enable designers, namely architects, to use the affordances of the physical scale models, by enhancing them with digital characteristics that can be easily changed, allowing an enriched interaction of the designer with such models. Our in-house developed Augmented Reality tool, referred to as ARch4models, augments the user experience with visual features and interactive capabilities, not possible to accomplish with physical models (see this video in https://goo.gl/5zbdTQ). The tool allows the coherent registration between the real and the digital in the same space. Satisfaction evaluation studies were conducted that have shown that ARch4models improves the building design process when compared with a traditional methodology employing solely physical scale models.*

**Keywords:** *augmented reality, architecture, physical scale model, 3D model, AEC design process*

## INTRODUCTION

Technologies are playing an important role in the recent history of our civilization and a large number of citizens use daily their computer, tablet or smartphone, for professional or personal tasks. Likewise, a large part of architects and architecture students use these tools in their daily professional or academic work. Simultaneously, architecture professionals and students use traditional means to express and explore their design ideas and concepts. Physical scale models are design tools still common because they allow a closer interaction with the designed buildings, increasing the understanding of the design.

Architects, engineers, designers, real estate promoters and other stakeholders that intervene in the building design process, adopt various methods to represent and visualize buildings. Two relevant scenarios are: i) the different design process phases, from conceptual to detailed design, when design alternatives have to be compared, and ii) when designs are being presented to clients, future users or in design competitions. Drawings at different scales, rendered synthetic images, or three-dimensional physical models at several scales, are some of the used techniques. This diversity of methods doesn't allow a clear comparison since they use different criteria for representing buildings. Whereas the traditional methods of visualizing architecture rely on drawings and on the construction of scaled physical models, the more recent approaches, rely on digital representations, either on 2D or 3D, using different commercially available Computer Aided Design software systems. Each method has its potentials and drawbacks, and only a minority of professionals or academics use purely one of them, whereas the majority usually goes back and forth between analog and digital, until the final design is reached, presented and constructed.

Our paper focuses on the representation of designs by means of physical scale models. Its affordances provide a good representation of the reality not reachable by a drawing and, given its three dimensionality, allow stakeholders to see them from different perspectives helping the perception of the constructed and void spaces.

According to Mills (2007) physical scale models can be categorized into two groups: primary and secondary. Primary models explore concepts and ideas and these are the ones more used for design purposes. Within this group Mills (2007) includes: conceptual models, volumetric models and presentation of models. In the group of the secondary ones, which are made with a greater detail, the author includes: inside, section facades and structure models.

Scale models help architects to understand a place. Volumetric models, in particular, show the city's fabric by representing its volumes and topography, partially or fully. These urban models give designers three-dimensional information on how the area is developed, and with them architects can study the environment surrounding their place of study. Mills (2007) considers that urban context models are relevant, specially to show the adjacent territory surrounding the proposed design and are useful to visualize and analyze simultaneously several design alternatives for a design brief. Particularly in the initial phases of the design, answering to the design brief, several proposals for the intervention place are discussed and analyzed in the relation with the adjacent environment. Physical model buildings are still commonly used in architectural offices and will remain to be so. Those models are often short in information and focus mainly in volumes. They are static objects and cannot be easily and quickly changed. If more information would be made available, the architectural design goals could become more explicit.

As stated in Luciano (2012), both physical and virtual model help to visualize the three-dimensional shape. In fact, in recent years, Augmented Reality (AR) applications available in smartphones and tablets, emerged in the academia and in the industry. City Lens (1), for example, is an AR app that shows extra information about the street the user is seeing in real-time, like the location of nearby cafes, hotels, etc. Urbasee (2) is an AR app that allows to view a digital model in a 1:1 scale at given place. SmartReality (3) and Augment (4) enables the visualization of building products and other elements superimposed to a image marker.

This paper is structured in sex sections. In this section we described related literature work that is in line with our research, notably about the use of representation tools in architecture design process and augmented reality in architecture. In section two we define the research hypothesis, the goals and the methodology used. Section three explains each step of the design of the Arch4models app, including the user interaction experience and its main functionalities. Section five presents the satisfaction evaluation studies. In section six we discuss our results and the paper end with a conclusion section.

## HYPOTHESIS, GOALS AND METHODOLOGY

In our research the aim is to understand how we can bond together physical and virtual representation modes by superimposing (or registering) them, to increase the understanding of an architectural design, while at the same time showing the alternatives or the evolution of such design. Our hypothesis is that designers, architects and students would benefit with an augmented reality tool that help them to visualize their designs, to compare changes and to analyses their proposals within the urban context (Figure 1). Urban physical models are those that we believe can benefit the most from such a tool, since the rehearsal of alternative design proposals is frequently done at this scale of design work. At a different scale other functionalities can be of help as well to the design process as we will show in the next sections.

Figure 1
Student's urban context physical model, with a hole in the intervention plot so that the proposed building can be placed and continuously replaced. (photo by Joana Gomes)

Given our hypothesis, our research work had the goal of allowing architects and other stakeholders to make a better use of physical scale models, providing them with more information than they have. To reach such goal, we developed and evaluated (with a satisfaction user study) an AR app to augment physical scale models. Our research methodology, included the study of the state-of the-art of the available technologies that allow to add extra information to what we see in our world, as stated by Azuma (1997): "AR allows the user to see the real world, with virtual objects superimposed upon or composited with the real world". Affordances and drawbacks of using physical models in the design process were also identified in order to propose solutions that took advantage of the potentials and surpass the drawbacks.

The methodology for the development of our AR app included six steps: i) definition of personas; ii) definition of scenarios used by personas; iii) definition of user requirements derived from scenarios, iv) development of the app that fulfils user requirements, v) satisfaction user evaluation study. The app was developed in a collaboration between architecture and computer science researchers from the Digital Living Spaces group of ISTAR-IUL and Microsoft.

## ARCH4MODELS

### *Definition of personas, scenarios and requirements*

In order to identify the requirements for the AR app, two scenarios and their corresponding personas, were defined: 1) a jury analyzing several proposals in a competition by different architects (Figure 2); 2) a team of architects assessing different alternatives during the overall design process. In the first scenario, the competition organizers would ask for participants to deliver their design proposals following a specific format of 3D modeling, to simplify its exchange with the Arch4models app. After importing those 3D models in the AR app, the jury could experience an augmented scale model in a Microsoft Windows tablet, where different design proposals could be superimposed into a same urban scale model. The second scenario assumed a similar scenario, but here the users would be more aware of all the presented proposals and would discuss smaller details. In both scenarios, the personas could have discussions about the proposed designs and its integration in the intervention places.

The final set of user requirements for the proposed AR system, were:

- Superimpose (register) in 3D and in real-time, the virtual model with the physical scale model;
- Perform augmented reality by means of texture (image) tracking, using in-house developed technique by Bastos & Dias (2008);
- Import several 3D models described in the standard 3DS format in one augmented reality session;

- Show and hide building components (architecture, structure, infrastructure);
- Perform real-time sections and floor plans.

Figure 2
Architecture competition juris evaluating design projects.

Figure 3
ARch4models: user looking at a 3D digital model superimposed on a 3D physical scale one. Augmented reality is achieved via texture tracking.

## Arch4models development

The ARch4models app is an extension of a previously available the ARch app (Lopes et al. 2014; Mendonça 2014; Miguel 2014), which was designed for a Microsoft Windows tablet (Figure 3). The interface was designed to be natural and simple so that the user can quickly and easly navigate through the menus. There is a menu that occupies 25% of the screen when a 3D model is open and the goal is just to explore the model in AR, leaving the rest of the screen free of graphical gadgets. Some features included in ARch4models were already available in the ARch app, which was previously designed to be used by architects during the design process, without any use of physical scale models.

## Augmented Reality technique

ARch4models uses a texture-based augmented reality system (Bastos and Dias 2008) to recognize and track in real-time features of a reference image, with known position and orientation in relation to the actual physical scale model. Thus, the tracking information is used to register in 3D the virtual model and the digital data corresponding to a building. Through the screen of the tablet, the virtual model appears superimposed at a location near the scale model, much like if it coexisted with such physical model (Figure 3), resulting in an augmented physical model. The procedure requires the following: a Windows tablet; a virtual 3D model; an image used as a marker; a physical scale model.

Recent developments of our recognition technique allow us to already identify the physical scale model as a marker as stated in the Discussion section.

## Arch4models features

**Change between 3D virtual models.** A menu enables the user to change the 3D model. This means that several 3D models can be loaded into the system simultaneously and seen whenever the user wants. When there is the need to change a 3D model, the user has to slide with the finger from the menu bar to open the "change menu", and in this menu the user needs to do a long click on the selected model. Then the user can close the change menu, sliding to the left direction in the same bar (Figure 4).

**Cut sections.** In the sections mode, the user can make horizontal or vertical cut sections to immediately observe the inside of the building designed (Figure 5). These real-time sections can be performed in any direction or angle.

**Show architecture, structure and infrastructures.** In selection mode it is possible to highlight, paint or hide the various specialties of the 3D building digital model (architecture, structure and infrastructure).

Figure 4
"Change model" menu activation, by sliding on lateral menu bar: (top) slide right to open the menu, (middle) slide up and down to see more models and chose, (bottom) slide left to close the menu.

For this purpose, the model is divided by layers (design specialties) and the app is able to show them one by one. We can e.g. see the structure layer highlighted in red (Figure 6).

ARch4models contains other useful features for improving design discussion. With the Highlight tool, the user can point to an element, highlight it and discuss it with another stakeholder. The highlight and paint tool can also be used to rehearse design alternatives with colors or materials e.g. The Hide tool, allows the user to hide a wall of any other element e.g. to see the inside of the building without slicing it.

### *Digital model preparation*

The ARch4models supports 3D models produced in any 3D modeling software, provided that they support 3DS export format. We require the building elements to be divided into specialization layers. Our app reads 3DS into a native OSG - OpenSceneGraph format.

## SATISFACTION EVALUATION STUDY

Usability and satisfaction evaluation studies were performed which involved 16 adult participants from ISCTE-IUL, students of architecture and architects. These participants were aged between 19 and 50 years old, 12 men and 4 women. All participants were experience users of physical scale models - 44% of participants said that they create models many times, 38% with reasonable frequency and only 19% rarely. The study included, for each participant, the following 4 phases:

1. A five minute demonstration of ARch4models performed by the authors;
2. A five minute free exploratory experience of the app by each participant;
3. Three prescribed tasks performed by each participant: i) change model; ii) perform a section or floor plan; iii) show structure or infrastructure;
4. Satisfaction questionnaires.

One of our goals was to assess the relevance of using ARch4models during the communication between various participants in the design process, like in reviews of architecture juries. For that we defined several questions that participants answered by using a scale of responses from 1 (not good) to 7 (very good). 94% of participants stated that the app makes it easier to understand the design in an urban contexts (Figure 7, responses 5, 6 and 7). 44% of participants said the application allows a very good (response 7) and more dynamic view of the model while 94% responded with values 5, 6 and 7 to the same question. With the help of the AR tool, 82% of participants said they would be interested in using it in their design processes. These results show that ARch4models can be useful to the architects' work. The app also had a positive vote on its usefulness for the evaluation of several design alternatives for the same place, as in a competition. In fact, 88% of participants agreed that the app would be an asset for the jury committee of architectural competitions, as enables juries to fully observe the design alternatives. Both students and architects involved in the test ranked 81% the possibility of adding more information to the models.

Participants were also asked what was their perceived satisfaction, namely, if physical scale models could become more informative when augmented with extra information added by AR. 38% said that 3D modeling satisfy them in a good way, 44% replied with a reasonable satisfaction while 19% said they were insufficient compared with the others. About technology, only 38% responded that they had prior knowledge about AR software.

## DISCUSSION

The results obtained with the ARch4models app enable us to discuss on the role of such an app during the design process as a whole.

Physical scale models are used to explore concepts and ideas during the design process and assume several detailing levels, some only volumetric, others more detailed and even others fully detailed namely showing construction components. Arch4models aims at several design stages since it incorporates features that help architects and other stakeholder along the design process. At an initial design stage, when architects are discussing urban design and volumetric possibilities, Arch4models enables the visualization of several design alternatives superimposed to an urban physical model. One advantage of such a tool in this stage is the possibility of having several design alternatives that can be interactively visualized superimposed in the physical model. In later stages of design, when solutions are more detailed, Arch4models allow to explore the interior of buildings by using features as Sections and Highlight. At this stage Arch4models enables to explore the proposals in several scales of detailing ranging from the urban position to the construction detail.

Figure 5
The user performing real-time horizontal sections in the 3D model.

Figure 6
Highlighting the structure of the 3D model.

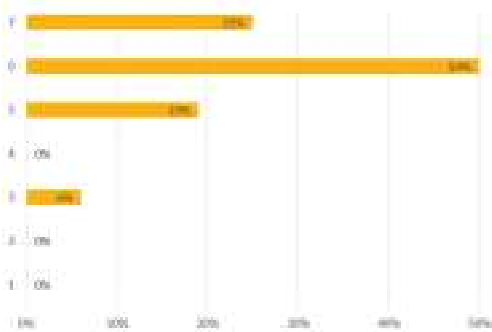

Figure 7
Responses for: does the app makes it easier the understanding of the design in an urban contexts (values form 1 to 7, 1 being no)

As a result of our user studies, both from qualitative assessment of participants and features that we defined and were not implemented, we have realized that there are some aspects of ARch4models that we need to improve or extend: i) in Presentation mode, introduce the simulation and animation of insolation; ii) in Section mode the vertical cut plan needs to be improved so that users can define the rotation angle; iii) both Highlight and Paint tools should enable to save the generated data.

As we stated before, our currently operational AR system is based in texture tracking, requiring a reference image to be in view of the camera, to correctly register the virtual model. Although it wasn't reported as a problem during the usability studies, this assumption limits the volume of interaction allowed, especially if we consider larger scale models or camera's close-ups. A possible solution would be the adoption of several reference images placed around the physical scale model. However, we decided to integrate an AR tracking solution that completely removes the need of images. We have experimented the use of Microsoft Kinect camera (5) and an available 3D reconstruction and tracking technology from Microsoft (Kinect Fusion (Newcombe et al. 2011)), to simultaneously reconstruct and track the geometry of the physical scale model and remove the need of reference images after an initialization step. At the moment, this experiment runs only on laptops with graphics processing unit (GPU) computing capabilities.

Using this version, the initialization step occurs in the first frames camera frame: Arch4models recognizes a reference image, performs Camera Pose Initialization (CPI) and calculates the transformation from camera to world coordinate systems. Afterwards, the reference image can be ignored and Kinect Fusion reconstructs and tracks the physical model maintaining both virtual and real visually consistent. Using these technologies is possible to walk around the physical model without losing the position and orientation registration of the virtual model in AR. The system requirements are the following: a computer with a GPU computing capabilities; Kinect for Windows (first version); a virtual 3D model; a reference image just for CPI; and a physical scale model.

To assess the accuracy of this setup, tests were performed with several scales of physical models and building materials (see Figures 8 and 9). We were able to perform CPI and track the camera pose in all scale models, although the frame rates were very low (around 5 fps) and the instantaneous pose still shows excessive accumulated errors. In Figures 8 and 9, we can see that with this technique we cannot reconstruct scale models smaller than 1:1000, because the volumes are extremely small. Also trees and smaller

Figure 8
A scaled physical model used in a design studio class (model by Micaela Raposo)

Figure 9
The same physical model of Figure 5 reconstructed by means of Kinect-fusion technology.

## CONCLUSION

Arch4models app includes a combination of features that makes it very adapted to the architectural design process. Most AR commercial apps have single features that enable to visualize architecture models but fail in providing the flexibility required by a professional use, namely the possibility of doing real time sections and visualizing it by layers while simultaneously the 3D model is superimposed on the physical model.

This paper focused on the use of Augmented Reality to improve the experience designers have with physical scale models. We hypothesized that augmenting the information present in a physical scale model, would improve the use of those models during the design process. The goal was to develop and evaluate an AR app able to augment scale models with dynamic design information, enabling architects and other stakeholders to interact with them in an easier and more effective way. We concluded that our approach promoted dynamism and simulation possibilities to the real scale models, previously unavailable. The developed app allows to select and perform sections on the virtual model in real time, which is registered onto a physical scale model. As a result of this work, the scale models become more dynamic and interactive. The user can test several design alternatives applied e.g. to an urban context, and easily perceive aspects to change or improve. Satisfaction tests showed that this application has the potential to be used both during the architect's working process and during the evaluation of designs competition.

We believe that our tool has the necessary features to help the stakeholders involved in design processes of buildings and urban areas.

## ACKNOWLEDGMENTS

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# A Visualization Dashboard and Decision Support Tool for Building Integrated Performance Optimization

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*Analyzing the results of multi-objective optimization and building performance simulation can be a very tedious process that requires navigating between different software and tools. There is a clear scarcity in visualization tools that combine methods for big data analysis and design decision support tools that integrate detailed information for each design and parameter. Having a single visualization tool that provides methods to both visualize and analyze a large amount of data, understand the relation between objectives and variables, and having the ability to compare and analyze the preferred designs thoroughly can support the process of design decision making. In this paper, previous attempts to develop better data visualization tools for both integrated building simulation and optimization outputs were analyzed, then guidelines and a visualization tool prototype that can be effective in decision making and analyzing multi-objective optimizations results was presented.*

**Keywords:** *Multi-objective optimization, Building Performance Simulation, Simulation, Visualization tools*

## BACKGROUND

Due to global climate change and the related risks and challenges, the need to reduce carbon emissions is more obvious than ever. Planners, architects, and engineers are the key players to create a more environmentally friendly and sustainable built environment. Building Performance Simulation (BPS) is an important tool to support the move towards more energy efficient buildings and is becoming an integral part of the current design decision-making process. BPS software and tools are being rapidly developed to be more user-friendly and accurate. Despite the high demand for more user-friendly interfaces, simulation results' visualization and analysis tools are not usually given the deserved attention.

Decision-making and data visualization tools have a great impact on the final design product. In a recent survey, nearly 25% of participants (architects and engineers) identified graphical representation as their top priority for the user interface of BPS software (Attia et al., 2009). However, another survey showed that most users were not satisfied with the Graphical User Interface (GUI) offered by commercially available tools. In the survey, 75% of the users pointed out the lack of a graphic interface for post-processing of the BPS optimization results (Attia et al., 2013). As a result, most of the surveyed users had to depend on their own post processing skills or self-developed tools to graphically present the simulation output, and analyze the data.

The scarcity of efficient data analysis and insufficient quality of visualization tools is even more evident in the case of an integrated (holistic) assessment or a multi-objective optimization. In an integrated design assessment, it can be necessary to have a dashboard that gives an overview of all the relevant performance aspects, and summarizing the performance of the building while simultaneously provides detailed information where needed. On the other hand, analyzing a large number of simulation outputs, such as results from a multi-objective optimization, requires more advanced tools to examine the whole set of data and to find relations between different objectives and variables. For multi-objective optimization of integrated building performance, there is no single visualization tool that combines methods for big data analysis and design decision support through detailed information for each of the relevant aspects. As a result, analyzing the multi-objective optimization results becomes a very tedious process and requires navigating between different software and tools. A single tool, that provides methods for analyzing and visualizing a large amount of data, clarifying the relations between objectives and variables, and having the ability to compare and analyze the preferred designs thoroughly, can support the decision-making process.

This paper presents guidelines and a preliminary prototype of a visualization tool that can effectively support the decision-making in multi-objective optimization. In a first step, existing attempts to develop better data visualization tools for both integrated building simulation and optimization outputs were reviewed and discussed. In a second step, effective techniques for the creation of a data visualization tool that can aid in the decision-making process were presented. And finally, a prototype of a visualization tool was brought forward as a proof of concept.

## PREVIOUS WORK

### *Analysis of optimization results*

Several research works investigated the analysis of building performance optimization results. Brownlee and Wright (2012) sought to analyze the relationships between design objectives and variables, using a simple ranking order and correlation coefficient. They used a combination of scatter plots and spreadsheets to graphically present the optimization results. Scatter plots accompanied by parallel coordinates graphs and graphic images were also used by Chaszar et al., (2016). Such graphs provided useful feedback, but it was noted that adding more interactive capabilities could further enhance the workflow. To help designers better understand the optimization results, Wortmann (2016) presented a novel method to represent the results graphically. His method, called Performance Map, helps in identifying the optimization problem, relating parameters and performance, examining promising designs, and guiding automated design exploration. Other effective methods were also addressed in other engineering disciplines (Pryke et al., 2007; Witowski et al., 2009). Nevertheless, while these methods can simplify analyzing a large number of cases, it does not provide detailed information on each performance aspect. For instance, while using scatterplots and parallel coordinates graphs can aid in finding an optimal design for daylighting performance, it does not show how the daylight is distributed within the space, or at which hours artificial lighting is needed. Such detailed information and context are necessary for the decision-making process. The ability to examine and compare several aspects at the same time is also equally important.

### *Integrated performance dashboards*

The importance of integrating graphical representations of diverse performance analysis in a single dashboard was highlighted by many researchers. The Daylight-Europe project (DLE) presented the "Integrated Performance View (IPV)", a multi-parameter dashboard to compare reference and as-built cases

(Hensen et al., 1996). This dashboard proved useful in comparing the overall performance of design cases, as it integrated different charts and graphs for heating load, energy consumption, visual comfort, thermal comfort and glare index.

The IPV tool was further developed to provide more flexibility and customization as well as several enhancements for better communication with users (Prazeres & Clarke, 2005). Struck et al., (2012) built upon this concept with a special focus on human cognition and more innovative graphs, such as temporal maps and motion charts. Other research works and commercial software also offer an integrated performance dashboard. However, most of these tools lack the ability to deal with a large amount of data, and thus cannot be efficiently used to analyze the results of multi-objective optimizations.

## INTERACTIVITY AND VISUALIZATION TECHNIQUES

Information visualization can be defined as "the use of interactive visual representations of abstract data to amplify cognition" (Ware, 2012). Scientific research on information visualization has resulted in several best practices and guidelines for visualization design (Cleveland, 1985; Few, 2006; Tufte, 2001; Ware, 2012). Interactivity plays a major role in the visualization tools. Yi et al., (2007) presented seven interactive techniques that can be effectively applied to the case of building performance optimization. The first four techniques, Select, Explore, Reconfigure and Encode, can help the user explore the whole set of data by switching between different graphical representations of data and marking preferred designs. The other three techniques, Abstract/Elaborate, Filter, and Connect, can be used to provide detailed in-


Figure 1
A screenshot of the visualization tool. A- Context and design parameters panel, B- Explorer panel, and C-Integrated dashboard

formation for selected cases. Adding two other techniques, such as Compare (for directly comparing selected cases) and Advice (as a tool for guiding further enhancements) allows for quick, yet thorough, comparison between preferred cases and supports informed decision-making. These two additional techniques were also suggested by Haeb et al. (2014), who highlighted the importance of spatial context and visual feedback as an essential component in the field of building performance simulation.

## VISUALIZATION DASHBOARD: GUIDELINES

Building on the reviewed literature, the following guidelines, and requirements for a new tool for visualizing the results of integrated building performance optimizations were defined. The suggested visualization tool can provide better ways to investigate the building optimization results by offering three levels of data analysis:

### *1- Design space overview and exploration*

At the first level, the full set of simulation results should be explored. Multi-dimensional graphs, such as parallel coordinates and scatter plots, are useful in this case. Switching between plot types, filtering the results and selecting favorite cases help in clarifying basic relations between the objectives and variables, in addition to highlighting optimal and preferred designs.

### *2- Sensitivity analysis and parameter relations*

On the second level, the direct relation between any two variables or objectives can be investigated. The use of sensitivity analysis and 2D charts can indicate the variables that drive the optimization process, the expected enhancement in each objective, and the relative importance of the design variables.

### *3- Detailed results and comparison between favorite designs*

At the final level, an integrated dashboard is presented with detailed performance data, which provides all the needed information about each selected design. To ensure an informed decision-making process, the visualization tool should offer the ability to compare the detailed performance and contextual reference (images and 3D model of the cases) of favorite cases.

## VISUALIZATION DASHBOARD: PROTOTYPE

As a proof of concept, a preliminary prototype was developed according to the above-mentioned guidelines. The prototype was built using the visual language programming tool Grasshopper and HumanUI, a plugin for Grasshopper that enables the creation of graphical user interfaces. Additional Grasshopper user objects and code functions were written to overcome limitations in the HumanUI Plugin. The visualization tool consists of the following panels.

**Context and design parameters.** The left panel shows the names of the selected design alternatives as well as a zoomable and rotational 3D visualization and the corresponding design parameters. The user can change the design parameters to specify they design alternative (Figure 1-A).

**Explore.** Alternatively, the user might choose to select the design from the Explore section. The Explore section contains a parallel coordinates chart that shows the design variables and results of the complete design set with the selected design highlighted. Additionally, it also contains a radar or bar chart for showing the performance of the selected design as well as a data table. The user can filter the design alternatives by limiting the values of any of the variables or the objectives. It is also possible to mark cases in order to be compared later to each other (Figure 1-B).

**Variable-objective relations.** In this panel, the user can choose a variable(s) and objective(s) to see

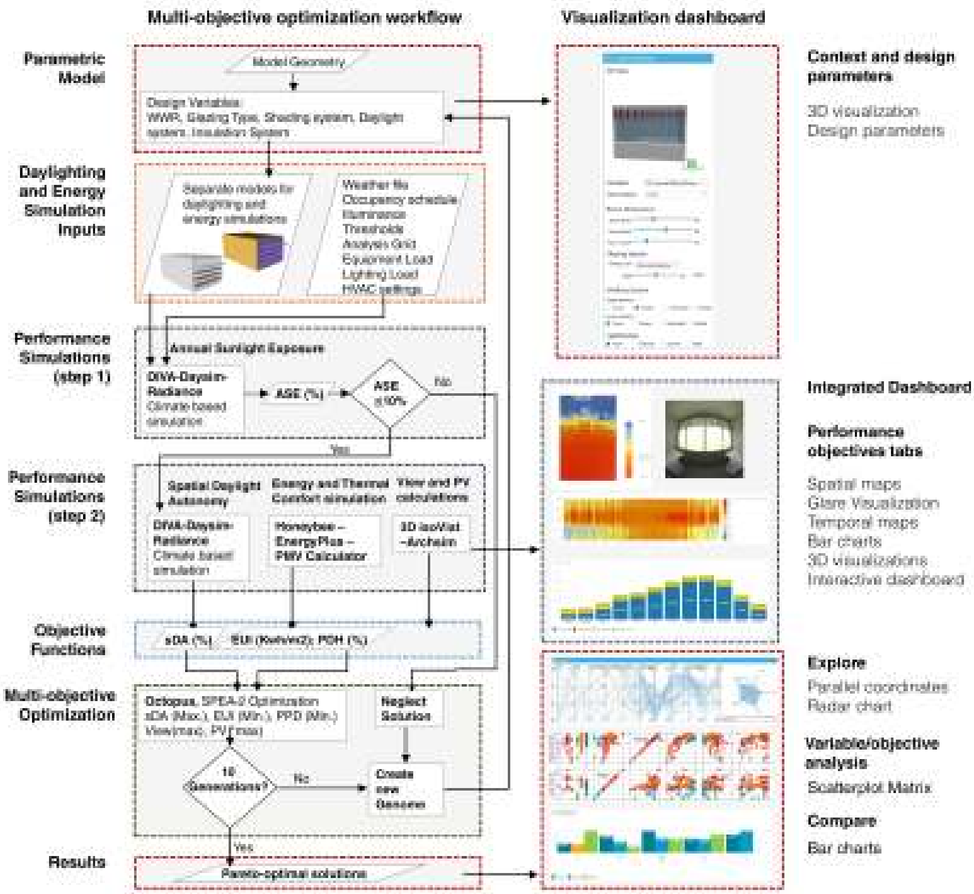



Figure 2
The workflow of the optimization process and the corresponding visualizations panels in the visualization tool.

the direct relation between them, which is rendered in the shape of a 2D scatterplot chart in the case of a single variable and single objective, or as a matrix of scatterplots in the case of several variables and objectives.

**Compare.** The compare panel offers a bar chart to compare the marked design alternatives as well as simple visualization of each performance objective.

**Integrated Dashboard.** Similar to the IPV tool discussed earlier in the literature, the integrated dashboard houses more details for all the performance objectives for the selected design alternative.

**Performance objectives tabs.** For each performance objective, a separate section that includes alternative ways of result visualizations an even greater detail of result analysis is provided.

To make it easier for the user to explore and choose preferred designs, the ability to show or hide

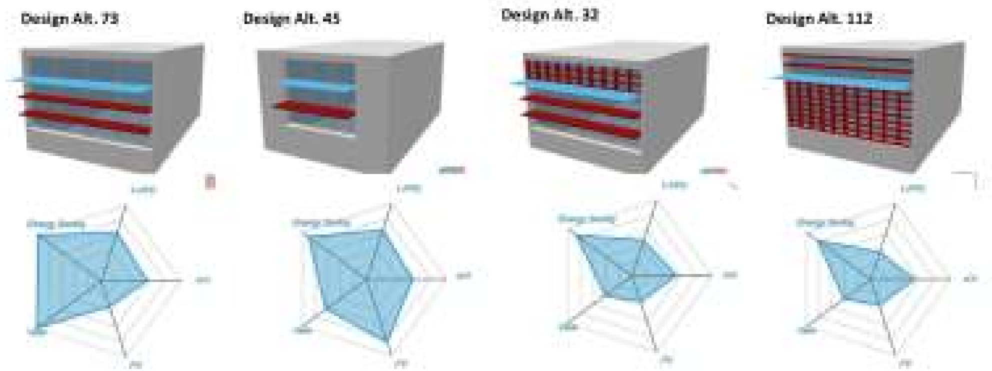



Figure 3
Different design alternative with similar energy savings.

panels was provided. This enables the user to focus on a specific panel or several ones, e.g., the Explore & Integrated Dashboard or the Explore & Compare. Figure 1 shows a screenshot of the visualization tool prototype with three active panels: Context and design parameters, Explore and Integrated Dashboard.

## CASE STUDY

The visualization tool prototype was used to visualize the results of a building performance optimization, in which a parametric model was optimized for the integrated performance of the following parameters: Energy consumption, Daylighting, Thermal Comfort, View and Glare and Renewable Energy. The parametric model was built using Grasshopper. EnergyPlus [1] and Radiance simulation engines, used through the HoneyBee (Roudsari, M. S. & Pak, M., 2013) and Diva (Jakubiec, J. A., & Reinhart, C. F. 2011) plugins, were utilized for the energy and daylighting assessments. A multi-objective optimization was carried out using the optimization tool Octopus (Vierlinger, R., & Hofmann, A. 2013).

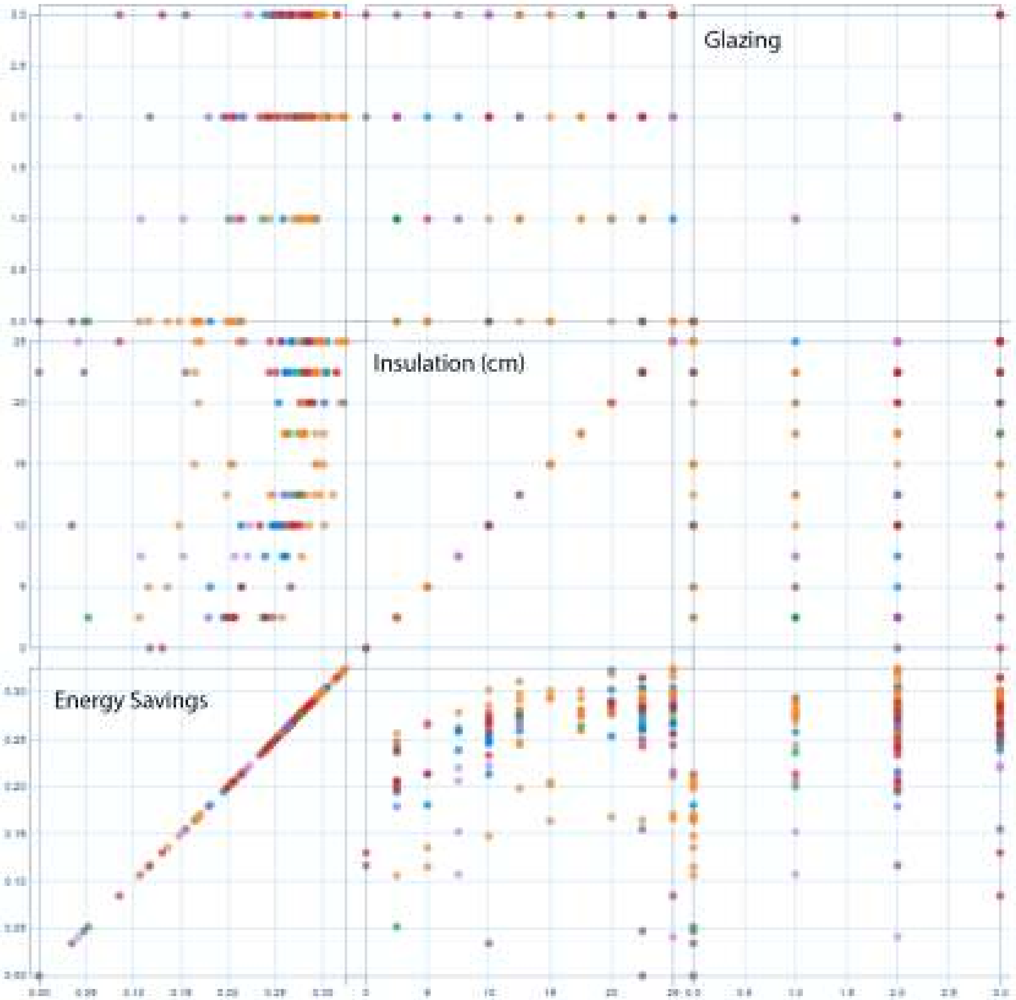
### *Parametric model*

The optimization was carried out for the south façade of a single office space in Munich, Germany (48°8'N 11°34'E). The office room was assumed had the dimensions of 4.00m x 6.50m x 3.00m for the width, depth, and height, respectively. The parametric model of the south façade provided different settings for the glazing area, glazing system, shading, daylighting system, and insulation system. The glazing area was divided into upper and lower parts, where the upper part acted as a clerestory window. Both window parts were introduced to the shading devices separately. Seven Window-to-Wall Ratios were studied together with four glazing systems, four shading systems, and four light-shelf settings. Additionally, the building insulation was increased gradually with 2.5 cm steps to a maximum of 25 cm. Overall, nearly 20,000 design alternatives can be generated.

### *Multi-objective optimization Workflow*

A multi-objective optimization was performed with the evolutionary algorithm SPEA2 using Octopus. A random generation was created at first, which contained different cases (genomes). Then for each

Figure 4
Scatterplot matrix chart showing the relation between energy savings, insulation and glazing type.




genome, daylighting, energy and thermal comfort analysis were carried out using DIVA and Honeybee. At the same time, the openness of the façade to the view outdoors and the possible area for building integrated photovoltaics was calculated. The results from the analysis phase were used as the fitness values for the optimization, namely the spatial daylight autonomy, energy savings compared to an unshaded base

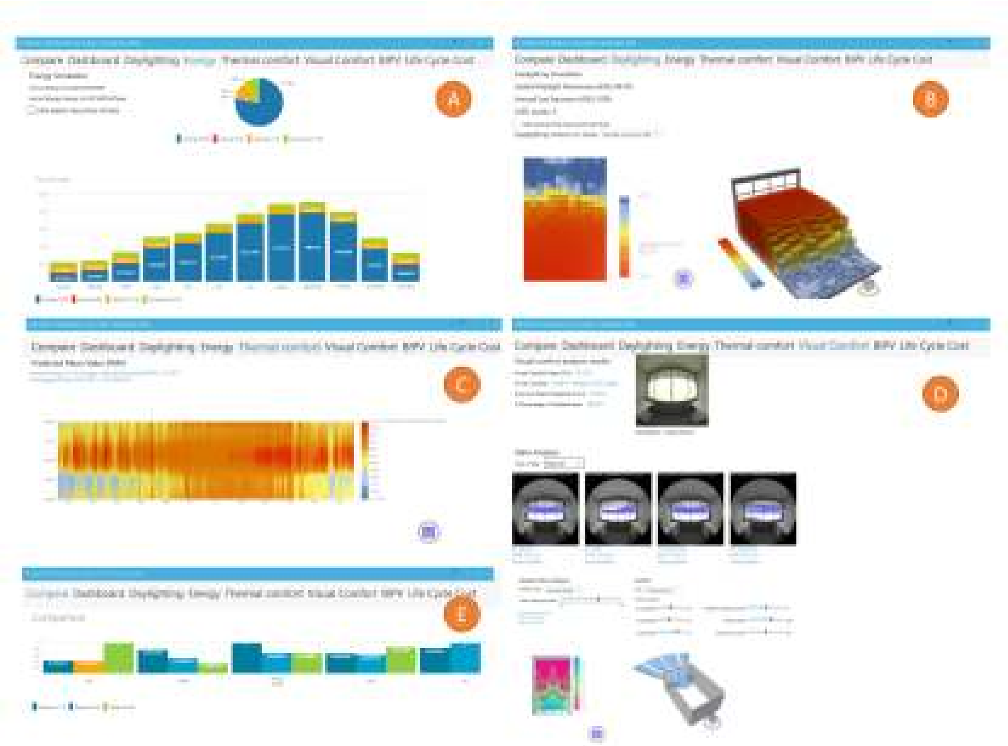



Figure 5
Examples of the contents of the performance tabs. A- Energy use analysis. B-Daylighting performance analysis. C- Thermal comfort. D- Visual comfort (Glare and View). E- The compare tab showing a simple comparison of three selected cases.

case, the percentage of comfort hours, view and PV percentages. The optimization process continued for 10 generations with a population size of 30. The mutation rate was set to 0.5, the mutation probability to 0.1 and the crossover to 0.8. Cases with very high solar exposure were neglected.

During the analysis, the results from the simulations were post-processed into different types of visualizations according to the results type. After the optimization ends, the optimization results are also visualized using parallel coordinates and scatter plot charts. Figure 2 shows the workflow of the optimization process and the corresponding data visualization in the prototype.

### *Optimization results analysis*

The optimization resulted in 150 design alternatives. The results were analyzed in several ways using the visualization tool prototype. First, the results and parameters of all the 150 cases were analyzed using the Explore section. The parallel coordinates chart offers an interactive tool by which the results could be filtered for a specific range of values for any and each of the variables and objectives. Additionally, the results in the data table could be sorted for any of the variables and objectives. A radar chart for the objective results is also shown for the selected design alternative. In this case study, the design alternatives were sorted for highest energy savings. It was found out that several design alternatives achieved energy savings between 30-32%. Although these cases achieve a similar energy performance, their design parameters and other objective performances differed greatly. Only one alternative, for instance, achieved an acceptable daylighting performance value (sDA more than 50%). This enables the designer to choose his design wisely by taking all the objectives and also the design features in mind. A trade-off between the different objectives is of course necessary. Figure 3 shows the four design alternatives with the highest energy savings and a minimum daylighting performance of sDA= 50%. Their corresponding performance for the other objectives is illustrated using the radar chart.

In a second step, the relation between variables and objectives can be studied using scatter plots matrix in a separate window. For instance, the scatter plot between the energy savings and glazing and insulation shows how triple glazing and double low-E glazing have a higher potential for energy savings compare to single and conventional double glazings. For the insulation, it could be noted that the potential for energy savings increase with the increase of the thickness of the insulation. Nevertheless, most of the cases with 10 cm insulation were able to achieve energy savings between 25% and 30% (Figure 4).

To compare the performance of the preferred designs, marked cases are automatically added to the compare panel, where a simple bar chart comparison is created. Finally, the integrative dashboard and performance tabs show detailed and alternative visualizations for each of the optimized objectives. Other simulation outputs can also be investigated such as lighting and occupancy schedules; heating, cooling and equipment's load; alternative daylighting performance metrics like the daylight autonomy, daylight availability, ... etc.; glare analysis for various times and dates; ... etc., Figure 4 shows part of the different tabs for a single design alternative and the compare tab with a comparison between the cases with the highest daylighting, energy and BIPV area (Figure 5).

## CONCLUSION AND DISCUSSION

Energy efficient and sustainable buildings are slowly, but surely, becoming the standard in architecture and building practices. As building performance simulation software and optimization tools become more common in the building design process, it is vital to have an integrated result analysis and visualization tool to support the design decisions. This paper presents a prototype for a visualization tool that can help analyze the results of building performance multi-objective optimizations. The visualization tool aids in investigating the whole design set, analyzing the relation between variables and objectives, as well as comparing and further investigating preferred designs. As a result, the user can define areas with potential enhancements, find the most effective design variables and compare the integrated performance between different designs in a visually-informative way. By achieving these different functions, the tool can help in the design decision process by shortening the time required to analyze the vast amount of data resulting from multi-objective optimization. In future works, other enhancements could be investigated, such as building the tool with a more sophisticated programming language like Python or Java, supporting dashboard customization, and validating the tool by focus groups. Implementing a guiding system can also be a valuable addition to the prototype to ensure that an optimal performance is reached by showing possible areas of enhancement.

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# Integrated Algorithmic Design

## *A single-script approach for multiple design tasks*

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*Many great architectural endeavors today engage in a multi software approach, as each specialty involved needs a different software, and different task required from the architect, such as 3D modeling, analysis or rendering, also benefit from the use of different tools. Combining them in the same process is not always a successful endeavor. A more effective portability mechanism is needed, and Algorithmic Design (AD) has the potential to become one. This paper explores the advantages of the algorithmic approach to the design process, and proposes a methodology capable of integrating the different tools and paradigms currently used in architecture. The methodology is based on the development of a computer program that describes not only the intended model, but also additional tasks, such as the required analysis and rendering. It takes advantage of CAD, BIM and analysis tools, with little effort when it comes to the transition between them.*

**Keywords:** *Algorithmic Design, CAD, BIM, Analysis tools*

### INTRODUCTION

The design process of an architectural creation has seen many changes over time, and more so over the past few decades, as new software emerges nearly every day. Representation methods are amongst the ones that shifted the most (Kalay, 2004).

After centuries of producing precise technical drawings, perspectives and models by hand, architects found these tasks facilitated by Computer Aided Design (CAD) software. Designed to help creative users in an "interative performance of 'man-machine' problem solving engine" (Llach, 2013: 18), CAD tools support sketching, drafting and image-altering, as well as 3D modeling and rendering (Brandon and McLain-Kark, 2001). Further along came the Building Information Modeling (BIM) paradigm, hailed as one of the most promising developments in Architecture, Engineering, and Construction (AEC) industries, as it pledges to bring the three closer together in a more integrated design and construction process (Eastman et al., 2008).

Despite the new methodologies introduced by these systems, architects still struggled to fully engage in a thoroughly digital process. A few decades ago, modeling tools were often incorporated only into later stages of the design process, where the production of precise and detailed construction drawings and specification documentation usually took place (Brandon and McLain-Kark, 2001).

In order for modeling tools to become more than documental assistants and actually play a deeper part in the design process, architects must be allowed to utilize them with the same authority they might apply to a pen or a compass. Even though the software spectrum is quite wide, each one has a particular workflow to which the user must adapt, conditioning his creative process. Currently, the stakes are changing, partly due to Algorithmic Design (AD), an algorithmic approach to architectural design. With the use of AD the user is able to transcend the limitations the software might impose on him (Terzidis, 2006), and make use of the modelling tools in his own way.

Adding to this collection of tools, another important group of software has been setting its ground in the design processes of the architectural agenda - analysis tools. These tools brought forth a new concept: Performance-based design - a design process informed by a deeper analysis and understanding of the environmental context of the project (Oxman and Oxman, 2014).

Never before have there been so many, or so diverse tools, techniques and methods for design. Architects are spoilt for choice and, because of this, post-digital design has become a task of curious manipulation, speculation and experiment (Sheil, 2008). The current architectural design process already makes use of different paradigms, like CAD and BIM, and many other tools. However, they do not effectively communicate with each other. Our goal is to merge some of the most relevant paradigms and tools in a seamless workable process that architects can follow.

## PORTABILITY ISSUE

The chronological order in which all referred tools have entered the market does not entail their sequential replacement. Each of these tools came as a response to specific needs that have arisen over time, and both CAD and BIM tools present distinct advantages to the modeling process.

Nowadays, practitioners are embracing the BIM paradigm, as it not only promotes a faster development of the models with the use of pre-modeled elements available in the libraries or families, but also automates time-consuming tasks such as arranging maps of quantities and costs, allowing the architects to perform alterations in their projects with real time feedback on the production's final numbers and expenses. In a CAD environment, there are no object libraries of families immediately available in the program. Hence, the user can either model the geometries from scratch or use pre-modeled blocks. CAD blocks, nevertheless, are not as flexible as BIM objects. While these present a set of parameters that allow several variations of the object to be created, CAD blocks must be modified by hand if more complex variations than for instance, scaling and moving, are desired.

Nevertheless, CAD tools, as free-form surface modeling tools, provide greater freedom in form creation (Zboinska, 2015). This may justify a preference in developing the early stages of the project, such as form and concept experimentation, in these applications. Furthermore, the idea of bringing architecture closer to the construction ideal, may somehow inhibit the creative potential of the designer. In a BIM environment the user is obliged to model in a sequential manner that follows the constructive logic. While this proves to be an advantage in resolving construction issues further ahead in the process, it possibly harms the creative workflow of the architect, which would possibly rather model his design in a completely different order and fashion.

In order to take advantage of both approaches, some practitioners begin their design explorations in CAD environments, and when satisfied with the overall shape, transition to BIM. However, the paradigms are so different, that transferring models from one to the other is hardly a simple task. In most cases portability cannot be achieved at all and the architect end up having to rebuild the models from the start.

The same case is verified regarding analysis tools. They are more important now than ever before, as higher complexity levels are being achieved in building design, making them less predictable, e.g., from the thermal, lighting, and acoustics point of view. Yet, analysis tools suffer from portability issues as well. Several demand a particular model of the building, different from the one used in the CAD or BIM modeling tool, thus requiring a translation process or, again, a rebuild (Aghemo et al., 2013).

Many great architectural endeavors today engage in a multi software approach, particularly when diverse companies participate in the project, such as engineers from different specialties, contractors, etc, each developing their respective part of the project in their work software. Ateliers Jean Nouvel's 100 11th avenue New York' curtain wall façade, required a variety of software interoperability, namely: Digital Project, Rhinoceros, AutoCAD, CATIA, Robot and Strand. PDF and IGES files were also used (Eastman et al., 2008). The Shanghai Tower, from Gensler and Tongji Architectural Design Institute, used Rhinoceros, Grasshopper and Revit for performance-based design (Kensek and Noble, 2014). The tennis center in Hangzhou sports park was essentially developed in Grasshopper (Miller, 2011), with different sets of scripts producing different files and models for different purposes: a wire frame model for structural analysis in another software and 3D DWGs were exported to Revit (Kensek and Noble, 2014).

A mechanism is needed that connects all these tools in a more effective manner. AD has the potential to become a portability mechanism on its own, since mathematical descriptions of the designs are oblivious to any software. Nevertheless, and for all the limitations it vows to surpass in the use of modeling tools, AD is still coming short when it comes to the issue of portability. A large amount of programming tools is already available in the market, for both beginners and/or more experienced programmers, which connect to either CAD or BIM tools. Some are also capable of connecting to analysis tools as well. Nevertheless, it is still difficult to port AD programs between different CAD and BIM applications (Ferreira and Leitão, 2015).

With so many possibilities regarding software and modeling techniques available, the architect has the unique opportunity of joining the best of different approaches together in his own design process. He needs only a tool that allows him to do so in a smooth and continuous way, with no effort when it comes to transitioning between approaches.

## INTEGRATED ALGORITHMIC APPROACH

We propose an integrated algorithmic approach to design - a methodology based on the development of a single script that, not only describes the intended model, but also the required analysis. Moreover, it takes advantage of CAD, BIM and analysis tools, with little effort when it comes to the transition between them. The proposed method aims to cover the relevant phases of the design process, exploiting the features of the different tools, without bending to their imposed workflow. Hence, the manner in which the designer seizes the tools becomes part of his personal creative approach.

The methodology presented is outlined in three main stages, explained in the following order: (1) CAD modeling for an initial exploratory form and concept stage - 1st phase; (2) BIM modeling for a more detailed stage in the process - 2nd phase; (3) analysis integration - may occur during the 1st and/or 2nd phase. A scheme of this practical application of the methodology can be seen in Figure 1.

Using a programming environment as modeling tool, the architect begins modeling his design intent within the CAD paradigm, and can visualize the result in a CAD tool. He may wish to include performance data in early stages of the design, hence, while still in the "CAD phase" of the process. The programming tool connects to the analysis software and exchanges the necessary data to the algorithmic model. In a more detailed phase of the program, the user shifts to the BIM paradigm, visualizing the modeled geometry in a BIM software. The performance analysis may instead be called upon on this stage, for which the process is identical. Finally, the detail modeled in BIM can not only satisfy construction purposes, but may also include additional decorative elements in order to sell the project's image to a possible client.

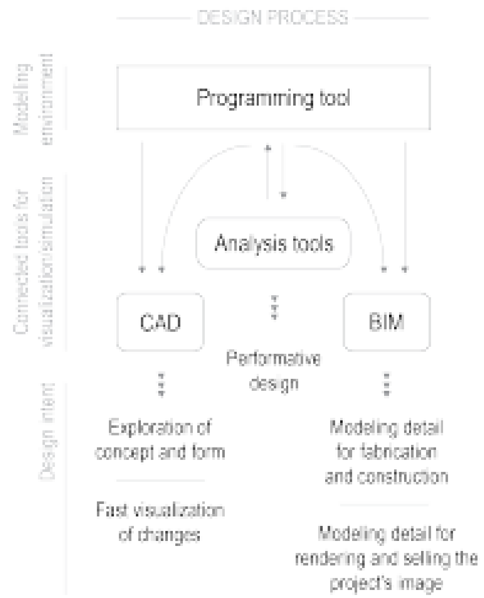


Figure 1
Integrated Algorithmic Design methodology

## *Programming Environment*

The modelling tool we use is Rosetta (Leitão and Lopes, 2011), a programming environment that supports portable AD, and thus allows the architect to experiment an integrated algorithmic design process. Rosetta supports algorithmic descriptions written in various programming languages and allows the generation of their respective results in a series of CAD and BIM applications. This is possible due to a front-end/back-end architecture: the IDE connects programming languages (front-ends) suitable for beginners, such as Racket, Python, and Processing, to CAD or BIM applications (back-ends), as well as OpenGL for fast visualization. Currently, AD programs written in Rosetta can be generated in SketchUP, Rhinoceros, AutoCAD, Revit, ArchiCAD and OpenGL.

Just as different CAD and BIM tools were integrated in Rosetta, several analysis tools are currently going through a similar process. The tool is presently being developed to include additional back-ends specialized for the generation of models for analysis, namely in Radiance and EnergyPlus. Most analysis tools require simplified versions of the 3D models, hence, from the same algorithmic description that produces a detailed model in a CAD or BIM application, Rosetta's simulation back-end generates only the simplified version of the essential elements needed for the analysis. For instance, depending on the analysis back-end, slabs, beams and columns might be interpreted as mere planes and surfaces. This automation process spares the architect from the tiresome work of adapting or reconstructing the model for analysis purposes.

## *Experimenting with Form and Concept*

As we have previously discussed, CAD tools are more advantageous in an initial stage of the model as they are more flexible and present a better performance when compared to BIM tools. Not only do they allow for the generation of more complex geometries that some BIMs just cannot process, but they also allow for a constraint free modeling workflow, where no sequences or precedencies are imposed. Furthermore, since they can generate geometry faster, an architect can test a wider range of solutions for their design in a shorter time span.

When modeling with Rosetta, architects are able to write parametric descriptions of their designs that allow a wide range of possible results depending on how the parameters are manipulated. While modelling for CAD, the designer can use almost every operation available in the software, through Rosetta. The abstraction layer contains the common functionalities amongst CADs, such as procedures to create geometric shapes, like circles and boxes, and procedures that apply geometric transformations, including, translations, lofts, extrusions and sweeps (Leitão and Lopes, 2011).

Furthermore, the abstraction layer also contains a set of instructions that convert BIM object functions into operations that CAD back-ends can understand. For example, a beam command with two given points as parameters, is understood by Rosetta/AutoCAD as a right cuboid placed in space from one point to the other. Much like the beam command, similar abstractions exist for slabs, columns, walls, etc. This means that the architect may choose to shift parts of his program to the BIM paradigm while still modelling for a CAD back-end. This will grant a smoother transition to BIM further ahead in the design process, while still allowing for form experimentation of the elements in a CAD environment.

### *Transitioning To BIM*

Differently from CAD, Modelling in BIM implies some significant loss of freedom, as some interdependencies are required and the order in which the elements are generated matters as well. The speed of the generation is also affected, since BIM applications must process more information in the creation of each object, as well as detect conflicts between the elements.

Nevertheless, as the project evolves into greater detail, shifting to the BIM paradigm has proven to greatly reduce time and effort spent on the modelling process, as well as on the production of documentation. In a BIM environment the architect can take advantage of all the information available in the libraries, saving a lot of time, as he needs not to model every single geometric element, as he would in CAD. In fact, in CAD, architects would not likely reach the level of detail needed for construction nor for detailed renderings, for example. These tasks are most commonly left to construction experts, in the first case, and rendering plus image editing software, in the second. However, BIM tools bring forth the possibility to reach higher levels of detail in the same model and with less effort than ever before for the architect.

Transitioning to BIM, the designer can take advantage of all the semantics embedded in his program, that in CAD was not as useful. Due to all the information included in Rosetta's abstraction layer, with the same program fragment that in a CAD back-end produced only geometry, the architect obtains, in a BIM back-end, more data, such as default materials and all information associated to it like weight, density, cost, etc.

### *Incorporating Analysis in The Design*

The design intent influences the way through which analysis data is incorporated in the process. For form-finding explorations, optimizations methods are commonly used. This process entails an established communication channel between the analysis tool and the algorithmic one, where the later provides the former with a sequence of variations of the original model, produced according to the results obtained by the analysis. The cycle is repeated until the optimization criterion is met. This is usually a rather time-consuming process and a computationally-intense one. Additionally, it is often difficult to understand if the obtained result represents the global optimum, or simply a slightly better solution (Nguyen, Reiter and Rigo, 2014).

For a more controlled enhancement of the building's performance, architects can opt for a direct approach. When considering few criteria, the design solution that performs best can often be deduced without an optimization algorithm. As a practical example, one can envision an architect wishing to base the design of the façade elements on the building's solar exposition, to guarantee the best thermal or lighting conditions in the interior space. In such a case, he would need only to perform the analysis once in order to collect the solar exposition data, and input it into his algorithmic description of the design. This process, while not so adequate for multi-criteria optimization, is simpler and faster than optimization methods and grants the architect full control over the process and the final result.

Using Rosetta, just as the same script can be interpreted by CAD and BIM applications to generate similar geometries in each one, the same is now possible with analysis tools, like Radiance and DAYSIM. Furthermore, these tools give back information retrieved from the analysis they perform. Using an algorithmic based approach with Rosetta, the results are simultaneously transferred to our program and can immediately be used in the modelling process, either in a direct input approach or in a continuous loop of information transfer between the model and the analysis tool.

### *Selling the Product*

Modeling non-structural detail for rendering purposes is also a crucial part of the design process. As selling the product's image is of fundamental importance in architectural practice nowadays, the ability to produce detailed renders of the described model is a great asset. We believe the same script that generates all the BIM elements relevant for construction, and simplified geometries representing the model for analysis tools, should also be able to generate a specific model for rendering. This should be a fully finished and furnished model, created for the sole purpose of generating quality renders capable of properly selling the building's image and aimed ambience.

The possibility of doing so in with a parametric model, allows the architect to take advantage of this marketing strategy at any stage of the design process. If the objects placed in the model are algorithmically anchored to strategic locations of the model, implementing changes in the project's shape will not affect them. The objects are automatically relocated in accordance to the changes made. This means the architect can present his ideas to the client through fully detailed renders, make changes to the model according to client's requests or other needs that may surge in the unfolding of the project, and generate new detailed renders at a click of a button.

Rendering, a task that is normally the last to be executed in a manual approach and, given the time it consumes, one the architect is usually unwilling to repeat many times, is a much faster endeavor when using an algorithmic approach. With integrated algorithmic design, this should be an exercise that, after the initial burden, can be repeated countless times without effort, for as many variations as the model may have.

## EVALUATION

To evaluate our approach, we selected as case study an adaptation of Astana National Library, from BIG architects. The shape and concept of the building place it in a category of those that clearly benefit from an algorithmic-based approach to design. Modeling such a composition by hand in either a CAD or a BIM tool would take considerable amounts of time and effort. Furthermore, manually handling changes that might need to be introduced in further stages of modeling is a largely time-consuming task that can be drastically reduced when using AD.

For the evaluation of our methodology we performed all the steps we have previously described, building our model parametrically. This means it is possible to change several aspects of the design, from the building's height, width, and diameter, to the number of floors, slabs, columns, beams, and façade panels, therefore generating other interesting variations of the original Astana Library.

### *Modeling For CAD*

The modelling processes used for our case study can be divided in two main sections: interior blocks and exterior façade. These two elements are relatively autonomous from each other and could be developed in parallel. These elements were conceived in phases, each one increasing the detail of the model and respecting the order of interdependencies that characterize construction and therefore, BIM modelling. This sequential arrangement not only ensures a correct placement of elements throughout the project but also assures the automatic propagation of changes all through the model when the code is modified. CAD applications do not necessarily oblige the architect to have this sort of concerns, but good programming practices dictate that we should not only consider the order in which the elements are created, but also the use of intermediate abstractions that organize the code in a logic and understandable way.

We began by modeling the interior elements. Primarily, we modeled slabs, columns, beams, and

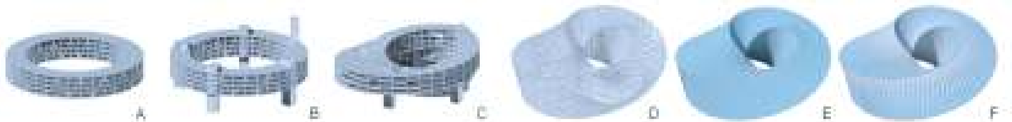


Figure 2
Six of the steps within Astana's generation sequence

walls, all of which could be modelled using BIM operations available for CAD back-ends. Figure 2.A shows the slabs of the middle volume with columns and crossbeams already placed. In 2.B we see the inclusion of the core walls holding the buildings weight. 2.C has the outer volume that circles around the middle one, in and out.

The façade structural framing consisted of a twisting grid of beams, as can be seen in Figure 2.D. Within that framing, triangular panels were added, representing the façade glass (Figure 2.E). Finally, the façade's third layer was done: a composition of triangular photovoltaic panels, secured over the framing, shading the interior, as shown in Figure 2.F. Both panel types were modeled using Rosetta's panel operation, that in CAD back-ends generates a surface and in BIM back-ends, a morph.

### *Detail Modelling in BIM*

After acquiring the overall shape with the essential structural elements, we completed the full transitioning to BIM, as the remaining elements left to model would greatly benefit from pre-existent objects available in BIM libraries. As previously mentioned, the basic BIM operations, can also be interpreted by CAD back-ends thanks to the Rosetta's abstraction layer. This means that our script was, at this stage, capable of generating equivalent geometries in both CAD and BIM applications, namely AutoCAD, Rhinoceros, ArchiCAD and Revit (Figure 3).

From this point on, we began modeling building elements of a more detailed nature, using tool-specific operations which meant a loss of portability. Library parts or families are exclusive to each BIM application, and while Rosetta was able to find matching characteristics in the most common structural elements that allowed the implementation of common operations in the abstraction layer, it does not go so far as to allow the portability of every existing element in both libraries (ArchiCAD and Revit back-ends). Hence, when using Rosetta as the programming environment for integrated algorithmic-based design, users must choose one back-end to program for, when delving into detail, and at the expense of portability, they will then be able to use all objects available in the BIM library of that back-end. It is to note that the model can always be generated in other back-ends at any given moment, only tool-specific operations will not work for all.

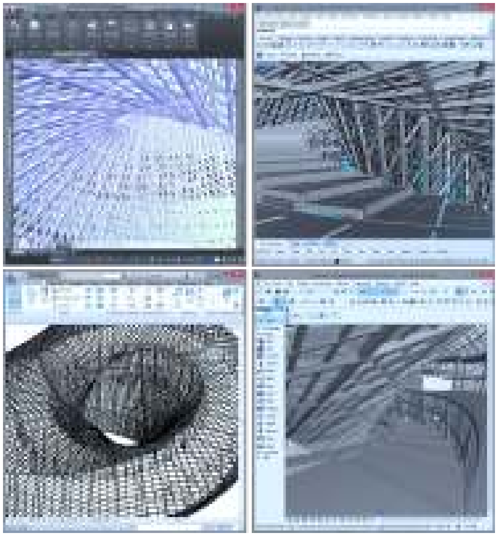

Figure 3
Astana's 3D model generated in AutoCAD, Rhinoceros, Revit and ArchiCAD

In Astana's case, we opted for ArchiCAD, the most recent of Rosetta's back-ends. Primarily, we modeled the staircases and the glass wall for the interior volumes. The BIM operations used were the stairs and the curtain wall. However, as we were still conducting some experiments in CAD, regarding the position of these elements, we had to model them in the CAD paradigm as well. The task ended up serving as proof to the advantages of using BIM objects.

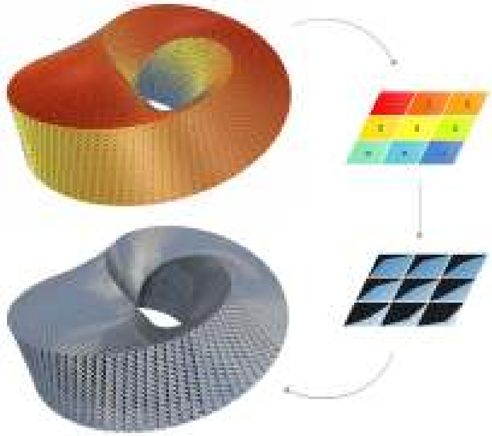

Figure 4
Scheme of radiation values converted to panel sizes in Rosetta

To model the staircases parametrically we had to compute the generation of each step separately and no attention was paid to railing or finishing layers. In comparison, the stair command for BIM is capable of generating the staircase as a single set and it gives automatic access to all these details. The curtain-wall, that in ArchiCAD presents a parameterized framing besides the glass panels, was reduced to single surfaces representing the glass. Other elements such as doors and elevators were modeled in BIM only for all the detail they entail.

### *Incorporating Analysis*

As mentioned above, an arrangement of triangular panels forms the exterior layer of the façade. These panels are in fact photovoltaic lattices that, not only provide passive shading, but also absorb energy from the sun. Due to the wrapping and twisting of the façade geometry, the thermal imprint has a wide range of intensities along the Möbius strip. Hence, the architects decided to base the design of these triangles on the façade's thermal map, creating an ecological pattern grounded on solar impact.

For a similar effect, we set Rosetta to perform a daylight analysis on the building's façade, using the Radiance back-end. Rosetta automatically places sensor nodes on the façade wrap for each panel and performs the simulation, in this case a Radiation Map metric on the winter solistice. The resulting radiation values for each node are then returned to our script. There, they are converted to a one to nine scale values and integrated in the panel modeling function. Each panel can have one of nine possible dimensions, creating lerger to smaller openings in the façade pattern. Figure 4 presents an scheme of this conversion.

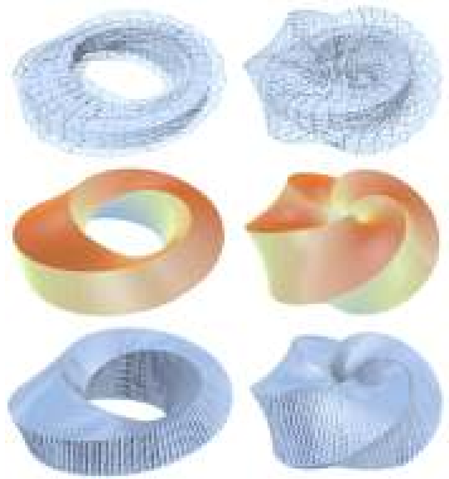

Figure 5
Structure, analysis model, and render of the final panels of variations one (on the left) and two (on the right)

The algorithmic integration of analysis tools offers the architects the possibility to analyze the building's shape at any given time of the design process with no effort at all, allowing for a more informed development of the form. The information exchange system between the design script and the analysis tool, allowed by the algorithmic approach, is even capable of running alone, when stimulated by an optimization algorithm. Regarding Astana National Library, that was not the architects' intent, as they merely pursued a direct use of the analysis information. For this reason, we did not pursue that path. However, the possibility is left open by our proposed approach.

Furthermore, we did take advantage of this feature to analyse a couple of variants to the original model, obtained by changing only a few parameters that define the shape of the mobius strip and the number of panels in the façade. Figure 5 presents two variation we tested, namely their structure, façade analysis and final result for the panel placing.

### *Render Detail*

For this task, we focused on the central volume and we algorithmically filled the space with objects that we felt would naturally decorate a library space. We used several of ArchiCAD's pre-modeled objects, namely book-shelves, book clusters, tables and chairs, people and lights. Most of these objects presented variable parameters, which we modified for Astana, in order to better suit the library's environment. Figure 6 presents a view of the furnished space.

In the case of the objects representing people, we introduced randomness factors that created variations, regarding their clothes and complexions. All elements were parametrically distributed, tending to the shape of the spaces. This means that if the number of floors, or their dimensions are altered, all the mentioned elements will adjust accordingly.

Figure 6
Render of the libraries interior space furnished. View of the spiral volume

## CONCLUSION

This paper presents a design methodology that explores a single-script approach, that includes not only the model's description but also the necessary steps for its analysis. Using the proposed methodology, the architect may choose to model his design using the CAD or BIM paradigms at any given stage of the design process. Moreover, he can perform analysis of his design directly from the script and incorporate the results in the algorithmic description. This integrated algorithmic approach to design mitigates the current CAD / BIM / analysis tools portability issues that practitioners face today.

### *Related Work*

Besides Rosetta, the chosen tool to evaluate the methodology, there exist other programming tools that allow portable AD. Grasshopper is one of them. This graphical algorithm editor, integrated with Rhino's 3-D modeling tool, offers several plug-ins that connect the program to different BIM and analysis tools. For instance: Lyrebird connects it to Revit; Hummingbird allows the creation of native Revit objects; Rhino-Grasshopper-ArchiCAD makes the connection to Graphisoft's BIM tool; DIVA-Grasshopper allows the setting up of analysis in DIVA's plug-in for Rhinoceros in Grasshopper; LadyBug allows the user to import weather data files from EnergyPlus into Grasshopper; and HonneyBee connects Grasshopper to EnergyPlus, Radiance, Daysim and OpenStudio for building energy and daylighting simulation.

Grasshopper is a visual programming languages. This means the user needs no prior knowledge of programming or scripting in order to use it, which is very attractive for architects with little programming experience. However, visual languages lack scalability (Leitão and Santos, 2011). As programs grow in complexity, they become harder to change and understand. Furthermore, the portability asset of Grasshopper's plug-ins has some limitations. While the majority of the program may be common to the various possible models, in order to connect it to each software the user must use specific components offered by each plug-in. This means that significant parts of the program are not portable, and many operations end up being repeated in order to generate the geometry in different software.

### *Future Work*

In the future, we plan to include another feature to Rosetta: the possibility to model project specific elements, when no object provided by the BIM library serves the design purpose. The use of pre-modeled elements should be an advantage to the modelling process but never a limitation to creativity. This asset aims to give the user more freedom, for we believe the architect should not have to feel compelled to change the design, only to adapt to the exiting objects. In order to allow this in our ArchiCAD backend, for instance, we may develop a GDL converter for Rosetta.

It would also be interesting to extend the number of analysis back-ends, namely structural analysis tools, and animation or rendering software as well. The render production we presented serves its purpose well in automating the task in non-final stages of the project where the ambience required is a generic one. However, for later stages of the project where more detail designing wall coatings, flooring, light spots and lamp choices, specifying furniture models, etc, the approach does not seem as fit. Some BIM tools have good rendering engines, but none compare to specialized rendering software.

## ACKNOWLEDGMENTS

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# Contemporary Stereotomic Trait, an Opportunity for the Development of the Volumetric Digital Architecture

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*Stereotomy is generally known in architecture as a stone carving technique for the purpose of constructing masonry assemblies. A deeper analysis reveals stereotomic design processes' ability to resolve multiple structure and construction constrains, derived as underlying geometries and their relationships, into architectural volumetric complexities. The paper argues that the trait, stereotomic geometric negotiations platform, re-examined in a contemporary context, lends itself as a theoretical model for the current digital architecture's pursuits of multiple constraints assimilations within design processes and their physical reflection in formal complexities.*

**Keywords:** *stereotomy, trait, digital architecture, digital design*

## INTRODUCTION

The contemporary notion of stereotomy in architecture is restricted to designate the stone carving technique for the purpose of constructing masonry assemblies.

The word's etymology defines a broader meaning of three-dimensional solid cutting into shapes to be assembled. Historic studies that encompass form taxonomies, their practical and theoretical evolutions, and cultural assimilations illustrate a wider polymorphic diversity (Sakarovitch, 2003).

Stereotomy, re-examined in a contemporary context due to its intrinsic qualities offers an opportunity to respond a volumetric lacuna within digital architecture.

More specifically, as this paper argues, the stereotomic trait understood as the Deleuzeian objectile lands itself as the crux for resolving multiple structure and construction constraints into volumetric complexities.

## VOLUMETRIC LACUNA IN DIGITAL ARCHITECTURE

Stereotomy originated at the overlap of several disciplines: architecture, mathematical geometry, technical drawing, structural theory, practical masonry, and military engineering. Shared by all, it flourished where definitions blurred, where one thing began to glide off into others, as an unrecognized border joining many diverse regions (Evans, 2000). A mutual knowledge exchange was generated between all disciplines involved due to the common reliance on geometry. As stereotomy was increasingly approached as correct understanding of geometry (Heyman, 1995) the knowledge exchange became more fluent. By the end of the nineteenth century this generated progress in all the disciplines in the areas of design, representation and fabrication of complex geometries, "freed from Euclidian metric" (Sakarovitch, 2003).

Figure 1
L: Arles City Hall Vestibule, Jules Hardouin-Mansart, 1637 (http://farm4.static.flickr.com/3765/19564585458_-3c1da000d7.jpg) R: Henry VII Chapel, William Vertue & Robert Vertue, 1519 (http://www.alamy.com/stock-photo/henry-vii-chapel.html)

Complex stereotomic geometries developed due to the design attitudes that regarded 'difficult' as a superlative. Difficulties were as much sought after as found (Evans, 2000): ever greater formal complexity, elaborate ornamentation, and daring statics that appeared as effortless as their visual comprehension (Figure 1). Their design processes necessitated concurrent handling of multiple structure and construction constraints and their interdependences. Structure, an abstract concept, was geometry-based statics (Sakarovitch, 2003) principle destined to cope with the contextual force flow. Construction, its concrete realization, was carried out in a number of materials (Sekler, 2009), tools, technologies and procedures, fabrication constraints, and design, geometric, and instrumental knowledge (Witt, 2010). Design processes derived structure and construction constraints as geometric constraints and formulated form as their continuous negotiations. Design knowledge on multiple constraints handling was deduced, embedded, and instrumentalized in geometrical tools and procedures (Witt, 2010) that enabled volumetric complexities, topological transformations, variations, and differentiations. In short, stereotomy became the epitome of architectural complexity by acknowledging the centrality of geometry, tools, and procedures in the design process.

In the twentieth century, there was a paradigm shift in architecture that prioritized economy of design, fabrication and construction. Efficacy-driven design processes abstracted machine constraints to achieve repeatability, speed, and mass production (Witt, 2010) towards structure and construction rationalization. As a result, design processes favoured steel and concrete as materials, standardization as modus operandi, and scarce geometries as aesthetic expression (forms that were assumed too complex to be machine produced were marginalized (Witt, 2010)). Stereotomy could not compete in this milieu. It required extensive geometric and tacit knowledge, intensive fabrication due to varied ashlar configurations, and lengthy, costly construction processes due to elaborate falsework. Stereotomy was shunned and abandoned into the realm of "forgotten geometries lost to us [architects] because of the difficulties of their representation" (Moneo 2001, cited Kolarveic 2004).

The advancements in resolving multiple design constrains as geometric complexities continued through the knowledge exchange between sciences and other industries. Since a great number of the industries (aviation, automobile, and shipbuilding) were based on sheet materials, the geometric research focused primarily on surfaces. The geometric research into volumetric complexities dealt with either the small scale (product design), or was not concerned with material resolutions (digital modeling and animation).

By the end of the century, the accumulated geometric knowledge was embedded in different CAD and CAM digital tools making it easily employable. Appropriated by architects, digital tools expanded the architectural formal repertoire by enabling the complexity of conceived forms and their transfor-

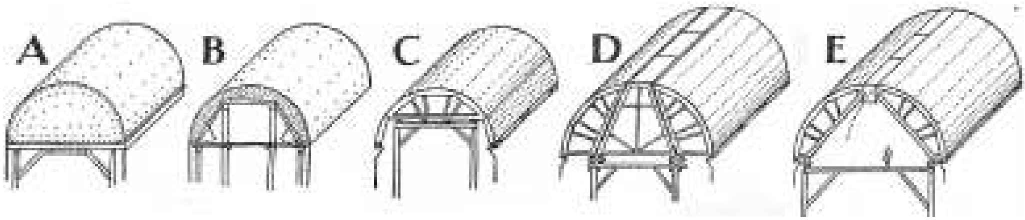



Figure 2
Possible Types of Barrel Vault Formwork and Centering (Fitchen, J. 1967, p.54)

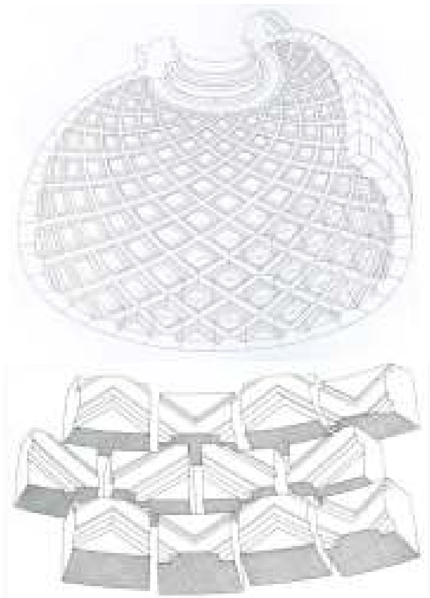
Figure 3
Anet Castle Chapel, Philibert de l'Orme, 1549-52 (Potié, P. 1996, p.54)

mations into viable construction assemblages (Picon, 2010). They provided physical resolves for the theory driven by the Deleuzeian Fold and the form defined by the rules of its variations (and variations of variations), an objectile (Carpo, 2011). Digital tools did not require users' understanding of the embedded complexities to handle their design, representation, fabrication, and construction. They were attained through instrumental knowledge that directly enabled or disabled the act of design (Witt, 2010). In this way, knowledge on resolving multiple constraints, directly borrowed from the other industries, was only partially assimilated into architectural design knowledge. Digital architecture did not establish large scale volumetric form actualization processes based on intrinsic, multiple constrains and remined surface-based. "Paradoxically, quest for depth led to an infatuation with the façade or skin, in other words with superficial, the two-dimensional" (Picon, 2010).

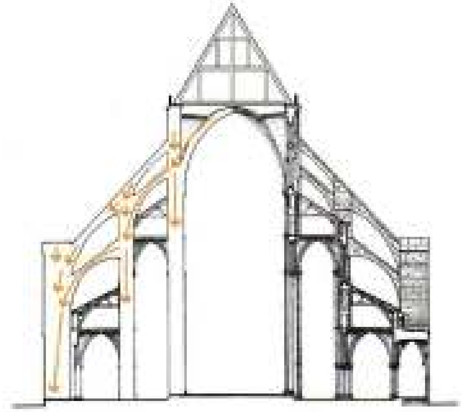
## STEREOTOMY, COMPLEX VOLUMETRIC ARCHITECTURE

Stereotomic design processes, as comprehensive resolutions of multiple structure and construction constrains, offer a valid framework for establishing digital architectural form formation processes. The central aspect of stereotomic design processes was deriving structure and construction constrains as geometric constraints and their relationships. Stereotomic form emerged from multiple, neither hierarchical nor discrete, underlying geometries: assembly geometry, ashlar geometry, structure geometry, falsework geometry, and geometry defined by tools and procedures. Their sub-stereotomic interdependencies were almost non-exhaustive.

The most evident, traditional, mutually-defining interdependency was between the assembly geometry and its constituent ashlar geometries: any assembly was concurrently a whole subdivided into parts, and a propagation of parts generating a whole (Figure 2). It is determined by material and fabrication constraints.



The structure geometry formulated structure and assessed its appropriateness and efficacy (Sekler, 2009). Jointly, the assembly and ashlar geometries were in a formative interdependency with the structure geometry: any assembly and its ashlars were subservient to structure, and concurrently, through their shape and proportions, ensured stability (Heyman, 1995), the validity of the structure geometry (Figure 3).



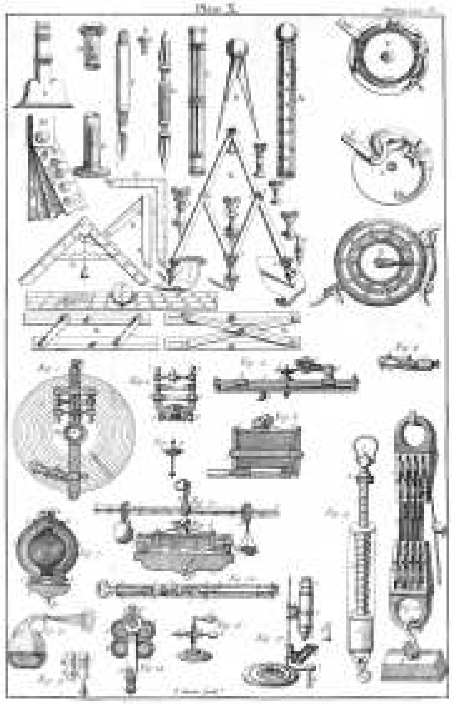
Further, structure geometry responded to the varied force flow at each construction process stage. Together with the assembly geometry and construction assembly constraints, it determined the falsework geometry. At the same time, due to its necessary optimizations (towards fast, simple mounting and dismantling, the ease of use and reuse, etc. (Figure 4)), the falsework geometry influenced the assembly and structure geometries formulations, and determined construction assembly sequencing.

Similarly, a continuous coevolution developed between tools and procedures, and their embedded knowledge. As a result, the geometric rigor, precision, and control improved and, in turn, improved the design of the drafting, fabrication, and construction tools and procedures (Figure 5).

Despite the immanent geometric presence throughout, stereotomy showed less obvious trace of geometric regulation: by using more geometry, it appeared to be used less (Evans, 2000). As the negotiations proficiency within the system of sub-stereotomic geometries increased, so did the pursued stereotomic complexities, and stereotomy became more stereotomic.

## STEREOTOMIC TRAIT

The platform for sub-stereotomic geometric negotiations was the trait. Traits were preliminary drawings that allowed design and definition of assembly and ashlar geometries, and regulated their configurations to ensure buildability. Simultaneously, they were layout drawings that enabled precise ashlar fabrication, falsework design, and construction sequencing (Figure 6). Traits enabled geometric generative rules formulations, form variations computations, and their executions.



The initial motivation for the trait establishment was to record and dissipate the oral secrets of the masons' lodges in a drawing format. Throughout history, their representational role transformed to a didactic one. The focus shifted from cataloguing the existing assemblies towards communicating the underlying ge-

Figure 4
Load paths of thrusts from main vault and buttresses, due to gravity (Addis, B. 2007, p.98)

Figure 5
Drawing Instruments, from "Traité de la construction et des principaux usages des instruments de mathématiques", Nicolas Bion,1709 (Witt, A. 2010, p.46)

Figure 6
Traits by Frézier, Planches 33, 34 & 70 (Frézier, A.F. 1738, Tome II p.116, Tome II p.123, Tome III p.24)

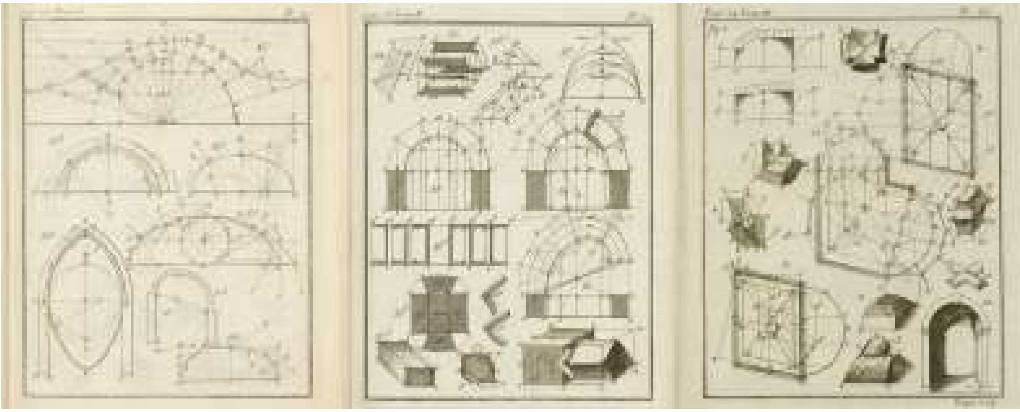
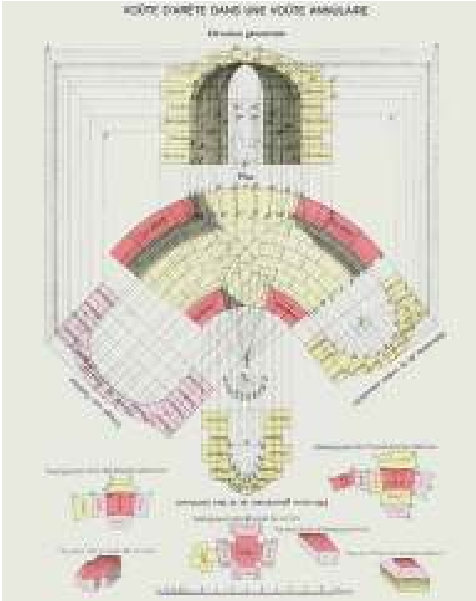


Figure 7
Trait from "Traité théorique et pratique de stéréotomie", Louis Monduit, 1889 (Witt, A. 2010, p. 60 & 61)



ometric processes to facilitate original designs and wider theoretical and practical explorations of two-dimensional into three-dimensional transformations (Sakarovitch, 1998).

Progressively, traits theorized and generalized stonecutting problems, abstracting them into spatial studies. Further, traits instrumentalized stereotomic design knowledge, derived from merging practical, traditional, local knowledge with universal, scientific knowledge, into geometric procedures. Traits embedded master masons' applied and mathematicians' erudite geometric knowledge (Sakarovitch, 2003) to become drawing 'machines' (Witt, 2010).

During the traits' evolution, graphical techniques based on geometric representation were initiated (Sakarovitch, 1998). Later a geometric language was established that enabled mutual interconnections, multiple interpretations and open-ended relationships. It made the embedded knowledge accessible and susceptible to development and assimilations. By the nineteenth century, traits facilitated knowledge exchange between stereotomic design, scientific geometry, conceptual geometric procedures, irregular stonecutting procedures, and drafting instrument developments.

The positive feedback loop outcomes were, among others, the Descriptive Geometry formulation, geometry of curves and curved surfaces advancements, drafting instruments with embedded complex geometric knowledge, and the stereotomic architectural peak (Witt, 2010) (Figure 7).

In the contemporary architectural theory realm, traits could be understood as objectiles. An objectile, an open-ended algorithm based on a parametrical function, determined infinite object variations, all different (from one parameter set) yet all similar (from the same underlying function) (Carpo, 2011). Similarly, specific stereotomic elements belonged to a general category and were differentiated by the trait. For example, the arch trait, a geometric procedure, differentiated a specific arch for the specific context from an infinite number of arches. The arch trait was the structure and construction negotiation expressed though underlying geometric interdependencies. As a fixed normative genus, the trait was exactly transmissible but nonvisual notation that embodied infinite variations, clearly different yet similar forms (Carpo, 2011).

Trait, like objectile, had two types of authors: the author that designed the (or a series of) generative notation(s) that are general, genetic, and parametric, and the author that specified the notion(s) in order to design individual forms (Carpo, 2011). Throughout history traits' author pairs changed and multiplied: master mason and stone carver, architect and master mason, scholars and geometers, etc.

The multiple authorships and geometric negotiations defined traits' multifaceted nature and varied legitimacy from practical validations through execution to theoretical rationale affirmations. Their role, in Deleuzeian terms, remained singular and clear: to differentiate multiple sensible forms from virtual, abstract ideas (Moussavi, 2009).

## DIGITAL ARCHITECTURE TODAY

The dominant design attitudes (New Structuralism (Oxman, et al. 2010), Material Computation (Menges, 2012; Menges, 2015), FABRICATE conferences (Sheil, et al. 2017), etc.) in the current digital architecture argue for necessary multiple design constraints (structure, climate, material, fabrication, etc.) assimilation within design processes and their physical reflection in formal complexities. Akin to stereotomic, digital design processes are driven by intrinsic structure and construction constraints and strive to formulate genuinely architectural form formulation processes. The technology context, instigated by diversity of contemporary digital tools, provides architecture with vast opportunities that, when translated into multitude of constraints, can concurrently hinder them. This is reflected in the challenge to resolve multiple constraints as large scale, volumetric complexities.

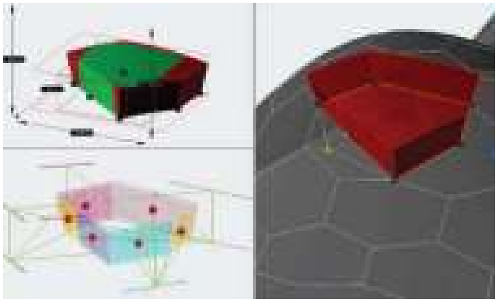


Figure 8
Rhino 5.0 custom-made plugin the design, fabrication, and material parameters manipulation and production process analysis, visualization, and simulation (Rippmann, M. et al. 2011, p. 186)

The renewed interests in stereotomy, facilitated by the digital tools availability, initially focused on previously difficult to achieve formal complexities designs and explorations, topological transformations, precise varied irregular ashlar configurations fabrications, and complex structural resolves. In the recent years, stereotomic rule-based design processes, parametrized into digital associative geometry models, enable a number of assimilations to directly informe form formations: contemporary geometric knowledge, material limitations, structural optimizations, CNC/robotic fabrication requirements, etc. (Fallacara, 2012; Fallacara, et al. 2015; Fallacara, 2016; Rippmann, et al. 2011; Rippmann, et al. 2017; Burry, 2016; Varela, et al. 2016; Fernando, et al. 2015; Weir, et al. 2016; Clifford, et al. 2015). The resulting forms illustrate the digital tools and procedures ability to proficiently control and handle underlying geometric negotiations, as an overlap of assimilated constrains (Figure 8) into volumetric complexities. Unfortunately, they preserve stereotomy's stumbling block that originally denied it viability: the costly, elaborate falsework (Figure 9).

Figure 9
Falsework for the Armadillo vault, Venice Biennale, 2016, (Source: <http://www.armadillovault.com/armadillo-installation/>)

## CONTEMPORARY DIGITAL TRAIT

The aim of this paper is to understand trait's historic nature and theorize its contemporary relevance and drawbacks towards its adaption to the digital realm. Contemporary digital trait, developed as geometry-driven objectile, offers "open-endedness, variability, interactivity, and participation [that] are the technological quintessence of the digital age" (Carpo, 2011). More specifically, it offers the possibility of becoming the crux of resolving multiple architectural constrains as volumetric complexities.

The contemporary trait necessitates reinstating of its intrinsic nature and certain adjustments. The primary role remains: computation-based platform for multiple structure and construction negotiations abstracted as geometric constrains and their interdependencies. The knowledge embedded in a trait remains open source: easily accessible, communicable, repeatable, hackable, and transformable (Witt, 2010). On the other hand, the trait's authorship requires redefinition from the demarcation and polarization of the historic types, into a gradient that spans the two. The fluid authorship enables multiple trait authors and concurrent knowledge embedding and activating to instigate collaborations and innovations at multiple levels. In this way, the contemporary trait can narrow, if not fully challenge, the Albertian splits as "the synthesis of architect, engineer and fabricator again controls the historical responsibility for the processes of design, making and building" (Oxman, et al. 2010). Further, the authorship fluidity through participation and novel connections sustains knowledge exchange, development and assimilation between theory and practice, industry and academia, traditional and contemporary, and local and global.

### *Conclusion*

Volumetric complexity is primarily the domain of architecture and its viable resolve is possible only through architectural design knowledge and innovations. Through comprehensive multiple structure and construction constraints negations, complex volumetric forms, differentiated through digital traits, articulate meaningful tectonics as a particular empathy manifestation in the field of architecture (Sekler, 2009). In a wider contemporary digital theory realm, the trait enables architectural tectonics that addresses a number of its pursuits: Moussavi's affects (Moussavi, 2009), Spuybroek's sympathy (Spuybroek, 2011), Picon's narrative and nostalgia (Fabricate 2017 conference lecture), etc.

The first step, though, remains to overcome the historic stumbling block: the assembly construction as feasible and timely process through all relevant constraints computation.

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# Free-form Transformation Of Spatial Bar Structures

## *Developing a design framework for kinetic surfaces geometries by utilising parametric tools*

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*This paper presents a design framework for free-form transformation of kinetic, spatial bar structures using computational design techniques. Spatial bar structures considered as deployable, transformable kinetic structures composed of straight, linear members, assembled in a three-dimensional configuration. They are often utilised in portable, mobile or transformable buildings. Transformable systems of spatial bar structures are mostly based on modification of primitive shapes (e.g. box, sphere, and cylinder). Each system is subdivided into multiple members having the same shape, the so-called kinetic blocks. Some diverse precedents made to develop other forms of transformation of these structures with some issues. This research project will investigate how a free-form transformation of spatial bar systems can be achieved, by redesigning the kinetic block in relation to architectural, technical parameters. In order to develop a physical prototype of the kinetic block, and assess its potential in enabling free-form transformation of a spatial bar system, a design framework incorporating parametric, algorithmic and kinetic design strategies is required. The proposed design workflow consists of three main phases: form-finding, stability validation and actuation.*

**Keywords:** *Parametric design, Kinetic, transformable, deployable, Free-form, design strategy*

## KINETIC TRANSFORMABLE STRUCTURES

The term 'Kinetic Architecture' has not a clear definition, but it could be described as the design of buildings in which transformable, mechanised structures, are able to change their shape in relation to climate, function or purpose. Kinetic structures consist of transformable objects that dynamically occupy predefined physical space or moving physical objects that can share a common physical space to create adaptable spatial configurations (Kronenburg, 2007).

According to Michael Fox (2009), kinetic systems in architectural applications can be categorised into three categories: 'Embedded', 'Deployable' and 'Dynamic'. 'Embedded' systems are the ones that exist within a larger structural whole in a fixed location to control the larger architectural system or a building in response to change. 'Deployable' systems are described as the ones that typically exist in temporary locations and are easily transportable. Finally, 'Dynamic' systems exist within a larger architectural whole but act independently with respect to control of the larger context. Dynamic systems can be sub-categorised into three subcategories: 'Mobile', 'Transformable' and 'Incremental'. The 'Mobile' category includes all types that can be physically moved within an architectural space to a different location. The 'Transformable' category includes systems that can change to take on different spatial configurations and that can be used for space saving and utilitarian needs. The 'Incremental' category includes systems that can be added or subtracted from (e.g. Lego), to create a larger whole out of discrete parts (e.g. metabolism projects) (Fox & Kemp, 2009).

There are some concerns regarding Fox's classification, especially in comparison to the ones made by Gantes (2001), Areil Hanoar (2009), Mazier Asefi (2010), and Esther Adrover (2015). Despite Fox statement that "each of these categories is not mutually exclusive" (Fox & Kemp, 2009), he made a segregation between 'transformable' and 'deployable' structures, which have many common grounds, such as the 'spatial bar structures'.

## SPATIAL BAR STRUCTURES

*'Spatial bar'* structures are considered as deployable, transformable kinetic structures, composed of straight, linear members assembled in a three-dimensional configuration; They share similarities with traditional space frames or space trusses with flexible vertices or intermediate points of their members (Asefi, 2010).

These structures can be sub categorised into two types, *'pantographic'* scissor-pair structures and *'reciprocal'* structures (figure 1) (Asefi, 2010). *Pantographic structures* employ Linear or angulated bars in scissor forms. Reciprocal structures employ even bars or plates mutually supported and placed in a closed circuit (Larsen, 2008). These structures are usually covered by flexible materials (e.g. fabrics, PTFE, ETFE), or rigid materials (e.g. Polycarbonate, Aluminium) with foldable plate mechanism. They are often used in portable, mobile or transformable buildings, being utilised in surface geometries for transformation of interior elements, exterior envelopes or roof structures of buildings (Gantes, 2001), and sometimes used in kinetic sculptures, artworks and space structures (Pellegrino, 2001).

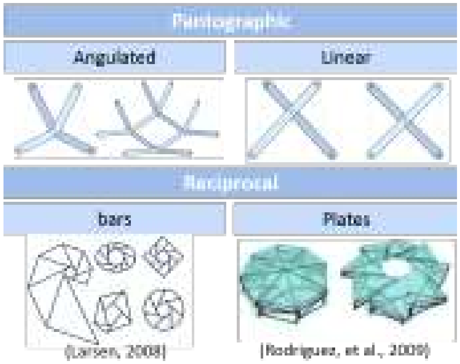


Figure 1
Types of spatial bar structures

According to Escrig (2010), these structures occur in six different forms (figure 2), 'Umbrellas', 'Bundles', 'Rings', 'Polyhedral', 'Planes' and 'Double arched'. *'Umbrellas'* have umbrella folding mechanisms and are covered by flexible materials (e.g. Madina Mosque, KSA umbrellas designed by Frei Otto and Bodo Rasch). *'Bundles'* contain modules of scissor mechanisms in planar or spherical shapes (e.g. deployable structures designs of Buckminster Fuller, Emilio Pérez Piñero and Felix Escrig). *'Rings'* contain multi-angulated bars with multiple intermediate joints, deploy towards their central point from the perimeter of the outer circle that they cover (e.g. Hoberman Iris Dome). *'Polyhedral'* bar structures can transform in a spongy way, as it shrinks and expands with respect to its centre(e.g. Hoberman Sphere). *'Planes'* have many pinned bars aligned together forming planar forms (e.g. Santiago Calatrava Milwaukee Art Museum). Finally, *'double arched'* structures, developed by Felix Escrig, can utilise foldable double-arched steel frames as space enclosures.

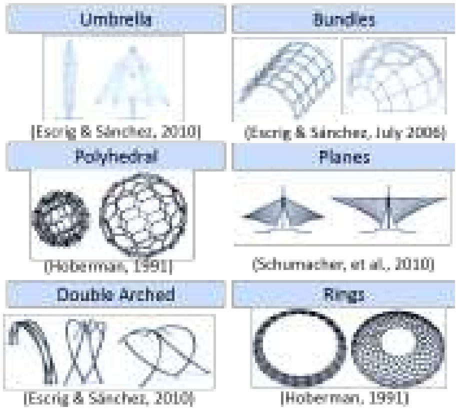


Figure 2
forms of spatial bar structures

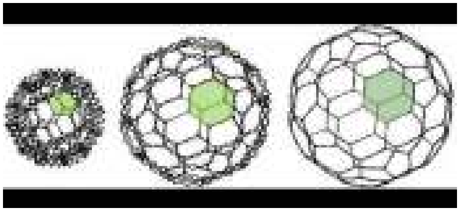

Figure 3
The kinetic building block and its transformation. (Hoberman, 1991)

Throughout the analysis of spatial bar structure types, it has been noted that these structures are based on modification of primitive shapes (e.g. box, sphere, and cylinder). Each system is subdivided into multiple members of the same shape, the so-called *kinetic blocks* (Hoberman, 2006) (figure 3). Modification of each kinetic block leads to transformation of the entire spatial configuration, and its design could be considered as one of the factors affecting the final form of transformation.

## EMERGENCE OF FREE-FORM TRANSFORMABLE STRUCTURES.

Zuck and Clark (1970) stated that kinetic systems can be categorised into *'closed'* and *'open'* ones. *'Closed systems'* can change their shape according to a predictable number of needs, in contrast to *'open systems'*, which cannot be completely predicted or predetermined during design conception, they accept modification and addition/subtraction throughout their lifecycle (ZUK & H.Clark, 1970). The lifecycle of a structure depends on its ability to satisfy design needs; the current solutions of spatial structures offer predefined ranges of options with a range of predictable possible states. The process of developing a kinetic motion should consider Ways and Means for operability (Fox & Kemp, 2009). Ways are the kinetic methods by which they perform including folding, sliding, expanding, shrinking and transforming in size or shape. Means, are the impetus for actuation and may include pneumatics, chemicals, magnetism or electrical systems.

There are some newly created precedents of Ways of transformations not listed on the classification by Zyck and Clark. A deployable *'hyperboloid Pantographic structure'* (figure 4) was developed by AE-Lab, Vrije University, Brussel, as a tower or truss like mast for temporary tensile surfaces, to ease its transportation (Temmerman, et al., June 2009). A Deployable *'Hyperbolic Paraboloid'* (figure 5) (i.e. saddle geometry) structure, proposed by Fufu Yang , Jimmin Li and Yan Chen, from Tianjin University, China , and Zhong You from University of Oxford, UK, using Bennett linkages with 1 DOF (degree of freedom), just to widen the deployable structure's geometrical possibilities (Yang, et al., 2015). These solutions are based on folding-expanding mechanisms regardless the actuation means required for transformation.

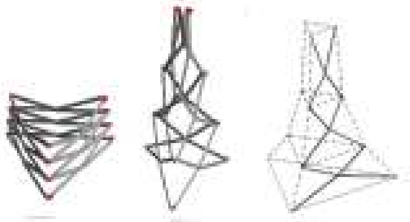

Figure 4
Deployable Hyperboloid pantographic Structures (Temmerman, et al., June 2009)

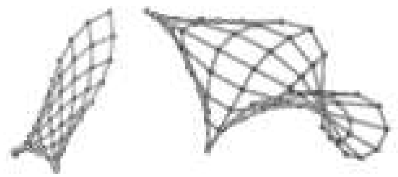

Figure 5
deployable Hyperbolic paraboloid structures (Yang, et al., 2015).

Other solutions proposed free-transformation based on redesigning the linear elements (i.e. 2D framing) and the scissor-pair mechanism itself. Yenal Akgün, in his PhD research at the University of Stuttgart, proposed a redesign of the scissor-hinge by utilising two joints at a specific point in the scissor mechanism and combining it with actuators to obtain unique extensions and rotation capabilities to each scissor (i.e. module) with basic 1 DOF joints (Akgün, 2010). This was to provide adaptive structural surfaces without changing the dimensions of the trusses or the span. He did some digital prototypes of linear elements in one-way (figure 6) and two-ways (figure 7) configurations.

Daniel Rosenburg, in his master of science research at MIT, proposed some prototypes utilising scissor-pair mechanisms with two off-centre joints with sliders, to control the degree of freedom utilising basic 1 DOF linkages, (i.e. to transform from centre to off-cen¬tre position and vice versa)(figure 8) (Rosenburg, 2009). Despite The solutions offered by these researchers depends on linear elements; they highlighted the effect of changing the basic module (scissor mechanism) on the transformation of the entire system.

Some researchers proposed solutions for making three-dimensional transformable modules without employing them in structural applications. William Bondin, Francois Mangion and Ruairi Glynn, researchers at BMADE Robotics Lab, Bartlett School of Architecture, UCL, created a project called 'Morphs' [1] (figure 9). It is a robotic mechanism with octahedral structure, which can move around public spaces and respond to its environment; utilising twelve actuated struts that shifts the CG (centre of gravity) of the entire structure.Robert L. Read, a computer scientist and a contributor in Public Invention repository, commenced a project called 'The Gluss' in August, 2015 (announced in September 2016) [2]. Inspired by the 'GEOMAG' toy, he developed 'Tetrobot', a robotic module prototype (figure 10), based on tetrahedral and octahedral geometries, utilising a set of linear servo motors and 3D printed open source 'Turret' joints, invented by Song, Kown and Kim (Song, et al., 2003), aiming to create metamorphic robots. Both researchers utilised joints with two DOFs, employing a large set of actuators that make it expensive; According to Read, the cost of 'Tertrobot' prototype is estimated around £2500 [2].

Figure 6
One-way Linear scissor-pair mechanism (AKGÜN, et al., 2007).

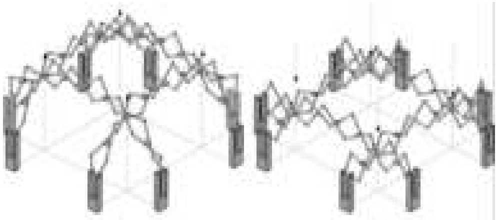

Figure 7
Two-way linear scissor-pair mechanisms (Akgün, 2010).

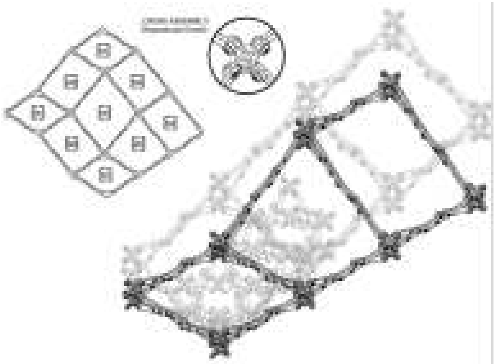

Figure 8
a latticework composed of scissor-pair mechanisms with two off-centre joints (Rosenburg, 2009).

Figure 9
Morphs robot [1].

While many researchers proposed solutions based on transforming the 'kinetic block', others proposed solutions based on bending the entire surface itself. In 2014, Jordi Truco and Sylvia Felipe, known as Hybrid architecture, built the 'Hybermembrane' (TRUCO & FELIPE, 2014) (figure 11), a 10 x 20 m prototype, in the 'Barcelona design hub museum'. The structure transforms by hydraulic masts, located on its perimeter, able to bend the elastic structure members connected with universal joints; and it is cladded with elastic materials.

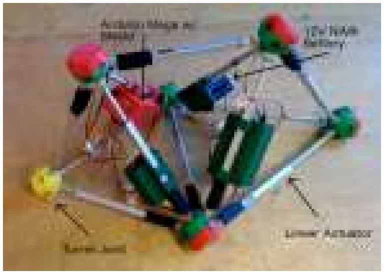

Figure 10
The Gluss Tetrobot
[2]

Figure 11
Hybermembrane
installation [3].

Another research team, Filipa Osório, Alexandra Paio and Sancho Oliveira, from the Vitruvius Fab-Lab in Lisbon University, Portugal, proposed a free-form transformation of surfaces by tessellating them with folding patterns (figure 12), placing the actuators horizontally in the surface base (Osório, et al., 2014).

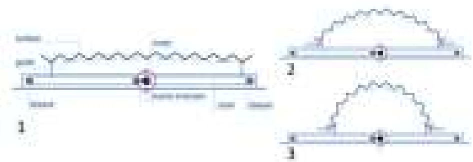

Figure 12
the bending
process of kinetic
folded surface
(Osório, et al., 2014)

Both solutions achieved free-form transformation of surfaces, however, compared to the previous solutions, the resulting surface (i.e after transformation) can not fit a designated form easily nor precisely.

Consequently, we seek to develop a reliable kinetic system for double layered spatial bar surfaces, which enables precise and controllable freeform transformation. This will be attainable by developing a system based one 3D kinetic blocks, flexible joints, fixed bars and a set of actuators, assembled together in a reliable configuration generated by computational design techniques. in relation to architectural, technical or design process related parameters. Considering such parameters in an early design phase could improve the system's transformation efficiency. In addition, investigating surface tessellation techniques in relation to the transformability of each kinetic block could contribute in optimising the number of utilised joints and actuators required to attain the designated transformation. In particular, we will investigate following research questions:

1. What is the relationship between free-form transformation of spatial bar systems and the kinetic block?
2. How does the modification of the kinetic block affect the entire system?
3. How can we achieve a controlled free-form transformation of spatial bar systems, achieving a designated form, by utilising parametric tools?
4. How can we develop an optimised and reliable spatial bar system, composed of multiple kinetic building blocks (i.e. controlling the DOF)?

## DEVELOPING THE DESIGN FRAMEWORK

In order to investigate the research questions, we will develop a physical prototype of a kinetic block, and assess its potential in enabling free-form transformation of a spatial bar system. Its development is based on introducing a design framework incorporating parametric and kinetic design strategies.

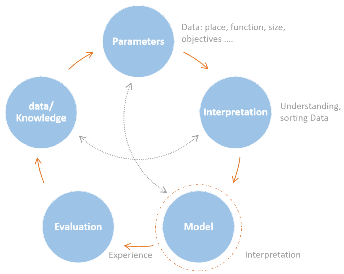


Figure 13
Iterative parametric design loop (Globa, 2015).

### *Parametric design Strategies*

Globa (2015) proposed a parametric design strategy based on an iterative endless process, aiming to achieve the optimum solution 'reality check'. Globa describes a design process starting by setting the modelling parameters, followed by interpretation, a digital model, evaluation, leading to data knowledge closing the circle back to reset the modelling parameters (figure 13). Each iteration increases the 'experience' of the evaluation process, which produces data to be used in resetting the modelling parameters.

Hudson (2010) proposed another practice-led research strategy integrating the Knowledge Development Strategy 'kDev', the Knowledge Capture Strategy 'kCap', the Model Construction 'mCon', and the Design Investigation'dInv', finally leading to the construction documents 'cDoc' (figure 14). According to Tedeschi (2014), this iterative process can be attainable by utilising a genetic algorithm (e.g. the Galapagos plugin for Grasshopper).

### *Kinetic Design Strategies*

There are other processes originated in structural and mechanical engineering. Gantes (2001) proposed a kinetic design strategy focusing on a stability check, requiring the following three steps: starting with the geometric design, followed by structural analysis under service loads in deployed state (i.e. after transformation) and finally concluding to structural analysis throughout the deployment process (figure 15) (i.e. during the transformation).

Wierzbicki (2007) described the mechanical design process of kinetic structures, after reviewing the design requirements and assumptions based on four steps. It can be utilised by starting with a structural component assembly fitting and movement check, followed by covering material components assembly fitting and movement check, a performance check after load simulation, finalised by generating manufacturing and information management data (figure 16).

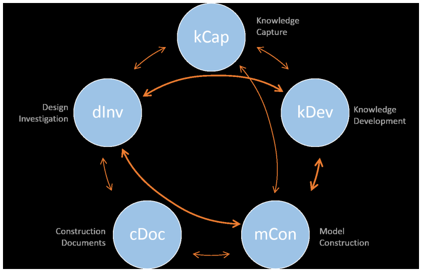


Figure 14
summary of parametric design strategies for practice-led research. (Hudson, 2010).

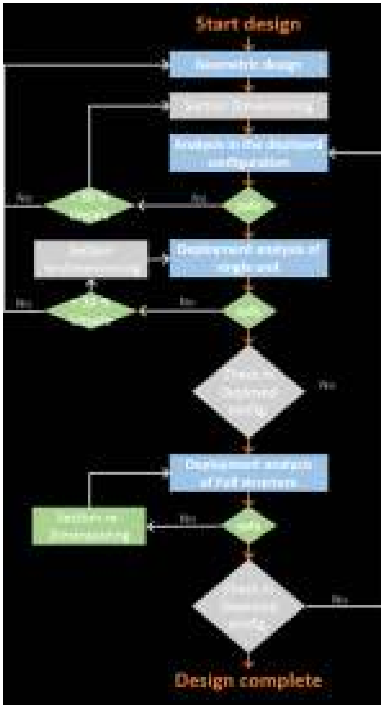


Figure 15
deployable structures design strategy (Gantes, 2001, p. 296)

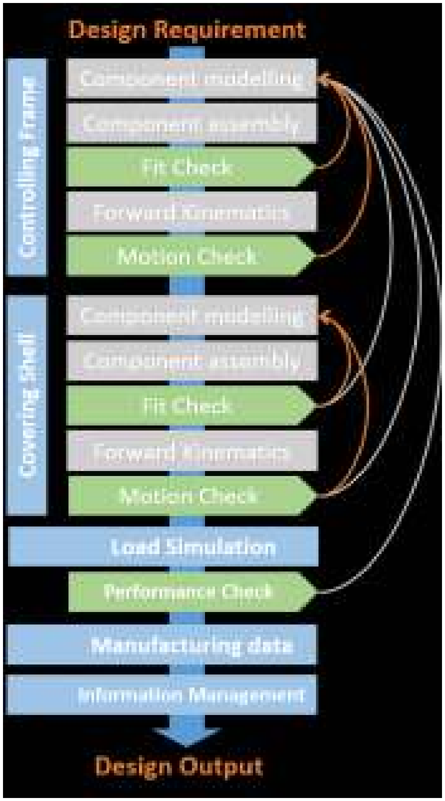


Figure 16
kinetic structures mechanical design strategy (Wierzbicki, 2007)

Finally, originated in an architectural point of view, Asefi (2009) proposed a transdisciplinary design process, focusing mainly in the early design stages. Each step should be reviewed and receive feedback from structural, construction, mechanical, manufacturing and material specialists. The design process, in that proposed design management model, has five outcomes after defining the design requirements (figure 17). First, a *'conceptual design'* phase, proposed by the architect. Second, an *'Initial schematic design'* phase, after defining the structure concept and reviewing it with specialists. Third, *' an advanced schematic design'* phase, after checking the transformable structure compatibility with the basic structure or substructure, and making simulations and tests. Fourth, a *'detailed drawings'* phase, after making prototypes, load simulations, and check the design requirements and specialist contractors. Finally, a construction process after preparing the *construction documents, maintenance program, and assembly tests* (i.e. porotypes) by the manufacturer. Afterwards, *POE* (post-occupancy evaluation) and structure monitoring should be imposed regarding maintenance program to assure the building performance through its lifecycle (Hussein, 2012).

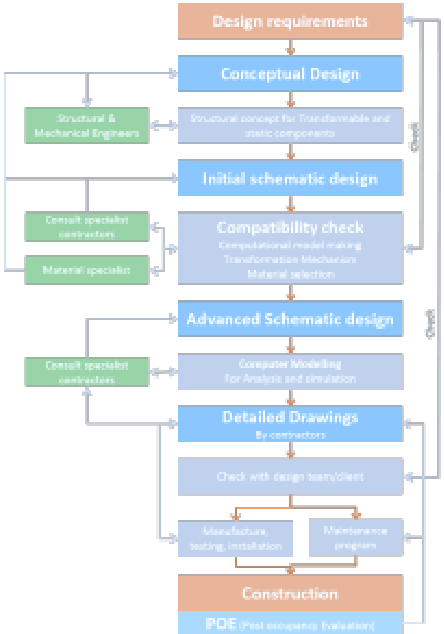


Figure 17
design management model ( Asefi, 2010), as edited before by the first author (Hussein, 2012).

Briefly reviewing the existing parametric design strategies, one could argue that they are commonly focusing on generic design processes and it is up to the researchers to tailor a suitable design framework according to their design needs. Moreover, the available kinetic design strategies are mostly focusing on managing problems occurring in non-architectural disciplines (i.e. structural, mechanical engineering etc.). Consequently, we will propose a new design framework in order to build the required prototype of a transformable free-form spatial bar structure.

## FREE-FORM TRANSFORMATION DESIGN FRAMEWORK

The proposed design framework is composed of a large set of internal iterative design processes and iterations (figure 19). Summarily, it consists of three main phases: form-finding, stability validation and actuation (figure 18).

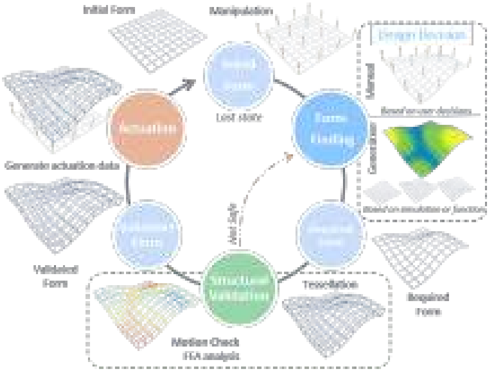


Figure 18
the proposed framework summary

The form-finding phase is focusing on the determination of the exact deformation geometry of the spatial bar prototype. It will operate as a parametric grid system allowing variable types of deformation by defining some manipulators or attractor points. It could either be adjusted to the user's individual preference (i.e. custom edit) or be based on a generative design strategy (e.g. genetic algorithms), incorporating environmental or functional requirements, regarding rules, equations, simulations or sensor data. It will be developed as a parametric model focusing mostly on resolving geometric-kinetic relationships, rather than function related considerations.

In the second phase, after determining the final state of the kinetic block geometry, we will continue with the block's stability validation, according to its actual function (i.e. application) and materiality (e.g. a roof structure, a façade system, a shading device) and the technical data of the structure components (i.e. bars, actuators and joints), (e.g. stiffness, inertia). This will be achieved by using structural simulation tools (e.g. finite element analysis (FEA)). Genetic algorithms (GA) may be applied, to achieve the optimal surface tessellation, which would provide optimum stability for the structure, in the final state and during its transformation. After doing so, a feedback loop will enable redesigning the kinetic block assembly, surface tessellation or the kinetic block itself, in case of the minor issues, or changing the system's components or re-formation of the initial geometry, in case of major issues, to overcome structural efficiency problems before moving to the third phase; the actuation of the physical prototype.

In the final phase, we will proceed to the development of the physical prototype. Its mechanism will consist of linear actuators, linear fixed elements and flexible joints. After the first iteration solution, the fabrication data will be generated based on the technical data of the structure components, previously defined by the user and adjusted by the previous process. Among the most important technical data, required for the actuation process, is the calibration of the linear actuators, in order to determine the relation between the numerical input and the actual movement. Equally important, the mechanical limitations related to the linear movement ranges of the actuators, as well as the angular movement ranges of the joints (e.g. 36 degrees for the turret joint [2]).

The actuation of the physical model will be controlled through the previously defined parametric model, by which the actuation data will be transferred from the computer to the actuator through controllers (e.g. Arduino). The transferred data will derive from a numerical list extracted from a linear actuation motion simulation of the parametric model and will be used as an input to the controller to produce the required actuation.

After the actuation process, the final configuration data will become the initial-form data for another transformation process; that may occur regarding any change of rules or states that impose re-

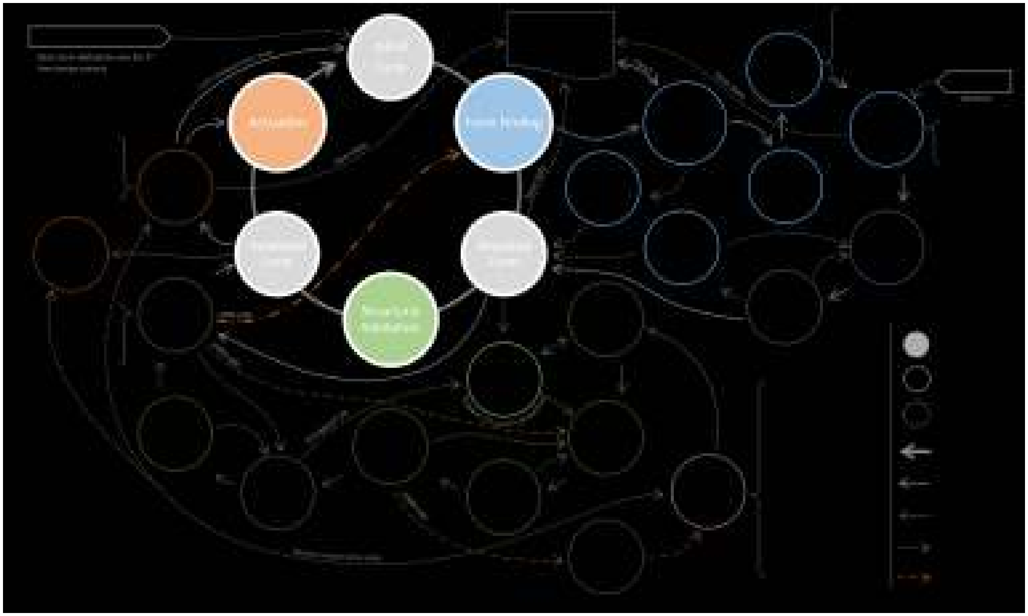

Figure 19
detailed design framework

designing of the surface. Afterwards, a database will be created listing each rule, condition, resultant form and actuation data for each transformation process. This will decrease the processing time required for the form finding process, as the design decision can be stated based on the stored data that match the same rules, states or conditions previously occurred throughout the system operation.

In addition to the user-based, top-down workflow described above, we will investigate a developer-based, bottom-up design approach. While the user based approach is starting by developing the kinetic block based on available components. the developer-based approach will start by designing and calibrating the actuators, followed by designing the linkages and joints and determining their limitations, moving backwards up to the definition of the necessary elements that should be used for the kinetic block. Then, configuring the basic kinetic block, and determining its stability/feasibility, validating its potential and possibilities, assessing the movement gained by transforming it and finally implementing the kinetic block into a spatial configuration (e.g. surface).

This research is still in progress; our expected findings from the following stage include a transformation mechanism and its design framework, which could be applied to different types of surfaces or geometries allowing them to perform free-form transformation movements. That can be employed for some applications and purposes, such as kinetic roofs, transformable ceilings, re-usable formworks, shading devices and other types of applications utilise spatial bar systems.


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# Evaluating the capability of EnergyPlus in simulating geometrically complex Double-Skin Facades through CFD modelling

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*This paper represents a preliminary investigation into the appropriateness of using EnergyPlus as a simulation tool for Double-Skin Façades (DSFs) that are considered geometrically complex. It builds upon previous research conducted by the authors in which a DSF was designed and simulated for an existing office building in Cairo. For this verification, the DSF was simulated once more using Computational Fluid Dynamics (CFD) to evaluate the accuracy of the previously obtained results. The cavity temperature and the volume flow rate of the airflow provided by EnergyPlus are compared with those obtained by OpenFOAM CFD software. The results give a credible indication of the reliability of EnergyPlus and encourages further investigations. The strengths and limitations of each software are discussed.*

**Keywords:** *Double-Skin Facades, Complex geometry, EnergyPlus, CFD*

## INTRODUCTION

With the development of computational design tools, architects are becoming increasingly interested in exploring more complex geometric configurations in their research and practice. Similarly, they are also becoming more interested in the environmental performances of such complex geometries. These interests are seen in façade design which plays an important role in the thermal comfort of interior spaces of buildings. Double skin facades (DSFs) in particular are popular for both aesthetic and environmental reasons, and are the focus of this research.

However, despite the advancement of the design tools that facilitate parametric explorations and evolutionary form finding for example, the simulation software commonly used by architects in the design phase to evaluate and choose among different solutions are not as advanced and not always appropriate to the problem at hand. This is particularly relevant in the case of DSFs in which many physical phenomena occur and interact with each other, such as heat transfer through radiation, conduction and convection (Poirazis, 2006). This affects the final performance of the DSF on which the architect bases his or her decision.

EnergyPlus is among the widely-used building energy simulation tools, and it is easily linked with parametric design software such as Grasshopper for Rhino, due to the presence of many plugins. However, the appropriateness of EnergyPlus is debatable (Zhang, et al., 2013; Sabooni, et al., 2012; Kim and Park, 2011) for modelling flat DSFs, let alone geometrically-complex ones. This represents the main problem addressed in this paper. Computational Fluid Dynamics (CFD) software are more suitable for such problems, however they are often not used in early design phases as they need much more time and expert knowledge for their use.

## AIM AND METHOD

This paper continues earlier investigations (El Ahmar & Fioravanti, 2015) of a folded DSF with perforated surfaces that attempted to decrease cooling loads of an existing office building in Egypt. The geometry of the façade was optimized using evolutionary algorithms in Grasshopper, and the fitness function was based mainly on results provided by EnergyPlus through the plugin ArchSim. The results were expected to contain inaccuracies due to limitations of EnergyPlus as will be discussed. This paper represents a preliminary verification phase of previously obtained results. The main objective is to know the degree of inaccuracy of EnergyPlus and whether it can be relied on in simulating the temperature and airflow inside the cavity of a DSF that is considered geometrically complex.

The paper starts with a brief overview of the software used in general to simulate the thermal performance of DSFs, highlighting the main approach used for calculations, their advantages and limitations. Then for this investigation a comparison is performed, in which the temperature and airflow values inside the DSF cavity are simulated using OpenFOAM which is an open-source software for CFD, then the results of these simulations are compared to those previously obtained using EnergyPlus. Another advantage of this comparison is getting a deeper understanding of the behaviour of the proposed folded DSF in terms of its temperature distribution and airflow patterns which were not possible to know earlier.

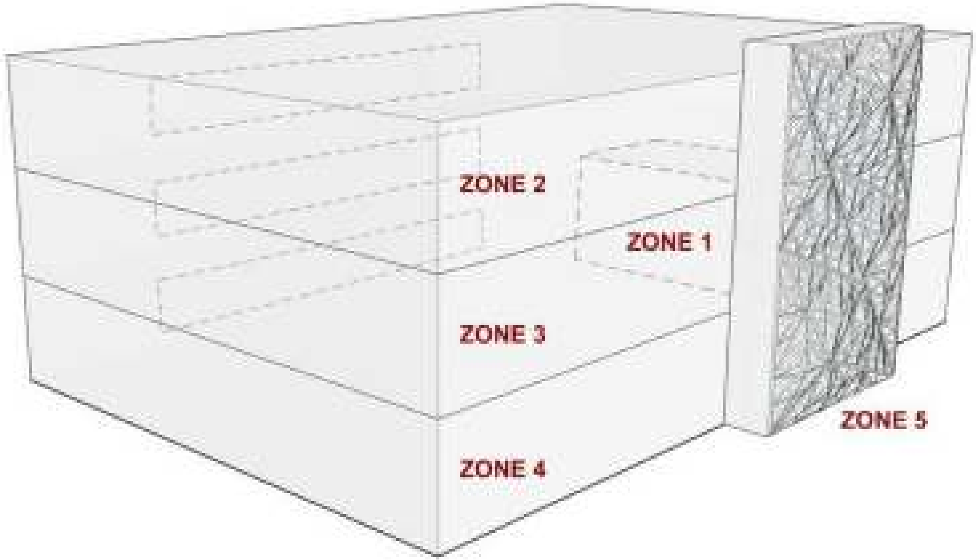



Figure 1
Diagram illustrating the zones of the thermal model of the folded DSF that was simulated using EnergyPlus. The DSF covers just part of the building since only one office room was studied.

## MAIN THERMAL & AIRFLOW SIMULATION METHODS USED FOR DSFS

Based on the level of resolution of building simulations, they can be categorised into either macroscopic or microscopic. The macroscopic level deals with whole building systems, interior and exterior conditions over periods of time. The microscopic level focuses on smaller spatial and time scales. Accordingly, thermal and airflow modelling in buildings also can be divided generally to two main approaches; Airflow Network (AFN) models for the macroscopic level and CFD models for the microscopic level (Djunaedy et al., cited in Poizaris, 2006).

AFN models treat every building component and relevant HVAC fluid flow systems as a network of nodes that represents rooms and parts of rooms. The concept of mass conservation for inlet and outlet flows leads to non-linear equations which are integrated over time to characterise the flows. Because of its abilities, it can be used with thermal models, in such cases it is integrated with a thermal network which solves the heat balance at each node. Each thermal zone has just one node at its centroid and is assumed to be 'well-stirred' (De Gracia, et al. 2013; Poirazis, 2006). A main advantage is that, compared to other airflow models, it is the main method used to predict the overall ventilation performance of a building (Chen, 2009). The main limitations of the AFN are that it is not appropriate in cases when the temperature distribution in a zone is significant, and that it only provides information about bulk flows of air (EnergyPlus, 2014).

On the other hand, CFD simulations calculate the desired flow quantities (such as velocity, temperature, etc.) at a large number of points that are connected and distributed throughout the physical domain at hand, forming what is called a mesh or a grid. In CFD models the geometry under investigation is surrounded by a two or three-dimensional grid of nodes and for each node the conservation equation for mass, momentum and thermal energy is solved. Limitations of CFD simulations in practice are mentioned by numerous authors such as De Gracia, et al., (2013), Hensen, et al., van Dijk and Oversloot, Ding, et al., Jaroš, et al. and Chen (all cited in Poizaris, 2006), most importantly; they are too detailed and sophisticated for the early design stage, need high computer power and time, and are not user friendly as they require advanced knowledge to be used.

## ENERGYPLUS MODEL

The DSF was assumed to be an addition to an existing office building in Cairo. The folds were intended to reduce the amount of incident solar radiation falling on the façade through self-shading. Additionally, the main structural elements of the facade contain 5x5 cm perforations that represent a ventilation network spreading across the façade area, to reduce overheating of the cavity. The DSF type is multi-story (no vertical or horizontal partitioning in the cavity space) that is 9 m wide, 13.3 m high (starting form first floor) extending 1 m after the ceiling of the last floor to include openings for ventilation. It is difficult to state all the settings of the model in this paper, however the most important material settings are mentioned as follows:

- Inner glazing: double pane, blue tinted, light transmittance= 0.37, solar transmittance= 0.43
- Outer glazing: double pane, clear, Low E, light transmittance= 0.74, solar transmittance= 0.5
- Insulated Aluminum cladding panels: 14 mm in width, with Thermal resistance: 0.0172 $m^2$K/W, Thermal conductivity: 0.35 W/mK, and Heat transfer coefficient: 5.34 $\frac{W}{m^2}K$

Simulations of the DSF facing the South-East orientation took place on a day that represented a typical summer day in Cairo (2nd of July) in which average ambient temperature is 32°C, average site wind speed is 4.9 m/s with an average direction of 287 degrees (North West). Furthermore, a specific timestep was selected which was at 16:00. This facilitates the comparison with OpenFOAM results as simulations can be calculated for a specific point in time. Figure

1 shows the thermal model used. It is composed of four zones representing a part of the office building and one office room which was studied, in addition to a fifth zone representing the proposed DSF itself.

Two values were selected from the simulation results for comparison; the cavity temperature (Zone Operative Temperature) which was 37.6˚C, and the total Volume Flow Rate at the outlet openings which amounted to 3.74 $\frac{m^3}{s}$. This value corresponded to 77 air changes per hour for the cavity that had a volume of 175 $m^3$. These airflow results were expected to be overestimated.

## OPENFOAM MODEL

An appropriate solver must be chosen depending on the physical phenomena that we wanted to simulate, which included heat transfer by free convection (buoyancy), forced convection (wind), radiation and conduction. After a lot of experimenting with various solvers, and their combinations, the task proved to be very difficult, as there was no solver capable of simulating all these phenomena together. The challenge was even more complicated due to the relatively complex geometry of the façade. This lead to the need of certain simplifications, which are briefly presented in Table 1.

The solver used in this simulation process is called rhoSimpleFoam. It is a steady-state solver used for simulating turbulent RANS (Reynolds Average Navier-Stokes equation) flow of compressible fluids. To simplify and proceed with the simulations, fluid flow due to buoyancy was neglected as it is considered weak when compared with the flow that is induced by wind, and also due to the fact that cavity was partially shaded from direct sunlight which reduced cavity heating. The standard k-ε turbulence model was used in this case.

A Stereo-lithography (stl) file format of the model was exported from Rhino 3d modeller. Different faces or patches were exported separately (Figure 2) to enable the specification of different boundary conditions for each of them.

There were numerous boundary conditions assigned to each patch, most importantly were those obtained from the EnergyPlus simulation results. They are the surface temperatures of the patches that ranged from 48.9˚C for example for the Top patch, to 37.2˚C for the Office Windows patch. The temperature of the inlet airflow itself was 35.6˚C. The Volume Flow Rate at the inlets was used to calculate the inlet flow velocity instead of the wind speed as it was the only output generated from EnergyPlus that gives information about the inlet airflow. Since all inlets have the same surface area, the total volume flow rate of all inlet openings was divided by their total surface area to calculate the velocity of air:

Total volume flow rate at the inlets ($\frac{m^3}{s}$) = total area of inlets x air velocity

3.74 $\frac{m^3}{s}$ = 7.3 $m^2$ x air velocity

Therefore, the air velocity at inlets = 3.74/7.3= **0.51 m/s**. The rest of the boundary conditions were given values chosen from the OpenFOAM settings.

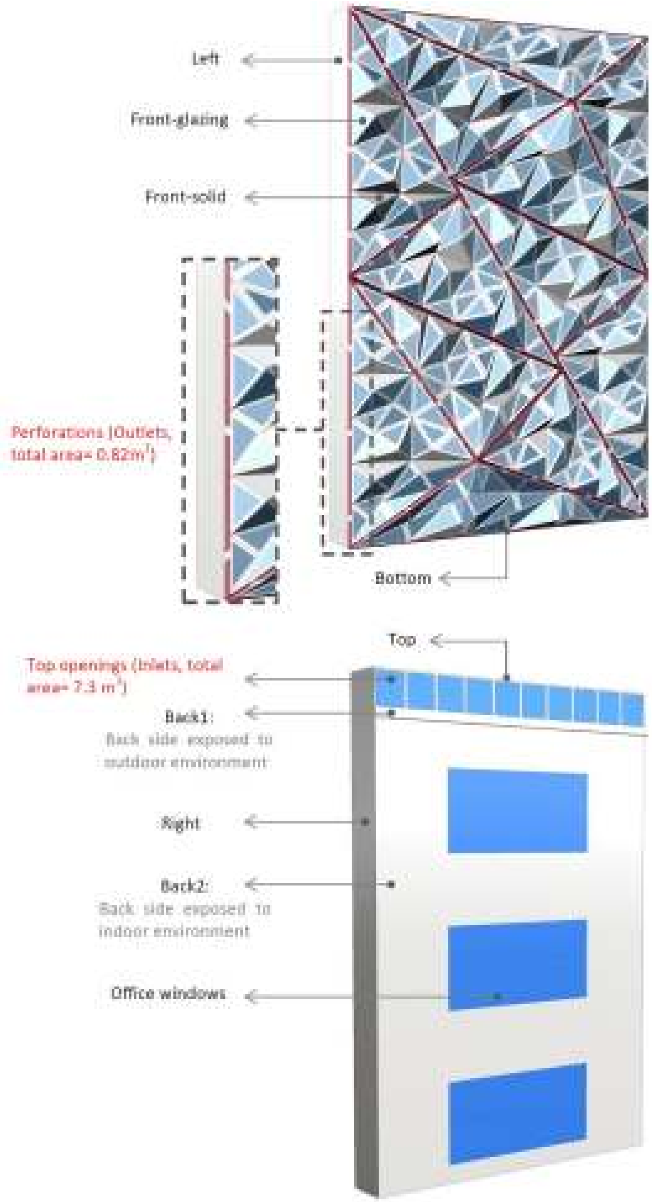
In OpenFOAM the simulated temperature is calculated at every single point of the mesh. Therefore, in order to be able to compare it with the temperature output of EnergyPlus, an average value is calculated for all the points in the mesh, and amounted to 309.6˚K (36.46˚C). The velocity at the perforations ranged from 0 to 5 m/s, with an average of 4.36 m/s. The average velocity should be multiplied by their total surface area to calculate the total volume flow rate.

Total volume flow rate = total area of perforations (outlets) x average velocity at perforations= 0.82 $m^2$ x 4.36 m/s = 3.62 $\frac{m^3}{s}$.

## OBSERVATIONS AND RESULTS

The temperature results in Figure 3 show the dissipation of heat from the hot DSF surfaces to the inside of the cavity either by forced convection or by diffusion. In certain parts of the cavity the effect of convection is stronger when the velocity is relatively high, while in others diffusion has a greater effect when flow ve-

Figure 2
Diagram illustrating the different patches of the OpenFOAM model in the front view (top) and back view (bottom), the inlets and outlets are written in red. The overall dimensions are 13.3 m in height, 9 m in width, and 1.25 m in depth. The cavity volume of the DSF is 175 $m^3$.



| Model aspect | Assumption/simplification |
|---|---|
| Physics simulated | Airflow due to wind and heat transfer by convection and conduction only |
| Geometry | Small perforations grouped into bigger ones with the same total surface area |
| Duration to simulate | Specific point in time: 2nd of July at 16:00 |

Table 1
Summary of assumptions and/or simplifications for the model prepared in OpenFOAM.

locities are low. Forced convection occurs due to the incoming air at the cavity inlets which is entering at a lower temperature than the surfaces and is equal to the ambient temperature of 308˚K (35.6˚C) which was assigned as a boundary condition. Other results showed that the incoming air pushes warmer air to the front folded faces of the DSF where it is trapped in some parts unless there is a perforation to act as an outlet and allow the warmer air to escape.

By comparing the visualised results of the temperature and velocity, it was observed that, in general, the cavity temperature is often lower in areas with higher airflow velocity and therefore have more heat loss by convection. It was also observed that the temperature in the middle of the cavity is higher than the bottom of the cavity despite having relatively higher airflow velocity. This is due to the thinner cross-section at the area so the heat transferred by diffusion has a strong effect and the flow velocity is not strong enough to ventilate it.

The comparison between the results of EnergyPlus and OpenFOAM showed an unexpected similarity between the results. It was expected that there would be inaccuracies in EnergyPlus, especially in the results regarding the airflow. However, EnergyPlus only slightly overestimated both temperature and airflow values by only 3.1 % and 3.3 % respectively. However, it cannot give us a detailed insight of the behaviour of the airflow and temperature distribution inside the cavity which is important for the evaluation of the proposed design solution. So even if EnergyPlus can predict the average velocity of the air, it is not capable of demonstrating, for example, that this air is not flowing evenly throughout the cavity and that only the upper half is considered well ventilated. Furthermore, since in this paper only one model was simulated using OpenFOAM, the results can give only a credible indication of the reliability of EnergyPlus. This reliability would be reinforced by repeating the comparison with different models having varying performances.

It must be mentioned again that simplifications were made to the OpenFOAM model, hence inaccuracies might be present in the results. Nonetheless, it is assumed that these results are more reliable than the ones obtained by EnergyPlus. What can be certain from the OpenFOAM simulations are the qualitative results, such as those regarding the flow pattern and behaviour, and temperature distribution. The quantitative results; the exact numerical values of the temperature and velocity, are subject to criticism as with any other software.

## CONCLUSION

This investigation demonstrated that EnergyPlus can give a general idea of the DSF performance, even if it is considered geometrically complex, and is most suitable in early design phases. However, the airflow pattern and temperature distribution results by OpenFOAM are important in understanding the behaviour and improving the design accordingly. CFD simulations need expert knowledge and much more computing time, and are important in later, more detailed design phases when final decisions must be taken.

The simulations of DSFs remains a challenge even with CFD software, and any simulation would be subject to a certain degree of error. A real veri-

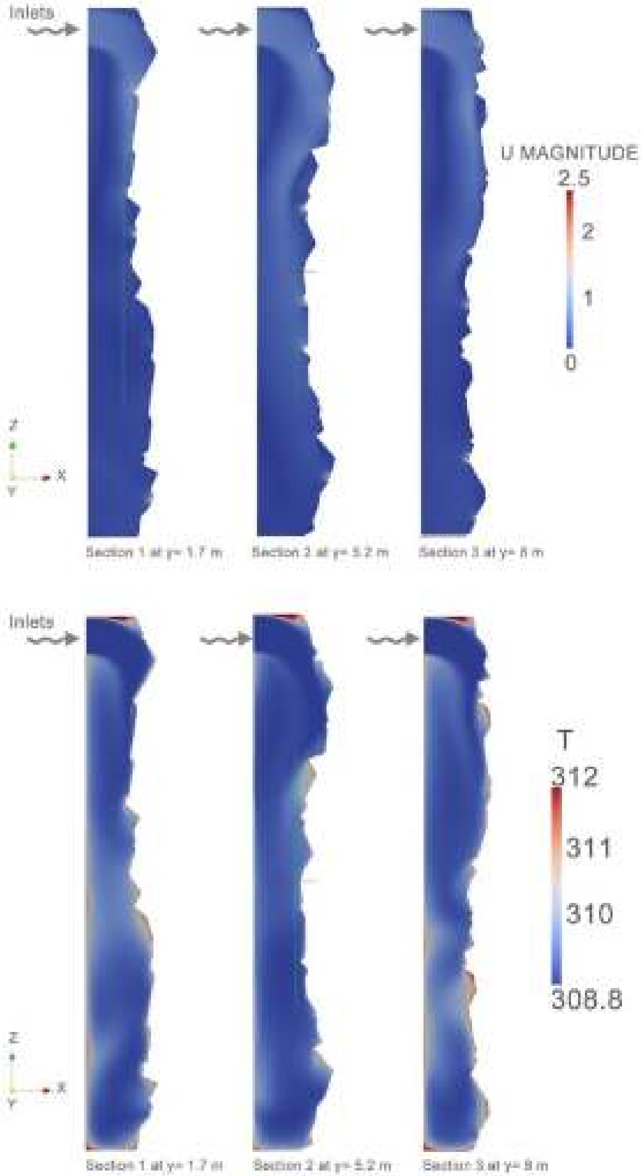



Figure 3
Vertical sections 1, 2 and 3 from left to right illustrating the magnitude (top) of the airflow velocity (in m/s) and the temperature (bottom) throughout the DSF cavity at the last simulated time step at which a converged state of the flow is reached in the CFD simulations.

fication, either for EnergyPlus or OpenFOAM results, would require physical experimentation which falls within the scope of future work.

## ACKNOWLEDGEMENT
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# Notes