Bespoke Fragments

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Materials and digital fabrication in architectural design

PhD Dissertation by Anders Kruse Aagaard

AARHUS SCHOOL OF ARCHITECTURE

BESPOKE FRAGMENTS

Materials and digital fabrication in architectural design

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Abstract

English

The PhD project *Bespoke Fragments* is investigating the space emerging in the exploration of the relationship between digital drawing and fabrication, and the field of materials and their properties and capacities. Through a series of different experiments, the project situates itself in a shuttling between the virtual and the actual, and control and uncertainty.

The project has established an experimental framework that consists of three materials and four types of processing. The materials are concrete, wood and steel. The processes are division, subtraction, addition and transformation.

Through tangible experiments, the project discusses materiality and digitally controlled fabrication tools as a expansion of the architect's tool box and workflow. *Bespoke Fragments* considers this expansion as an opportunity to establish a connection between forms of digital drawing and the specificities of materials. Through that connection, the project seeks to use the realisation to generate developments and findings and, through an iterative mode of thinking, establish a dialogue between drawing, materials, and fabrication.

The use of digital fabrication tools through digital drawing opens up a new approach to materials in an architectural context. The knowledge and intention of the drawing become specialised through the understanding of the fabrication processes and their interface with materials. When drawing embeds, not form, but capacities into the materials through fabrication, the emergence of the virtual extends into the materialisation. Based on this understanding, the project produces a series of 'bespoke fragments' through the materials and the machining driven design experiments.

A transverse exposition of the experiments provides an unfolding of their influential elements. The elements are understood as connected interfaces that each impact the outcome of the experimentation. This understanding of the process contributes with a perspective on how the material experimentation can affect and be affected through the discipline of architecture.

Dansk

Ph.D.-projektet *Bespoke Fragments* undersøger det mulighedsrum der opstår i udforskningen af relationen mellem digital tegning og fabrikation, og materialers egenskaber og kapaciteter. Gennem en række forskellige eksperimenter placerer projektet sig i en pendulering mellem det virtuelle og det aktuelle, og mellem kontrol og uforudsigelighed.

Projektet etablerer en eksperimentel ramme som består af tre materialer og fire bearbejdningsmetoder. Materialerne er beton, træ og stål. Bearbejdningsmetoderne er division, subtraktion, addition and transformation.

Gennem konkrete eksperimenter diskuterer projektet mulighederne for at benytte digitalt styrede fabrikationsværktøjer som en udvidelse af arkitektens værktøjskasse og arbejdsgang. *Bespoke Fragments* anser denne udvidelse som en lejlighed til at etablere en forbindelse mellem digitale tegningsformer og materialernes specificiteter. Gennem denne forbindelse forsøger projektet at benytte realiseringen til at generere udviklingsmuligheder og resultater og gennem en iterativ tankevirksomhed etablere en dialog mellem tegning, materialer og fabrikation.

Anvendelsen af digitale fabrikationsværktøjer gennem digital tegning åbner op for en ny tilgang til materialer i en arkitekturmæssigkontekst. Viden og intention bag tegningen bliver specialiseret gennem forståelsen af fabrikationsprocesserne og berøringsfladen med materialerne. Når tegningen ikke indlejrer form, men kapacitet, i materialerne gennem fabrikationen, udvides det virtuelle til at være indeholdt i materialiseringen. Baseret på denne forståelse skaber projektet en række 'bespoke fragments' ('skræddersyede fragmenter') gennem de materiale- og fabrikationsdrevne designeksperimenter.

En tværgående fremstilling af eksperimenterne udfolder en række elementer der hver især påvirker eksperimenternes helhed. Elementerne skal forstås som forbundne berøringsflader, der hver især har en indvirkning på udfaldet af eksperimenterne. Denne forståelse af processen bidrager med et perspektiv på hvordan materialeeksperimenter kan påvirke og kan blive påvirket gennem arkitekturdisciplinen.

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INTRODUCTION

Motivation and research environment

The motivation for this PhD research project is founded on an interest in and knowledge of materials. The interest has emerged from and been established in an architectural context. Obviously, materials are needed in the construction of buildings. However, the use of materials in architectural production is not limited to the phase of realisation. Materialisation through drawing and modelling is a frequent event in architectural discipline. Whether the materials in use are belonging to a solely representational domain or are linked references to an expected built environment, the architectural production is both connected to and set in a field of materialisation. In the context of representation, the materials might sometimes imitate or substitute the actual materials, and sometimes just exist within the premises of the representation on their own terms. The presence of those materials will, however, always influence the representational work in progress regardless of their intention (Borden, 2014, p. 11).

In continuation of the material interest followed an interest in material machining, especially digital machining. At first, the digital machining seemed like a way of extending the role of the architect into one of involvement in fabrication and construction. The mastering of the digital drawing was the connection to the digital machining. The machines, however, quickly proved to be very popular in the creation of representation. Many students of architecture have proven that an industrial 5-axis CNC machining centre, the size of a room and the price of a house can actually produce a landscape model.

With the growing introduction of digital machining in architecture and the education of architects, a few questions arose: How can these machines be used to inform the process of architectural design? How can architects use digital machining of materials in a way that does not solely process components for buildings or produces things of representation? Can these machines somehow be used to bridge representation and realisation?

The abovementioned interest evolved in the course of several years. The interest in materials was established in the early years of studying architecture. Later on, around Master graduation and as a practising architect and part-time teacher at Aarhus School of Architecture the interest in digital machining was evolved.

Around winter time 2012, Aarhus School of Architecture started to intensify its focus and investment in the workshop facilities. From having good facilities for traditional crafting, a digital upgrade brought the school's facilities to a state-of-the-art digital machining environment. The workshop upgrade is in an ongoing development but has so far seen a continuous upgrade from 2012 to 2016.

Parallel to the physical changes at Aarhus Scool of Architecture, a change happened at the research level. In 2013, a reworked version of the PhD school was implemented. This included a new batch of PhD positions and a new Head of PhD school. The new PhD school supported and called for research anchored in the method of research-by-design, which would thereby allow a more creating and practical attitude towards architectural research.

This PhD project, and this concluding dissertation, were born and grown in the combined environment of the motivating interest, the evolving digital workshops, and the possibilities of the newly founded PhD school. This environment has matured through the course of the project. The PhD school has expanded and evolved. The workshop upgrade has literally been a parallel to the progress of the PhD project. The arrival of new machines and direct engagement in the process and implementation of the digital upgrade has naturally affected the work done through the period. While the project *Bespoke Fragment* was founded on knowledge on materials and an interest in digital fabrication, the course of the project has been situated, but also contributed to, an environment in progress.

Construction of the project

The project is based on a series of experiments carried out by the author, alone or in collaboration with others. The experiments serve as the central basis for discussing potentials and possibilities of using material investigations and digital fabrication in an architectural design and form finding process. The experiments exist as physical artefacts or constructions *and* as the process and realisations built around these during their development and execution.

The project is a two-sided piece of work where the physical fabrication of knowledge can be discussed as both a type of methodology for architectural research itself and as knowledge relevant for the architectural discipline in a wider perspective. The intention with this construction is to build an argument that unites the qualities found in the enquiring, investigative nature of the produced research *and* the pursuits of realisation that forms the practice of architecture. This union can be seen as a methodological strategy relevant for both research and practice *and* as a series of associated outcomes that are pertinent to both research and practice.

The project is formed and developed in the format of physical production but discussed and articulated through this written dissertation. While the written dissertation both sums up and puts the physical production into perspective, the intention is not to extricate the experimental making from the written part. Ideally, the dissertation could be read in the context of the physical. Since this is not a possible scenario, the dissertation instead contains a rich and diverse series of photos that documents and explains the experiments. At the event of the presentation and defence of the project, it is, however, the ambition to establish an exhibition. The exhibition will expose the physical production in whatever condition and state it exists at the time. Some element has gone through modifications and rebuildings through the experiments. Other parts have started to decay. The situations that are shown in photos within this dissertation thereby depict constellations that once existed, but might not do anymore.

For the assessment committee of this PhD-project, the exhibition will be a further elaboration of the research. For others, the exhibition might be an introduction to the research.

Dissertation structure
This dissertation is organised around four chapters. These chapters are 'Introduction,' 'Methodology,' 'Experiments' and 'Conclusion.'

The 'Introduction'-chapter provides the context and relevance of the research project. This chapter has been expanded, clarified and unfolded throughout the project, but represents the interest and field from where the idea and motivation for the project were born. The chapter is written to provide a general introduction to the research area but points towards the specific agenda and ambition for *Bespoke Fragments*.

The 'Methodology'-chapter explains the type of research and methodological approach of *Bespoke Fragments*. Like the 'Introduction'-chapter, this chapter gives a general framing but gradually focuses on the particulars of this project. This means that the general delimitation of the methodology is structured around a set of theories and referenced methods, but the chapter, section by section, becomes more and more particular for this research project. Unlike the 'Introduction'-chapter, however, the 'Methodology' is very much developed throughout the PhD-project. Thereby, the methodology should be seen as a parallel to the 'Experiments'-chapter. The 'Methodology' bridges the 'Introduction' and the 'Experiments'-chapter by structurally demarcating the general and the specifics of the research field of the project, and by being a corresponding research development to the experimental quantity of work.

The 'Experiments'-chapter contains, at least quantitywise, the largest amount of work and contributions of the project. The chapter consists of seven sections describing and discussing six experiments and a mass of work named *Continual Accumulation*. The six experiments are *Stretching the Steel*, *Workshop: Digital Matter*, *Concrete Moves*, *Alleyway Points*, *Intermediate Fragment,* and *Rebar Inside Out*. The series of experiments are not presented chronologically but instead try to show a stream of thought that has formed the project. Each experiment takes on a specific discussion and perspective. Some of these discussions could potentially have been established numerous places within several experiments. However, the chapter aims at being as faithful as possible to the real unfolding and development of the experimental work. During the project, the thought process of the experiments has evolved in partnership with the shaping of the methodology. The 'Experiments'-chapter seeks to reflect this process even though the linear format of the dissertation does not adequately communicate the overlapping and cross-fertilisation among the experiments. The reader should, however, be welcomed and encouraged to jump between the experiments within the chapter and back and forth between the 'Methodology' and the 'Experiments' chapter.

Throughout the project, numerous theories, writings and research projects have been used either as tools for initiating or situating experiments or thoughts, or for discussion and reflection. These references and state-of-the-art projects are introduced ongoing in the dissertation. They are presented in what connection and at what stage in the project they were actually used. Many of them, however, could potentially feed into several experiments and discussions and their effect on the project often goes beyond the point of their introduction.

The 'Conclusion'-chapter sums up the work of the experimentation through a transverse exposition. This cross-reading of the series of experiments as a whole provides an unfolding of the influential elements in processes that connects the domain of digital drawing with the domain of realisation. The elements are understood as connected interfaces that each affect the outcome of the experiments.

Contextual anchoring

A rapid development in both computer-aided drawing and designing software and digital fabrication tools are changing the interface between representation and realisation. Digital drawing and designing software have long been well-implemented instruments in the production of architectural ideas and architecture. They often play a vital role in the total process, including sketching, development and realisation.

This well-implemented and substantial group of tools is going through a never-ending development that continually brings new possibilities and strengths to the hands of the architects. The interface that has arisen between architect and computer has opened up new ways and powers for handling, processing, converting and sharing data and has in many respects changed the ways architects work, but also directly how architecture appears (Callicott, 2001; McCullough, 1996). Consistently, the software and interfaces are gaining wider abilities. Among those abilities are closer relationships to the tools used in the world of manufacturing and fabrication. Possibilities of engaging with production are getting easier to access for people not directly involved in industrial manufacturing.

Simultaneously, the technologies that employ digital fabrication tools are getting cheaper and more accessible. They are now present from consumer to manufacturer level and anywhere in between. Today, it requires no more than a laptop, a 3D printer and very basic computer knowledge to start up a digital fabrication workflow. The fact that manufacturing technology and user level designing are increasingly overlapping is starting to change the tools we have at hand and the way we regard a design process. However, the current development does not only mean a downscaling of industry machinery to a plug and play user level. The possibilities and courses are multi-directional. Integration of software and hardware creates similar opportunities for designing into, or at least closer to, an industry-grade production. Digital drawing software can be used to instruct the machines to move, orientate and process. In industry, these machines process real materials with high precision. What they do is not new. They create parts and components used in a variety of industries and production. How they are controlled, however, and how easily they are controlled, creates the foundation for a new and tight connection between the world of digital drawing and digital fabrication (Sheil, 2005).

Architects can utilise the connection between digital drawing and digital fabrication to engage directly with materials. Direct intervention with, and continuous feedback from materials allow architects to explore them in new ways in relation to architectural production. New material possibilities create a foundation for the discovery of new aesthetics, tectonics and constructions. It is the claim that this fused space of digitality and reality, immateriality and materiality, can allow architects to access and unfold options and opportunities for design. The correlation between digital drawing and materials through fabrication can establish an unbroken, but highly susceptible, link between early experimentation, design and component development and potential final fabrication.

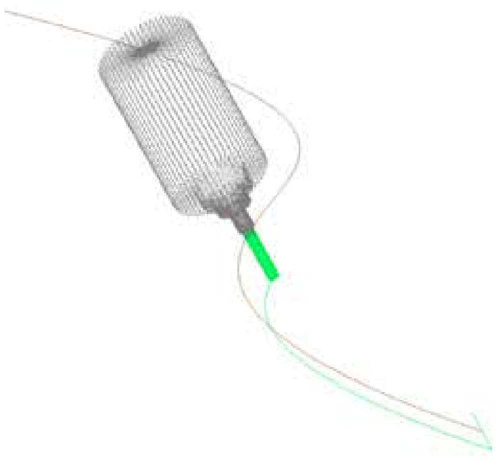
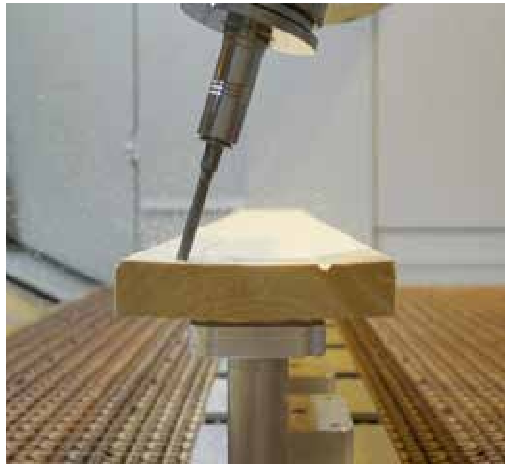
Representation and realisation

Traditionally, the realisation is an essential objective for architects. However, the realisation, or construction, itself, is not the job or responsibility of the architect. While architecture as discipline, both looking at the past and into the future, seems to be bound to the consequence of a physically constructed outcome, the event of success is apportioned on, and complicated by, many shoulders.

A division, or split, of the role and responsibilities of the architect, engineer, builder and craftsman, has often been ascribed to Italian Renaissance architect Leon Battista Alberti, and specifically his works and treatise *De Re Aedificatoria* (1404-1472)(Alberti, 1988; Bonner, 2012, p. 229). While some kind of separation between designing and making can probably be traced back to the origin of the discipline, the Renaissance has been imposed the burden, or honour, of extricating architecture from being an applied art to being a liberal art. Alberti positioned the architect as an almost divine designer who was disconnected from the work of construction and instead appointed to the mastering of representation. This split of designing and building focused the architect's work towards a universal notational system through which spatial design and construction can be created and disseminated. The representational system of drawing became the language of the architect and has since been the dominant medium for the profession (Carpo, 2011; Ingold, 2013; Pérez Gómez and Pelletier, 1997).

Whether this positioning of the architect happened solely because of Alberti, the discourse of the period, Alberti's articulation of the discourse of the period (Grafton, 2000, pp. 267–269) or something more complex can be discussed and scrutinised, but nevertheless the division of responsibilities and the depiction of the architect as an autonomous figure belonging to the world of the arts has strongly defined and characterised the discipline since around that time. Today the architect is often depicted as a source of creative intentions and innovative ideas and even often personified as a star or starchitect, thereby following Alberti's definition and proposed hierarchical placing of the architect as a divine innovator, instructing, but detached from, the actual realisation.

Alberti's description of the architect and promotion of the universal drawing was also a relentless quest for the identical copy. Alberti sought to

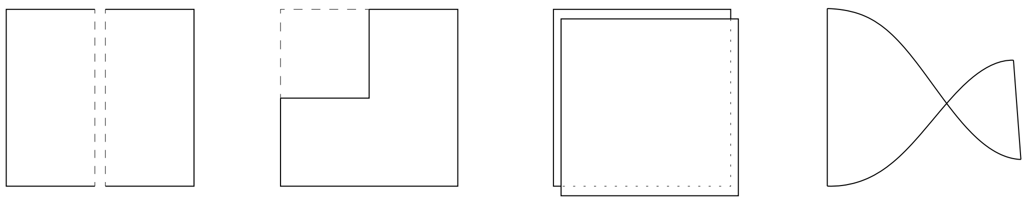
Digital drawing and digital fabrication can be closely interconnected.

break the design free of the making and set up a system that could inform production without directly engaging it. The idea of the identical copy was first realised as the consequence of the Modern Age and the mechanical technologies it brought along. The Renaissance idea of architecture as an authorial, allographic, notational art has until recently defined the architectural principles. Today's digital turn is, however, unmaking this. (Carpo, 2011, p. 44)

The use of modern digital tools and instruments ranging from software to hardware have managed to shake the foundations of Alberti's distancing from materialisation and view on the architectural discipline. The overlap of information created by architects and the information needed for production blurs the lines between representation and realisation. The drawing of the architect can act as both, and the materialisation can be an extension of the creation of the drawing. Even though the general practice of architecture is still more or less unchanged, the potential of a reconnection with making becomes more and more evident. By taking advantage of the transgression from drawing to making (Sheil, 2005), architects can establish a new connection to materials that can inform the designing in a coherent way. The design does not need to end with a drawing set. The traditional representation can maybe be challenged, and design can develop through making and drawing simultaneously and end up as either or both. Potentially, architectural production can be a type of representation that transcends its own borders – or partly realisation itself.

Experimental framework – materials and machining

The project is established within an experimental framework that consists of materials and machining approaches. This framework is regarded as a dogmatic core throughout the entire project. Every experimental setup is insisting on establishing a discussion that includes elements of the framework. However, externally found elements can be added to the experiment if this makes sense. The structure is created to be a tangible frame from where more intangible thoughts and arrangement can be tested. These more speculative constellations are continuously born throughout the unfolding of the project's intention and queries of interest. The framework is also a way to anchor the entire project



within its intended context. The project is aiming at being relevant for the practice and discipline of architecture, and thereby committed to a production and discussion that are, somehow, linked to these.

The experimental framework involves three materials and four types of processing. The materials are concrete, wood and steel. The processes are division, subtraction, addition and transformation.

Processes of machining

The processes in the project are all linked, but not limited, to different types of machines or fabrication strategies. This is to ensure that they can function as straightforward and active ways of engaging materials and not only as conceptual labels.

The act of dividing is derived from machines that cut. Those can be laser cutters, knife cutters, hot wire cutters, water jet cutters, etc. Subtraction is taken directly from the type of machining done when milling or routing. Additive manufacturing is generally known from the 3D printing industry – but is not limited to this. Addition is considered a more general level involving all types of posing and composing of the materials. Transformation refers to actions that change a mass of material from one condition to another. This can be related to a state, form or anything else, but is distinguishing itself from the others by not interfering with the amount of material but instead the circumstances or distribution of the material. The four types of processing are not set up as a limit of interaction – other possible processes can join in interplay with them. Likewise, the processes can be combined in the experiments.

Properties and capacities

The materials – concrete, wood and steel – are selected both because of their different characteristics and because of their direct relevance and connection to building and thereby to architecture. They are not novelties themselves, but they represent an assortment of materials that are bound to long traditions of processing, constructing and refining and at the same time still very present and prevailing in contemporary buildings. All three materials can be found in almost any building today and are impossible to ignore, no matter what agenda one might have, in the context of building construction.

From top and down: Concrete, wood, and steel are important and non-ignorable resources used in the building and construction industry. Photos from studytrips in US and Canada.

The materials chosen are also rather different in the state in which they are usually processed. Concrete, is when looked on at a larger scale, an isotropic material. It is fluid for a limited period of time in which it can be given a shape, then cures hard as stone. The fluid state makes it not only possible to shape the material on the basis of other things, but also to combine other materials or agents into the mix. Concrete has a high density and the great mass can impact the formwork and context during casting and curing.

Wood is a naturally grown material that comes from an almost infinite number of species each with specific characteristics. A general characteristic for wood is fibre directionality. Based on the particular species of wood the strength and elasticity of the grains will vary. The grains in the wood make it an anisotropic material that will respond differently to machining depending on the orientation of material and/or tool. The machining of wood is also dependent of the moisture content of the material. That will vary from species to species and be a result of the amount and type of storage prior to the machining. Due to following drying, wood will generally warp or crack after machining.

Steel can be shaped from its fluid or solid state. In order to cast fluid steel it will need to be heated intensely in a forge. The shaping of solid steel can be done using several machining types. In its solid state, steel is isotropic but often limited by industry standards to specific dimensions, geometries or sheet thicknesses. Often, parts constructed in steel will either bear references of prior given geometries or dominated by flat surfaces. Parts routed from a single steel block will have uniform material appearance with tool imprints defining the surface.

As outlined here, the combined range of material characteristics gives a good basis for different types of experimental exploration. The behaviour of the materials in relation to the processing is of keen interest and seen as a starting point for making discoveries. The encounter of materials and tools will result in consequences related to both. To expose these occurrences and thereby the experiments, differentiation between material properties and material capacities is made. Material properties are defined as objective characteristics that can be listed. Capacities, on the other hand, are relational. A capacity to affect always goes with a capacity to be affected (Aagaard, 2015; Delanda, 2007).

The distinction between properties and capacities is crucial when determining the sequence of events that occurs when material experiments are established and gives a valuable perspective about decision-making during experimentation. Of course, any machining applied to a material will directly be influenced by whatever properties the material is holding. A well-matching combination of machining type and materials will likely give a controllable, maybe even predictable, experiment, whereas a non-matching combination might get totally out of control and, ultimately, result in physical damage. It is in-between these extremes of material consequences that the experimentation is intended to be carried out.

Establishing and utilising the experimental framework

The selection of processing methods and materials is seen as a framework in which the experiments can arise and unfold. If the processing strategies and materials are considered a matrix, the experiments can happen at any intersection. The experiments, however, are not confined to a combination of just one material and a single process. The framework set the outer borders, but inside these, the experiments can sprawl into fields that include multiple materials and methods of processing. The framework should also not be seen just a tools for the initial combination. The possibilities within the structure exist throughout the timeline of the experiment meaning that the investigations can expand or limit their inclusion of materials and processing methods during the execution.

The experimental framework should be seen as an instrument for focusing this particular project within a larger field. The approach of directly engaging materials with an experimental attitude to the use of digital machining is both a strategy to investigate the unknown potentials of the materials and develop a very close relationship to reality using drawing tools and explorative methods already established in architectural designing.

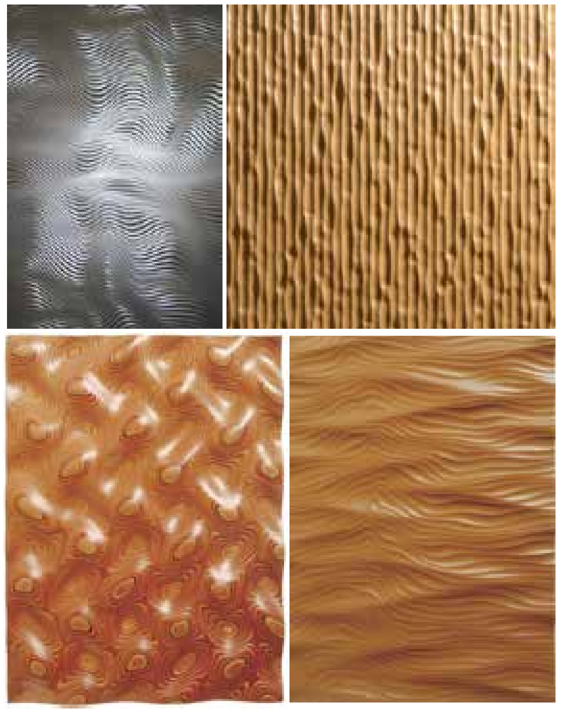
Designing by materials and machining

An example of a material experiment is the work *Objectile* (Beaucé et al., 2007; Cache, 1995) by theorist, philosopher, architect and industrial designer Bernard Cache. *Objectile* consists of a series of tiles made by the machining of different

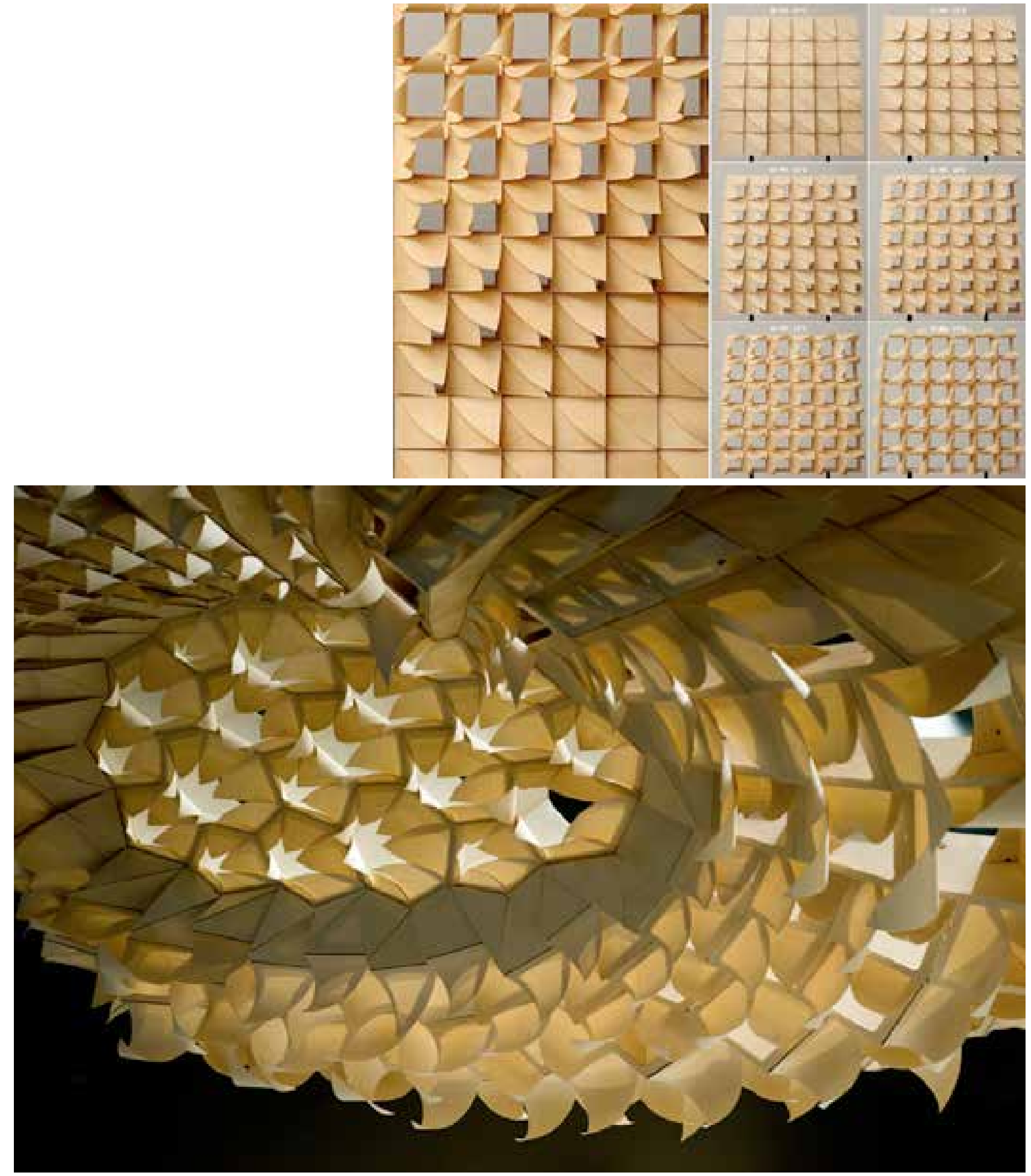
laminated wood sheets. The machining was based on parametrically defined digital drawings and a CNC router. The encounter of the tool and the material revealed the layering of the sheets and formed the three-dimensional shapes in the materialised results. This direct, tangible relation between information and materials moves the designing closer to material reality and at the same time expands its means into the computational world. For Cache, and his practice, this has resulted in interconnected historical, mathematical and philosophical research in today's computational and material technologies and the traditions of the past (Cache, 1995), and creation of a series of physical artefacts labelled "non-standard architecture".

Another more recent example of material experiments in architectural design is the meteorosensitive morphology research by Achim Menges in collaboration with Steffen Reichert (Menges, 2012). This research is based on a systematic testing of wooden fibre's ability to naturally deform in response to the surrounding humidity. Through years of studying the behaviour of different types of machined wood, Menges's research group found a connection between the wood's inherent properties, the machining and the wood's reaction to humidity changes. This knowledge made them able to control and design specific machining strategies that resulted in wood with explicit deformation features. From these designed processes the material research formed into *HygroScope* (2012) – an installation in Centre Pompidou Paris – and *HygroSkin* (2013)– a pavilion at FRAC Centre Orleans.

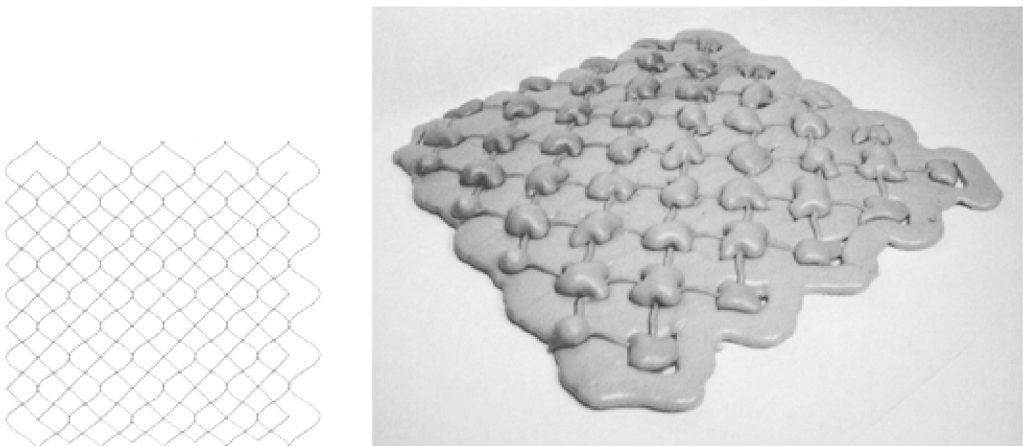
At ETH Zürich, under the professorships of Fabio Gramazio and Matthias Kohler, countless combinations of tool and robots have taken place. A smaller but conceptually very strong experiment is the combination of robotic control and a continuous deposition of expanding polyurethane foam (Gramazio et al., 2014, pp. 84–99). The project named *The Foam* (2007-2008) explores the space emerging when digital drawing is used to control an uncertain material process. The robot moves accordingly to the accurate drawing and deposits foam along its path in correlation to its speed and tolerance. However, the result is profoundly influenced by the expanding of the foam. The foam is reacting after being deposited – often while the robot is still working. The appearance of the outcome is a consequence of the combined process of the



‘Objectiles’ by Bernard Cache are clear outcomes of machining and material. Both parts play an equally significant role in the forming and appearance of each tile.



The behavior of thinly sliced wood informs the design of HygroScope. Experimental studies and systematic documentation of machining techniques and material properties bring new aesthetics to architecture.



The uncertain premise of the expanding foam and the planned tool path of the robot combines into a realisation in the early Gramazio Kohler research project 'The Foam'

deposition and the expanding of the material. Both the behaviour of the foam and the drawings are readable in the results. This is an example of the encounter of process and material capacities.

While the three examples of projects are quite different, they all share the fact that they are combinations of specific types of processing strategies and specific properties and capacities of the involved material. The examples are just a small selection of relevant projects within the field. However, they represent a potential of the investigations and outcomes that can happen within the experimental framework of this project. The examples are utilising their content in a highly explorative way that in every case result in materialisations that are determined or designed through the process of the experiments.

An interesting and important aspect of the exemplified projects are the connection between process and outcome seen in relation to acts of designing and drawing. None of the projects are realisations of predetermined designs. The designs are created through the making and based on the findings of the experimentation. This point to the vital fact that design and drawing are not just a production of information alone. Every process of designing needs a medium in order to exist, and that medium will always affect the design. Designing will always incorporate a degree of making that actively responds to the process. Thereby, designing is a much more susceptible practice than just being the capturing of ideas in the medium (Chard, 2012; Spiller et al., 2012). And the process is two-directional: making will also comprise a degree of designing. This tacit, but strong, relationship between what architects do and how architects do it becomes essential in the understanding of the potential scope of this project. Designing and drawing is a form of thinking that evolves into a formulation of an idea (Groák, 1992). The three examples shown above point to the potential of transferring this way of thinking into processes and materials belonging to the world and scale of realisation.

METHODOLOGY

Experimenting

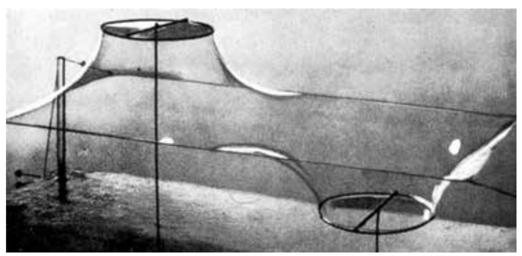
Bespoke Fragment is built around experiments, the act of experimenting, but also the discussion of experiment and experimenting in the context of architecture and architectural research. Experimentation as a word or action sits comfortable in the discipline of architecture. Being experimental or conducting an experiment seems like a familiar concept as a part of producing architectural design. Experimentation are either demanded or taught in most architectural educations as well as the behaviour of 'being experimental' is something many practices are utilising as a working method in order to create innovative ideas.

Within scientific research, the experiment is, as well, a very well established way of gaining knowledge. Often has experimental methods been articulated as equivalent to the 'scientific method.' An experimental strategy can take many forms, but in all situations the act of experimenting and setting up an experiment is a construction to engage a present actuality.

Experiments play a central role in this project. The general reason for this can be explained by the ability of the experiment to reach out and engage. This articulation is, however, quite broad and it will need further unravelling. The use of experiments in general and in connection with architecture and building requires further elaboration.

The relationship and the hierarchy between theory and experiment seem to be an ongoing, turbulent affair. Through the history of science, the highest acceptance and appreciation of the one or the other appears to be a, if not shifting, never finalised discussion.

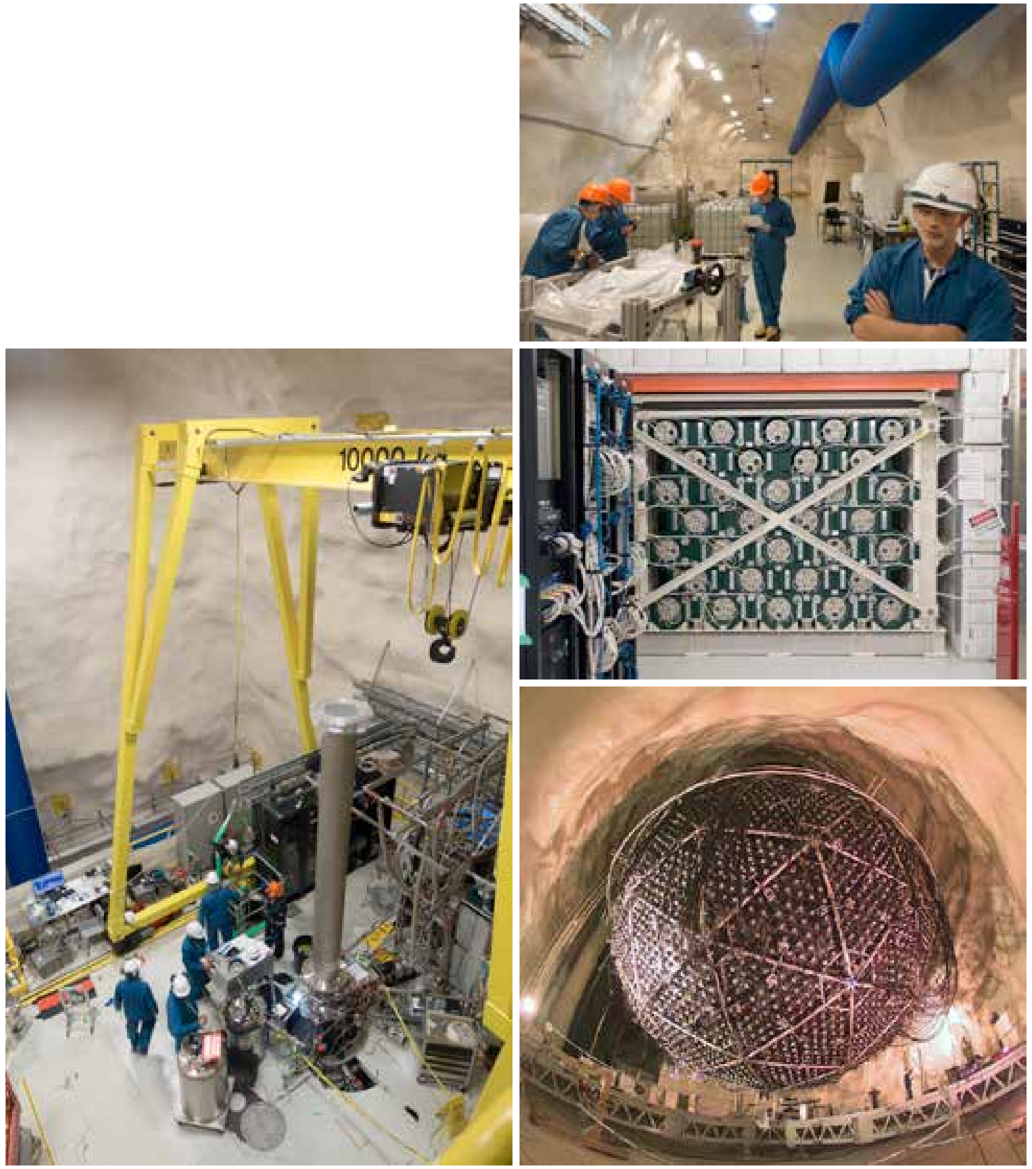
Nicolaus Copernicus and Galileo Galilei are often noted as the founders of the methodical, experimental approach to science, physics, and nature, and Isaac Newton as the formalising force of this methodology. The founding and formalisation of this type of scientific work were based on a

Left: Gaudi's hanging model for Colonia Güell.
Right: Soap bubble experiment by Frei Otto.

combination of observations and mathematical description of those. The approach was calling for an inductive-deductive strategy. Generally speaking, mathematical or theoretical descriptions or explanations were made from large quantities of observations. These descriptions then functioned as a structure for a deductive, general understanding of the properties and behaviours of objects in nature (Kotnik, 2011, p. 27). This experimental approach allowed observations of actual viewable or readable responses of existing, performing phenomena to be the basis for a universal thinking that then again could be tested on specific observations.

In architecture and building the use of an inductive-deductive experimental method has proven a valid, though limiting, strategy. Good examples of the use of the experimental method as a controlling design principle are found in the works of Antoni Gaudi and Frei Otto. Gaudi's hanging chain model is an excellent example of how a specific experimental method is used to identify correlations, derive design principles and use those for building construction (Huerta, 2006, p. 331). Similarly, the studies and descriptions of Frei Otto's tent-like soap structures are an observation-based research strategy that leads to mathematical descriptions of optimised geometry. His deductions opened a world of construction types probably not imaginable without the prior experimentation. Frei Otto himself has strongly advocated for the use of experimental research as an essential path for architectural development (Songel and Otto, 2010). However, Otto also acknowledges fundamental problems with his integration of scientific experimentation in architectural practice. While being able to extract form and optimised geometry from his physical testings, he argued that this as a design work was not comparable to that of a building project. Buildings are not individualities but integrate into surroundings and society. This statement is expanded upon by Toni Kotnik (2011, p. 29) and explained by the fact that in a scientific-experimental arrangement the number of possible determining parameters must be reduced. This is needed to focus and target the experiment on the phenomenon in question, but naturally also only give an equivalent focused set of results. The nature of scientific experiments can thereby limit the design space dramatically if architectural work is carried out only on the basis of this. In cases where the experimental



Visit at SNOLAB, Sudbury, Canada, Summer 2015: SNOLAB is an underground science laboratory specialising in neutrino and dark matter physics. The laboratory is located at a depth of 2070m and comprises 5000m2 clean room facility. Through a continuous series of particle detection experiments, SNOLAB seeks to ascertain - prove or disprove - established theories of sub-atomic physics. More information at https://www.snolab.ca

output dictates the governing design principle in a meaningful and substantial way this might not be problematic, but nonetheless, it eliminates the possibility of a general direct translation from experiment output to design concept.

In his book 'Representing and Intervening' Ian Hacking (1983) is processing the historical relationship between theory and experiment as well as putting forward his own thinking on the subject. Hacking brings a series of philosophers of science and their arguments into discussion and debates their positions. Hacking himself is generally rejecting any argument that demands theory before experiment (Hacking, 1983, pp. 194, 155), but concludes that any one-sided view on the matter is wrong. Hacking is favouring a 'Baconian' (Hacking, 1983, pp. 149, 166) understanding of the experiment which praises not only the experiment as an inductive way of understanding the actualities, but a way to, by the words of Francis Bacon, *'twist the lion's tail.'* This is explained by Hacking as to *'manipulate our world in order to understand its secrets'* (Hacking, 1983, p. 149). Hacking's comprehensive exposition of the relationship between theory and experiment has not only inspired *Bespoke Fragments* to embrace the unplanned and uncertain aspects of experimentation as both necessary and valid elements but also to some extent to abandon any prejudice related to the experiment as a method.

The presence of 'the architecture' within the concept of 'architectural research' sometimes seems to let the field fall between two stools: Experimentation is an established type of knowledge production within scientific research. Nonetheless, architecture is an area which exists in both the categories of humanities and art. The built-in focusing and reducing consequence of scientific experimentation is therefore not necessarily making the relation between architecture and architectural research easily applicable when the experiment is implemented in the format found in scientific research. On the other hand, the intuitive nature of an architectural design experiment is not necessarily and immediately accepted in a traditional research context. The relationship between art and science is a paradox (Kjørup, 2006).

This project is utilising experimentation as a research method, but do not attempt to evaluate the outcomes from the perspective of a scientific method. Concretely, this means that the experimentation called for in *Bespoke Fragments* intends to engage actualities, observe occurrences and challenge the actual through manipulation, but does not intend to deduce universal thinking or general models or unambiguous theory based on those experiments. Instead, the experimentation will call for more discussion-based round offs that reflect on the outcomes from an architecture-oriented perspective. It is important for this project that its attitude towards experimentation is seen as a premise for the project, but not as a specific agenda. From a historical perspective, utilising the experiment as a method of engaging the completely uncharted seems like a well praised practice. However, history also points to the fact that the experiment as method can take many forms and that the relevance and regarding of the experiment might be more a discussion of discourse and context than about outcome.

Throughout the PhD-project experiments based on material exploration are carried out. The processing of materials is a main driving force in the research production. However, in conjunction with the material revelations, the behaviour and role of the experiments seen from a design methodological perspective are discussed. It is not the intention to directly translate material output to architectural suggestions or dreams – even though this is a possibility. The act of the material experimentation as a design tool is, in itself, a case for inductive reasoning. A notable payoff from both the material output and the act of experimenting is the experience. Experiential knowledge is a result of continuous experimentation, but also, traditionally, what causes the friction with theoretical knowledge. Experience is, naturally, anchored in its origin, thereby not in itself an autonomous type of knowledge. Since this, aforementioned, discussion of hierarchy is a mainly scientific-philosophical matter, it is not the intention to unravel it here. Instead, this project takes advantage of the character of experiential knowledge gained by experimentation. Because the experiential knowledge is directly connected to whatever process and material it is gained from, it constitutes an action into reality and an extraction of information back to the intention from where it came. An amassing of this information is the setting for experience and thereby a possible induction of specific principles – still with an unbroken link to the realities.

When an experiment is established and carried out, information from its experimental framework is feeding it and an opposite stream of

consequence-based information feeding back. This information would, under a more traditional scientific-experimental circumstance, be the resulting data from which inductive reasoning could be made to create a more general assumption. As said to earlier, this could be challenging when considering the potential of bringing the experiences into architectural design. Moreover, this is the point where the intention of using experimentation within this research project can be unfolded. The material experimentation in this project is not triggered by the eagerness to create general material-physic assumptions – and for that the data quantity is also too small. Likewise, it is not the primary expectation to invent new material systems or types of processing – even though this is a very welcome by-product. Instead, the aim of experimenting directly with materials is to seek out the possibilities when an inquisitive design intent navigates the experimental course. Therefore, the decisions and the points of decision-making throughout the experiment becomes of interest. In that way, the unfolding of an experiment can be seen parallel to the development of a design and the actions made within the experiment as similarly crucial for the outcome.

Feedback through production – an iterative approach

The types of experiments suggested and carried out in this research project call for developments and findings through discoveries of uncharted territory. The kinds of experiments suggest an iterative approach that allows a cyclic development and refining based on the ongoing process. Outcomes should be looked upon, potentials considered and a new iteration triggered. The nature of an iterative process allows the experiments to evolve asynchronous, meaning that each element of the operations does not need to progress for every iteration (W. Royce, 1970). Instead, the totality of the process is redone multiple times with different elements of the process improved for every iteration.

Before actual implementation of the experiments, a strategy and perspective for the operations are created. The research is not planned in terms of how exactly the experiments are executed or how they are expected to end. That is an ongoing and quite a fluid process. However, the way experiments are structured in relation to manoeuvrability and reflection is considered beforehand. It is important that the experimental setups are created so they,

Persistent Model #1 and #2 by Phil Ayres: The series of inflated steel constructions is an iterative process that evolve through each materialisation.

in an operative way, can react and reshape based on the progress of the experiment. The experiment designs will, in other words, need to be quite agile constructions that simultaneously frame the investigation and adapt to it. The experimental setups will need to both output and call for feedback in order to let the findings guide the progress. The utilisation of feedback as an active input to the experimental process can create an iterative workflow where improvement and discoveries can be explored on the basis of recently produced output.

In order to maintain a reasonable overview and be able to follow and interact with the experiments they are looked upon from two perspectives: Their linear construction and their cyclic possibilities. This might not give a full overview of all experiments or describe all types of reflections or interactions made during the progress. Nonetheless, these two perspectives were defined at an early stage of the project in order to or prime an awareness and attention of the experiments to be.

The linear description of the experiments is a simplification of the not necessarily, completely linear mode of processing that each experiment consists of. All experiments are, given the overall framework of the project, comprised of materials and processing. The combination of those is done through a workflow that will always to some extent be linear or partly linear. The workflow, and the associated production, consist a number of phases or elements. Often, all of these phases might not be immediately evident. The workflows need to be stretched open to reveal all aspects of their construction. The mapping of phases is the valuable perspective on the experiments' linearity. By finding and understanding the details of the specific workflows they can be scrutinised in a search for possible connections and interactions. This view upon the workflows is thought of as a strategy to localise otherwise overlooked approaches towards the experiment, but also necessary in order to initiate a comprehensive iterative process that can include development on all levels.

The cyclic potentials of the experiments are looked upon in direct relation to their linear constructions. If an operation offers a series of phases that provide possible input and output, those phases can potentially be linked into processes that can evolve cyclically. Given the overall iterative approach to the experimentation, every experiment can be seen as a cyclic process in its totality. However, the iterative approach is also sought to be implemented on a sub-level, allowing linked phases of the experiments to develop in parallel with the overall experiment. Potentially, this can disrupt or distort the experiment. However, since all cases promotes finding over proving, this consequence could possibly be a welcome feature. The acknowledgement of potential found in the experiments can, hopefully, allow a varied progress that comprises branchings and deviants.

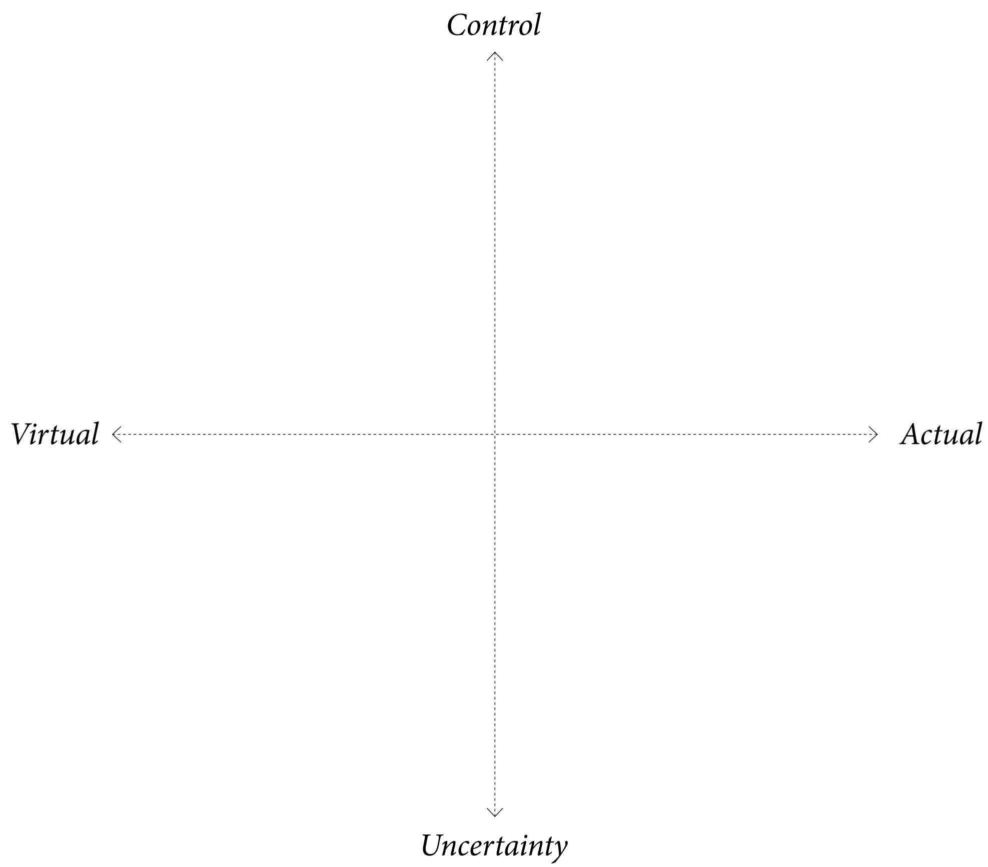
The iterative attitude to experiments that is suggested practised in this research project should, of course, be seen in continuation of the specific topic, and thereby the particular type of experimentation in the project. The transgression from drawing to making using digital fabrication tools almost by itself call for an iterative approach to making (Kolarevic, 2008; Sheil, 2005). The ability to materialise based on drawing capabilities and following inform the drawing through the evaluation and feedback from production provides a connected workflow that, in an architectural context, sets a much better circumstance for iterative design and realisation than previously seen.

A specific example of an integrated feedback loop and utilisation of iterative development is seen in Phil Ayres' project *Persistent Modelling Project* (Ayres, 2012a, 2012b). *Persistent Modelling* both exists as an articulation of a type of workflow and as a series of experiments exploring the inflation of steel sheets, turning them into structural components. The project aims to reconsider the relationship between architectural representation and architectural artefact by setting up a workflow where corresponding digital and physical developments are informing each other. Computer simulations of seemingly uncertain output are made, and physical materialisations are carried out as real, but conceptual, experiments. Digital and physical creations are compared and informing each other, thereby pushing the development, iteration by iteration.

Ayres' approach to both digital tools and iterative experimentation are exemplary. The methodology exhibits a model for a very integrated relationship between input and output in both the digital and physical domain. Ayres' work has indeed informed and inspired this project on both a methodological and material level. Nonetheless, the view on feedback and iterative production is slightly different within this project. Where Ayres seems to seek a corresponding information between digital and physical, the iterative experimentation in *Bespoke Fragments* allows a higher degree of interpretation and asymmetry between the two. The suggested approach in this project seeks to push both domains forward through a mutual feedback, but allow quite a gap between what they represent. They do not necessarily need to simulate each other, but are instead a concerted set of information that, when combined, conveys the content of the iterative experimentation. This discrepancy between the setup in *Bespoke Fragments* and the referenced work by Phil Ayres is a result of a strong commitment to embracing the uncertain aspect of material experimentation. This is reflected in the articulation of the aforementioned expounding of the linear and cyclic construction of the experimentation in this project.

On a very concrete level, this project seeks to move operative information back and forth between digital and physical. While the feedforward is often done through the experimentational framework – the materials and the machines – the processing that defines the experiments do not necessarily include the ability of feeding back. The feedback that triggers the next iteration, and for instance affects the drawing, is thereby often based on the experience, understanding and interpretation of the machined outcome. The experiment will be evaluated based on the result and process at hand and premises will be changed and adapted accordingly. Sometimes, however, the feedback needs to inform the next iteration in another, maybe more analytic, way or the feedback from a materialisation is an incorporated step within the linearity of an experiment. The use of digitised actualities then becomes useful. Photogrammetry, digital metrology and 3D-scanning are utilised tools within this project. The ability to go from reality to digital with information that is not easily geometrically described, can become essential when working with highly uncertain material consequences. The process of 3D scanning is widely used, and also discussed, within the experiments. However, the technology is purposely articulated as another category than the methods of processing. The feedback gained can be essential for the processing, but the relation to materials is different.

The iterative experimental approach applied in this project should be seen not so much in relation to whatever finalisation that might eventually remain, but more as a tool to break down every process into phases that can be understood and influenced. The iteration-based process is, in this project,



not an instrument for debugging or prejudiced correcting, but a way to find relations and define parameters that can push forward the exploration of the experiments.

Setting up the experiments

To implement material research and material experiments as a part of the earliest architectural design phases, an open minded and non-deterministic approach to the material investigations is required (Kolarevic, 2008). Discoveries made by studying and exploring materials through machining can be of a highly unpredictable character and lead to many surprises. These surprising outcomes of the encounter of machining and material properties should be considered qualities in the phase of exploring form and design as well as an opportunity to let further investigations shed light on the relations between particular machining techniques and certain material properties or capacities.

To position the processing of materials as an essential experimental way of discovering and initiate design, it seems natural to move the existence of machining and materials from the end-result oriented manufacturing phase to the earlier and more inquiring architectural design phase. Results of material experiments made with an investigative objective in mind will contain a type of knowledge that is tangible, but not primarily technical. The outcome will not be a realisation of a design, but instead hold the potential of initiating a design or facilitate the beginning of further research.

A combination of this aforementioned iterative approach and the experimental framework sets the basis for every experiment carried out in this project. The drawing is regarded an instrument to embed information into materials through fabrication, and in that way, altering the capacities of the materials on the basis of their properties. It is when new material capacities are created that findings and revelations unknown prior to materialisation are believed to surface.

Navigating (within) the experiments

Within the possibilities given by the experiments, a constant act of, interaction and decision-making is required in order to both search for and intercept encounters with architectural or spatial interest. The experimental framework for the project gives numerous combinations of materials and machining types and the intention of exploring is calling for a non-deterministic approach that occasionally relaxes the level of control. The machining is seen as a continuation of architectural drawing thereby moving the structure of sketching and designing from a mainly representational domain into a realising domain.

Through the execution of experiments a kind of cartesian system of orientation has been created. The system establishes an experimental field by uniting two spans. One span is defined by the extremes of *virtual* and *actual*, and the other by the extremes of *control* and *uncertainty*. Experiments are seen and conducted as being moving and living within this compass. The system is both a result of the experiments carried out through the entire project and a methodological strategy used to navigate within and across the experiments. The development of the experiments has created the system, and the system has created the experiments simultaneously.

While some experiments might operate in some areas of the system more than others, the situation and orientation are in flux. The experiments will be seen moving around within and across the two spans. The position of the experiments will change throughout the execution and development, thereby placing the orientational system in a compass-like role describing a momentary course, never labelling the entirety of an experiment or the project.

The articulation of the system has taken it from being a subjacent, implied existence to an applicable tool during the full timeframe of the research project. At its current state, this system of orientation can provide the key to understanding the research development in *Bespoke Fragments*. However, it is important to recognise the genesis of the system as a consequence of the experimentation and not the other way around. The system should be seen as an active strategy that has steered the exploration of the experiments within the experimental framework, thereby helping the unfolding of the investigations along, both during the planning, through the execution and in the following reflection. Sometimes, the experiments will explicitly refer to the system of orientation and other times, the system will exist as an underlying, implicit construction. The varying obviousness of the system should be seen in the light of its reason of being: it is a tool for the experiments to use, not a claim for the

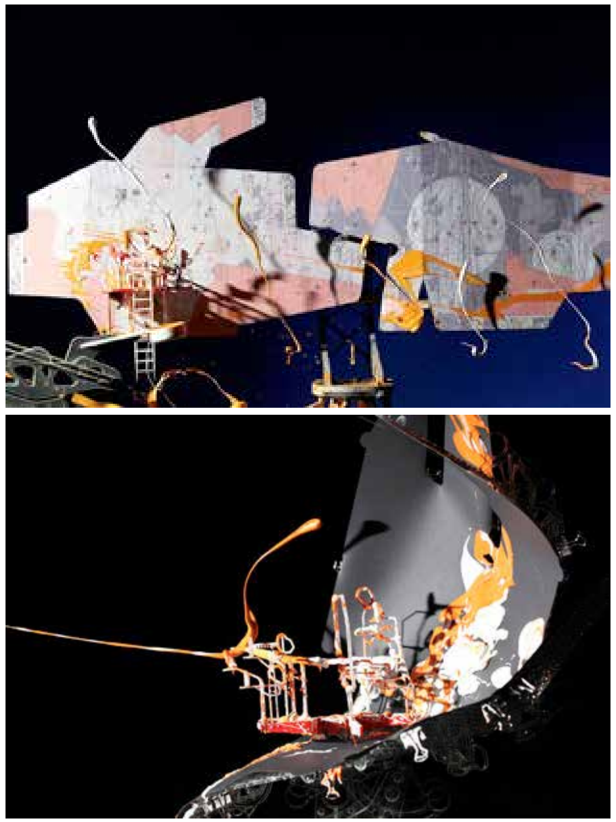
experiments to prove. Whether definitely expressed or not the development and existence of the system is always an implied and functional part of the experimentation.

Uncertainty and control

To understand the system, the spans, or axes, need to be explained. The two extremes of control and uncertainty are describing the element of exploration or investigation required and desired in an experiment. The material exploration initiated through experimentation is in need for uncertainty or risk-taking in order to exist. A premise for seeking to find the unknown is logical enough not to know it to begin with. Therefore, a level of uncertainty plays a central part of the material investigations. Another premise is that of inductive reasoning. To establish a correlation between observations, an amount of systematisation is needed. Coincidence or pure luck can make discoveries, but to understand them well enough to utilise them, testing and verification are required. This means that, for example, an initiating phase of an experiment can be driven by a high level of uncertainty to find possibilities through the encounter of material and machining. The following phase of controlled testing can then be used to understand the findings. Control can also be the initiator of an experiment. For example, systematic testing starting off with known behaviours can widen the established field of knowledge by gradually moving from a controlled situation into uncertain areas. A shuttling between control and uncertainty can, of course, be related to several aspects of an experiment. It can be the actual control of machining, how drawing information is created, the result of the meeting of material and tool or anything else. The extremes of either complete control or the total lack thereof may be less interesting or useful than the area existing in-between.

Indeterminable drawing

An example of an exploration of uncertainty is seen in the works of professor Nat Chard. Chard has produced several interesting pieces of work through the years but his series of 'drawing instruments' carries a certain, well-developed discussion on uncertainty and architectural drawing or production (Chard, 2015, 2012a, 2012b; Chard and Kulper, 2014).



'Drawing Instruments' by Nat Chard. The uncertain path of the flying paint is captured midair.

Chard's series of numbered 'instruments' discusses an extended understanding of drawing and the drawing plane in an architectural context. The instruments are active drawing devices, and the most recent of his constructions contains paint catapults that utilise a combination of model-like scenic orchestration and uncertain flying paint. The instruments incorporates sophisticated storytelling, but also contains an incredibly high level of precision and carefulness. Every detail seems thought through. However, the instruments eventually end up throwing paint at each other. The flying paint is captured midair by high-speed flash photography and the event carefully and systematic documented. The collision between the rigorously controlled construction and the uncertainty of the result is fascinating. What makes it truly relevant, however, is Chard's anchoring of his research in a fundamental discussion of drawing and how architects work. Chard explains that architecture is quite an unreliable occupation and that the discipline has consequently concentrated on the predictable elements within the creation of design. Chard argues that the conventions around architectural drawing are an example of this. Architectural drawing tries to be explicit and non-interpretive. Therefore, Chard seeks to engage drawing types that are outside the conventions and instead investigate the indeterminate and uncertain aspects that architecture actually deal with (Chard, 2015, pp. 122–125). The notion of drawing becomes expanded into the instrument, and the actions of the instruments are regarded as acts of drawing. Eventually, the production – the drawings – are much closer related to the actual meaning than the ordinary creation. Consistency between working methods and the material seems to develop.

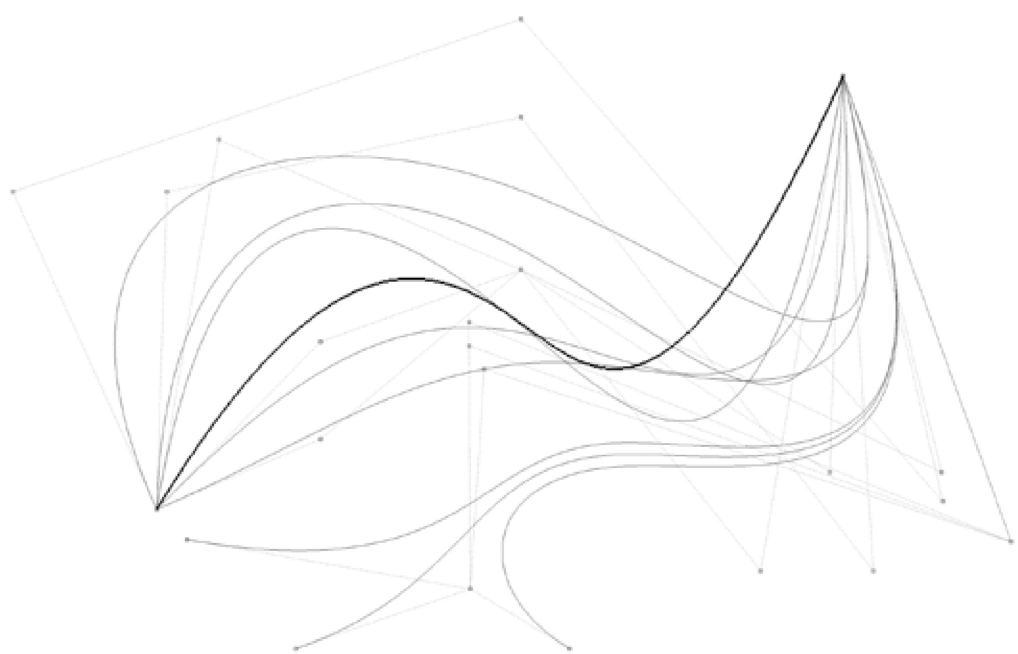
The correlation between the high level of control and systematisation in the drawing instruments and the uncertainty they embrace and unfold are fine examples of architectural experimentation and research. The relevance and direct connection to the discipline is distinct, but the alternative approach to the matter creates the possibility of discussing essential elements and paradoxes of architecture on a level deeper than the surface commonly regarded as the production of architecture. The debate about the role of the drawing is maybe a bit intangible but encapsulates what Chard sees as central issues of the discipline.

When *Bespoke Fragments* introduces control and uncertainty as conducive parameters for experimentation, the agenda and means are somewhat in line with Chard's articulation of his instruments. A coherent connection between controlled and uncertain operations is a premise of architectural design. While maybe not visible in a representational set of drawings for a building, the premise is often evident in the types of drawings and actions related to the initial development and sketching. When trying to expand this exact phase into involving materialisation through digital fabrication, the inclusion of control and uncertainty seems obvious. The action of drawing can like Chard's drawing instruments, be seen as not limited to the traditional acts or mediums but as including the reality and thereby the uncertainty, of the fabrication. In doing so, this intentional utilisation of the terms become not only a consequence of the indeterminate outcome of experimentation but also rooted in the phenomenon of architectural design.

Risky Realisation

The relationship between material and design is undeniably connected to the traditions of crafting and workmanship. Good design cannot exist on its own as well as such a thing as 'good materials' do not exist (Pye, 1968). It is through the acts of processing and working that design is realised from the substance of materials and those processes are traditionally, or at least historically, bound to the experiential knowledge of crafting and workmanship. In *The Nature and Art of Workmanship* (1968) David Pye defines workmanship by setting up two contrasts: *the workmanship of risk* and *the workmanship of certainty*. The latter is defined by a predetermined output and related to manufacturing and repeating, automated processes. These methods rely on standards and routines securing an endless production of similar products. The other type of workmanship, *the workmanship of risk*, is craftsmanship defined as *…workmanship using any kind of techniques or apparatus, in which the quality of the result is not predetermined, but depends on the judgement, dexterity and care which the maker exercises as he works* (Pye, 1968 p. 20). This sort of workmanship rely on the craftsman's skills, constant awareness, ability to learn from the material's behaviour and most importantly; the willingness and confidence to put his work at risk. The worksmanship of risk can fail, but the outcome of a failure will still result in an experience that can be utilised in future works.

Even though Pye's personal preference and admiration for the workmanship of risk and the criticism of the workmanship of certainty are clear in his text, and the fact that his writings are almost half a century old, the twofold definition of workmanship is still referred to nowadays. Today, almost everything is mass-produced by automated machining and craftsmanship is something rare and expensive. This could suggest that real craftsmanship belongs to the past. However, in order to set up automated processes, experience and know-how is needed. Before a mass production is established, an experimental phase, involving risk, must undergo. Furthermore, during the half century elapsed since *The Nature and Art of Workmanship* was written, new kinds of technology have emerged, and computational power, capacity and availability have changed the workflow from design to production. Automation does not necessarily need to be a repeating process anymore; it can be based on changing parameters. Furthermore, making and crafting, the events of the workmanship of risk, might not even be limited to the physical world. Digital craft is characterised by a direct ability to manipulate digital material without the delay of mechanical operations. Like the traditional craftsman has direct access to materials through his processing by hand, the digital craftsman has a continuous feedback from and the ability to respond to the digital domain. (McCullough, 1996 pp. 23-29). The possibilities of crafting within the digital domain have created a new kind of medium that permits an increased level of communication between digital work and the more traditional craft. Craft can now utilise procedures that before were limited to the processes of manufacturing. And manufacturing equipment can gain new potential through computational control. This opens up for production workflows that can shift its manufacturing patterns or even produce series of unique, bespoke or customised elements. It could seem that Pye's contrasting extremes are fusing together, or overlapping, in the middle, blurring the boundaries between design, craft and manufacturing. The potentials of this utilisation of digital craft or design within the digital realm and the use of digital fabrication tools as direct, but uncertain, approaches to the materialisation of computational



Digital lines can be editable and interactable as long as their controlling premises are accessible.

designs is discussed by Branko Kolarevic in his text *The (Risky) Craft of Digital making* (Kolarevic, 2008). Kolarevic argues that the designer, the practitioner of the digital tools, is in a position similar to that of the craftsman practising the workmanship of risk. The designer is not only designing but also able to test and try the relation between the digital information and the tools and materials in use. This creates a feedback loop that informs the design in development and creates a basis for gaining experience but, following Pye's argument, at the cost of every decision being a risk.

In the continuation of Koleravic's connection of risk to digital making, one could argue that the presence of materials in the combined process of designing and making intertwines the relationship between 'good design', 'good materials' and realisation. Undoubtedly, being able to act as both designer and craftsman simultaneously requires an extended set of skills, experience and knowledge, but certainly also brings new possibilities for materialisation and therefore for designing.

The span of control and uncertainty applies to the full extent of the experiments in *Bespoke Fragments*. In order to implement an exploring approach to materialisation, the experiments must be open to elements of uncertainty throughout the planning and execution. This requires a constant reflection and evaluating, experiential practice parallel to the type of risky craft mentioned above.

Virtual and actual

The span of virtual and actual is brought into the system to discuss the underlying interest of the project throughout the experiments. The possibility to reach into the reality of materials through digital drawing and fabrication can be of multifaceted use for architects. However, to bring the qualities of material knowledge into a phase of architectural design, where it can make an actual difference, the type of connection made between the architectural working methods and the material is of importance. The connection must bring designing and drawing in close relationship with the materials and machines in question. This can either be done by adapting the existing tools of the discipline to serve the technologies or to bring technology closer to the current type of working methods. This project suggests no clear-cut solution but attempts to set up a shuttling motion where existing and new qualities can suggest new additions to practice through an interrelationship. In order to do this, the experiments must not only bridge, but also overlap. Therefore, the notions of the virtual and the actual are used as active understandings within and across the experiments.

The virtual is in opposition to the actual – but the two are connected and mutually dependent. The concept of virtuality is taken and adapted from philosopher Gilles Deleuze (1991, pp. 96–98; 2002, pp. 148–150) and serves an operational role in the construction and execution of experiments throughout this project. Deleuze's virtuality is a potentiality that can be fulfilled in the actual. The actual does not exist alone, but will always be related to virtualities that render it possible. To every action follows an amount of possibilities that will always connect to this action whether materialised or not – therefore the virtual is real but not material. This Deleuzian notion of virtual is described as a surface effect produced by actual causal interactions. Virtualities can exist as latent possibilities.

The concept of virtual and actual is, in this project, proclaimed as directly relevant in the establishing of a generative two-way connection between drawing and realisation. The virtual is a mode of possibilities and, therefore, a mode from which decisions and interactions can be made. The consequence is, often, actual and materialised – but also likely an altering of the virtualities at hand. Architectural drawing or digital drawing can be ways of establishing a field of possibilities – or a domain of virtuality – from where many actions can be taken. The digital drawing can offer a space of possibility beyond its immediate performance and representation. Digital lines are able to change position and value. The appearance on the computer screen is real, but highly interactable, thereby not actualised information, but virtual. The virtual is a generative mode capable of change. However, virtuality should certainly not be seen as limited to drawing – or the digital for that matter – but instead pursued in realisation as well. Similar to the virtuality of the digital drawing, physical existence is surrounded by latent potentials. The overlapping field created in the meeting of digital drawing and physical presences is believed to create new virtualities. This is directly linked to the capacities of the materials. Capacities exist in and around all material their state and configuration

unregarded. Nonetheless, they can be altered or new capacities can be created in the materials through machining based on digital drawing. Capacities may or may not be directly visible as consequences of the fabrication but when actuated they affect the material behaviour. Capacities are material virtualities. If a workflow, in which virtualities are available as input from both drawing and realisation, can be established, it is believed that this workflow can be used as a way to include both in architectural design.

In the understanding of the span of the virtual and the actual, it is important that one notes and accepts the particular use and relation to the terms as well as the discursive construct employed in *Bespoke Fragments*. In this project, the virtual is seen as an opposite to the actual in continuation of the Deleuzian coining of the words. Following this thinking, the virtual is a potential that awaits or anticipates an actualisation. This understanding is seen as a benefit when trying to extend the potential found in the current digital architectural tools into materialisation. The requirement for the kinds of triggering actions or active events creates room for possible interaction and decision-making in the process of materialisation.

The technical relation

The use of the term virtuality relative to material and machining experimentation becomes as key to segment and disrupt existing processes, aswell as a way to establish new ones. Some types of machining – and some machines – that are included in this project are quite particular and very well-developed, in what they are traditionally used for certain categories of fabrication and material processing. When these machines are looked upon at first, one seems to understand their capability and usability immediately. However, this immediate understanding of the machines, and especially their type of output, can maybe shield the full scope of potential behind the overshadowing specialisation of the process. Combinations of specific types of tools and specific types of materials tend to output uniformised materialisations that then end up defining our understanding of the combination and processes behind. By dissecting these processes and not limiting their potential to the input and output of the ordinary entirety of the process, new possibilities can be found within their existence.

A varied look at the processes can become a blossoming of virtualities in the sense that a process or workflow normally regarded as specific and limited can suddenlty be unfolded to multifarious potentials.

The traditional understanding of processes and related outcome might exist due to several parameters, e.g., cultural construction and traditions, but is certainly related to the technological development of those processes and the understanding of technical development. Gilbert Simondon explain this development as a 'concretisation' towards 'technical objects' (Dumouchel, 1992, pp. 411–414; Simondon, 1989; Simondon et al., 1980). According to Simondon, the 'technical object' is opposite to the 'abstract object' and defined by an integrated and complete technical invention that functions independently. The abstract object lacks integration and "*...the processes are concatenated, or sequentially related, but they are rarely interdependent, the realization of one process does not rest on the virtualities and potentialities of another.*" (Dumouchel, 1992, p. 411).

While Simondon's philosophy is both detailed, complex and far-reaching – as well as intensely debated – his understanding of technical development is inspiring, especially in the context of this project. The complexity and development stage of digital fabrication tools clearly places them into the category of being abstracts object; these are assemblages of several widgets, technologies and technical elements combined into processing machines. Nonetheless, they are sometimes seen – and marketed for that matter – as much more complete and integrated solutions. By viewing the processes involved in the experiments of *Bespoke Fragments* with the philosophy of Simondon, their composition and dependencies on internal virtualities become evident, and thereby open for external decision-making or interaction. One could say that Simondon's account of the technical objects here becomes a tool for de-concretisation of the processes into their real components before initiating an experiment that re-orientates the setup towards a concretisation. On more general level Simondon's approach can provide a way to avoid a distancing of technology and instead construct an informed and engaged relationship with the processes.

Simondon's discussions are relevant as they consider both the refinement of machines and tools and their relation to humans. The concretisation and adaption of processes are happening at the intersection of two worlds: the world of their own internal requirement and the world in which they are used. Hence, the technical objects are being influenced from opposite directions. The role of human relation or mediation that lies in-between can be a consequence or solution, or the technology can develop into true 'technical individuals'. The relevance here is not whether or not technology can exist in its most refined form, but the acknowledgement of the autonomous human as a part of the process. Since this project involves experimental processing and thereby technological advancement in a highly segmented form, the engagement of human autonomy and decision-making is precisely the exigent circumstance that is needed order to reorient the involved machinery.

While it is not the intention to concretise any process within this project, the investigations of materials and machining types can in several experiments be seen as an initiated concretisation or at least as a suggestion of a particular, yet unrefined, process. It is clear that a good tool is regarded as one where the interactions between the functionally distinct parts have been harmoniously resolved. This is done by concretisation, and thereby an actualisation of different virtualities between the distinct parts (Dumouchel, 1992, p. 417). Or the other way around: by utilising virtualities found within a procedure or an experiment, the process will be directed and thereby limited but particular. This consequence should be seen in the perspective of the system of orientation and the experimental framework of this project. The regarding of digital fabrication and materials not only as tools and medium for the sole purpose of realisation, but for active experimentation results in the search and utilisation of potentials within the full extent of the processes. This means that an actualisation of virtualities, based on a series of decisions made throughout the process can take place. The simultaneously creating and executing of experiments become a shuttling between virtual and actual through the exploration of an open set of possibilities. These possibilities then eventually converge in a process that starts to suggest a type of equilibrium, or at least a balancing, that defines the experimental process. This shuttling between extremes happens in conjunction with the shuttling between the extremes of the orthogonal extremes; control and uncertainty. Hopefully, it is now evident that even though the two spans are different, they are interconnected. The exploration of the axis of uncertainty and control will involve either the creation or actualisation of virtualities, and the other way around. The relationship between the two sets of extremes will, however, be dependent on the precise moment of that experiment and associated decisions are made.

The system of orientation is created in order to navigate the experiments. The navigation is intended, both in terms of planning or positioning the experiments among themselves and within each experiment, as an ongoing tool. The system has been partly developed in parallel with the experimentation, meaning that the understanding and articulation of the spans have been produced and specified in the continuously reflective partnership with the experiments. The system of orientation is as such an outcome of the *Bespoke Fragment*-project as well. The system is also believed to have a meaningful purpose beyond the experimentation in this project. In spite of its simplicity, it provides a tool for anchoring explorative experimentation to the premises of architectural production. The spans provide two pairs of related terms that reflect upon essential and general concepts in architectural production, though specifically angled and articulated towards an expansion of the established design domain to the embracing of a connected realisation. It is believed that the system of orientation can provide a helping hand in the employment of new tools and domains in architectural design production.

Understanding and assessment of the realisations

At this point, it should be clear that the explorative research of this project is structured around experiments involving materials and machining. What might be less clear is what the output of those experiments are and how the outcome is looked upon.

Bespoke Fragments is not the only project in architectural academia trying to incorporate physical, digital production in research. Fortunately, this has generated discussions on how this materialisation can be seen in relation to both research and architecture. The field is diverse and in constant development and numerous types of work have already been produced. Some research projects focus on very technical and computational-specific findings within the digital fabrication field, where others seek to use the overlapping of computational power and materialisation for optimisation or reduction of time, cost or materials. The experiments set up and executed in *Bespoke Fragments* are not as straightforward in their target or assessment. However, they have clear intentions and concrete output backing them up.

The output of digital fabrication can have different forms, uses, and meanings. The output can range from being a component or element meant for actual construction of a building or structure, to being early mock-ups or tests made to investigate form or function. The outputs can be the realisation of architectural ideas represented in drawings, or it can be representation or models themselves. The output can originate from information created by architects – but can just as well be the materialisation of data generated by computers, ungraspable and unrepresentable by humans alone. There is no clear-cut strategy for the potential use of digital fabrication in architecture. While this is not a problem at all, it is important that the discipline acknowledges the consequences during the adoption of these new possibilities.

A significant consequence of the many implementations is a blurring of the definition and the meaning of modelling and the model (Burry, 2012). This blurring comes as a consequence of the emerged overlap of drawing and making (Sheil, 2005). The models and the making in architecture have never been as intensely discussed and theorised as the drawing, but nevertheless, the process of materialisation has never left the architectural design practice. (Frascari et al., 2007, p. 231). While modelling, making and construction might have been marginalised to a second-rate activity in the production of architecture, the cause of which is the historic split between designing and making that began in the Renaissance (Carpo, 2011; Ingold, 2013; Pérez Gómez and Pelletier, 1997) there is no doubt about that the drawing alone cannot account for the explorative progress in architectural design. Materials have sometimes wrongly been regarded as passive recipients for ideas, but their behaviour, resistances and affordance influences both the design and realisation of architecture through the making and craft (Ingold, 2013, pp. 20–25; Riedijk and Walker, 2010). Making can, just as well as drawings be an interface for exploration of the architectural and spatial invention. This potential of making and materials precisely coins what *Bespoke Fragments* is about. The question is, however, how this exploration of materials is articulated when the making is neither representations or models in scale, nor component for buildings, but is instead being formed as material experiments or sketchings in materials. It is an important task for this project to shed some light on this question and to try to formulate a strategy for an answer.

Olafur Eliasson argues that models are informing reality and that models should not be seen as representations in the first place (Eliasson, 2007). Model and reality are not polarised – the models are indeed real and direct tools for informing the real. One could then continue this argument and suggest that if both models and materials belongs to the realm of reality and the modelling at the same time is a way to progress design or are seen as *"...coproducers of reality."* (Eliasson, 2007, p. 19), then there should be no problem in following this method of designing and to include adapted materials or material creations as parallel existences within the drawing and the model.

In *Bespoke Fragments,* the set of chosen materials is limited to steel, wood and concrete. Similarly, the machining strategies for this project are singled out. The view upon the production of this project should, however, also apply to a potentially larger group of possible combinations. The outcomes of the experiments in this project are material. However, their existence as research objects are justified because of the underlying, but highly articulated, experimental process. As described, the experiments are seen as evolving processes that adjust and adapt based on the feedback and decision-making that is created. The decision-making is, nonetheless, based on some kind of evaluation of the outcome. The mere acceptance of the material consequences as an extended result of designing, drawing and modelling does not outline the parameters of the evaluation.

The physical results of the experiment are judged on their readability in relation to the experimentation framework and to the imaginable architectural potential. The outcome of the experiments should, in other words, both be anchored to their origin in the research project and to a more subjective, conceptionally driven idea about architectural potential.

Whatever the experimental results are, they must have an anchoring in the material properties and capacities and the types of machining utilised in the experiments. The experimental approach is set up with an intention to push the investigation as far a possible. However, the processing of the materials will need to leave room enough for the materials to affect the behaviour and perception of the outcome. Likewise, the processing will need to leave specificities that are significant to the type of machining involving. The experiments call for realisations that suggest new approaches to the machining of materials and thereby for results that are surprising, interesting and unexpected. These values must however, when looking closer, always have a clear relation to the research framework and thereby to materials and machining used in the experiment. If, for instance, an investigation results in the material specificities being unimportant for the machining, not being particular to the actions involved to initiate the machining the experiment will likely be heading in the wrong direction. The constant evaluation of the experiment's orientation should make it manageable to assess the tendency of the experiment.

The results are aiming at being relevant in an architectural context. This does not mean that the production of the experiments needs to be directly applicable to buildings. This is not the intention. The results will, nonetheless, need to enter a supposition of potentially being an initiator or a part of architecture. The results are responsible for their own existence, their material, and their production, but moreover, they should suggest or point in the direction of being something that potentially could be a constituent element in a larger and more complex architectural scenario. The results of the experimentation could be described as 'protoarchitecture' (Sheil, 2008, pp. 7–8) – a type of artefact that, as the word suggests, is a mixture of a prototype and architecture. Protoarchitecture suggests something that is a construction of the physical and the virtual. Protoarchitecture needs to exist physically, but instead of being assessed on this solely, the value of this type of object lives in the kind of architecture it suggests through its physical existence. The term protoarchitecture is coined by Bob Sheil and used in his writings and in the articulation of several projects. The term is flexible, but substantial in that it tries to incorporate values and methods of architectural design and design methodology into a new domain that includes both analogue and digital tools and the potentials to produce something that transgresses the traditional field of representation but is not actual architecture yet. The term has been widely adopted and used to describe numerous research projects. Even though Sheil's description of protoarchitecture seems fitting at first, the term has not been actively used to describe the outcomes of experiments in this project. The kinship with the prototype suggests that protoarchitecture belongs to a type of construction that could be or aims at being an actual element in architecture. The protoarchitecture seems like something that aspires to be a finished result. This is not the case for the production of this project. Instead, this project seeks to produce a kind of realisation that holds the materiality and material scale of a prototype or component, but with the manoeuvrability of a sketch or working model. These types of outcomes have instead been named 'bespoke fragments'.

Bespoke fragments

In addition to giving a title to the project, the term 'bespoke fragment' covers a bridging of actual and virtual existences and seeks to embrace a material level that can be found outside the extensiveness of the meaning imposed in prototyping and architecture. A 'bespoke fragment' can thereby be something that suggests a type of design or architectural approach but does not necessarily need to appear as an element or component. Unlike the prototype the bespoke fragment is disconnected from a striving for being final.

The bespoke fragment introduces a 1:1 approach to material that links to the digital drawing. The implementation of the bespoke fragment is thereby both an expansion of the existing realm of designing and a connection to it. The intended use of the bespoke fragment both is material and experimental. The bespoke fragment borrows the nature of designing through experimentation, previously exemplified by the Gaudi and Frei Otto cases, but at the same time it differs dramatically from them by not being a scale model. Where both Gaudi's and Frei Otto's spatial inventions were based on tectonic findings in completely other materials and scales than their eventual architectural outcome, the bespoke fragment specifically introduces materials on their actual premises. The potential of the bespoke fragment is to establish a relation to a type of making and creation anchored in material specificities. The ambition of the bespoke fragment is to create an output that scale-wise is relevant as a artefact, but also to include potentials of being a fragment. The nature of fragmentation means that the bespoke fragments are to be seen as isolated or incomplete parts of something. They are 1:1 in their specific existence, but do not provide a complete overview or understanding.

Material properties and capacities combined with digital machining belong to their actual scale and thereby these parameters natively belong to the bespoke fragment. The bespoke fragment incorporates parameters that enter the domain of the fragment undistorted and unscaled. The scale of the fragment itself is essential and absolute; therefore, the bespoke fragment is different than the model.

Throughout the experiments, the term bespoke fragment plays a role in the genesis and the intended conception of both the digital and physical production. They are to be seen as 1:1 existences both in their form and their behaviour. They should be perceived directly and not be interpreted or assessed in relation to another scale. They should, however, neither be regarded as concluded objects. Rather, they are to be seen as openings, preludes or fragments that could potentially be a part of, or inform, a component or part of an element in a larger context or construction. The bespoke fragment can also inform the production of representation. Seen exclusively as physical objects the bespoke fragments are not whole. They require that their potentials are considered and imagined within their context of machining and material capacities.

The assessment of the realisations through the understanding of the bespoke fragment is used to guide and develop the experiments.

EXPERIMENTS

CONTINUAL ACCUMULATION

CONTINUAL ACCUMULATION

Materials
Steel, sheets - 0.25 mm, 0.50 mm, 1 mm, 2 mm, 3 mm, 6 mm
Wood - plywood, pine, ash, beech, oak
Concrete - different types

Machines
TecnoCUT 5-axis abrasive water jet
CMS 5-axis CNC machining centre
ABB IRB 6620 robotic arm
EURO laser cutter
Zünd digital knife cutter

Software
Rhino with Grasshopper and HAL plugin
AutoCAD
TechnoCAM
AlphaCAM
RobotStudio

Quantity and size
Several smaller material tests and compositions

Comments
'Continual Accumulation' was presented and discussed at the 'NAF 2016 The Production of Knowledge in Architecture by Ph.D. Research in the Nordic Countries'-symposium in Stockholm as well as in the associated paper in the proceeding. A revised and elaborated version of the paper will also be included in the upcoming 2017 publication by 'The Nordic Association of Architectural Research'.

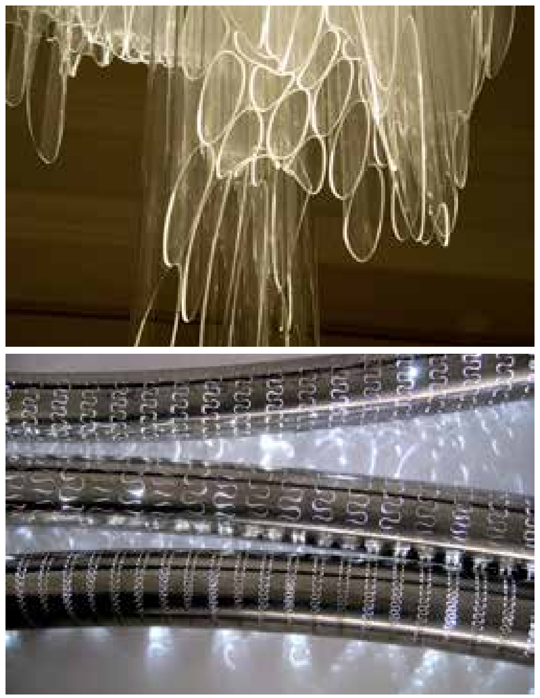
Aagaard, A.K. (2016). Bespoke Fragments: Experiment and experience-driven knowledge production, in: NAF 2016.

Amassing curiosity

A fundamental premise of the entire research project is an inquisitive attitude towards materials and processes. Therefore, series of physical tests and investigations are carried out during the whole stretch of the project. This includes a high degree of impulsive and only partly planned experimental accomplishments without unequivocal ambition or intention. In most cases, these are driven by curiosity and a search for consequence and surprises found in the combination of materials and processes.

While some experiments are investigated in-depth and some are left at a less developed stage, they all start on a level of simple testing. A testing can be initiated out of pure material and machining interest or from a more methodological, or phenomenological, point of view. The testings share a physical output and their relation to and information about material and process. Despite their different origins, they share a status of being initiators and therefore together constitute a group or accumulation of knowledge.

The continual amassing of smaller, connected or individual, material and machining test is seen as a type of collective experiences and knowledge. Unlike the more coherent experiments found in *Bespoke Fragments*, this collective assemblage has no defined start or end. There is no long-term focus or aspiration for a greater unfolding of potentials or technics within this knowledge pool itself, but instead a desire to create ever-growing accumulation of inspiration. This *Continual Accumulation* is not being articulated as an experiment, but instead functions as a framing and an incubator for the experiment, within the project. The accumulation of material tests is an ongoing process that has informed and initiated the focused experimentation during the full research period.



Examples from Barkow Leibinger's 'Atlas of Fabrication' exhibition. Upper photo shows acrylic tubes cut to create cohesive double-curved surfaces that catch the light. Lower photo shows steel pipes that have become flexible because of the revolving laser cut patterns.

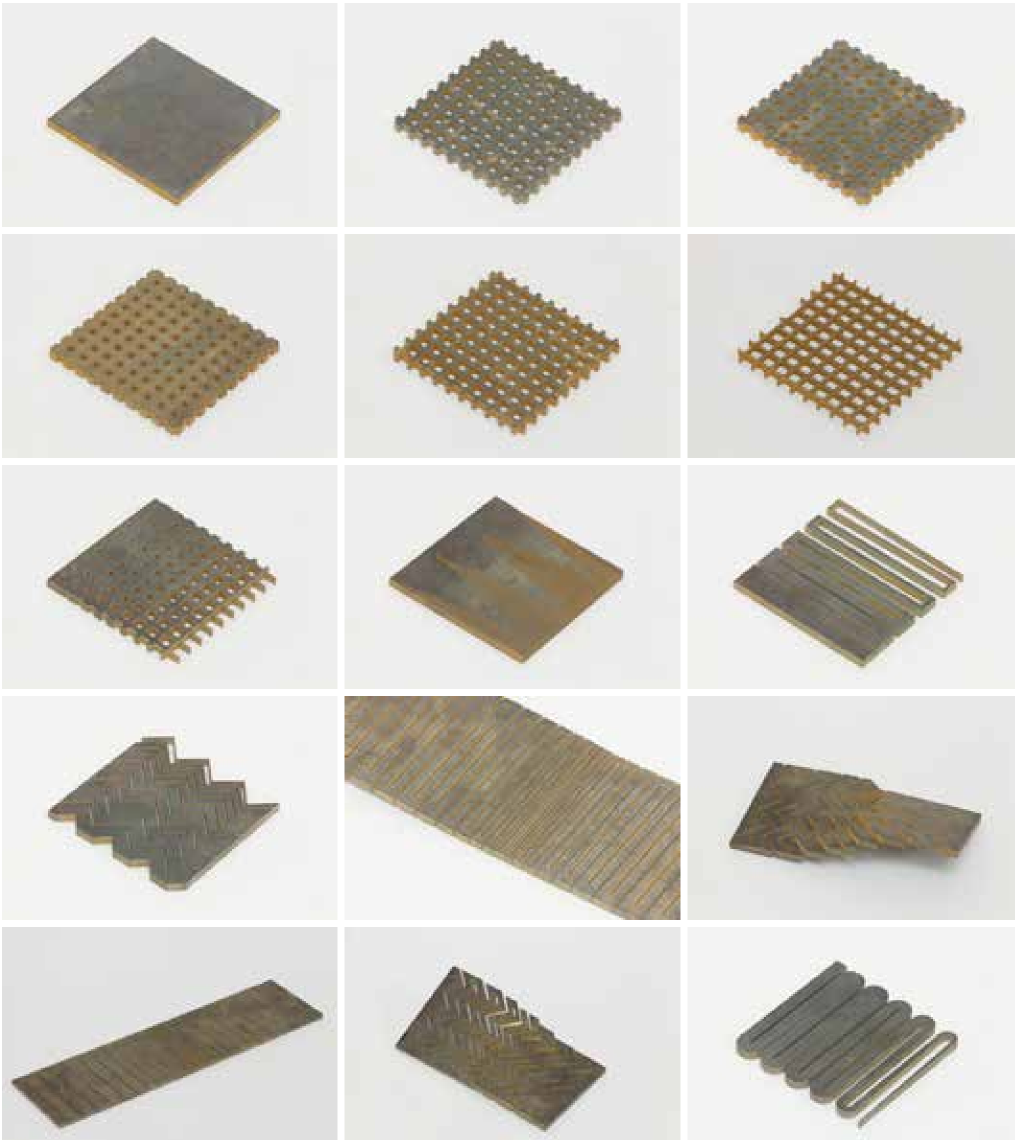
Continual Accumulation should be seen as a kind of introduction to the specific type of experimentation in *Bespoke Fragments*. The thinking and explanation of this mass of work is fundamental for the project. *Continual Accumulation* has functioned as very concrete way to provide a constant flow of both mental input and material production throughout the project. This varied collection has been in constant production simultaneously with the actual experiments.

The concept of *Continual Accumulation* is somewhat inspired by the work of architectural practice *Barkow Leibinger*. Exhibited and published under the title *An Atlas of Fabrication* (2009) the work presents research into materials and tools done parallel with the more traditional architectural design work in the office. Barkow Leibinger approaches different materials, digital fabrication strategies and computational resources in order to discover new architectural potential. *"..., we use our research within the field of new tools and capacities as a source catalogue, folding this knowledge into ongoing building projects unburdened by the orthodoxy of the competition system. A prototype begins as an experiment which may or may not become a building"* (Barkow et al., 2009, chap. "Introduction"). The admiration of the work is twofold. First, the material research done within the practice seems to be a way to wrench free from the compact and rigid systems that define the daily grind. Secondly, it is clearly an active strategy of feeding the architectural design work with fresh and unbiased resources that can eventually improve the architecture. Seeing a practice that uses material investigations as starting points for architectural designs is highly treasured by the author of this project.

While the *Continual Accumulation* series does not resemble the work of Barkow Leibinger, there is an overlap in agendas. *Continual Accumulation* seeks to be a space for curiosity experimentation that can contain everything, without initially having a detailed aim or trajectory to follow. Theses will unfold from the series and become their own experiments, while still being the offspring of a very basic interest in materials and digital fabrication tool.

Material information

The production within this ongoing work is demarcated by the experimental framework of the project. The materials of wood, steel, and concrete, along



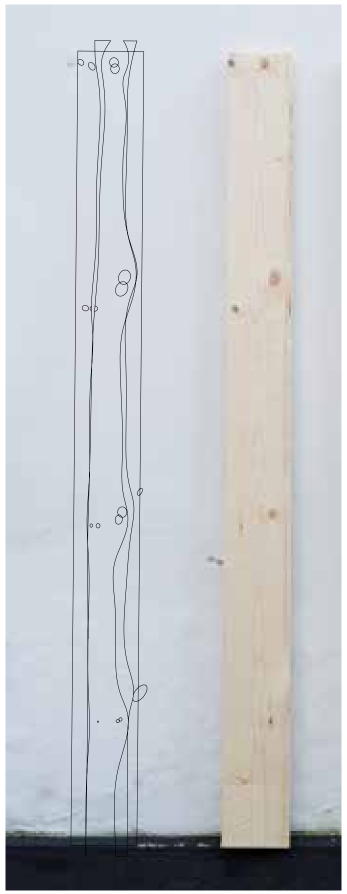
Manipulating steel: Different and simple, but effective, samples for testing strength, flexibility, and elasticity. The 6 mm steel is cut with a water jet and investigated. Some samples allow a permanent bend, other bounce back, and some are unmanipulatable.

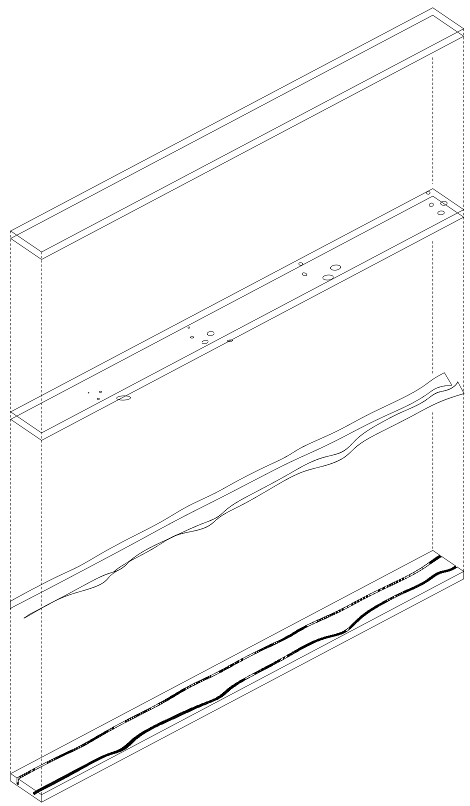
with the processes of subtraction, division, addition, and transforming, define the starting point for every material investigation. The studies can incorporate as many or as few of both materials and processes as needed and be supported by other relevant materials and processing strategies. The encounter of material and machining will play a significant role in all arrangements, but the juxtaposition of materials, as well as the combination of machining types, can be just as relevant.

An unremitting and shared focus for the investigations is the exploration of material properties and capacities. This includes the study specific of materials' behaviour and response, as well as tolerances, in relation to the specific types of processing. The materials and processing are always looked upon as actual existences and causalities, meaning that they are involved on their own term - not as representations for other scales, materials or notions. The role of the material and the processing changes, depending on the setting for each investigation, but are in every case sought to be explicitly articulated.

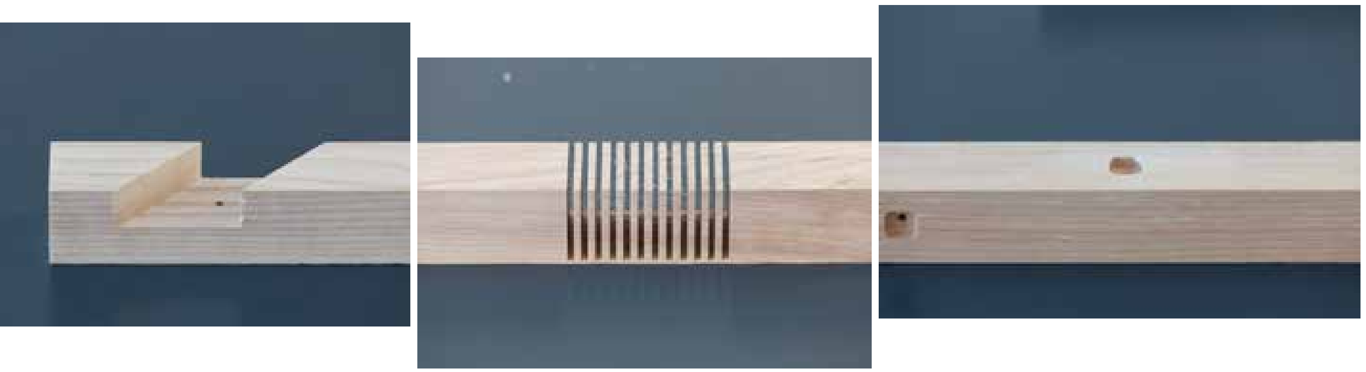
For every experiment or sub-experiment, an amount of information is needed to perform the processing. The information required for machining can either be coded directly in the language native to the machine or derived from digital drawings. In the latter case, the digital drawing can have many forms and its underlying data come from many types of geometry or descriptions. Throughout the project, the machines have been instructed by both coding and drawing. The drawing has by far been the most frequently used starting point for the instructions. Sometimes, the drawing has been direct instructions for tools to follow; other times, tool paths have been extracted from geometry or surfaces. Both types of information have been generated by drawing by either 'mouse clicking' or by parametric inputs depending on the particular intention or applicability. Combined, these possibilities of using instructions and drawings open up for quite an extensive field of exploring. Not every choice made in this regard has been thought through, but the consequences have been collected and scrutinised in order to create a qualified pool of knowledge for further development or more focused experiments.

The accumulated mass of experimentations is especially materialised in collective physical outcome. The material objects serve as entities on their own, open for rendition, refinement or development. But they also operate as





The timber as the starting point: Based on either 3D scanning, digital measurement or simple, double-sided photography, the grains running through the timber and the knots are extracted and converted to digital geometry. The geometry is then used for the creation of 5-axis machining information. The tool paths thereby follow the grains and avoid the knots, making the machining particular to each piece of timber. As a consequence, the machining runs incredibly smooth since there is no collision of grain direction and tool paths. No fraying or splintering is occurring.



The machining of wood can be seen as the embedding of capacities into to the material. The capacities can open for several types of potential occurrences with the wood. A material capacity can, for instance, allow the wood to connect with other pieces of wood, be able to transform itself or facilitate specific material systems.

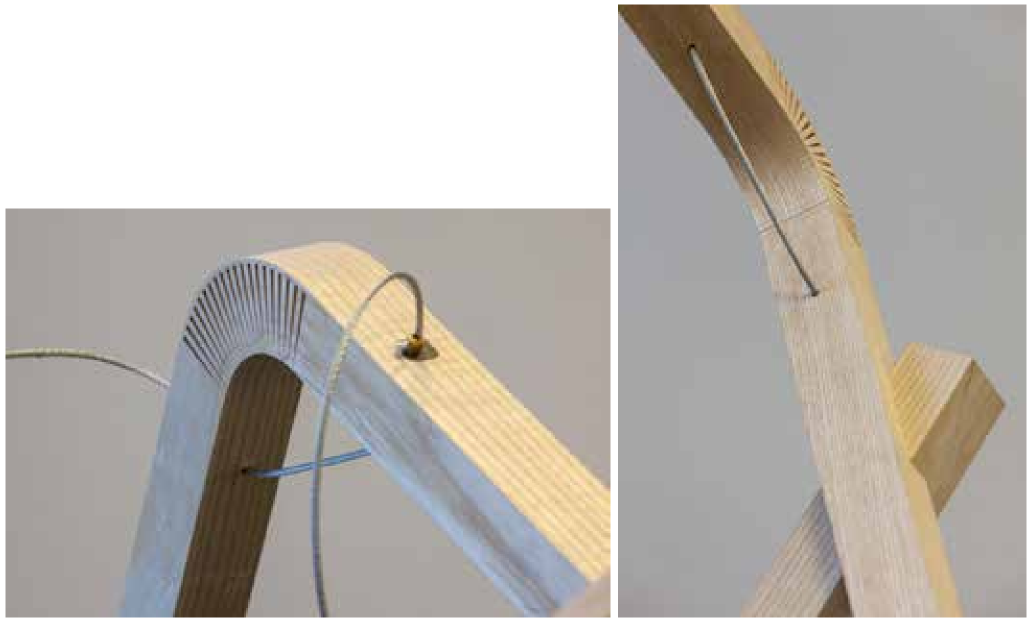
coordinators and summaries for the processes and findings correlated to their emergence. In every object, marks, traces, and memories of the underlying actions can be revealed.

Uncertain transformations

In the meeting of machining processes and materials, new forms are produced. It is, however, not always the final form that occurs as a result of the machining. The results of the machining are in many cases intermediate elements that set a necessary framework for further work. This can be in a situation where the machining is happening in a supporting material – e.g. in the production of formwork, where concrete will eventually take advantage of a machined framing. In another situation, the goal of the machining might not be to achieve a predetermined form, but to simply be a preparation for further processing. In these settings, the machining can be described as being embedding capacities into the materials through the processing. The capacities, in the form of physical change to the material piece, can be the starting point for a further transformation.

Similar to the drawing, the materials' different roles in the process create a spectrum of exploring. The material can be almost passive and receive the form directly from the acting machine or formwork. Or it can adopt a more active role and bring forward potential transformation through or after the processing. These different scenarios have played a considerable role throughout the arrangement of and reflection on the experiments. For all experiments, the altering or transformation of materials have played a significant part, but for some material tests or experiments, additional transforming processes after the initial machining have become essential.

Regardless of the number of transformations or if these are based on digital processing or manual post-processing, the aim is the same. The investigations are insisting on pushing the boundaries of what is known into uncertain discoveries. The recognition of uncertainty and unplanned outcome as a progressive and valuable parameter is important for the project *Bespoke Fragments*. This plays a significant role throughout the sub-experiments within the ongoing *Continual Accumulation*. By encouraging the unplanned and praising the unknown, the series is able to reveal entirely new consequences



This page and overleaf: Series of machined ash wood pieces can interplay with series of different machining types and thereby create new material and spatial situations. The embedded capacities becomes the mean, not the goals.

and relations among materials and techniques of processing. Some results will bring an immediate fascination, while other might, at first, be regarded as errors or imperfections. In order to push the investigations further, these error-like material transformations are welcomed by the project and seen as potential trajectories and information for further discoveries and understandings – and possibly a refinement or evolution of those. The key attitude towards this experimental approach is found through non-deterministic experiment setups and well-founded reflections and decision-making responses to the outcomes.

Decision-making

With many variables ranging from initial drawing, material choices, machining parameters, the role of materials, transformation possibilities, unplanned and uncertain outcomes, etc, the combined workflow consists of many options that called for choices to be taken. Some choices can be planned or sketched out ahead, but due to the uncertain nature of most experimentations, the decision-making will in many cases need to be adjusted, reconsidered or made during the execution. This circumstance becomes the focal point in the amassing of material. Compared to a situation where a drawing relays exact information on how the final result should be, these experiments are based on an investigative nature where the result is a consequence of interactions. The domain of decision-making is stretched out over several elements of a process, meaning that in order to make a change or a new iteration the point of engagement does not need to be situated in the beginning, but can just as well be an intervention in the middle or in end of the process. The possibility of changing and modifying is well-known to architects. This is an essential part of sketching and developing designs. When this is done digitally, the immediate responsiveness is even more outspoken. The powerful utensils of digital drawing – repetition, copying, moving, mirroring, parameters etc. – create a design environment of virtualities. By introducing this way of thinking in to the world of materials, and the machining of those, the virtual space seems to extend beyond the digital interface of computation. The widening of the virtual design space is explored and demonstrated through the collective pool of production within

This spread and overleaf: Different types of timber and plywood are CNC-milled or cut with different patterns to make them bend or distort. Some strategies involve variations of kerf bending, while others make use of the wood grain's natural contraction when drying out. Steaming and soaking were used as needed. The process of first machining, then transforming is a workflow that first introduces control through precise fabrication information, and secondly the uncertainty of the unforeseen reactions. During progression from drawing to transformation a series of moments that need decision-making arises. These are opportunities to inform or guide the design - or occasions to let the inherent nature of machining and material decide.

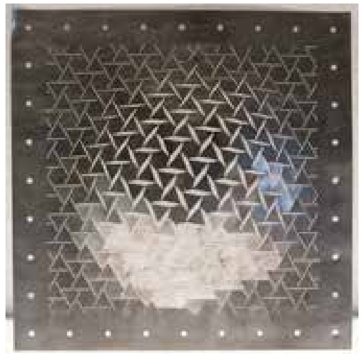
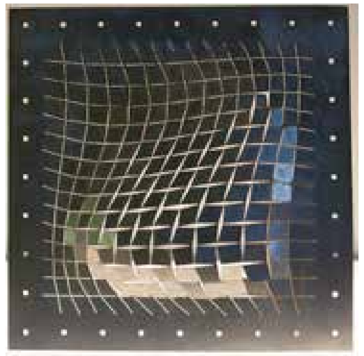
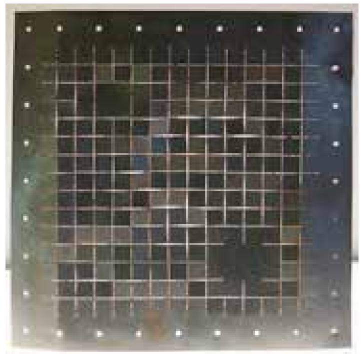
the accumulation of material investigations. The widened palette for engaging both opens up the experiments, but simultaneously demands a disciplined decision-making in order to push the experimentation forward.

Based on the outcome and decision-making the forming of this ongoing accumulation serves as an initiator for other more focused experimentation or as inspirations or eye-openers for relevant areas that need exploration. The growing of this accumulation in concurrence with more focused experimentation ensures a pipeline of potential new findings that can be explored next. But it also functions as an apparatus for assisting and qualifying the discussion across activities. Photos and examples from this unfinished collection of material experimentation show creations that are clearly stepping stones for other experiments, but also creations that are reflections of absences in other experiments. This continual production is anchored in *Bespoke Fragments* but has its starting point before and life after.

Non-deterministic digital fabrication

Continual Accumulation demonstrates a series of exploratory realisations based on more or less intuitively set up encounters of materials and digital fabrication tools. The outcomes are actual manifestations of the processes behind, but also concurrent agitators for an open-minded approach to materials and technology. The processes behind demonstrate an alternative fabrication workflow where intention becomes the consequence of realisation – and not the other way around. The experiment suggests using materials and digital fabrication as mediums and tools for sketching, testing and developing – just like pen and paper have traditionally been used. By freeing the phase of fabrication from solely the production of final results the substance and power of materials and machines can be harnessed by those methods belonging to much earlier phases of architectural design. These phases are usually characterised by explorative and non-deterministic driven workflows that incorporate surprises and uncertain moments.

While not being a replacement for neither established production or design methods, the experiment merely suggests that the inclusion of materials and fabrication tools could be a valid and prolific way of initiating architectural design. A real potential lies in the ability to constantly iterate and

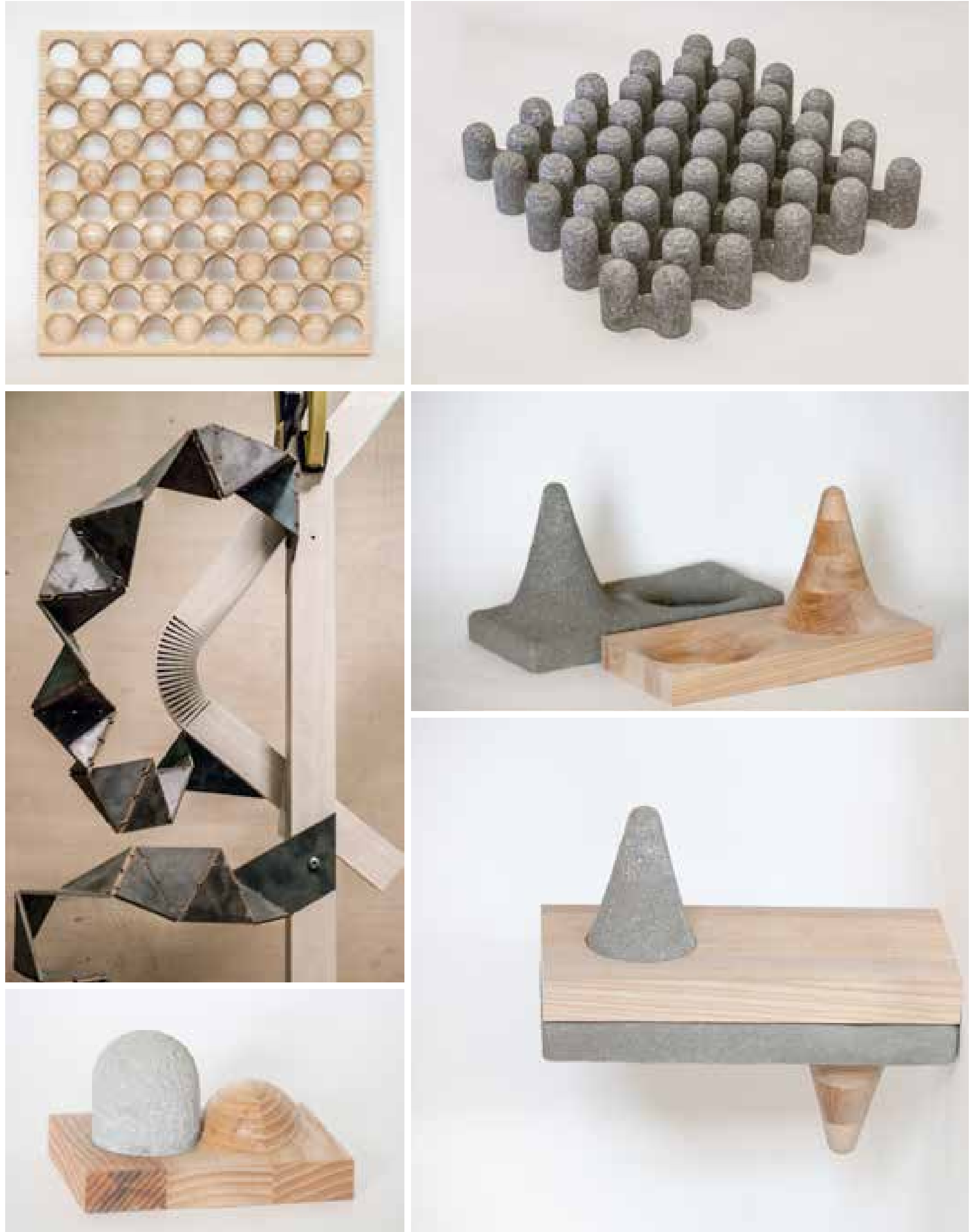
Slitting and cutting patterns in steel sheets allow them to be deformed and displaced. In most cases, the pattern has the capacity to transform the steel into multiple forms. The translation from drawing to the actual and physical pattern in steel is more or less an actualisation of the digital intention, whereas the mode of transformation, in reality, becomes an abundance of virtualities. The potentials of transforming the steel may be infinite, but interrelated; a push or bend in the steel causes a displacement of material that consequently influences the overall object. Unlike in the digital world, real world transformations are limited by the amount of available material.



The different copy: Series of identical steel strips with 'dotted' articulations. For every segment, the steel can be bend 'forward' or 'backward' at any angle. The decision made for every bend will however both influence the final appearance of the overall strip and actualise the segment. Since the bend will cause a plastic deformation, the steel will only bend once. A second attempt will break the piece: material capacities are relational but not, necessarily, perpetual.

try out new design approaches based on the feedback from a previous result. This argument is, among others, put forward by Branko Kolarevic (2008). Kolarevic is advocating for the use of parametric modelling as a key factor in digital fabrication. Parametric modelling and design provides the designer the ability to iterate geometry at a high pace – and combined with the flexibility of digital fabrication tools, the geometry can leave the computer relatively quickly and inform manufacturing. Thereby, the architect is able to test design geometry and fabrication consequences fast and effortlessly – at least compared to previous technologies and fabrication methods. The fabrication can become a tool for decision-making.

Both the working method and agenda of *Continual Accumulation* borrows from Kolarevic's (2008) argument and way of thinking. However, by having a broader approach to the potentials of different kinds of digital drawing, this experiment seems to point towards an even wider understanding of the non-deterministic use of digital fabrication. Instead of thinking of fabrication as a set of procedures to realise or test out geometry, the fabrication itself can be considered a way of iterating design. The parameters of the materials and the machining itself can inform the types of information that will eventually be digitally created. The non-deterministic approach to form-finding can be pushed forward in terms of both material findings and digital development, starting from the point where tool meets material. The essence of including material as an initiator for both research and design development is found not only by the inclusion of certain types of digital design or drawing but by searching for new strategies of developing these. When looking at digital specific drawings or modelling types like parametric design or geometry, it is, for instance, obvious that digital fabrication is not only a way to demonstrate computational parameters through realisation but indeed also a way to inform the parameters or generate new types of parameters with information found within reality. Utilisation of non-deterministic digital fabrication means a new type of sketching, testing and prototyping that can potentially drive both material and digital development in architectural design. The experimental series *Continual Accumulation* should be seen as both an example of this at a general level and as a driving element for the research project *Bespoke Fragments.*



Material encounters: Through the investigation of the individual materials' similarities, potential cohesion and cross-fertilisation are found. Different discoveries start to merge into hybrids and develop their own mode of expression or way of informing and sharpening the origins.

'Continual Accumulation' evolves as a way of thinking, but also as a pool of knowledge and as a physical archive, summing up the work done and initiating new potentials.

E1: **STRETCHING THE STEEL**

E1: **STRETCHING THE STEEL**

Materials
Steel, sheets - 0.25 mm, 0.50 mm, 1 mm, 2 mm, 3 mm, 6 mm
Bolt and nuts

Machines
CMS Tecnocut Idroline 5 axis water jet system
Custom built stretching equipment
Modified strength testing equipment
Faro Focus 3D laser scanner

Software
Rhino with Grasshopper plugin
TecnoCAM
Faro Scene 5

Quantity and size
Multiple series of smaller test
5 medium sized fragments

Comments
The 'Stretching the Steel' experiment has been published and presented at the 'What's the Matter?' conference 2014 in Barcelona and published in the ArchiDoct journal in 2015:

Aagaard, A.K. (2014). Designing through Material: Virtual and Real Approaches into Material Exploration. I M. Voyatzaki (red.), What's the Matter?: Materiality and Materialism at the Age of Computation. Barcelona.

Aagaard, A.K. (2015). Material and Virtuality. Archidoct, 2(2), 57-71. [4].

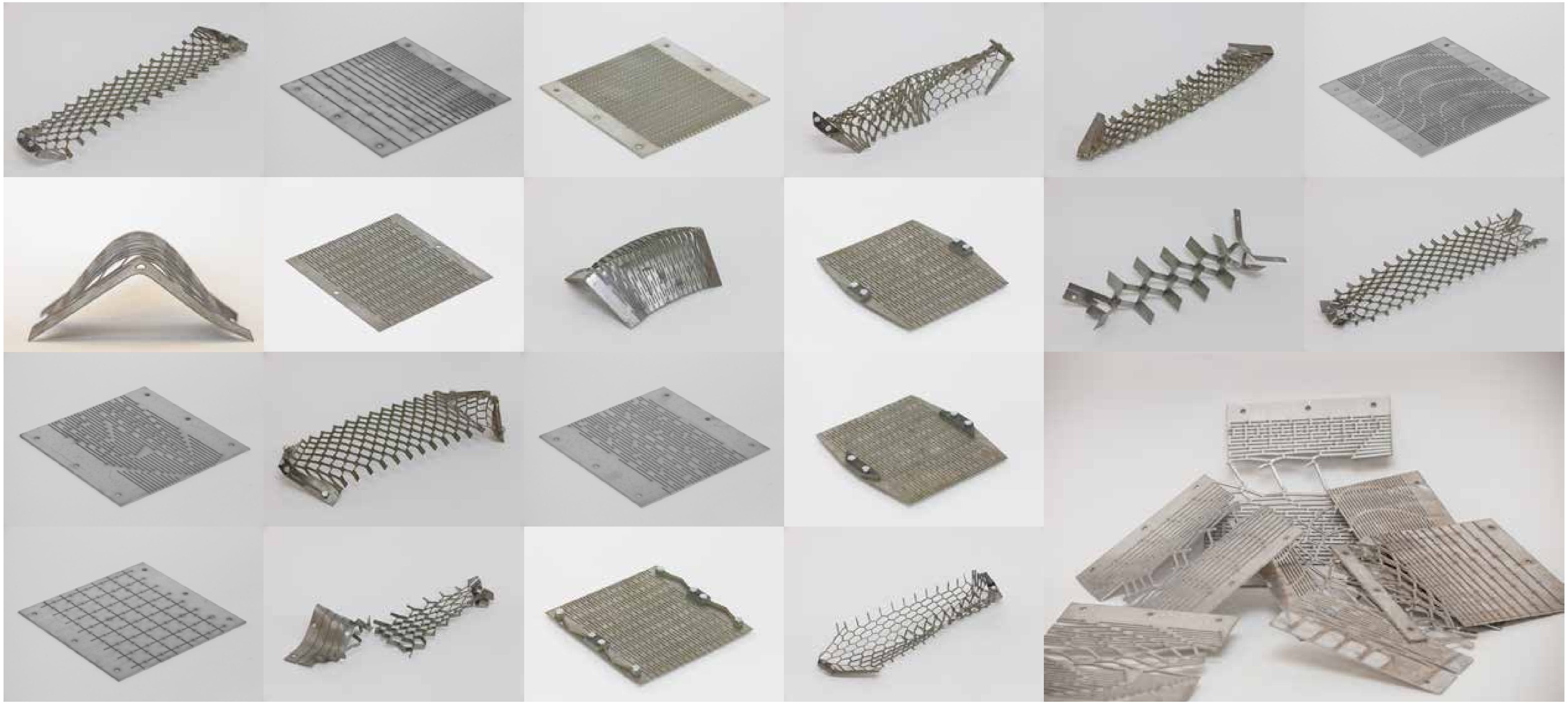
Exploring the potentials

In this series of experiments, the material sheet steel is combined with the dividing processing of a water jet cutter. This experiment follows a trajectory acquired in the *Accumulated Transformations*. Here, a multitude of different tests were made. Sheets of steel in thicknesses varying from 0.25mm to 12mm were cut in various patterns, then bent, stretched or otherwise transformed or combined. A particular focus arose around stretching patterned steel into three-dimensional shapes and combining these with folding.

The execution of the experiment is based on an iterative process of constant action and observation. The possibilities and virtual conditions of both drawing, material and processed steel are not known beforehand, neither are they simply presumed. They are investigated through drawing, processing and transformation.

It is the intention to treat the process of drawing as not solely a digital action taking place on the computer. Instead, it is the aim to treat the full process, including processing by water jet, the transformation and the stretching of steel, as an expanded notion of drawing where the physical presence of machines and materials can play a significant and playful role towards the development of a design space. Materialisation is meant to act as an element in a drawing-like process that claims the virtuality of the traditional drafting or sketching, but harnesses the actualised output found outside the domain of representation.

The material properties of steel are seen as a dominating factor of this experiment. They are the foundation for any physical materialisation and a basis for embedding drawing-based geometry into the material. Through this embedding of information, it is the ambition to realise new capacities in the material, thereby expanding the virtual qualities of the drawing domain into the material itself. While using the process to create virtual circumstances around



Diverse testing of different types of steel sheets, cutting geometries and stretching methods initiated the experiment. Spontaneity and uncertainty characterised the preliminary investigations of the material properties.

Balancing uncertain and controlled results.

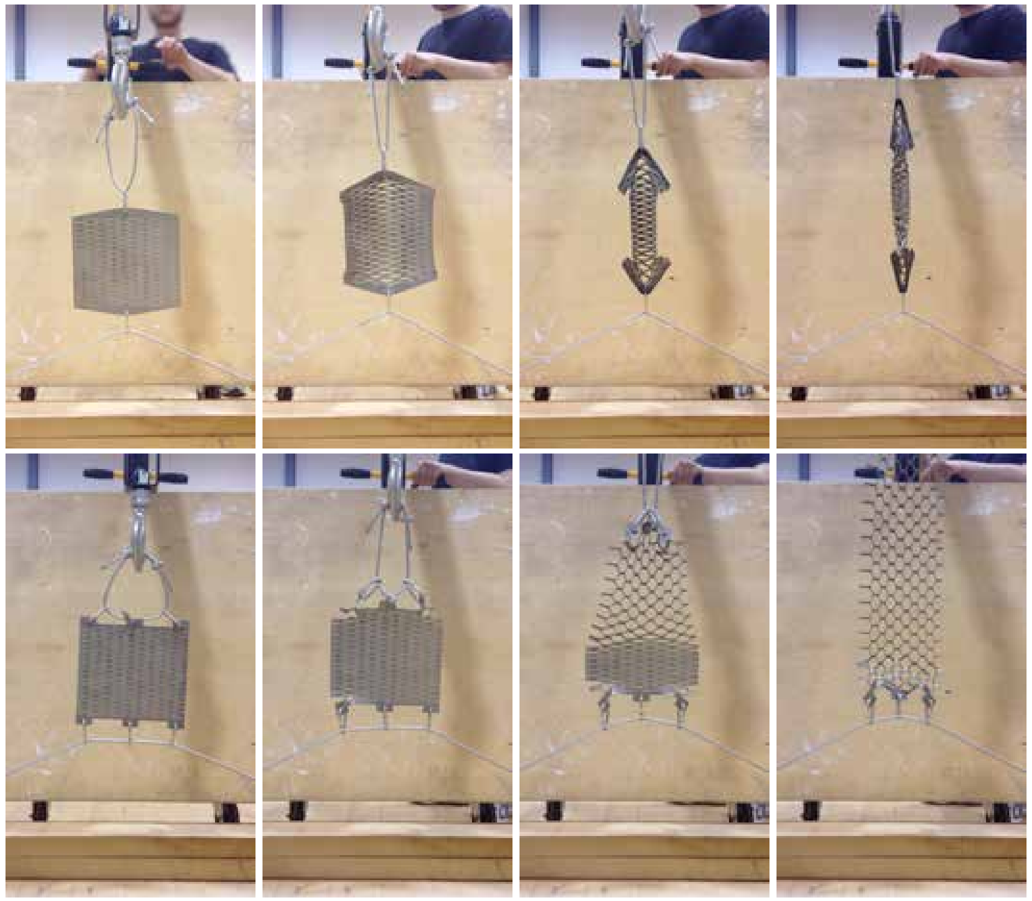
each piece of processed steel, this combination of cutting and stretching or folding also deals directly with the inherent material properties. The utilisation of a given virtuality can result in materials with changed behaviour and capacities. It is the idea to investigate the tectonic and aesthetic consequences of the processing and the interactions with the steel in order to locate outcomes of potential. Potentials are searched for, both in relation to geometric scenarios that reveal themselves during the transformation and on a material level, where properties or change of properties result in a change of material behaviour and capacity.

The process of transferring drawn lines onto steel using a waterjet, and afterwards manipulating these results by bending and stretching, is not a clearly defined type of processing with certain criteria for success. Instead the experimentation is expected to more instinctively find its way during the unfolding of its potentials.

Building a process

The method of stretching the patterned steel into more three-dimensional objects is inspired by a similar procedure found in industrial made expanded metal mesh. The traditional expanded metal, however, is made with a process that combines slitting and stretching in one single procedure. In this experiment, the slitting is done by waterjet and stretching performed afterwards by special equipment. In industry the combining of processes serves an optimising purpose, while here the separation of processes a widening of the field of possibilities within the experiment.

The series of experiments started with a substantial testing of patterns. Different types of patterns were cut in steel - then stretched. Initially, both the pattern design and the stretching were done more or less spontaneously. This resulted in a rather playful course of actions where lines were drawn without any specific expectation but solely out of curiosity. The resulting steel was then stretched and reflected upon. In the beginning, the stretching was performed literally by hand. This technique had several limitation due to the amount of force required. Consequently, stretching was soon moved to a slightly modified manual, hydraulic workshop crane with of lifting power of 1000 kg. This made stretching of larger, thicker and lesser sliced sheets of steel



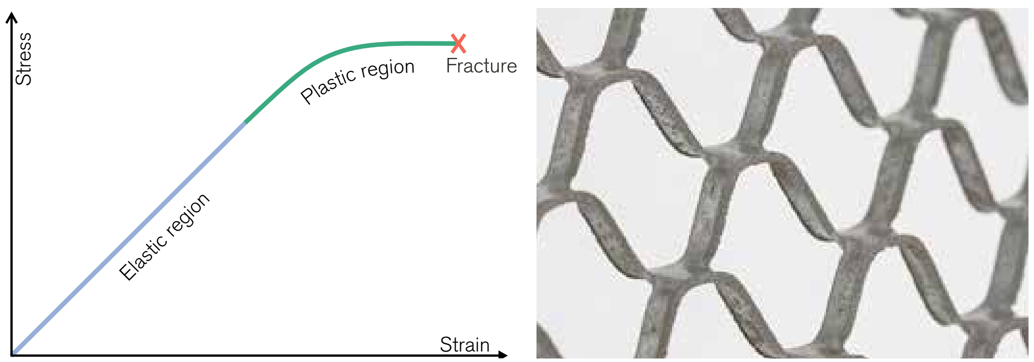
The stretchings were done with a modified workshop crane. Different types of stretching, both regarding amount of force and type of fixation, results in diverse shapes.

possible. It also introduced a greater comparability across the tests since better control of stretching direction and length was possible. Gradually, the more improvised initial testing drifted into a more systematic experimental approach where the behaviour of each parameter and action were attempted localised and understood. This part generated a rather large series of objects where the spacing of slits, the geometry of slits, slit length, stretch length and stretch mount type were investigated. This investigation founded a basic understanding of the connections between drawing, processing and transformation .

Understanding transformation

An instantly visible effect of stretching slit steel sheets in the direction perpendicular to the slits is an opening up of the material into a kind of 'lip' or 'shuttle'-like shape. As the steel sheet is stretched, the length along the direction of the stretching is obviously increased, whereas the width, or the dimension parallel to the direction of the slits, is decreased. However, of greater interest is the orientation of the steel in between each slit. These 'ribs' of steel rotate or displace themselves from their original position and create a double curved geometry in every joint. The reorientation of the ribs results in a much stronger and stiffer structure than the steel sheet in both its original state and after water jet cutting. This transformation alters a piece of material from being highly unstable and floppy into being very rigid and able to withstand a significant amount of pressure.

The material transformation is, however, not limited to the displacement or rotation on a geometrical level. A transformation also happens on a micro level. A plastic deformation ("Deformation (engineering)," 2014) is occurring during the stretching. This causes shape changing inside the material down to an atomic level (Ayres, 2012, pp. 222–225; Gordon, 1978, pp. 33–34). This forming of the material, as a consequence of the stress from the stretching, transforms the material properties from being elastic into being hardened. This hardening occurs when the stress pushes the material into a plastic region, allowing a deformation to happen and consequently the material to strengthen – and thereby the ability to carry more strain. If too much stress is applied to the



Deforming metal: Bringing the metal from its elastic to its the plastic region is an irreversible process. The result is a strengthening of the metal on an atomic level and permanent shaping.

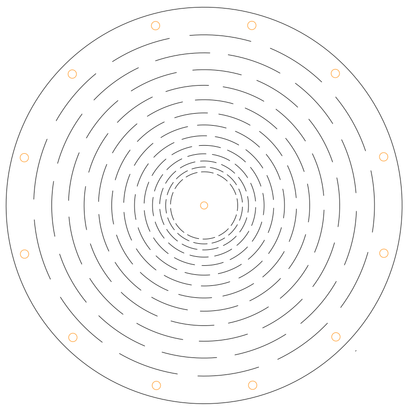
slit steel – for instance by stretching it too much – the plastic state of the steel, at a certain point, converts into a state of failure where fracture will occur and the material will break. This happened frequently in the initial testing phase.

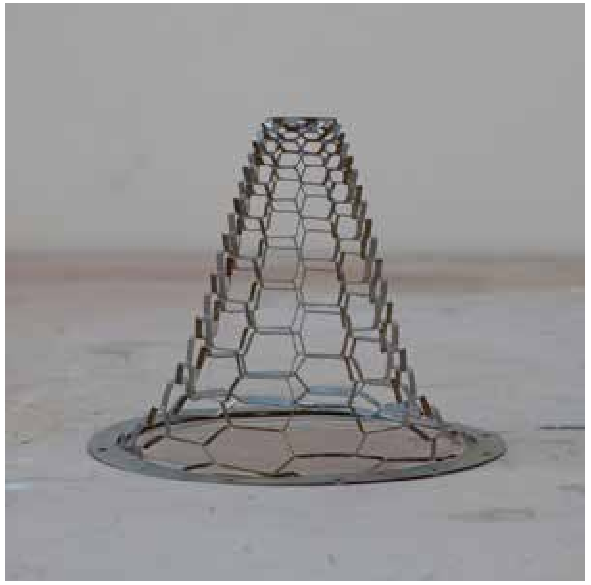
Finding form and use

The fact that the transformation interacting with the material on both a micro and macro scale, leads to the discovery of an interesting link. While the material acquires strength due to the activation of invisible material capacities, the visible part of the transformation creates a three-dimensional result that transforms both the physical and spatial behaviour of the steel sheet. The two scales of transformation are mutually resulting and combined they are an amassing of the actualised virtualities imposed through a collective process of drawing, fabrication and transformation. The tectonics that is eventually offered is a consequence of a series of choices made throughout the creation of the objects.

Through systematisation and refinement of the drawing-cutting-stretching workflow, two types of objects were especially and repeatedly brought into focus. One was a kind of rectangular sheet with patterns of slits flowing in a parallel direction. In this case, the stretching would be performed in the direction perpendicular to the slits and in the plane of the sheet. The other type of object can be described as variations of circular patterns with a defined centre. Around this centre were swirling slits. Circles were primarily used, but more amorphous geometries also sometimes defined the borders. This type of stretching would be done from the centre point in a direction perpendicular to the metal sheet plane. The combination of geometry and stretching creates a cone or dome-like structure that offers enormous strength – most objects made from a 0.5mm steel sheet were able to carry a grown up man at around 110 kg without any problems.

During the more systematic phase of the investigation, a new device for stretching was build. This device was structured around an existing pressure strength testing machine with a digital Newton meter. Instead of using the machine for testing breakage point or material failure, a frame and centring attachment were built and mounted in order to apply a force precisely to the



Cutting path geometry, cut steel, stretching, three-dimensional result.

Systematic testing of different sizes of slits. Finding the material limits was necessary for building the process.

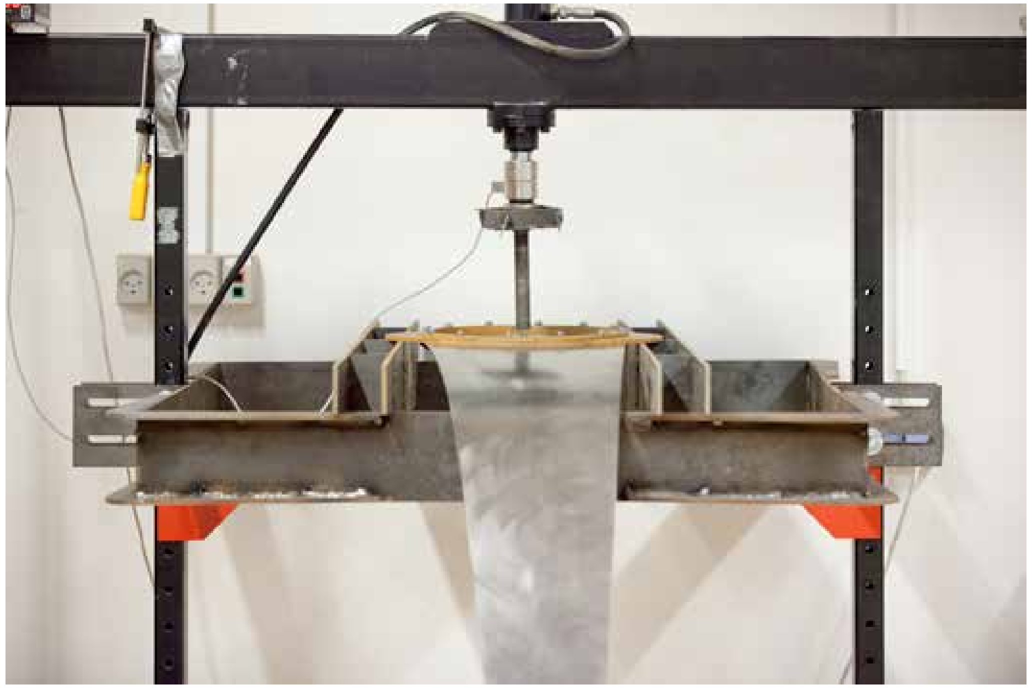
metal sheets. This system allowed for a more controlled stretching, both in terms of stretching point and direction and control of the amount of force. The centrally stretched objects were shaped with a force of 5000N.

Utilising control and uncertainty

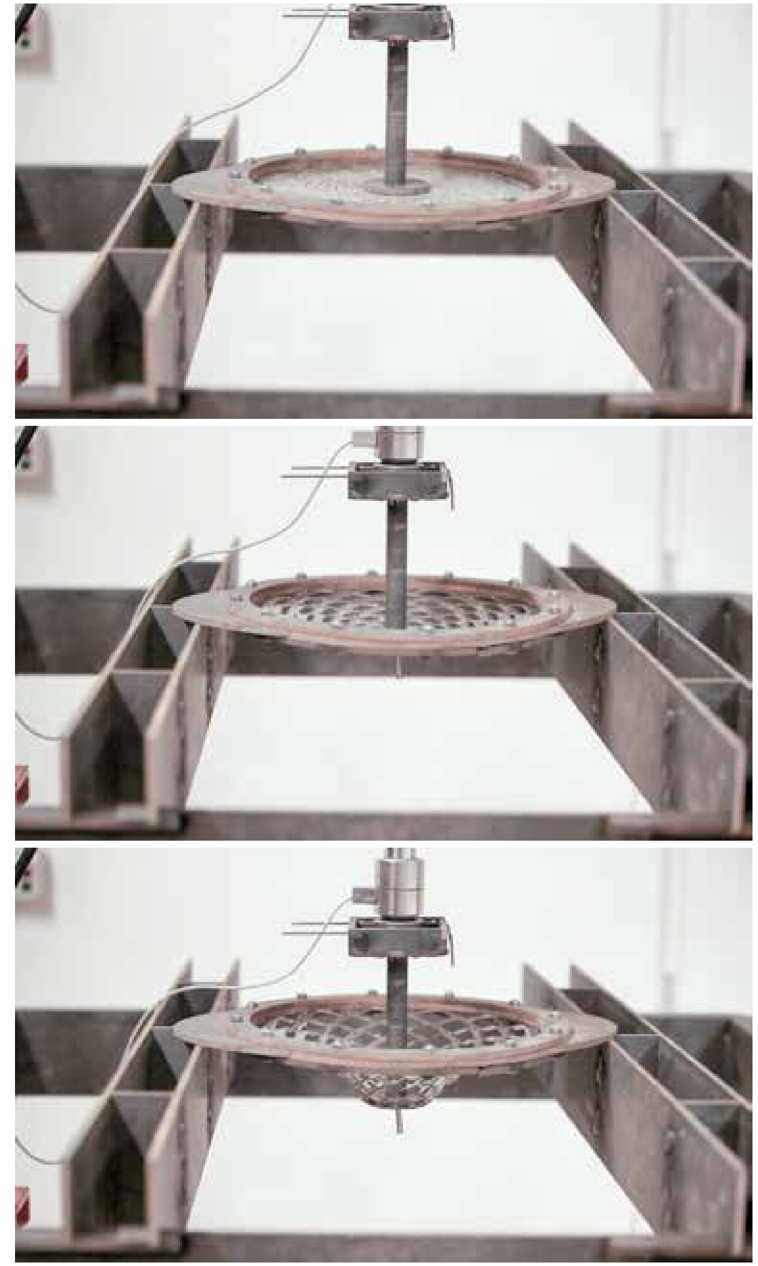
The creation of stretched rigid objects from the thin steel provided a great inside in how materials can be engaged, explored and manipulated through a combination of drawing, fabrication and transformation. The workflow created a field of knowledge on the method of stretching and through that gave a level of control that could be applied to the material when a certain result was sought. The origin of the experiment, however, was a much more open and non-determined approach towards the material. From the high level of uncertainty explored in the beginning, to the high level of control established through the systematic testing, a spectrum of varying degrees of control and uncertainty was found. As a way of embracing this new-found spectrum and anchoring the experiment in its explorative attitude towards material, a new series of production was started. This production aimed at combining different levels of control and uncertainty into a series of objects. The series approaches this by combining different cutting and slitting types in composite and slightly more complex objects.

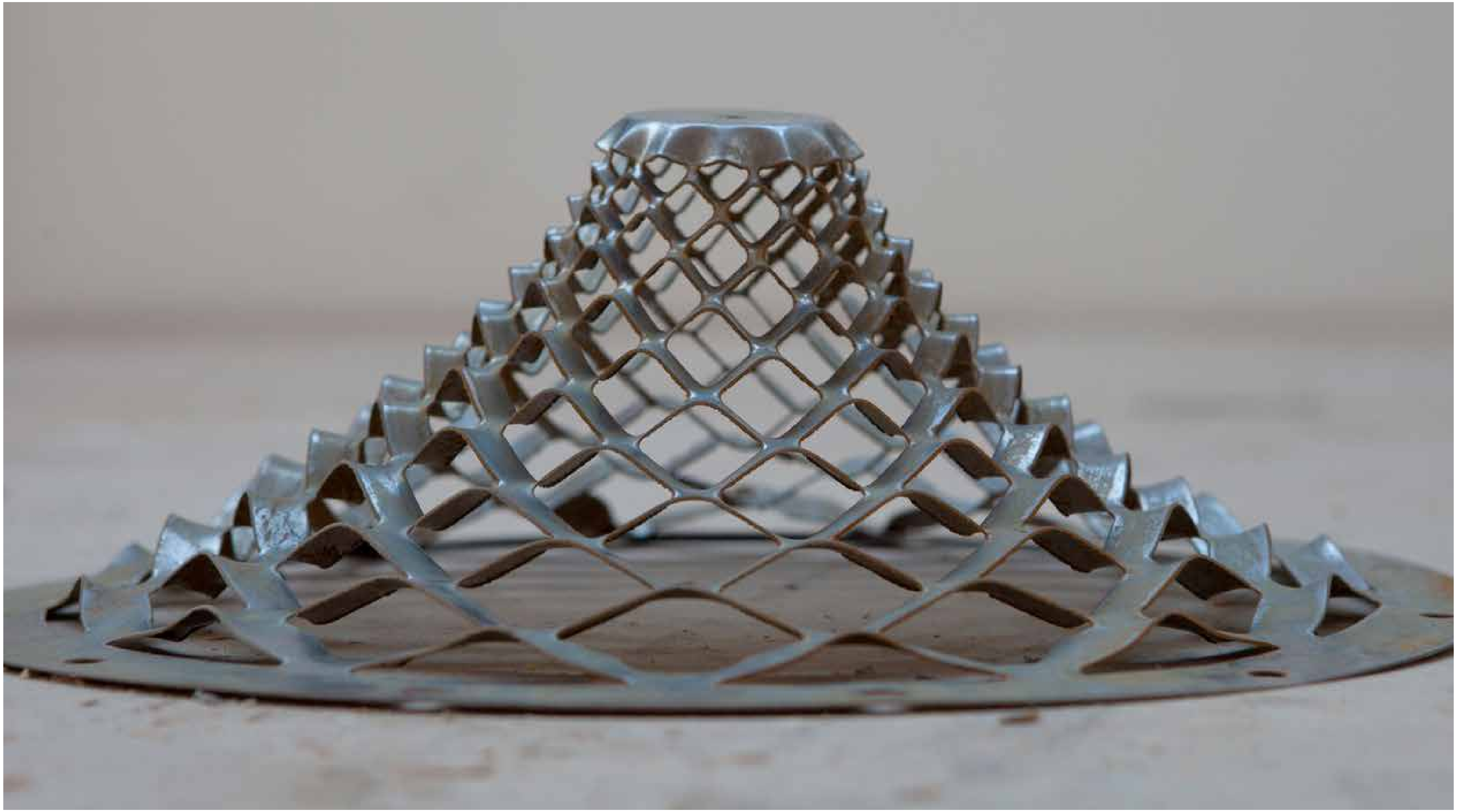
By deploying the knowledge and built equipment from the stretching along with other types of paths for cutting, bending and folding a new breed of objects was realised. These objects are distinguishing themselves by allowing the decision-making to be spread across the entire process. Additionally their increased size and complexity starts to imply more spatial constructs and mimic architectural fragments.

The steel mesh provides an exciting contrast to the floppy 0.5mm steel it is made of. The structural capabilities of the mesh emphasises the level of precision and control that can be achieved in the production. Simultaneously the simple, individual lines converted to toolpaths, then used to pattern the steel, both maintain and emphasise the unmanageability of the thin steel sheet. In between these two – the controlled result and the uncertain result – is a kind of crossing over or overlapping of strategies and structures. This can be geometries that through the drawing define a certain space of possibilities, but



Improved stretching device made from a retrofit pressure strength testing machine with a digital Newton meter. This method ensures consistent application of force to the steel, thereby allowing consistent, reproducible results.





The overall geometry and multitude of small plastic deformations create an unyielding three-dimensional, spatial object deriving from a flat piece of steel and two-dimensional machining data.

A composition of several stretched steel objects is starting to form a spatial strategy. This limited structure is seen as a fragment of a possible larger configuration with a potential increased complexity and variance.

This page and overleaf: Unique fragments are utilising different material potentials. Some regions are processed employing plastic deformation other parts are kept elastic. Combined the different capacities can form a multitude of fragments or structures with varying or gradient properties.

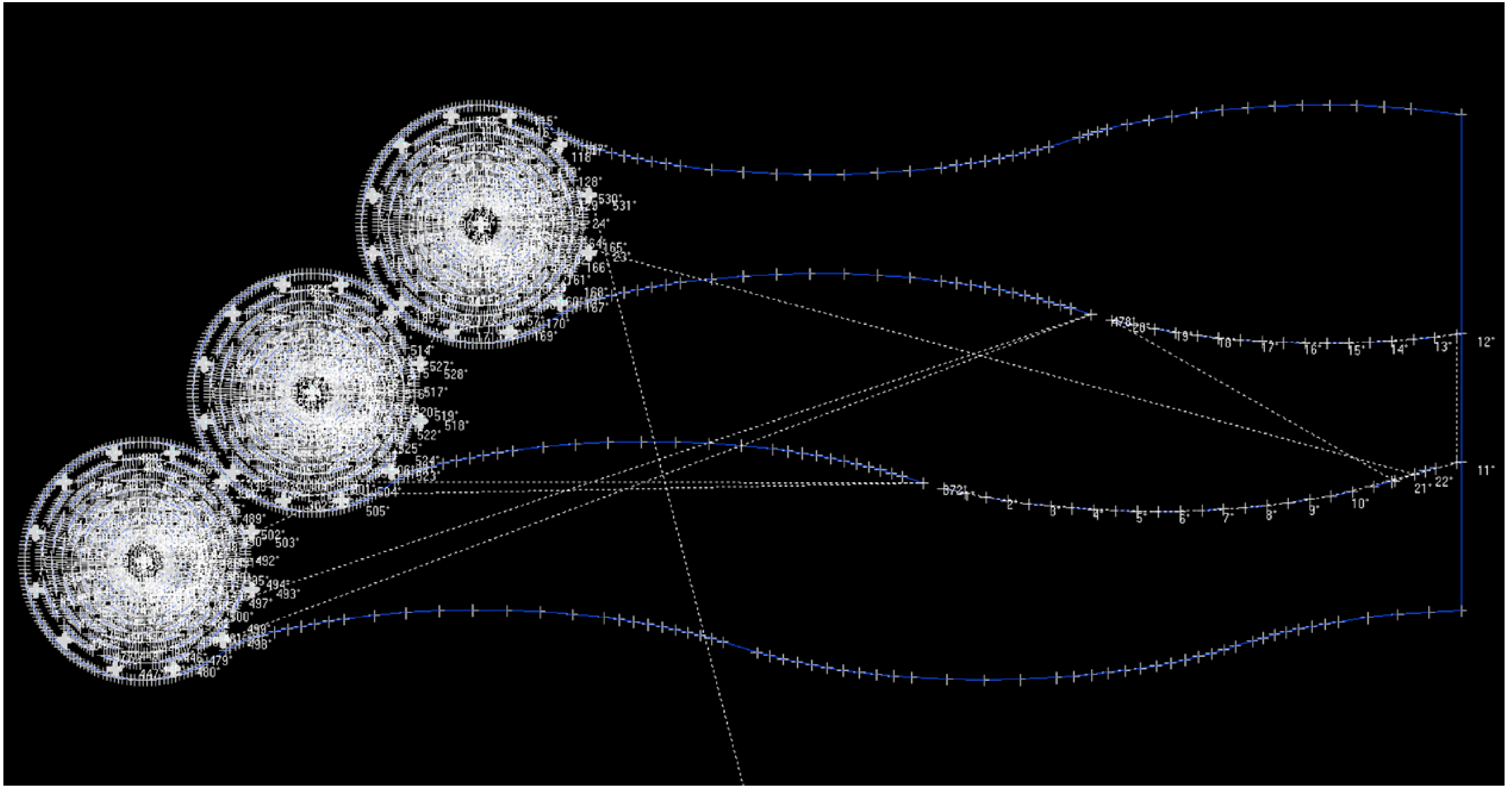
do not imply or specify exact conditions. A series of lines can, for instance, create a basis for folding or bending without requiring any decision on which direction or how much the fold or the bend should be. These decisions might first be taken in the particular situation where the steel is in the hand of the decision-maker – that being an architect, a designer or someone else – and in relation to whatever context or whatever other piece of material it has to co-exist and partner with.

The last series of steel sheet experiments explores the material on several levels. The manipulation and utilisation of material properties are used to create specific situations in combination with the uncontrolled, natural behaviour of the steel. The forming is created by the embedding of information into the material through fabrication and the activation of the capacities, brought forward by the information. Some parts of the objects are planned in the initial process, while others are created during the process or made unintentionally. This creates outcome that holds a larger spectre of the material capacities, and constructs with more and varying elements.

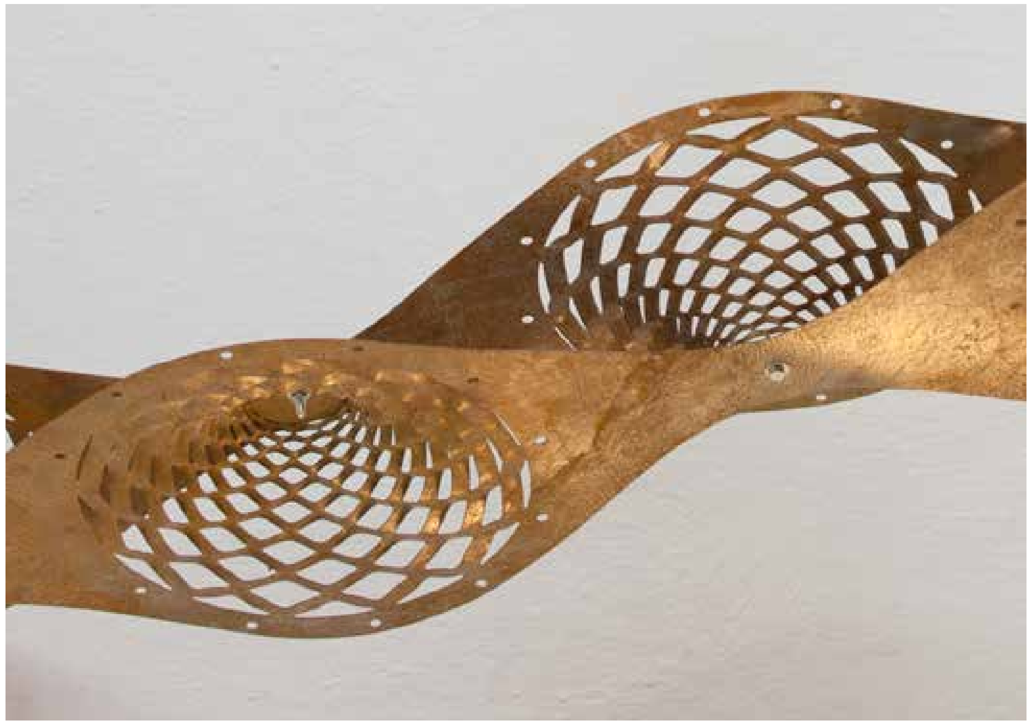
Thinking about architecture

The latter objects let this experiment embrace a more architectural scale and characteristic. The more complex and composite objects are both of a size more relatable to the human scale and have compound structures that start to suggest construction types that hint towards fragments of architecture.

These bespoke fragments try to discuss components from the world of building and construction by adopting simple modes of expression. The fragments are a kind of paraphrases of terms like stacking, the beam, a shift from vertical to horizontal and structural variation. The intention is to delegate them to an imagined, but specific architectural situation. They are in all cases non-contextual in terms of their fragmented physics, but their appearance hint at fictional scenarios. This points the experiment towards a setting where the objects are no longer limited to material test or abstract discussions, but mediums for spatial design.



Screenshot from CAM software. The graphic shows coordinates (white) and simulated tool path interpolation (blue) in between defined points. This visualisation of processing data is embedded in the steel fragment shown on the previous leaf. Depending on the processing and the underlying geometry, the steel will gain different capacities for controlled or uncertain deformation.



A composition of stretched steel objects supporting each other. The result is a fixed beam-like fragment with little weight and high strength. A varying approach to material machining and material capacities is not limited to each element, but extends into the combination and composition of those elements into possible, larger components or structures.

Representing the realisations

Throughout this experiment, the created tests, objects and bespoke fragments originate from a dialogue between the computer's digital domain and the physical materialisation. The experiments have provided continuous feedback that has instrumentalised the relationship between digital drawing and material capacities. The direction of the process, however, is clearly one-directional. There is no materialisation without a fabrication, no fabrication without information and thereby, in this case, no information without some kind of drawing. While the physical result can serve as input for the next iteration or a new experimental trajectory the increasing materialisation and actualisation through the process is predominant.

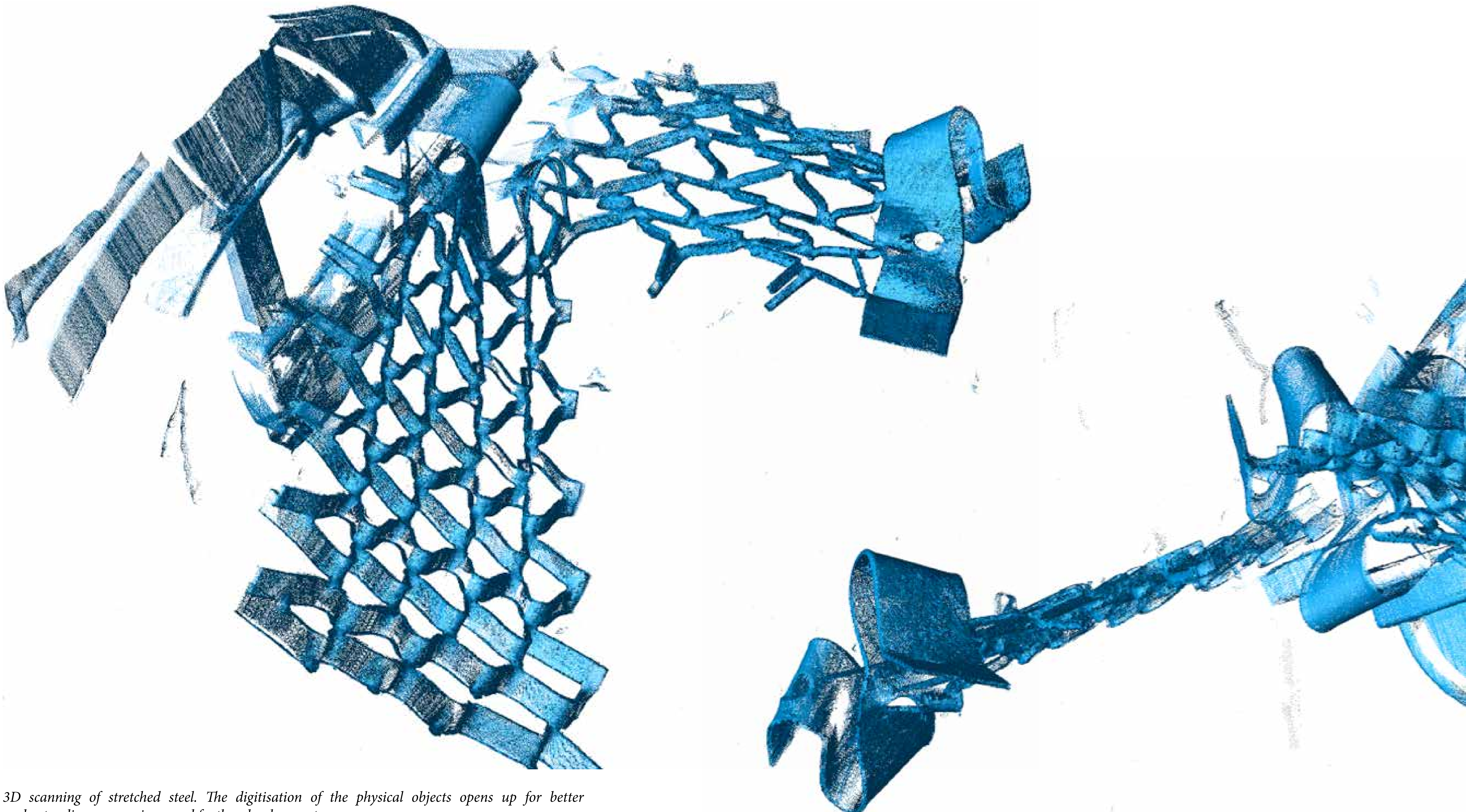
The method with which the objects have been developed is characterised by a continued approval of the unplanned and autonomous. Therefore, no exact description, drawing or simulation of the constructions exist. The final results only exist as themselves, that being physical outputs comprised of utilised information from drawing, fabrication and material. The artefacts might in certain places hold highly controlled portions, which precisely correspond with intention. Other places, they consist of curves or folds that are a dialogue between material and a lesser controllable type of processing. The steel might just curve a certain way with no predefined set of instructions, beside the context of its outer shape and original thickness.

Within the transformation processes and formal output a lot of qualitative information is embedded. The natural curves and unplanned output might outline useful ways of advancing and the relationships within and between artefacts might hold interesting spatial information. In both cases, the workflow precludes the possibility of extracting this information from the data basis from where it came. While having the complete set of realisation information distributed throughout the whole process is not unusual, it is rather abnormal within architectural practice to not have a representational drawing set that describes portions of the overall construction. This type of drawing is none-existent in this sketching-like material investigation. However, it becomes relevant at the point where the creations are being articulated as potential architectural objects or fragments. In order to be incorporated into the higher complexity, found in buildings, some type of drawings and specification

Different techniques can be used for 3D scanning or digitisation of physical objects. In this experiment, two types of laser scanners were used. A Faro Focus for spatial registration and a, as shown in the photo, Faro Edge handheld scanner for objects and details. The process allows digital extraction of geometries and curvatures created in physical space.

must exist. Likewise, the classical architectural drawing set that includes scaled sections, plans and elevations ensures a kind of readability and comparability across the material.

In order to combine the knowledge gained through the materialisation and extract the specifications of the materialisations themselves, a digitisation of the bespoke fragments is made. Therefore, to measure up the fragments, a 3D laser scanner was used. The fragments were arranged in space – hanging, standing, and lying – to create an orchestrated, spatial situation. Through a series of 3D laser scans in the room and around the fragments, a set of point clouds was created. Each point cloud is a 360 degrees view from a specific point in space. The point clouds were combined into one unified point description of the situation, thereby being a merging of multiple perspectives of the arrangement. The unified point cloud is consisting of coloured points. Each point is a measurement in space and combined, the points provide a spatial description. The understanding of the point cloud is, however, based on the way it is looked upon. The understanding of space and surfaces relies on the rendered views. Due to sophisticated software, this is usually not considered about – the point cloud appears as being descriptive geometry from the real world, but actually it is simply a registration of a myriad of points seen from several central positions of the scanner. The point quantity and data amount is massive, but also, isolated, quite non-operational. The interaction with the represented space is very limited and provides no immediate and easy way of being engaged. While created with super high precision, the digital representation of the reality is, when actualised in the computers spatial domain, providing little virtuality and potential on its own. The point cloud is a combined description based on reality, but existing in the most abstract digital way. Every point has a place, a coordinate, in digital space, but with no length, width, reach or mass their relation to the real origin is limited to being a specific type of representation. In other words; 3D laser scanning makes it possible to jump directly from one extreme to another. The existing reality, with an indefinite amount of indefinable information, can be digitised into points. The points have no other property beside their relative position in a digital space. The point cloud is the extreme of a solely digital existence, yet its relation to reality is easily perceived.



3D scanning of stretched steel. The digitisation of the physical objects opens up for better understanding, comparison, and further development.

This page: A series of bespoke fragments were composed into a spatial constellation. The steel objects were moved around in a sketch-like process to find potential relations between the fragments. They were not tied together, but conceived of as being possible individual fragments in a larger, connected structure.
Overleaf: The composition was scanned using a Faro Focus 3D laser scanner, thereby creating a digital, but fixed, representation of the real world environment. The screenshot shows a section through the point cloud. The points that are further away from the section cut appear brighter for a better visual representation and spatial understanding.

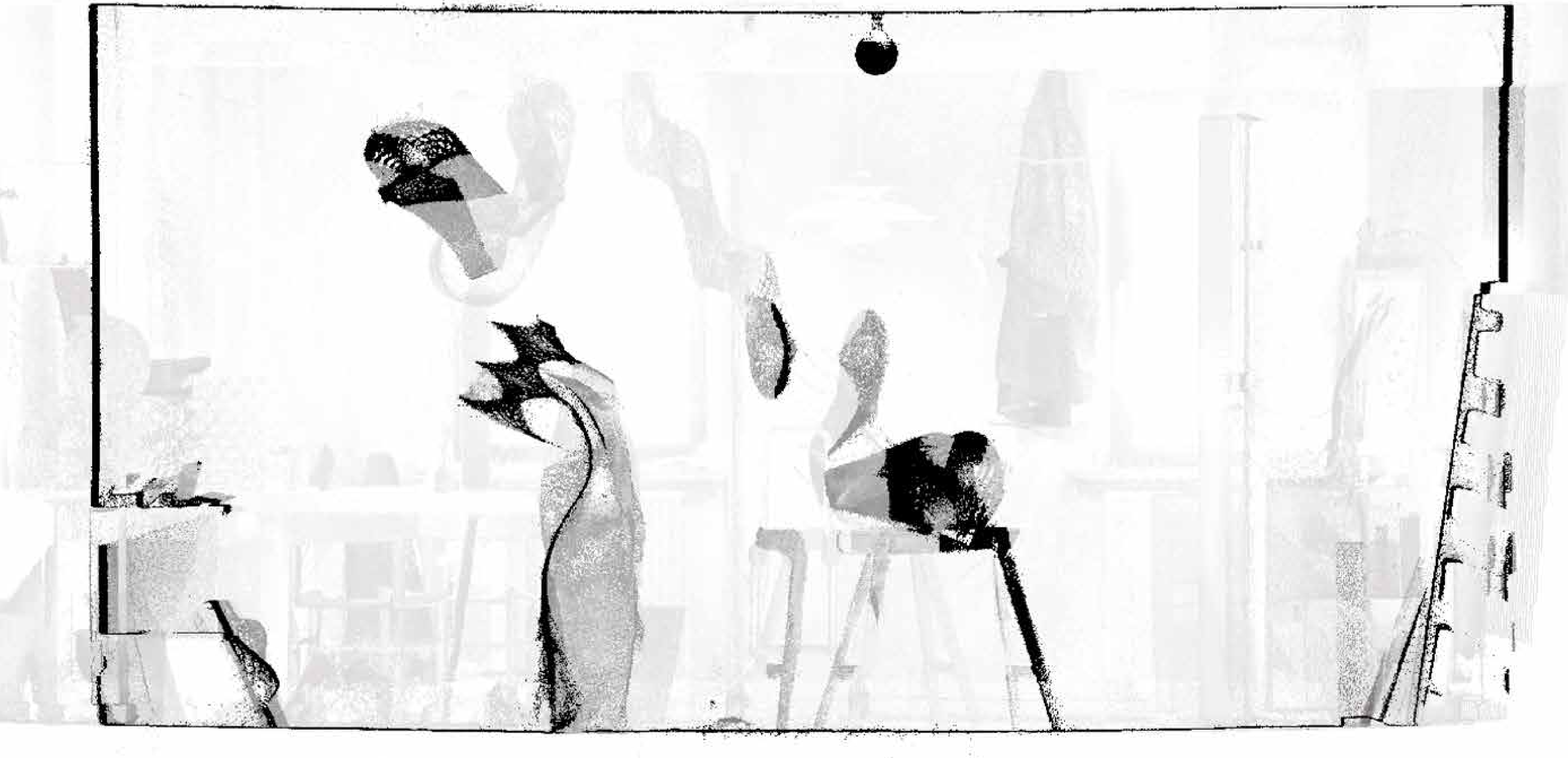
While the point cloud itself is almost dissociated with both the physics of reality and the virtuality found in digital drawing, it can serve as a type of abstract matter. The relations between points can be used to create a virtual description of what the point cloud mimics through its massiveness. By selecting and extracting points, and groups of points, and using these as the basis for the creation of spline curves, new types of descriptions were made. These curves are a type of interpreted data that replaces the pixelated information of the point cloud with scalable, editable data. The curve is a mathematical description in the same virtual domain as you would expect from a digital drawing.

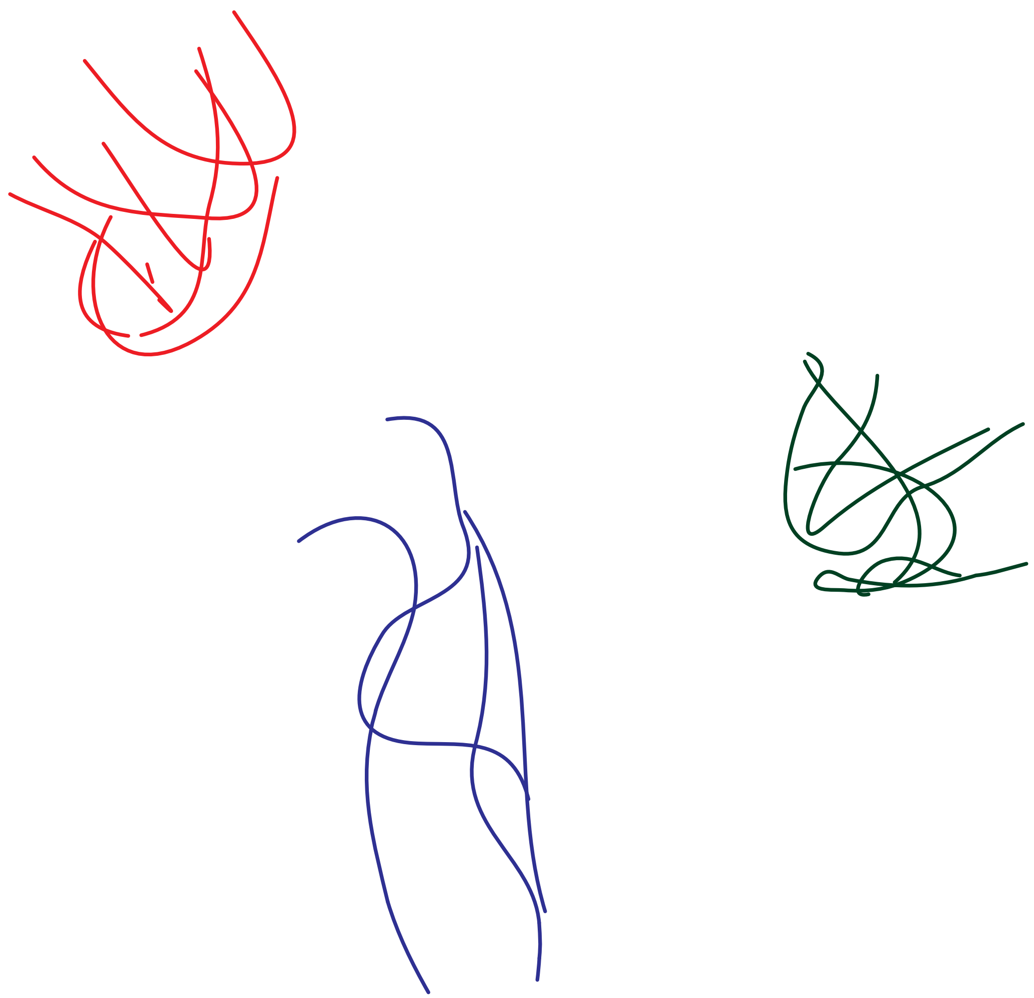
With a series of curves extracted from the point cloud a number of NURBS-based surfaces were drawn. Thereby, a virtual companion to the situation existing in reality is established. The constructed NURBS-curves have a clear relationship with the real fragments but are without any materiality themselves. They are formal extraction and simplification of the complexity of the realisation and thereby, they end up being similar to more traditional architectural representation. The realisations can, from that perspective, be regarded as sketches or models for the representations.

In this experiment of scanning, no further action was taken. Potentially, the representational information could have been passed on to the next iteration of the steel fragments or into other types of materials or machining. The process of scanning and extracting information, nonetheless, demonstrates a practice of translation where information can be passed back and forth between digital and physical space with the insistence of being able to not only represent each space within the other, but to interact with and react on the potentials arising within these spaces.

Drawing, coding, designing and machining material capacities

The described experiment ends slightly open-ended but exposes discoveries through its range of processes. The experiment shows a way for digital fabrication equipment and materials to play an active role in the development of form and design. Following this, the experiment points to the fact, that the designer will need a reflecting attitude towards balancing uncertainty and control in order to harness the unexpected and unknown possibilities





Splines extracted from the point cloud shown on the previous leaf. The lines are the 'edges' of the curved steel, reconstructed by interpolating multiple points into smooth curves. The lines might not resemble reality, but they are rationalisations of the steel fragment's situation at the time of 3D scanning.

of machining and materials. The experiment shows how this type of process can lead to explorative alterations of material capacities through drawing and machining.

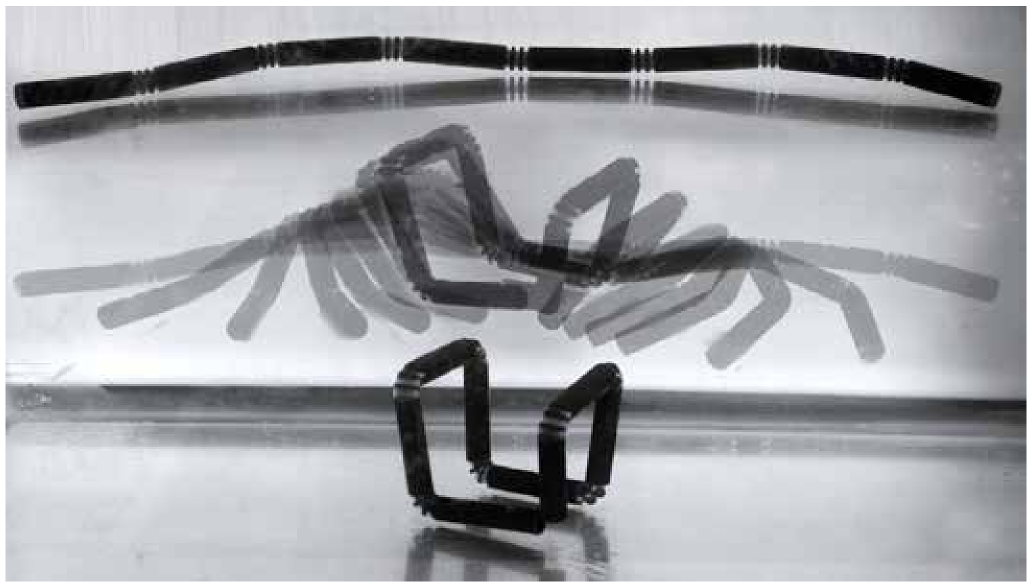
Even though the experiment produces a series of steel fragments, that somewhat mimics types or elements of architecture, the experiment settles on a tentative and suggested level. The relevance of the approach, seen in a wider architectural perspective, is, however, unmistakable.

Recent research within both materials, fabrication and architecture has shown great results in areas that seek to develop materials with special variable capabilities. It has shown an intense focus on materials on a micro-level, which make possible a development of smarter solutions with either graded properties, responsiveness or self-assembly capabilities.

The PhD-dissertation by Norbert Palz (2012) shows in-depth studies of computational strategies for material design with tunable capabilities. Palz' work shows an interest in developing architectural potential on a micro level by making materiality adjustable on a much more detailed scale than conventionally available in architecture. In his work, Palz puts forward different 3D-printable material designs that can varies in density and flexibility depending on whatever material capacities is needed. The inventions combine geometric and algorithmic work into materials with tunable properties. The designs can be seen as recipes for additive manufacturing that utilise a specific technological approach to the creation of materiality. The designs are bound to the materials available in additive manufacturing, normally metals, elastomers and polymers, but build up materials composition from a granulate level.

A similar, but more processing and fabrication-oriented, approach is seen in Sarat Babu's 'architectured objects'(2014; Beckett and Babu, 2014, pp. 122–116). Babu specifically uses laser sintering based additive manufacturing to create different types of microstructures that supply the finished object or piece of material with varying, specific properties. Babu's research in materials shows a layered complexity that clearly aims at delivering a macro performance on an architectural level.

At Skylar Tibbit's Self-Assembly lab at MIT, the bridging of micro and macro scale is taken even further. Several strategies and technologies are used for creating material systems that assemble themselves through a built-in logic.



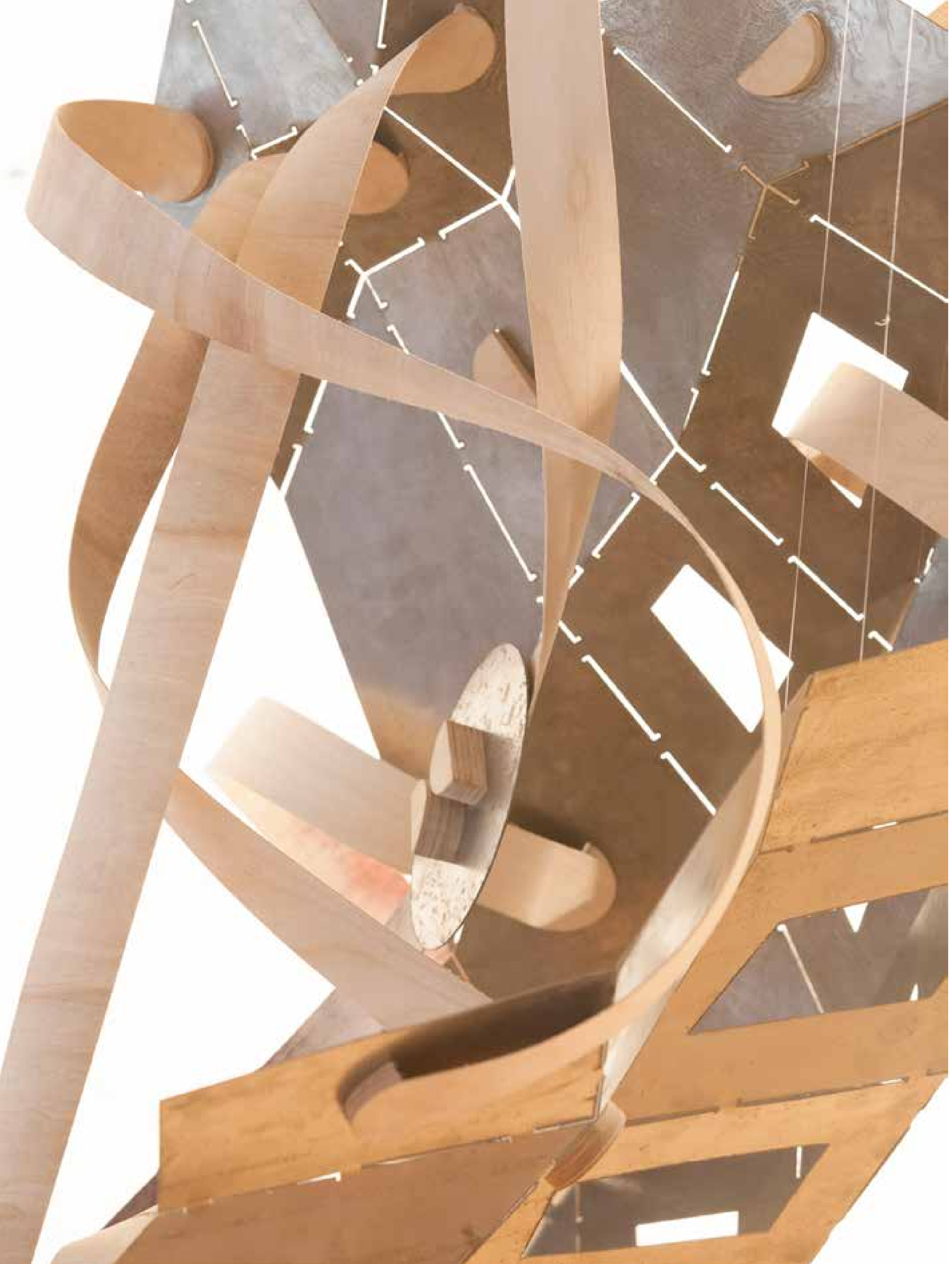
Upper two photos: Detail of 'architectured material' by Sarat Babu. Microscale geometry is configured to provide a material with very specific properties and behaviours.
Lower photo: 4D print from MIT Self-Assembly Lab. The material is printed with the capacity to fold into specific shapes by itself.

The 'Programmable Materials'-research at the Self-Assembly Lab uses different fabrication approaches to modify and create materials that can change shape based on external output or information. The use of 4D printing (Raviv et al., 2014; Tibbits, 2014) introduces an active layer to materials, either in relation to assembly or shape-changing strategies. The research is fascinating since material properties can then be seen as not only varying parameters through a piece of material but as a set of changing capabilities anywhere.

The above-mentioned body of research shares an intention of embedding potential into materials. They do that by establishing design spaces on a deeper material level than conventionally employed in architecture. While being much more technologically advanced and working on a smaller material scale, the intention of creating varying material capabilities through the design of processing is parallel to the work in the *Stretching the Steel* experiment. Palz, Babu and Tibbits are all working with a, mainly, computer programming approach, in order to, often quite controlled, create bespoke microsystems. *Stretching the Steel* uses a more drawing-like type of investigation to manipulate larger material elements. The similarity lies in the intention. The difference in scale and method across the two groups of experiments could, however, suggest a future material thinking bridging the micro and macro scale in architectural design. While micro-scale development will be needed in order to create the widest possible array of material properties, the larger scale and more component sized approach will be necessary in order to facilitate an implementation of the approach in architectural design. Both scales are related to the design of materials or material fragments with varying and/or specific capacities. The architectural drawing could, if developed with the material properties and behavior in mind, introduce premises for material manufacturing that could potentially supply an architecture with a level of material integration not experienced before. Hopefully, coming years of research will offer suggestions on how a bridging of microscale material research and architectural design can take place.

Notes

1 See http://www.selfassemblylab.net/ProgrammableMaterials.php (retrieved 8/23/2016 at 10:21) for outline of the research.



E2: **WORKSHOPS: DIGITAL MATTER**

E2: **WORKSHOPS: DIGITAL MATTER**

Materials
Steel, sheets - 0.25 mm, 0.50 mm, 1 mm, 2 mm, 3 mm
Plywood, birch, 3 mm, 6 mm, 12 mm
ABS filament thermoplastic
Plaster powder

Machines
TecnoCUT Idroline 5-axis water jet
CMS Antares 5-axis CNC router with various flat end and ball end router bits.
uPrint SE FDM 3-printer
ZCorp 3D-printer

Software
Rhino
TecnoCAM
AlphaCAM
CatalystEX
ZPrint

Quantity and size
Series of smaller test and constructions
One 0.5-1 m3 construction per group.

Comments
The workshops described in this experiment were planned and executed together with Maya Lahmy. Content and reflections of this work were published and presented at the 'Adapt-r Creative Practice Conference' in Brussels and at the 'What's the Matter - Materiality and Materialism at the Age of Computation' in Barcelona:

Aagaard, A.K., & Lahmy, M. (2014). Agile Drawing: Expanding the Territory of Architectural Drawing Through Digital Fabrication. I J. Verbeke, H. Van Den Biesen, & J. Van Den Berghe (red.), Mediators. Brussels.

Aagaard, A.K., & Lahmy, M. (2014). Agile Drawing: Expanding the Territory of Architectural Drawing through Digital Fabrication. I M. Voyatzaki (red.), What's the Matter?: Materiality and Materialism at the Age of Computation. Barcelona.

Some of the following text is based on the two above-mentioned papers and the literature and material presented to the students attending the workshops

Special thanks to all the students from the 2nd year 2014 at Aarhus School of Architecture that took part in our workshops. Most the illustration shown here in is work done by the students during the workshops

Expanding the territory of drawing

The basis for this work, executed in the form of two student workshops, titled *Digital Matter*, is the claim that digital fabrication can be used to rethink the understanding of drawing in an architectural context. It is the argument that both the act of drawing and the role of the drawing can be expanded through digital fabrication. By using this point of view as an applied approach and as a conceptual mindset, the intention is to establish a non-deterministic sketching-like workflow from where discoveries and revelations can be made, through the joint effort of processing and a combinations of materials.

The workshops build on an, at the time, ongoing research by Maya Lahmy and Anders Kruse Aagaard. Cumulative discoveries and discussions frames the basis for the experiment. The preparation of the teaching plan was a shared responsibility.

Drawing within a reflective practice

Architectural drawing changes mode of operation as it passes through different stages of a design process. It moves from a conceptual position of inducing and anticipating ideas, to a descriptive position of translating ideas into realisation in a built environment. Anthropologist Edward Robbins opens a discussion of the architectural drawing's twofold character. *"Drawing, as idea and as act, embodies within itself the relation between society and culture, the relation between realisation and imagination, and the relation between object and subject."* (Robbins and Cullinan, 1994, p. 7). Despite the acknowledgement of these characters coexisting, the crystallisation of an architectural design process, from initial idea to material creation, traditionally consists of a sequence of autonomous drawings with separate roles. In his essay *Translation from Drawing to Building,* Robin Evans (1997, pp. 160–161) points to the

After the final crit: Drawings and objects from the second 'Digital Matter' workshop.

possibility of interweaving the abstract and tangible aspects of the architectural drawing; *"The two options, one emphasizing the corporeal properties of things made, the other concentrating on the disembodied properties in the drawing, are diametrically opposed: in the one corner, involvement, tangibility, presence, immediacy, direct action; in the other, disengagement, obliqueness, abstraction, mediation and action at a distance. They are opposed but not necessarily incompatible. It may be that, just as some fifteenth-century painters (Masaccio, Piero, Mantegna, Pinturicchio, Leonardo) combined the pithy irregularities of naturalism with the compositional regularities of perspective construction, so architects might conceivably combine, in such a way to enhance both, the abstract and the corporeal aspects of their work."*

With the introduction of digital fabrication tools in both architectural research, education and practice, another aspect of drawing is made possible. From merely mediating spatial ideas, organisation, and form, the drawing is now additionally capable of acting instantaneously together with materials by extracting and converting drawing elements into digital tool activating processes. By the end of the twentieth century, some aspects of direct data interchange between architectural practices and parts of the building industry had already been introduced through digitalisation of drawings and production. As Bob Sheil (2005, p. 23) explains: *"The drawing was no longer a static document, but an evolving bank of parametric data from which multiple subsets were extracted."*

Lines, drawing and fabrication

Lines are the obvious and concrete content of a drawing. Traditionally, in architectural representation, lines are what defines the borders tbetween space and matter. Considered in relation to fabrication, lines, can furthermore form the information with which the drawing is deployed in a digital machining process. The lines of a drawing can directly affect the mode of fabrication and are, to some extent, embedded in the material output. Like the drawing will be discernible in the fabrication, the fabrication can in return affect the way the drawing is drawn. Looking at both lines and fabrication as potential relational, susceptible elements, the exact moment that the mode of process is changed becomes of importance. The drawing becomes a carrier in between this change

of mode, and whatever the intention and type of drawing is, at a certain time, it will affect the further development of how both the lines, drawing and fabrication can be employed in architectural design processes.

By default, there is a variable distance between drawing and fabricated object relative to the type drawing and fabrication involved. A three-dimensional, solid-modelled digital drawing can be an almost direct input for additive manufacturing, and a two-dimensional line-based digital drawing can straightforwardly act as cutting lines for a laser cutter. More complex forms of fabrication, such as multi-axis CNC routing or robotic fabrication, require more explicit types of parameters to move tools around. The greater the distance, the more the drawing will have to transform and acquire specific qualities, which can be obtained through code writing, post-processing, or CAM software. The distance can be incorporated into the drawing and add to the width of the process.

The drawing will need to consider not only the type of fabrication, but also the specificities of materials involved. Transforming a drawing into fabrication information and subsequently performing the fabrication, can necessitate an introduction of material tests in an early phase of a project, thereby adding an early material perspective as an integrated part of the drawing.

The implementation of fabrication as an investigational instrument and the knowledge gained through material studies can feedback and accumulate in the drawing. The drawing becomes agile and manoeuvrable, branching in multiple directions to reconnoitre the field of investigation. This allows for an oscillating exchange of information between idea, drawing, and fabrication, and thereby brings an opportunity to extend the reflective process into architectural practice (Gramazio & Kohler, 2008).

When the drawing develops into fabrication, the lines morph from specifying contour into a relational role with the fabrication tool. The appearances of those lines are shaped by the properties of the machine, the tool and the operational concept of fabrication. Movements of tool points are executed along drawing lines; directly defining the positions, directions and approaches of the machine, but might not having any immediate visual correlation with the shape that is intended or the object that is created. Nevertheless, those actions

A look down into a water jet cutter. This type of machine is primarily used in the metal and stone industry for manufacturing final components for all kinds of buildings, vehicles, vessels, etc. Today, however, machines like this appear at schools of architecture. What can these machines infuse to the process of designing?

of tangible manufacturing are creating the shapes and surfaces of the actual, materialised object. Whether the lines are representatives of boundaries of space and matter, or information for fabrication, the lines in the digital drawing have the potential to mediate the information between idea and comprehension. In the unfolding from concept, through visual representation to fabrication, the body of accumulated drawings fosters the collective understanding of the intention.

To set up a method and mindset where the fabrication is seen as an expansion of the drawing, it is crucial to found a thinking that regards every drawing and every production as a motive power *towards* a creation of a conceptual idea. This is as opposed to a deterministic thinking where drawing and production are used to achieve an already imposed idea. Fortunately, this mindset is not alien to architects or architecture student. Investigations in the creation of architecture often build on this or similar working methods. However, the distinctive working method and intention of *Digital Matter* is not a traditional design scenario, but instead, an approach and intention heavily built on digital fabrication machinery and material. Built into this intention is the action of moving industrial machinery, and their supporting systems, from their intentional and traditional position as end-result manufacturers to a situation where they can be used as tools in an early exploration of materials and their potentials in relation to spatial and architectural design. This action is, on the current, general, architectural professional level, an abstract move, fairly distanced from the realities of architectural design in practice. However, for the purpose of investigating fabrication as an expanded notion of drawing, this move serves an essential role in this research and its experimental workshops.

Roll out the machinery

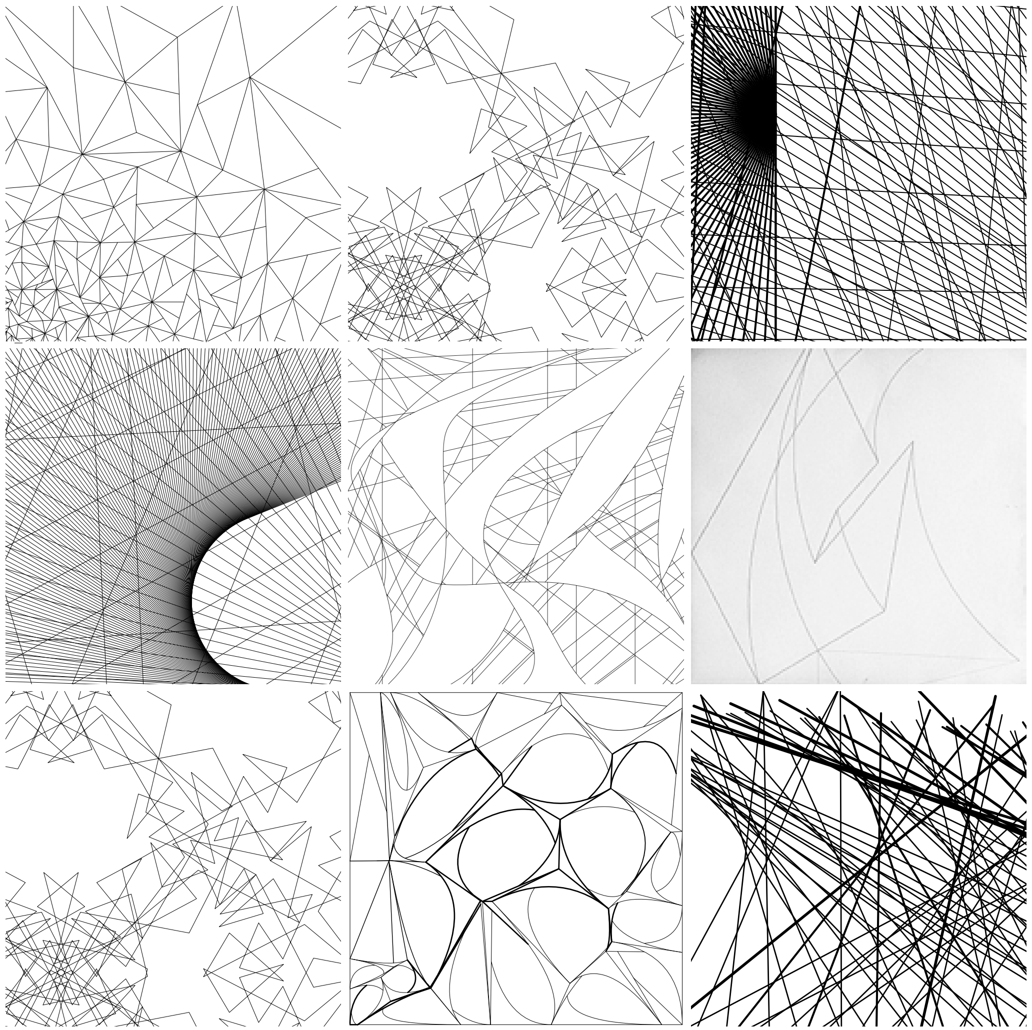
The method of using industrial digital fabrication machines in the experimental and early, developing part of an architectural design process was tested and carried out with a group of 2nd-year students in two workshops, each of a two weeks duration, at Aarhus School of Architecture. The overall conceptual base of the workshops was to bring computer-controlled machines into use in the very early stage of a project development and deploy machining and material knowledge in the initial sketching and drawing process.

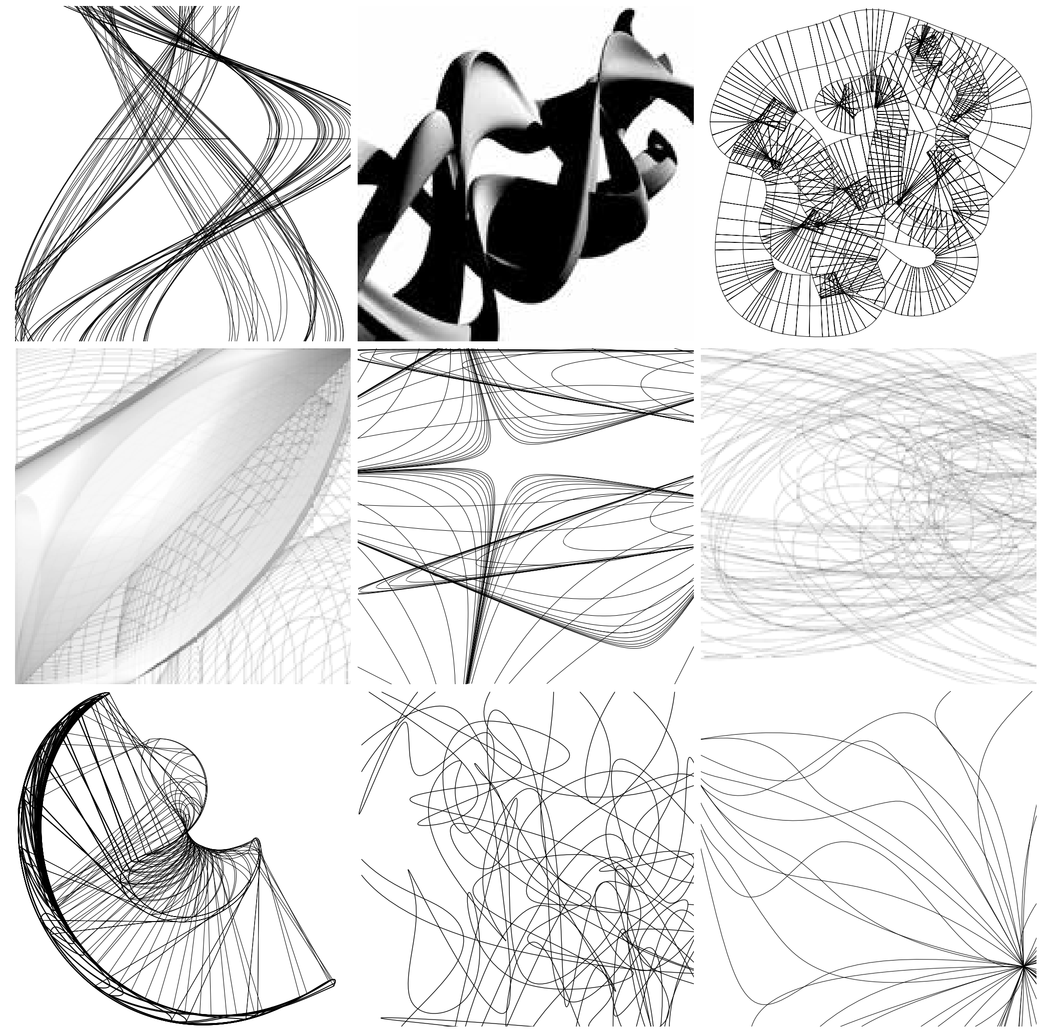
Machines and students at work during the first workshop.

The machines used in the workshop were a 5-axis waterjet cutter, a 5-axis CNC-router, and 3D printers. The machines can be divided into two categories: The water jet and CNC-router are industry fabrication machines normally used in end-result production and to process materials also belonging to final production. The two 3D printers are rapid prototyping machines, typically used in product testing and development. These machines build with materials that create results dissociated from final products. The machine line-up is representing different parts of a design and fabrication process, though all conventionally located further ahead in the process than in these two workshops. In the first workshop, the students had access to the waterjet cutter and the CNC-router – with the matching materials being sheets of steel and plywood. In the second workshop, the industrial fabrication was limited to a CNC-router and plywood. This difference demanded one course facilitating a widening and combination of materials and another focusing on one material and deeper understanding of the associated machining. Both workshops utilised two types of 3D printers; one printing with ABS plastic, the other printing in plaster.

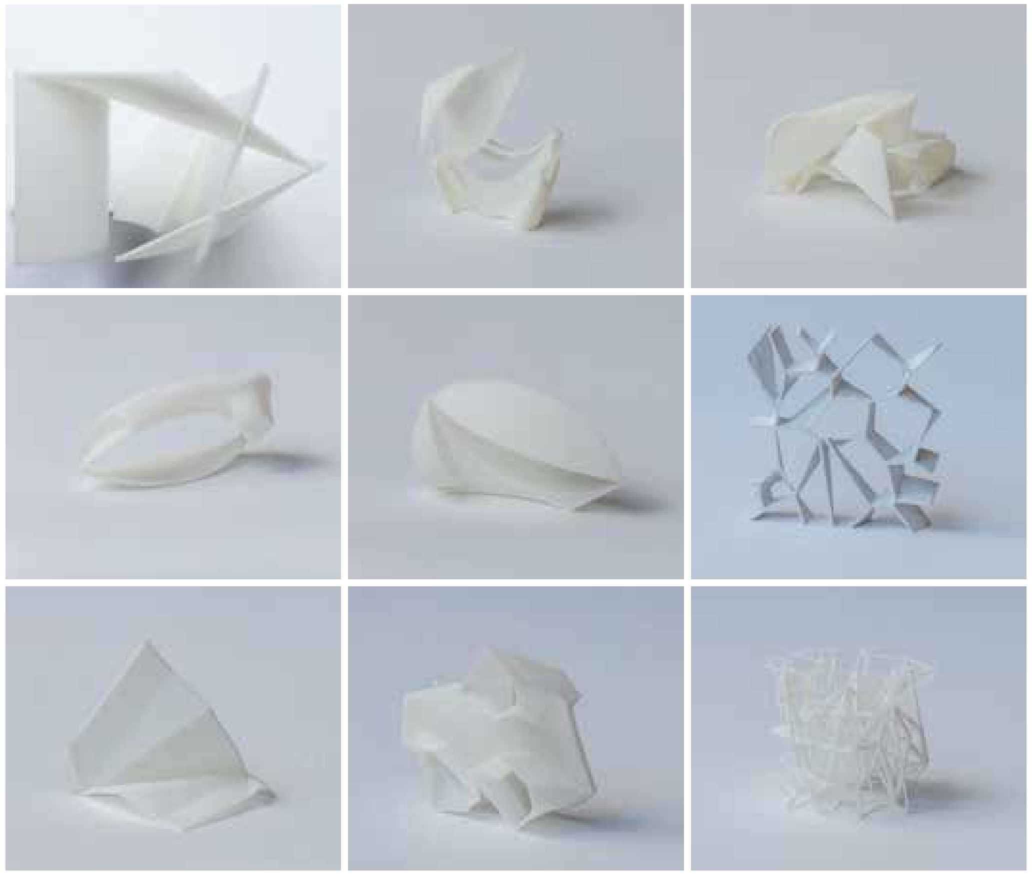
While the students were to master basic digital and three-dimensional drawing, they had no prior experiences with digital fabrication. To promote an expedite workflow, where drawings could quickly be converted into machine code, both drawing and machining were introduced on a somewhat easily accessible beginner's level. Prior to the workshops, a series of introductions, presentations, and ambitions regarding the amount and type of outcome were planned. A number of example files for various types of software were produced, as well as fabrication samples made with different drawing strategies and with different materials. Some of these test were fetched from the *Continual Accumulation* experiment. In that way, the objective of the workshop was formulated by a supporting frame of content.

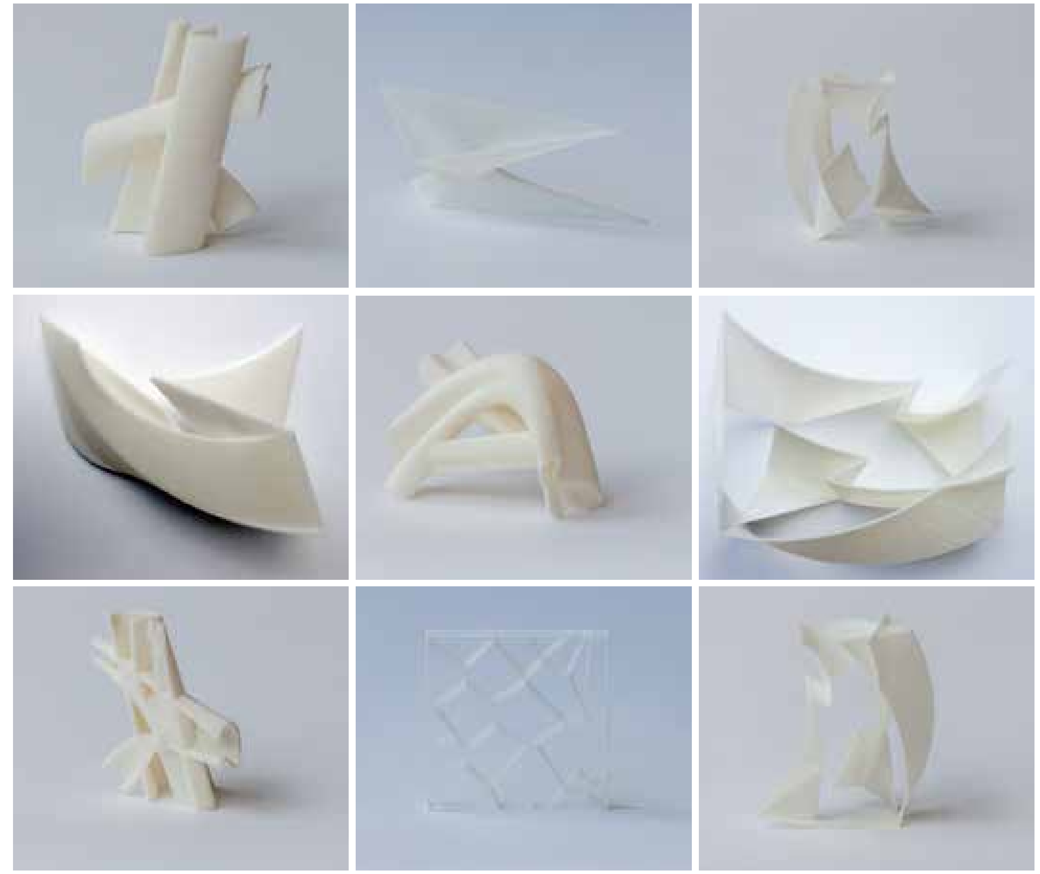
In addition to introducing the students to the claim that digital fabrication can be used to rethink the understanding of drawing in an architectural context, the workshop also had the more general purpose of familiarising the students with file preparation and basic machine control and, hopefully, boost their interest in this emerging field within architecture. All machines were put into operation within the first two days of the course.





Selection of drawings from the workshops generated by a list of operative verbs: Stack, accumulate, overlap, melt, merge, blend, repeat, alternate, mirror, progress, confuse, contrast, radiate, graduate, expand, inflate, split, branch, nest, offset, bend, twist, intersect, compress, fracture, pinch and puncture.





The line-based drawings were given geometrical thickness, surfaces, and depth, and printed using two types of 3D technology. The printing transforms the drawings into new spatial constellations while keeping a relationship with their origin.

Drawing, machine, material

Whether on not the lines are drawn on paper or digitally created, the drawing is a frequently used form of initial expression in a design process. The drawing often becomes the first materialisation of thought and operations, connecting the thinking of architectural space or concept into an actual or virtual environment.

Hence, the very first task for the students was to produce drawings based on fundamental architectural principles. Spatial concepts generated from an array of operative verbs were translated into series of drawings. The drawings were instructed to be line-based but not limited regarding technic or software combinations. The drawings were printed on paper and discussed as spatial narratives. Concurrently, parts of chosen drawings were given a geometrical thickness and then 3D printed. These results were likewise discussed. The ambition was to move the students from a known, but abstract, drawing medium and into a new, fabricated three-dimensional medium. Throughout the workshop, a variety of drawings originated, mediating the thoughts, visions, and directions of the individual student group's projects.

With a series of drawings, prints, and associated spatial discussions, the drawings or parts of the drawings where used as catalysts for fabrication. The drawings themselves were not seen as images of intention but instead as raw material for a production-based discussion and development.

Going from drawing to fabrication can be done in many ways. The abstract nature of the produced drawings was met with an open-minded translation of lines into tool paths. Either all, a selection of, or modified lines from the drawing were converted to paths for either the water jet or differently sized router bits to follow. This process actuated the drawings as investigative information set for material and machining exploration. The ongoing discussions, related to the original drawing ,were maintained, but the production itself was allowed absolute freedom.

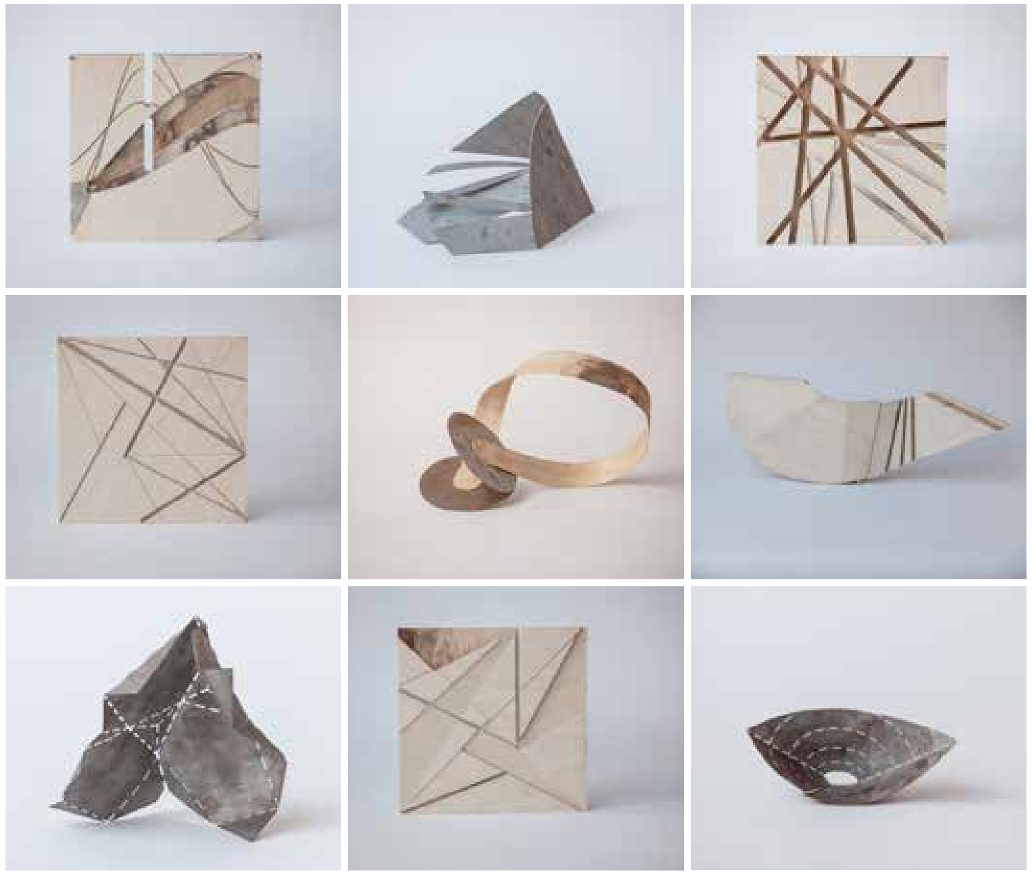
With software and machining workflows set up, a continuous investigation was made possible. The line-to-toolpath conversion resulted in each material output to have a clear kinship with the source drawing, but importantly also added several other aspects. Tangible realisations related to both material and machining were instantly made. On a more abstract level, the production began informing both the discussion established around the drawings, and an occurring spatial creation found in the amassed production. The simultaneous obtainment and utilisation of knowledge gained through the fabrication was urged upon and considered as direct input to the development of drawing data. Quickly, the established workflow resulted in a swift, iterative process where discoveries could be chased, focused, and unfolded.

Exploring machined material

A specific way to, with immediate results, to expand the drawing-to-fabrication workflow as a material-exploring tool was to proceed with the sketch-like attitude to the objects after machining. Depending on the cutting directions, material orientation, tool depth, and other machining parameters, the material output would behave differently. Some machining is purely a geometrical transfer from drawing to the material, while other types push the material into gaining new potentials. Machining the plywood thin in certain parts might cause it to either break or bend depending on grain direction. Or, allow light to pass through the fibres. Metal sheets might get floppy or rattly if cut in long thin strips, or they might fold into a strong, rigid structure if, by way of cutting, the sheets are allowed to bend. These types of transformation simultaneously put the drawing and the drawing-fabrication relation into new positions. The drawing becomes a carrier of possibilities that can be utilised when embedded into the material. Machining is thereby not only interacting with material properties to create shapes, but is also adding functions or tectonics by embedding capacities to the material objects. By transforming the material after machining, the drawing also steps further away from being a representation. The geometry and visual appearance of the transformed material are not resembling the drawing anymore. Instead, the drawing and material complement each other and start to develop a synergetic relationship.

The transforming step became a critical phase during the workshops. It both showcased how using materials and machining in a sketching process can unveil new discoveries of material potentials, and accentuated the benefits of the drawing as an inquisitive tool instead of a solely descriptive tool. The passage of drawing to fabrication and further into transformation introduced a high level of uncertainty and interaction to the process. Most fabrication results

This spread and overleaf: Jumble of different steel and plywood objects. All produced with line-based drawing as origin, but transformed through selection, file preparation, machining, and/or physical transformation. There is a clear kinship with the drawings. However, the produced objects are not realisations of representations. Both drawings and material objects collectively form a budding spatial intention and direction. In some instances, the plywood and steel start forming hybrid objects.



were not easy to foretell before actually having them in hand, and most were also providing more than a single possibility. In many situations the students found themselves in a in a similar condition when having the machined material in their hands as when making the drawing; the possibilities were endless, and decision-making was needed.

Pursuing discoveries

Taking the two-dimensional, line-based drawings to 3D-print, cut steel and machined plywood immediately widened their objective and intent. While being initiated by a set of verbs and different drawing strategies, they suddenly gain a more complex and diversified potential. The addition of materiality introduces a new thinking to the drawing. The new meaning of lines as information for processing material broadens the objective of the drawing and when the resulting machining of those lines enables the material to transform into completely new and unexpected configurations both the intention and the potential of the original drawing grows tremendously. While the workflow is set up with different trajectories to follow, each step will trigger uncertainty and surprise. Consequently, each step will also contain a possibility for new discoveries. Combined with the open minded and non-deterministic thinking pushed forward in this experiment, the drawing-fabrication-transformation workflow becomes a strong method for discovering new material possibilities and spatial consequences.

Working in groups, the students created a wide-ranging amount of drawings, 3D prints, and material experiments. Each time a new creation was made, it served as input for the next iteration or as a starting point for a new branch of experiments. This created a feedback loop where particular lines, files, and programs were refined throughout the process, but also a workflow where the architectural and methodological discussion of each output served as input for the further progress. Sometimes, the work evolved at a conceptual, abstract level and other times in a very tangible way. However, always with the pursuit of discoveries in mind.

Continuous evaluation

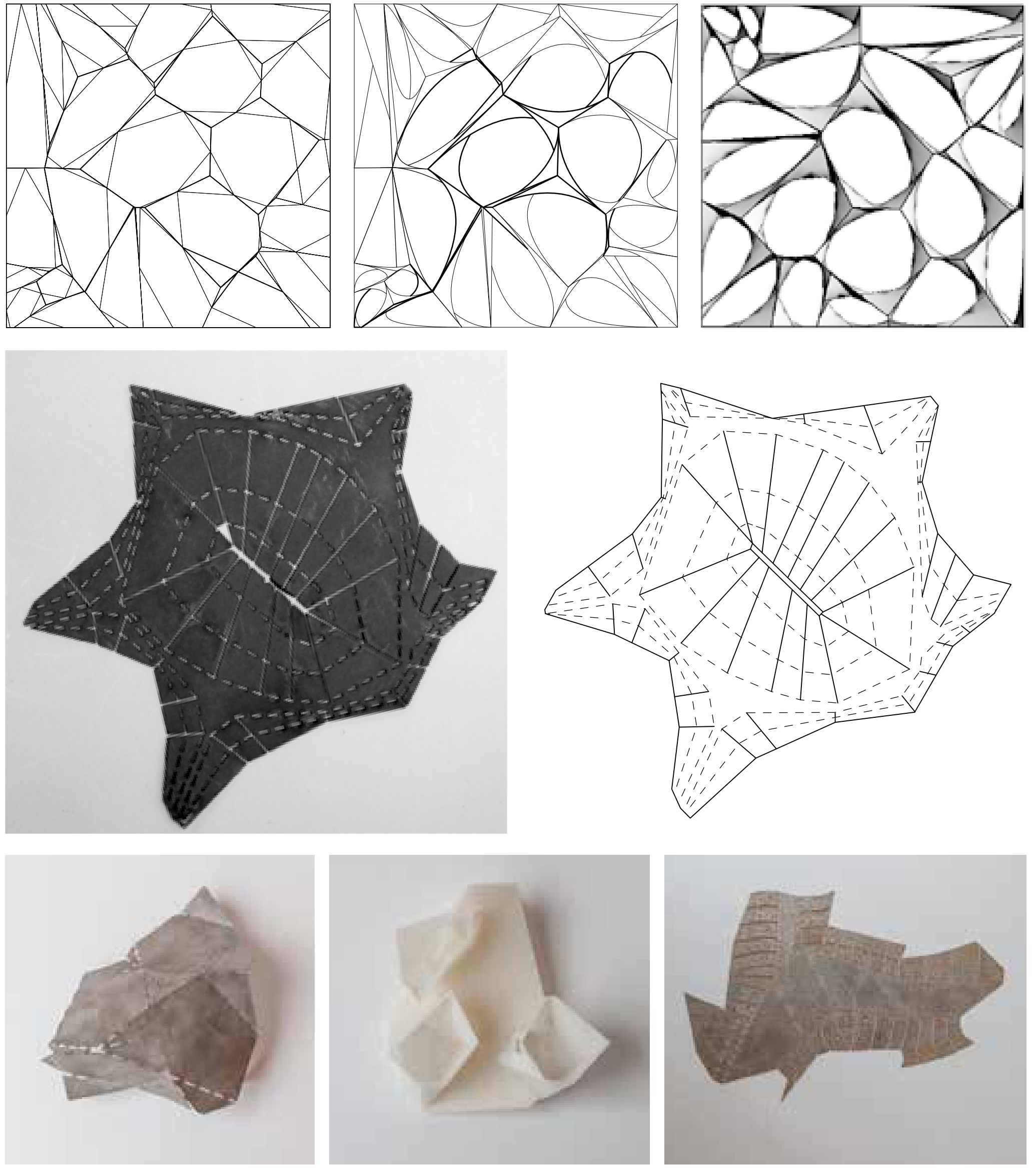
The large quantity of drawings and material investigations produced at the workshops was subject to constant evaluation. The constant iteration and discussion of each creation were an essential and embedded part of the workflow. This ensured critical reflection and realisation in an alternating process.

The earliest translations from initial drawings into material tests consisted largely of direct line-to-machine-path conversions. Cropped, slightly altered, versions of the drawings became cutting lines and router paths. This directly moved the digital information into the materials; wood, steel, or print. These first results were evaluated with considerable attention to the machining challenges, the tool possibilities, and the material properties and capacities that these artefacts revealed. The bendability of steel, the router's unveiling of the layering of plywood, and the neutral textures of a 3D print are examples of concrete, but undetermined, aspects exposed through making. These processes, along with real material revelations, can function as direct input with which the forthcoming work can be enriched.

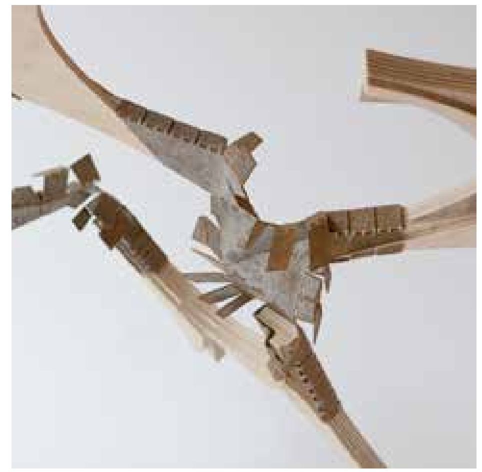
The material output was evaluated and discussed in relation to the drawing it originated from. Hence, the drawing was not limited to solely serving as digital information to fabrication processes but also catalysed initial spatial intentions. Both drawings and material output held the possibility and legitimacy to be studied, analysed, and confronted with these intentions. If, for example, the conceptual mindset behind a drawing addressed a transition from a solid condition to a flickering, dissolved situation then the processed, materialised outputs originating from that drawing were challenged with these intentions as evaluating parameters.

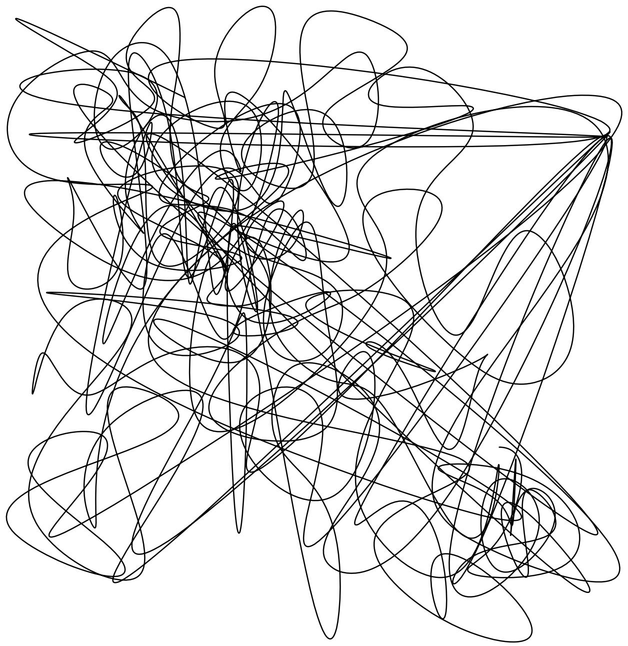
The shuttling, sometimes pondering, dialogue between all amassed creations disperses a linear process to an iterating, but forward moving, workflow. The target was always to refine the combined quantity of work and clarify a common thread throughout the investigations in a non-static environment where new information was constantly created.

One of the concrete goals of the workshop was to develop a coherent mass of investigations and, through this, suggest conceptual structures or spatial



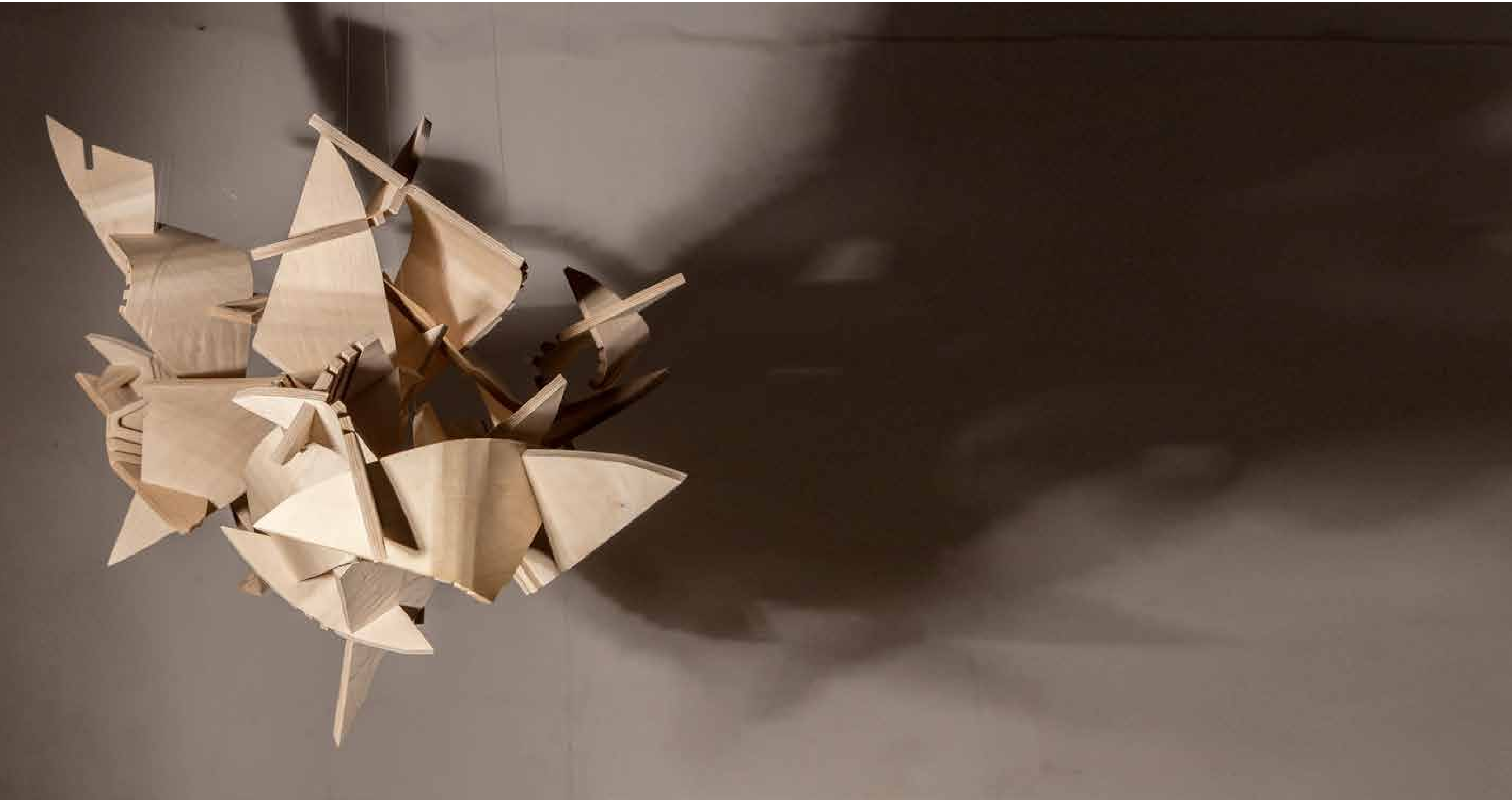
This spread and overleaf: Drawings, fabrication files, 3D-prints, cut steel, and milled plywood, starting to form mutual directions and aesthetic.





This page: Initial drawing and selected material investigations from one group of students.
Next page: The final construct formulated through the drawings and material investigation.

This spread and overleaf: After the workshops, all drawing, test, fabrications, and constructions were collected into a combined crit and exhibition. These photos show work from the second workshop that focused on plywood and CNC-milling. The work shows exploration of material and machining possibilities, and interesting spatial outcome found through the investigations.



constructs. Not as final conclusions, but as a tool to push the dialogue between drawings, machines, and materials towards a well-developed architectural phrasing.

In the constantly evolved workflow, drawings made their own respective statements as well as functioning as production information. They were, however, never an illustration or guide for assembly. As drawings and artefacts started to formulate strong, mutual ideas, the pieces themselves began to act as suggestive elements in a spatial construct.

In order to create convincing and sound proposals with a qualified articulation behind, the overall coherence of the produced work was necessary again. The production moved from smaller creations into more complex and larger compositions, but always with the aforementioned continuous dialogue and evaluation in mind.

Finding new spatial potentials

The architectural drawing acts within a spectrum of roles between imagination and realisation, exploring different approaches and intentions. Branching out to fabrication produces a faceted landscape of drawing; it helps establish a close and mediating link between idea and material emergence.

Through the drawings, fabrications, and discussions, each group of students in the workshop formed a direction within their production. These directions emerged within the acts of concurrently exploring through the digital fabrication tools, through the drawings, and in the specific materials. From these unpredictable directions and their amassed work each group created a larger architectural construct. The constructs were considered fragments of a larger system and were built with the same spontaneity as the experiments that went before it. The combined readings of the drawings and material experiments served as a launchpad for both the creation of parts and the organising logic for the systems.

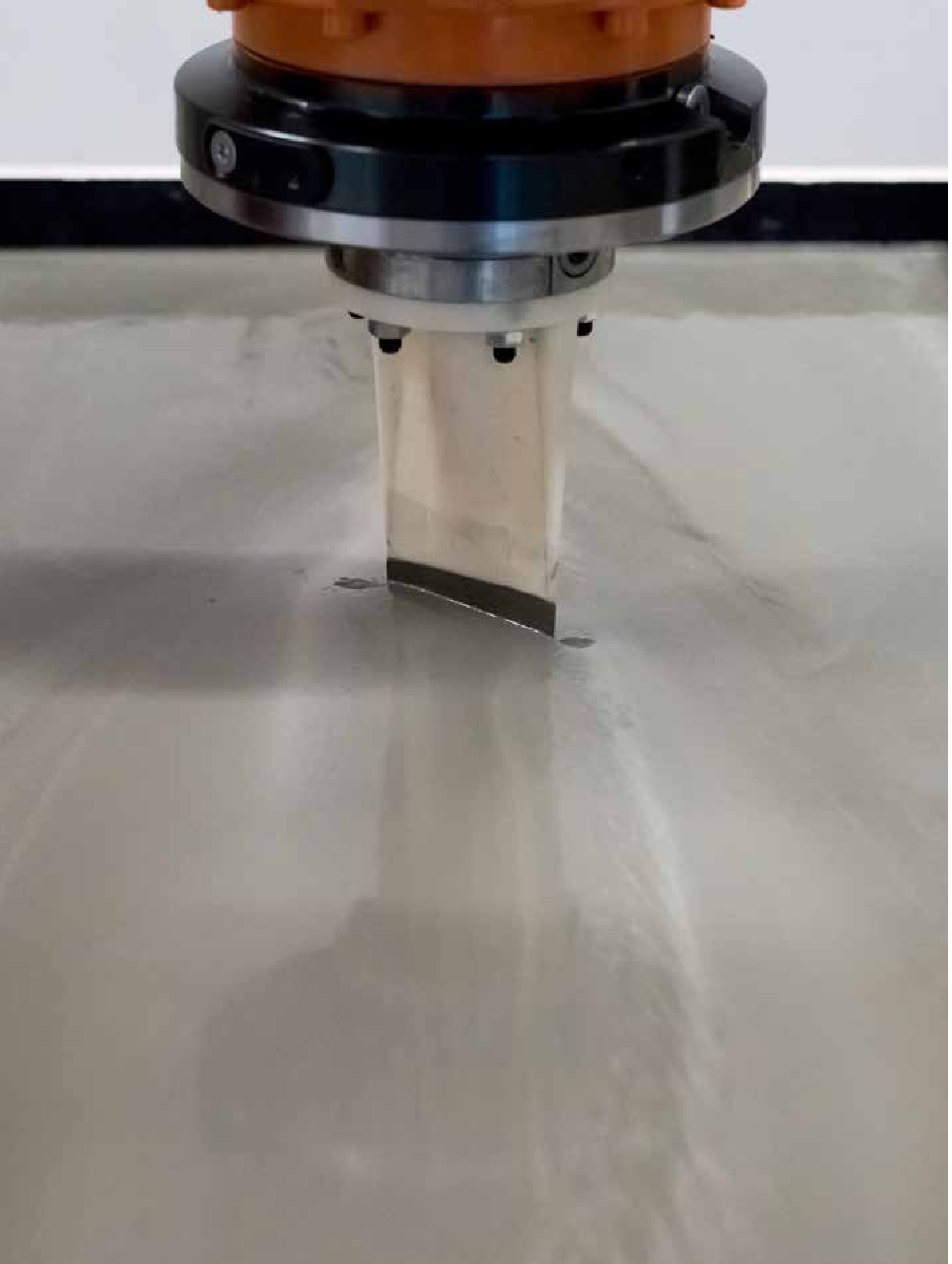
As expressed by Evans (1997, p. 166) *"It would take more than an article to reveal the full extent of drawing's intrusive role in the development of architectural forms, or to investigate the way in which it creates a translator medium of this or that consistency."* The experimental workshop and its underlying thinking are not trying to unfold the full extent of drawing as a powerful medium in the architectural design process, nor stating that the closeness between drawing and making is unprecedented. The workshop, nonetheless, draws attention to an opportunity that has emerged through the engagement with digital fabrication methods and technologies.

Traditionally, pen on paper-"*sketching is a notational system that is not only rapid and ready but also a mode of accessing information.*" (Belardi et al., 2014, p. 30). Similarly, the new settings that have emerged with digital fabrication processes can be used to sketch directly into materials and very quickly get an understanding of material and physical constraints and potentials. This increased territory gives an opportunity to rethink the idea and the act of architectural drawing. Experimental practice is made possible through digital fabrication tools because it allows an immediate, reflective access and exchange of information, and an investigative interplay between drawing and making.

The workshop results point to a potential type of workflow in which digital fabrication can take an active part in the translation between ideas and reality. Employment fabrication knowledge in an early phase of a project expands the drawing spectrum and can help propose a link from imagination to realisation. This can move fabrication from an at-the-end task to an active partner during the whole process. Designing can be '*...a creative and experimental process that occupies the full extent of architectural production...*' (Sheil, 2012, p. 6). Instead of seeing the drawing in an architectural process consisting of successive numbers of separate steps, drawing, combined with digital fabrication processes, can become a dynamic design space. The space can grow by amassing information and give the opportunity to oscillate continuously between imagination and realisation.

The workshops, however, also point to the fact that even though the type of method called for in *Digital Matter* is not unknown, but probably widely demanded and used in architectural production, the implementation of digital machining as an extension of a non-deterministic thinking is not without challenges. While the students showed great enthusiasm in both the proposed agenda and the elements of the workshops, the greatest challenge was to prevent them from considering the machining as a finalising process. This challenge might by partly due to the fact that industrial machinery can be technically intimidating, but was clearly also founded in a prevailing understanding of the positioning of realisation in a design workflow. Repeatedly, groups of students were caught in the process of overthinking and refining. They did not want to fabricate before their idea was well-developed - quite contrary to the intention of the workshop. Hence, a lot of attention was spent on reiterating and pointing out the concept of the workshop. Fortunately, this eventually caused a solid understanding and adoption of the thinking. More importantly was, however, the general enthusiasm and creative blossoming that every event of fabrication caused. When students were convinced to push their unrefined drawings and intentions into the making and actually use the digital machinery and the material as sketching tools, focus was quickly moved from speculating to doing, and to discussions of potential instead of being at a standstill in a phase of problem-solving.

The workshops were, of course, limited in time. They, nonetheless, point to both potentials and inherent challenges of the approach that it calls for. To further develop the educational value of the thinking and approach to materials and digital fabrication, it could be interesting to test out the setup in a context of longer timespan and with an ambition of a more elaborated architectural outcome. This could also shed some light on how the strategy of the workshops could work in cooperation with other and more traditional tools and medium used in the discipline.



E3: **CONCRETE MOVES**

E3: **CONCRETE MOVES**

Materials

Cement, Aalborg Portland RAPID, grey
Beach sand
Water
Superplasticiser, Sika

Machines

ABB IRB 6620 robotic arm with different custom-made end-effectors for concrete
ABB IRB 120 robotic arm with custom-made end-effector for sand

Software

Rhino with Grasshopper plugin
HAL robic plugin for Grashopper
ABB RobotStudio

Quantity and size

Several concrete panels, 50 x 120 cm

Comments

The experiment was concluded with an exhibition at Aarhus School of Architecture. 7 + 5 concrete panels were accompanied by a short movie. The movie was later accepted for the RobArch 2016 conference in Sydney.

Please watch the video online:

Aarhus School of Architecture: https://vimeo.com/146367373 or

Association for Robots in Architecture: https://vimeo.com/158804656

Special thanks to Ryan Hughes for great help and assistance with everything related to the robots.

Concrete potentials

Concrete is a commonly used material in the whole industry of construction. Industrial production of concrete components plays a significant role in the realisation and outcome of today's architecture. The production is focused on a high level of control and standardisation of the components. This results in a high degree of reliability, but also an arguably limited investigation and utilisation of the possibilities that this specific material holds.

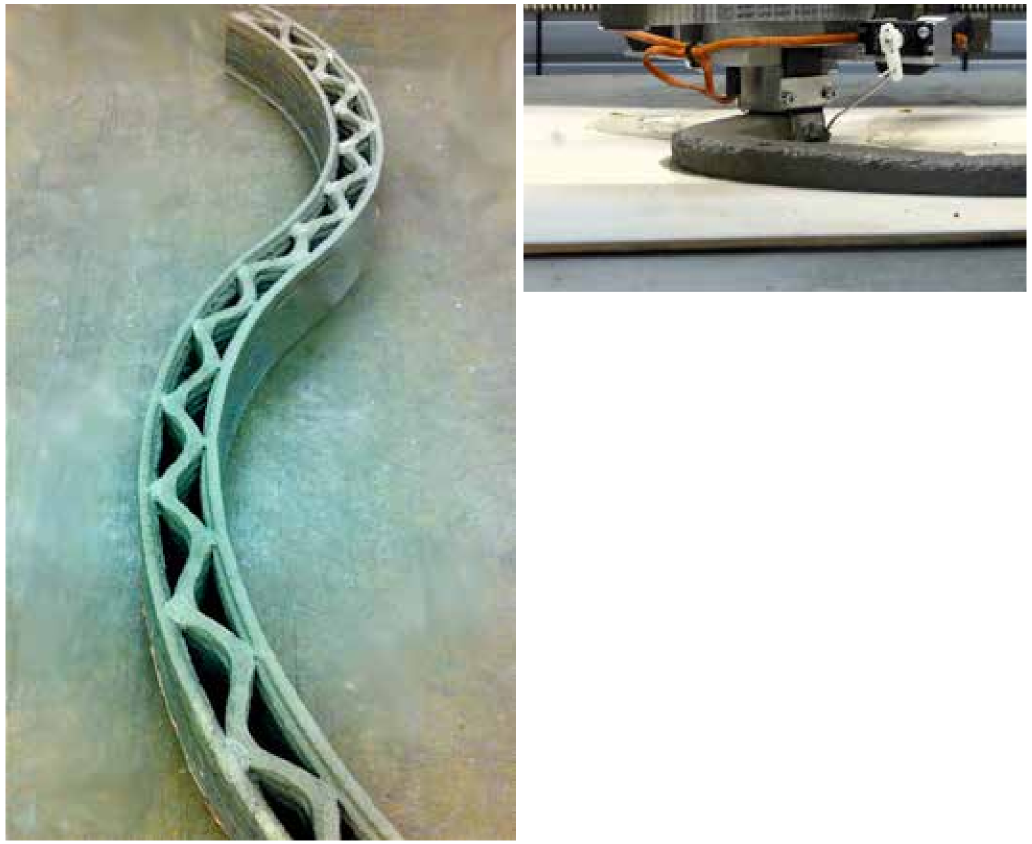
Several projects in research and industry have looked into possible strategies for expanding the potential of concrete components. This effort has mainly been revolving around, but not solely limited to, the development of more advanced and/or active formwork solutions. An example is the outcome of ETH's contribution to the TailorCrete-project[1]. Under the Chair of Architecture and Digital Fabrication,[2] a concrete casting system that utilised a production of reusable wax formwork using a robotically actuated mould was developed (Gramazio et al., 2014, pp. 216–223). This invention suggested a new strategy for inserting tailored formwork into standard scaffolding and by doing this expand the possibilities of onsite concrete casting. A series of prototypes and a demonstrator showcased the promising results. The conceptual intervention, however, is founded solely on the development of a new type of formwork that allows the fluid concrete to obtain a complex surface shape. The surfaces are highly controllable throughout the workflow, but are not novelties themselves. Likewise, the formwork strategy is proposing a more efficient way of producing double-curved concrete surfaces, but is not broadening the spectrum of concrete casting in a general sense.

Another approach to expanding the possibilities of concrete in a building or building component scale can be seen in an emerging field of concrete additive manufacturing. Through the recent decade, and especially

ETH's 'TailorCrete' process allows complex double-curved concrete casting through reusable formwork.

the past few years, several '3D-printing' approaches to concrete have shown new attitudes to how we use this fluid material in the creation of building-like components. A pioneer in this field is Dr Behrokh Khoshnevis, a professor at University of Southern California (USC) and founder of the company Contour Craft. Contour Craft has established a knowledge base of applying a process of layer-by-layer manufacturing to fluid materials, including ceramics and concrete mixtures. Their work and research ranges from smaller component production to strategies for full-size building printing and even into a lunar version of contour crafting[3]. Contour Crafting uses a nozzle design, controlled by a cartesian coordinate robot, to build up concrete constructions layer-by-layer, thereby enabling the construction of complex forms without the need for any formwork. This part of the process is, on a general level, similar to the way fused deposit material (FDM) 3D printing with thermoplastics works. Typically, the distribution of material is based on a strategy in which a contour is first built solid, and a following hatching pattern fills the interior. On top of having done significant research in material analysis and flow patterns, the team behind the Contour Crafting technology has also developed sophisticated strategies of spackling the layering during the extrusion. By using a trowel with the ability to adjust its angle during the extrusion, not only can this process help smoothen out the layering but also make cohesively curved surfaces (Khoshnevis et al., 2006; Kwon, 2002, pp. 100–105).

The technic of Contour Crafting takes advantage of concrete being a state-shifting material. The process forms the material layer-by-layer in its fluid state and utilises the strength of the cured concrete in the final components or constructions. The geometry that can be realised therefore has to be found in the union of the possibilities of fluid concrete and the cured concrete. The trajectory of the method of Contour Crafting is clearly to expand this union, mainly by gaining control of the forming of the wet material. The research group is attempting this by analysing and modifying the material itself, but to a greater extend through a focusing on the technic of the application. The development of Contour Crafting might primarily be an extensive development of tools and technology, on both a hardware and software level, rather than a pure research in the utilisation of concrete.



'Contour Craft' is an additive fabrication method refined for fluid materials like concrete. The mouldable concrete can be spackled as an integrated part of the building for a better finish.

Khoshnevis' Contour Crafting is far from being the only project that is involved in concrete additive manufacturing. A similar approach in terms of technique, but radically different conceptually, is found the works of by British-Indian sculptor Anish Kapoor. Through a series of pieces and exhibitions[4], Kapoor also explores a layer-by-layer, extrusion-based practise towards the material of concrete. Similar to Contour Crafting, Kapoor's machine consists of a 3-axis Cartesian robot arrangement with an extruder as end-effector and also underwent several incarnations in search for refinement. Eventually, the extruder was referred to as the *Identity Engine*. Adam Lowe, who worked on the extrusion project together with Kapoor, describes the intention behind the works as "*An interest in the relationship between forms with an inherent resonance and the material transformations that these forms undergo…" (Kapoor, 2009, p. 43)* and, later on, continues to describe how the Identity Engine works: *"Data is entered into the Identity Engine in a regular and ordered form then the artist, the engine, the operators and various concrete mixes are allowed to take part in constrained random walks. Although a relatively simple machine, the many variables in play when digital data enters the physical world prevent predictable repetition. This uncomputability may help explain why these objects are so compelling – an artful balance between deterministic mechanics and free play" (Kapoor, 2009, p. 43).*

When looking at both the results and the intentions, the work related to Contour Crafting and the Identity Engine are very different. Contour Crafting is clearly developed from the perspective of an engineer, whereas Kapoor's use of his machine is an artist's work. One could argue that the main difference between the two projects is their attitude towards uncertainty and control. Where Khoshnevis is using several technological approaches to gain control of the concrete printing, Kapoor lets the material loose in relation to both intention and control. In both cases, the aim is to expand possibilities and find new forms of or for realisation, but this is done on very different premises, even though the core technology is similar.

The three described volumes of work - by ETH, Khoshnevis, and Anish Kapoor - all somehow have their starting point in a fundamental relationship between material, technology, and form. The form is the consequence of the fusion of material and technology. From the perspective of the architectural

Artist Anish Kapoor is 'printing' with concrete on the concrete's terms. The result is a direct, readable effect of the material and technology in use.

discipline, the described work also establishes a range of different approaches to unveil new knowledge through material and fabrication. It is evident that the projects by ETH and Khoshnevis are more directly related to the process of building construction than the art pieces of Anish Kapoor. Kapoor's project, on the other hand, refers more directly to the process of generating form and design and resembles more a drawing or sketching-like act. Where TailorCrete and Contour Crafting are searching for ways to realise form from a type of drawing, Kapoor's work is more reminiscent of a drawing itself.

Both approaches have relevance and justification on their own, but combined they also serve as a starting point for potentially more architectural approaches to material investigations. Both the engineering and artistic trajectory can act as a tactic to intervene with the architectural discipline and the material industry. Research in fabrication and realisation methods expend the current possibilities of design realisation, but a direct involvement with materials and the processing or manipulation of matter might be a way to link the realities of these in order to bolster the design at an earlier stage. Therefore, the inclusion of both engineering and more artistically inspired approaches towards material investigation might be helpful in the uncovering of the architect's potential role within this research field.

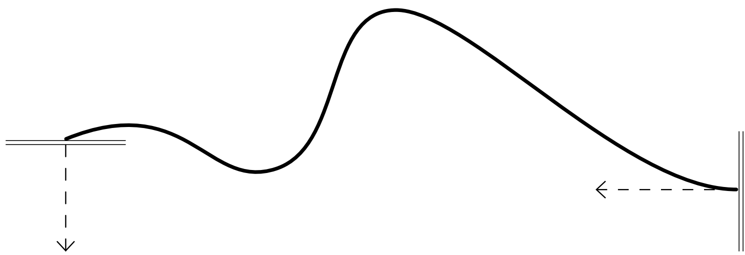
Engaging with the material

The experiment *Concrete Moves* is anchored in multiple hands-on experiences with concrete. A general interest in the material's behaviour and possibilities had aroused over several years. This has led to studies of established concrete research and works – like the above-mentioned examples. It has also resulted in a number of observations regarding how concrete is given shape and how it reacts during this transformation.

Partly, the inspiration for *Concrete Moves* was awakened during the mixing of concrete. Seeing the wave-like formations in the fluid concrete, sloshing around in the rotating mixer built up a desire to extract these natural forms directly from the process. The purpose of keeping the concrete in constant rotation is to avoid it setting; therefore, a parallel process not including continuous stirring had to be invented.

A look into the concrete mixer: Fluid concrete in motion creates certain types of forms and curves that are normally not visible in the final result.

Manuel manipulation of fluid concrete. The materiality is captivating. The constantly changing viscosity is also a continuous change of potential form.



Top: Illustration of tool path and tool orientation. The tool turns 90 degrees from the start to the end of the tool path, in this case meaning a change from being perpendicular to the path to being almost parallel to the path.
Middle: The wet concrete after manipulation with the scraper tool.
Lower: The hardened concrete shows waves and foldings from the manipulation.

The initial tests was done by hand using a mortar scraper. Different types and mixing ratios of concrete were made, all poured in a flat box and set into motion with a scraper. In all cases, the force from the scraper would move the concrete, and the concrete would then flow back towards its original position. The extent of latter action being dependent on the viscosity and amount of the specific concrete mix.

The simple mortar scraper established an interesting realisation of the complexity of the concrete's flow pattern as a result of simple shifts in orientation and direction of the tool. The tool was functioning as a surface normal in constant reorientation along a path, and as the interface between movement and material. Followed by this thinking, the concept of the experiment developed around the idea of mounting a scraper-like tool on a robotic arm. It would thereby be possible to utilise the precise and repeatable motions of a robotic arm in combination with the material fascination of the fluid concrete.

Consequently, *Concrete Moves* has its starting point in a basic, but strong, relationship between material, technology, and form. The form is created in the encounter of material and technology. Technologies are often developed and bound to particular types of materials and thereby to certain industries and sometimes uses. New technology, or new combinations of technology, has, nonetheless, the potential to affect materials in new ways, thereby interfering with established industries and ways of thinking.

Concrete consistency

The intention with the setup around *Concrete Moves* is to engage selected, but truly specific, properties of concrete with the likewise specific characteristic of a type of processing. Concrete has the material capacity of transitioning from a fluid substance to a stone hard material through a chemical process. Concrete is a composite material consisting of cement, aggregate and water. When mixed, the chemical reaction between cement and water start to solidify the mixture through the process of hydration, over time resulting in the hard, stone-like material widely used in the building and construction industry.

The mixing ratio between the three components, as well as the specifications of these components, makes up the core set of parameters that

The setup is just a robot with a scraper and a table. The investigations are direct and immediate. Early on, it became obvious that even simple manipulation results in a complex materiality.

defines the properties of the final material. For example, a lower water-to-cement ratio will result in more durable concrete. The presence of the aggregate in the mixture also increases the durability, but a high aggregate-to-cement ratio will yield a weaker result.

The process of the hardening establishes a phase where the concrete is semi-liquid and can therefore be moulded. Thereby, the parameters of time and viscosity become an active part of the material forming process. Low water content will result in a high viscosity and consistency with a low slump. High water content will increase the workability and also extend the initial setting time. Furthermore, additives can be included in the mixture to manipulate consistency and setting time. A superplasticiser can dramatically decrease the viscosity, making the concrete almost liquid with limited addition of water. Accelerator additives can speed up the curing and reduce both the manipulative period and the hardening time.

Traditionally, the shaping of concrete relies on a formwork defining the final shape. The formwork method utilising the concrete's fluid state and high mass to fill the formwork and obtain the desired shape. In *Concrete Moves* the intention is to eliminate the formwork as the shape-defining element and instead search for expressions and aesthetics within the specific capacity of transitioning from fluid to solid. In order to do that, all of the above-mentioned factors should be taken into account.

Manipulation

To investigate concrete during its hardening period and explore shapes and expressions found within the concrete's fluid or semi-fluid state, the material needs to be affected by external forces.

The robotic arm is a flexible manipulator that requires specific decision making and action in order to perform in any given situation. It needs to be given a set of instruction to move, and it needs to be given an end-effector to interact with its surroundings. In this experiment, the idea is to feed the robot with minimal instructions data and create simplistic end-effectors. This is done in order to align the interaction with the material properties with the natural behaviours and movements of the robotic arm. The concept is not to force the robotic arm into making predetermined shapes in the concrete, as it is not

Solidified fluidity: The forms and curves of the flowing concrete are captured by the concrete's own hardening process. The motions applied to the concrete during the hardening are apparent in the result.

A total of 6 mechanical axes defines the freedom of motion for the robotic arm. The interplay among the axes composes the movement of the end-effector.

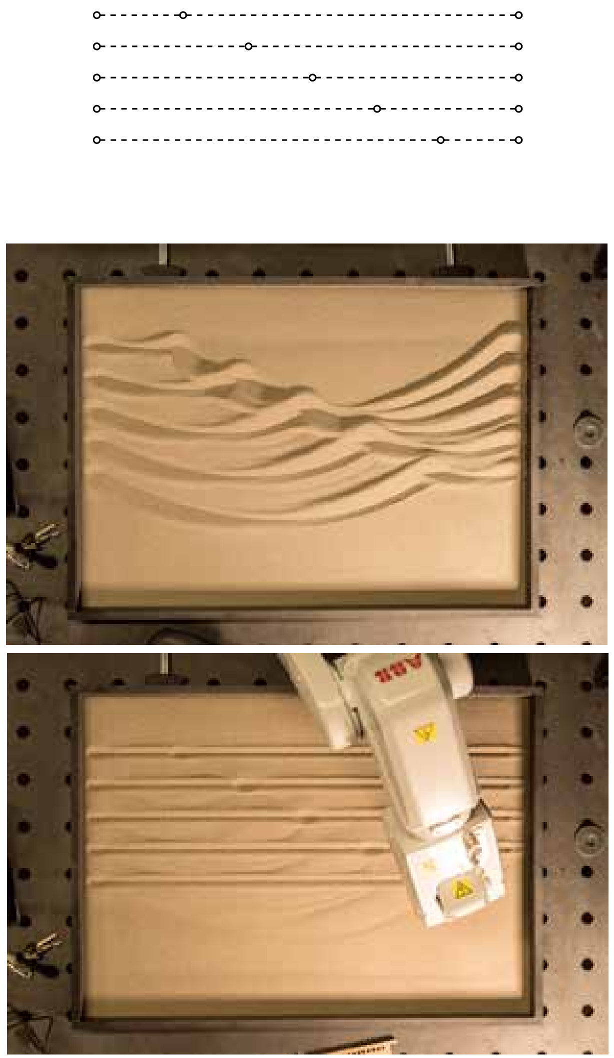
the idea to shape the concrete based on anything else than its own properties and a limited external input. By creating a foundation based on elementary characteristics and principles of the material and technology, it is the ambition to investigate forms and aesthetics, naturally occurring in the encounter of these.

The base setup for this series of experiments is a worktable with a frame for concrete mixture, placed next to a robotic arm fitted with an end-effector. By the instructions of RAPID code, the robot moves the end-effector tool through freshly mixed concrete. This results in a redistribution of the concrete within the frame. Since the concrete is in its liquid state, it will flow back towards its original position after the tool has passed. The robotic arm will repeat its instructed motion and transform the concrete once again. This process of reshaping and flowing back will through a number of iterations, create unique possibilities for manipulating the concrete through its hardening phase and exploring the resulting forms.

Robotic motions

The planning of robotic motion paths will impact the robot's handling and movement of the tool and thereby the transformation of the fluid concrete. In this project an ABB IRB 6620 industrial robotic arm is used. The IRB 6620 is an articulated robot with a 6-axis vertical joint arm coordinated construction. This type of rotary joint robotic construction is widely used in this category of machines. The construction gives 6 degrees of freedom (DOF) meaning that the end-effector can move by six independent motions.

In order to put a robotic arm into motion, the robot will need to receive instructions written in its native language – RAPID code in ABB's case. In most cases, the code will be either written or generated using preferred software and then loaded on the controller, or, the code will be made by manually jogging the robot into desired positions and teaching these positions to the robot using the teach pendant. Effectively, the robotic programming can either happen in a workflow of going from computer programming to physical movement – or through physical movement to code generation. Typically, articulated robots



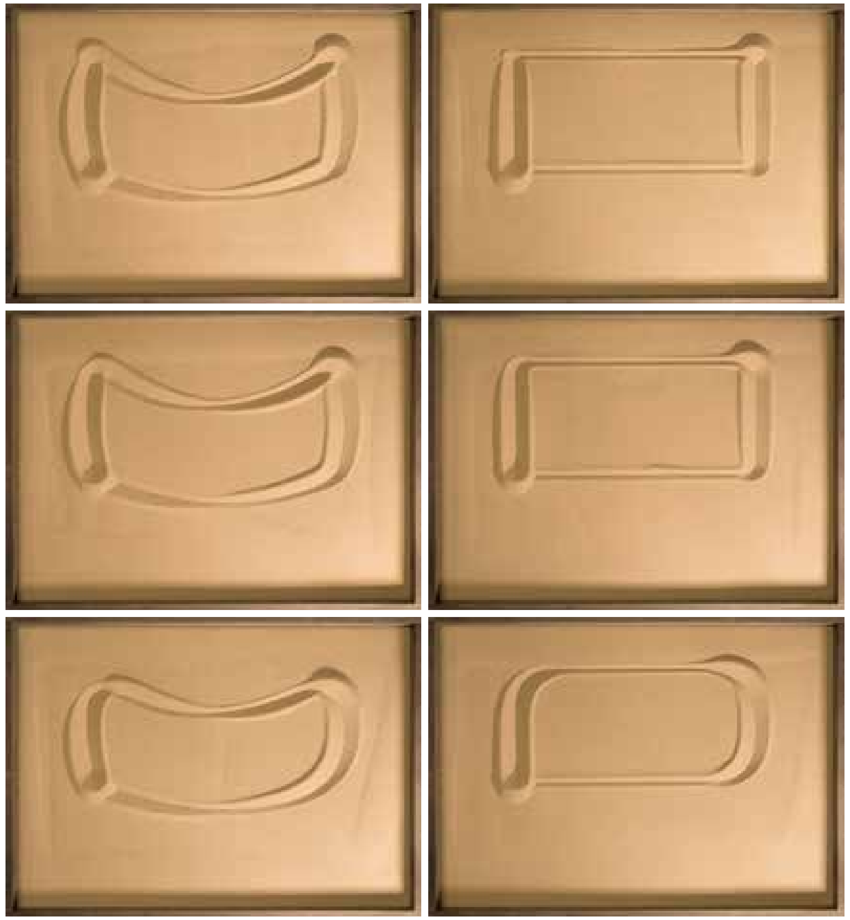
Joint interpolated motion and straight-line interpolated motion compared. Top figure illustrates the drawing information from which the code is extracted. Five sets of two curves describe the processing. Each of the five sets holds three points - those points define the code. The robot moves the end-effector from point to point using different interpolation strategies. The middle photo shows how the robot connects the points using joint interpolation (MoveJ). The lower photo shows the robot using straight-line interpolation (MoveL). In this case, the straight-line interpolation closely resembles the source geometry, whereas the joint interpolated motion adds an entirely new interpretation of the connected points.

in the industry are programmed by the teaching of physical points. In this project, the code will be generated using dedicated software, thereby creating a workflow that links the motion planning to a digital drawing interface.

Fundamentally, robotic movements are described as either *forward* or *inverse* kinematics. These two calculation strategies refer to the relationship between end-effectors and the joints. On an articulated robot, forward kinematics will be calculated, using the joint angles as input, and result in coordinates for the end-effectors. Inverse kinematics function the other way around and will use the end-effector's coordinates to calculate the angles of the joints. Forward kinematic are by far the easiest type, mathematically, but inverse kinematics are often the most practical solution since the position of the end-effector is often more important to know, than the position of the joints (Serdar Kucuk and Zafer Bingul, 2006). Inverse kinematic control was used throughout this experiment.

Robot code consists, generally speaking, simplified, of a list of situations which the robot needs to realise. Each situation, in the form of a line of code, will contain coordinates defining place and orientation in space, as well as information about velocity and orientation plane. Each of these lines will also declare what type of movement interpolation that the robot should use to reach the listed target position.[5] The kind of interpolation used by the robot eventually became a topic of interest in the experiment.

While a line of code will instruct the robot precisely where to be and how to be in a given situation, the code does not include explicit information about what happens in-between these defined targets. This is, roughly speaking, up to the robot to decide, based on what type of motion interpolation that is pointed out in the code. In between the defined target points, the robot controller will interpolate the information into a tool path while moving the manipulator into position. The interpolated tool path will be a transition from the explicit start and end targets and a transition between the associated velocities. A piece of robotic code can have a high or low resolution compared to the corresponding physical reality, but in-between the explicit information the manipulator movements will always be motions decided by the controller. The interpolation strategies can be seen as the robot's natural movement behaviours and are in this project utilised as operative parameters in the shaping.



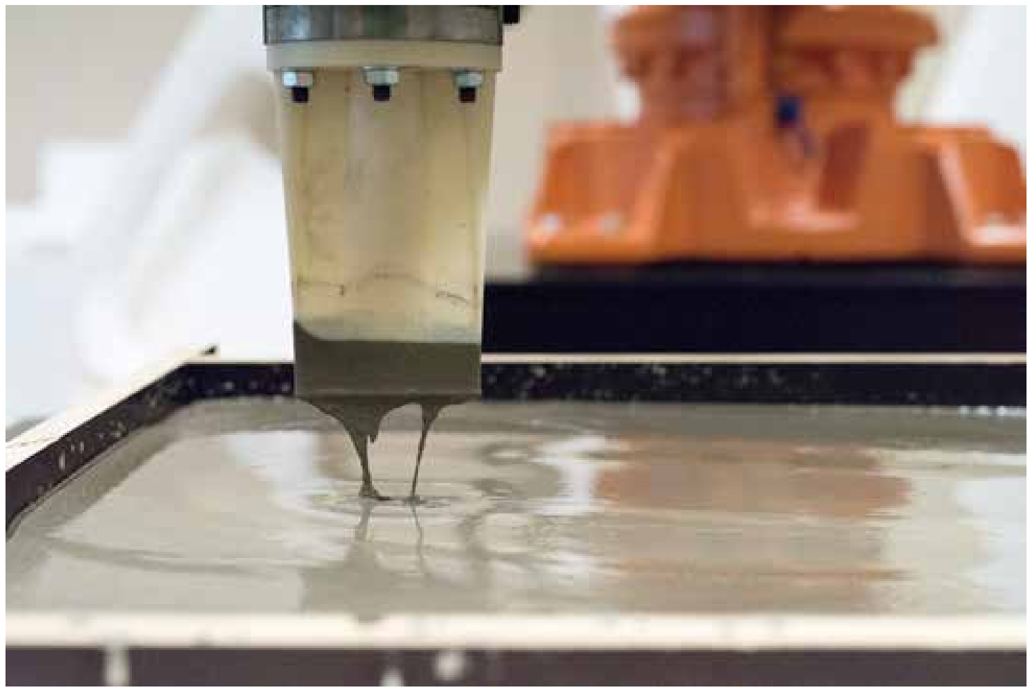
Interpolation type and accuracy zone setting combined: The six tests in sand shown above are tangible manifestations of the same four coordinates. The first column shows tests with joint interpolated motion (MoveJ). The second column shows straight-line interpolation (MoveL). The rows, from top to lower, shows accuracy zone 'fine,' z30, and z100.
The combination of interpolation type and accuracy settings is an interface of control that can result in quite uncertain outputs.

Generally, a robot manipulator can offer four types of motions when travelling from one position to another; slew motion, joint interpolated motion, straight-line interpolated motion, and circular interpolated motion. In this experiment, the joint interpolated motion and the straight-line interpolated motion were used and investigated.

When using the joint interpolated motions, a start and end position of the end effector is given to the controller, resulting in two possible manipulator postures. The controller will calculate the transition time from the original posture to the new posture for each joint at a given speed. The slowest joint movement will be selected and the calculated time will be used on all the axes. Consequently, all joints will start and stop moving at the same time. The result is a combined transition with an overall smooth arm movement, but with a nonpredictable end-effector path in between the defined start and end position.

The straight-line interpolation aims, as the naming suggests, to create a repositioning of the end-effector in a straight line from start to end point. The controller will interpolate the movement of the manipulator so the motion of the end-effector will be the shortest move possible. Specifically, the robotic motion will consist of a high-resolution series of planes through which the end effector moves. The result is an end-effector movement that is highly predictable, but likely to be carried out with constant changing speed and acceleration on each joint, which can likely result in a less smooth overall arm movement.

To explore the consequences and the potentials of different types of robotic movement, a series of explorations with sand was made. The sand experiment was used to gain a visual and tangible insight in the results of different interpolation strategies and code instructions related to the movements. In addition to the consequences of joint and straight-line interpolation, different settings for tool velocity, reorientation velocity, and zone value were tested out. Zone data can be described as the accuracy that the interpolation uses. The zone is a millimeter value that describes how close to the defined point in space the end-effector needs to be before it is allowed to start moving towards the next point defined in the code. With a high zone value, the robot will be allowed to 'cut corners' and it will reach the defined point on the 'fine' zone



Change of state: Initially, the concrete is quite thin due to the addition of superplasticiser. When the setting kicks in, the concrete starts to absorb the movements of the robot.

value. The zone will, therefore, interpret the data given by the code, through the interpolation, and in combination with the interpolation type create a physical tool path in space.

It is interesting to look at the described robotic motions from the perspective of both the experiment *Concrete Moves* and the overall project *Bespoke Fragments*. Digital drawing is a way to engage materials through digital fabrication. The data generated in a digital drawing can be used as data for fabrication, but never as an indifferent data set. The data will always be transformed and coloured by the preparing processes and the fabrication itself. Looking at the robotic arm, this becomes evident on a very obvious, but also very operative level. In order to instruct the robot, some positions have to be described within the code. These positions are, in this case, extracted as planes from a digital drawing. This sectionalises the line by any chosen resolution. The extracted points are combined with data concerning velocity, type of interpolation, and zone and then recomposed as a curve, or path, by the robot when it moves. Consequently, using digital lines as the input for robotic movements will always involve a redrawing of the lines based on the robot's logic and physics. Fabrication processes will always affect their source data, and interestingly enough the way it is done here is quite similar to the way digital drawings are made – by interpolating or interpreting points into curves.

The concrete moves

Using the described setup, a series of concrete panel-like objects were created. The panels were made using an open-minded approach regarding what use or potential the outcome could be related to but conducted in a very systematic way. Every setting on the robot, every decision in terms of code strategies, and every mixing ratio and quantity of the concrete mixture used were written down. This way each parameter could be adjusted individually.

Several fabrications used the exact same set of code and concrete mix, but with a different number of processing iterations. Like with the initial handmade test, the movement through the concrete was repeated several times. With the robot, however, the repeated motion is identical every time. During the repeating motions, the concrete is changing. While it takes around 12-20 hours for concrete to harden and around 28-30 days for it to gain its maximum

The end-effector is repeatedly moved through the concrete while it starts to set. The motions are accumulated in the material as wavy forms that eventually shapes the concrete.

strength, the changes of flow properties and viscosity are quite impactful during the first 30 minutes. The flow properties indicate how much impact is needed for the concrete to flow, whereas the viscosity determines how fast the concrete flows. Both of these are affected by the chemical reaction that starts during the mixing of the concrete, but interestingly so, also by the applied motion. The concrete starts to set within the first 5 minutes, but repeating motion will delay this process. Normally, the motion is done by a concrete mixer mixing the full batch of concrete continually, but in this case, the motion is caused by the robot and only applied locally to the concrete. The end-effector will therefore not only take advantage of the concrete's flow properties but also directly influence them.

An observation made during the experiment was the sudden shift in viscosity. To start with, the concrete mix is very fluid and immediately flows back after being affected by the end-effector. Only a visible pattern remains on the surface. Suddenly, quite quickly, the concrete sets, especially in the non-affected part of the work, and the flow back becomes limited. Since the setting is more distinct in the areas not affected, the most set part of the concrete will start to release water into the parts in motion. The greater the number of movement iterations, the more water is released. This separation results in some areas with dry concrete and some areas with very wet concrete. The results were visually interesting, but, nonetheless, not ideal seen from the perspective of concrete strength – the concrete needs a certain amount of water to harden, neither too much or too little. In order to investigate the interesting shift in material state and the influence of the moving end-effector, the time period in which the change happens was sought prolonged. This was, eventually, done by adding less water to the mixture and instead adding a small amount of superplasticiser. After a series of tests, a suitable mixture was found. The mixture extended the duration of the transitioning state with the consequence of enabling the study of material's flow behaviour without completely ruining the ability to harden sufficiently. The tuning of the concrete was not an original intention, but seemed logical in order to calibrate the experiment based on the input gained from the initial test. Time was taken into account. The fine-tuned

concrete allowed a longer period of workability while still setting at around the same total time. Consequently, a new concrete test panel was produced every 2-4 hours, securing a swift succesion of iterations.

End-effectors

The end-effector tools were seen as a kind of mediator between the concrete's materiality and the robotic movements. They supplied an interface between the two dominating elements of the experiment. However, from the very beginning, it was clear that their task was never transparent. The shape, size, and material of the end-effector had a clear impact on how the concrete was formed. Therefore, parallel to the ongoing investigating, a larger quantity of simple, but different, end-effectors were developed and manufactured. The end-effectors were all 3D-printed using different printing technologies. The series of end-effectors comprised both impulsive tests of different raker-like shapes and an iterative testing and refining of a scraper-style type of tool. Especially the width, or rather the relationship between the width of the tool and the width of the working area, had a great impact on how the concrete behaved when affected by the robot's motions. The production of end-effector tools continued during the whole experiment.

Serial investigation and scattered attempts

The experiment *Concrete Moves* revolves around the production of a series of concrete panels. The amassed scope of the project, however, embraces both a material-technical aspect and thoughts about robotic motion. The actual movement of the robotic, the connecting of point based on parameter, can be understood as an extended version of drawing practice. The experiment might have started as a reflection around concrete development and investigation, but grew into a broader discussion as the specificity of the experiment intensified.

Unfolding from the expounded fabrication setup and thinking, a series of concrete castings were made. The experiment evolved both as a serial investigation that sought to establish a systematic reflection on the material tectonic and aesthetic consequences of the developed fabrication setup, and as a number of more independent or conceptually scattered pieces in concrete.

Several different end-effectors were produced and used in the experiment.

To round off the experiment, a series of seven concrete panels were made. These were made with the exact same settings, concrete mix, and motion repetitions. The input data was reduced to an absolute minimum and consisted of only three extracted planes from a line parallel to the work area. The mid-plane includes a rotation of the end-effector. The transition from the start point, to the rotated mid-point, to the end point was done with a straight-line interpolation. For every panel, the rotation was amplified, resulting in an increased opening as the series went on. The resulting foldings and waves in the concrete had a readable kinship throughout the panels, but also a clear development in both their overall and local shape. The series of unique, but related, panels tied together a group of the involved parameters to an easily readable serial investigation.

After repeating motions, the concrete sets and is left to harden. The hardening solidifies the amassed form and details. The hardening will capture the movements that were once alive and preserve them as final form. However, the process itself is not accessible anymore. As part of the rounding-off of the experiment a short movie was, therefore, produced to accompany the, now hardened, concrete. The movie was thought of as a counterpart to what was evident in the concrete panels. Therefore, the movie was composed of close-up shots of either the concrete or the robot in motion. The movie never exposed the totality of the setup or revealed the results. Instead, it focused on a narrative about interface and movements between material and machine.

As a concluding act, the serial investigation and a handful of independent panels were exhibited together with the produced end-effector tool and the movie. The venue for the exhibition was the canteen at Aarhus School of Architecture.

Articulating virtuality – extending the process

Concrete Moves involves numerous interesting layers of not fully controllable events. The two dominant factors are the flowing concrete and the robotic motion interpolation. Together, they offer a kind of immediate uncertainty even though their framework is quite controlled. Ignoring the possible fluctuating parameters of humidity and temperature the concrete can be mixed quite identically every time. In this experiment, sensitive industrial scales were

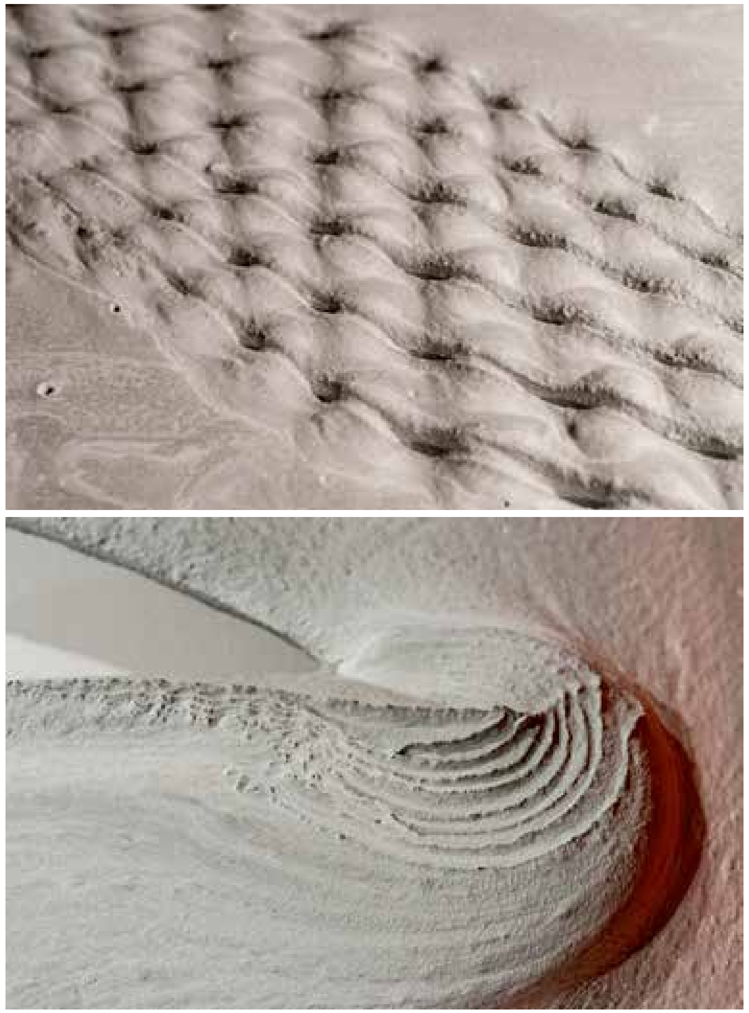
End-effectors working in the concrete. Size, shape, and configuration of the end-effector will impact the reactions and appearance of the concrete.

Selected screenshots. Please watch the short movie online:
Aarhus School of Architecture: *https://vimeo.com/146367373* *or*
Association for Robots in Architecture: *https://vimeo.com/158804656*

used to ensure an invariable consistency. The robotic interpolation can be a unforeseeable happening, even though it is controlled by the robotic controller. Movements can be simulated before running the code on the robot, which is a highly recommended thing to do, but the consequence of the motion is not foreseeable from the data lines or plane inputs extracted from a drawing. Isolated, both the concrete and robot offer access to interfaces of control, but the encounter of the two is resulting in a layered outcome of uncertainty. Only when motion and concrete meet will the consequence appear as a tactile feedback. This type of process is looked upon with keen interest. The experiment builds on the underlying interest in establishing relationships between types of digital drawing and discoveries found within material properties and capacities. Within the project *Bespoke Fragments,* the experiment positions itself in the orientational framework defined by the axes of control and uncertainty *and* virtual and actual. This is clearly intentional. However, the exact outcome and orientation remained uncertain until the experiment unfolded. The elements of control and uncertainty have already been pointed out. They are nonetheless connected to the way the concepts of virtual and actual is perceived through the experiment.

The actualisation happens at different stages, directly connected to overlaps of processes in the workflow and the moments where decisions are made. For every parameter resolved, the experiment goes from an open mass of possibilities towards an actualised outcome. The experiment thereby exemplifies a situation where actualisation is comparable to a degree of control, but also a freezing of material potentials. The mixing of a batch of concrete is both a zeroing-in on potentials and an establishing of specific material's capacities. These capacities offer possibilities for the subsequent manipulation. They are affected by the robotic motion, and the concrete and motion combined affect the set of potential scenarios for the outcome. The scenarios are virtualities that provide the possibility of interacting with the matter. The unique situation in this experiment is that the virtualities are very much delimited by a time frame. The mixing of the concrete offers several ways to convey the direction for the experiment – but after mixing, the concrete cannot be unmixed. Instead, it starts to set. Concurrently, the robot control offers strategies of motion and control of parameters, but when the end-effector starts to manipulate the concrete, the

Concrete panels exhibited in the canteen at Aarhus School of Architecture. Left side shows a serial investigation where a gradually increasing rotation of a mid-plane opens up the concrete panel by panel. The right side shows individual, scattered explorations either focusing on robotic movement or variables in the concrete mixing and handling.
On an opposite wall, the short movie was showing selected close-ups from the process.



The result of the concrete panels offers forms and material texture with a distinctive high complexity.

scenarios are actualised and irreversible. This is provided that not only is the manipulation an amassing process, but the concrete is already in its state of change. The number of iterations of manipulation is, however, the last point of accessible control – the last virtual interface in the workflow. The repeating motions can be stopped whenever and the number of iterations will actively alter the resulting outcome. This is both due to the fact that the motions affects the forming directly, but also because they prolong the time of the setting of concrete. After the motion is interrupted, the hardening will speed up and restoring of the motion will soon not be possible. Consequently, the full process can be seen as overlapping steps of virtual interfaces. The material capacities provide the basis, but continuous series of points of interaction prolong the active process far beyond the interface of the digital drawing that initiates the machining part of the workflow. This extended process, articulated as virtual parameters, allows the actualisation to be affected through a series of actions that define the process as an entity, instead of being a point or a cutoff.

Materialisation as a gradient happening throughout the process means potentials for engagement, decision-making, and designing during the entire process. However, the process is also characterised by the fact that these possibilities of involvement are also dependent on the process itself. There is no way to establish full control since the point of actualisation is not following the determination of the interaction, but following the consequence of the material process. In other words: the created process is to some extent dominant – or at least has the final say.

The outlined scope of the experiment provides an interesting perspective on the potential role of the architect. The operation goes beyond bridging the representation and the realisation. In fact, both of these extremes are suddenly, more or less, out of reach from the perspective of designing and the designer. The conception seems to be implemented in terms of framework and process, but never as a full control of the outcome. Nonetheless, there is a physical outcome – based on a type of processed drawing and realisation in concrete. This suggests a positioning where the architect can maybe use acquired literacy and knowledge to set up workflows or productions that, to some extent, react uncertainly or self-solving in terms of output. In this specific experiment, the uncertainty is existing as a consequence of material capacities and a very particular type of processing, but the potential could undoubtedly expand beyond that. The effect is that the architect will in some way give up control and the idea of being almighty and instead assent to a reality in which the design becomes a creation of established processes.

The experiment shows a focusing on a very material and processing-oriented workflow that started with a very experiential interest. The direct relation between the first test done by hand and the almost autonomous outcome of robotic motions and concrete viscosity seems a little distanced. The process never becomes controlled, but the series of investigations puts the experimentation in a system. The series of created concrete panels open up an interesting new domain of aesthetics, but are also somehow quite similar discoveries within this domain. One could argue that in order to push the experimentation further, some type of additional parameter would need to be introduced. This could potentially be the direct hand-based handling of the concrete that kicked off the experiment. One could easily imagine a workflow where the drawing was not made on a computer and then interpolated to robotic motion, but instead was extracted through handmade movements in the concrete. This could be done using several types of motion-tracking technology. The hand of the architect could explore concrete and its reactions to the hand - and interesting appearances and potentials could then be replayed by a robotically controlled end-effector. This type of exploration could push the investigation further and make direct exploration in the concrete more rapid and less cumbersome, while at the same time create a set of virtualities that encourages to a more involved experimentation.

This experiment ends with an open process and open-ended results. The alternative approach to the handling of concrete seems to have wider potential than what is made use of in the experiment. The experiment, however, manages to point at a method of designing where material behaviour is brought into focus and used as an initiator for both creation of the processing and the aesthetic findings.

Notes

1 TailorCrete was based on a grant from the European Union's FP-7 research program. Several academic institutions and industrial partners contributed to the program. See http://www.tailorcrete.com

2 Chair of Architecture and Digital Fabrication is directed by Prof. Fabio Gramazio and Prof. Matthias Kohler. See http://www.gramaziokohler.arch.ethz.ch/

3 See http://www.contourcrafting.org for more information on the Contour Crafting project and http://www.bkhoshnevis.com for an overview of Behrokh Khoshnevis's work.

4 Notable pieces and exhibitions:

Greyman Cries, Shaman Dies, Billowing Smoke, Beauty Evoked (2008) shown at Royal Academy of Arts in 2009.

Between Shit and Architecture, 2011, Galerie Kamel Mennour, Chapelle des Petits Augustins, Beaux-Arts de Paris.

Ga Gu Ma, 2011-2012, Gladstone Gallery, New York

5 Specific literacy and knowledge about robotic coding and robotic behavior are mainly gained through hands-on experience and collaboration with talented and/or wise colleagues. However, the ABB RAPID Reference Manual has been used to gain specific types of necessary knowledge.

E4: **ALLEYWAY POINTS**

E4: **ALLEYWAY POINTS**

Materials

Concrete (main material)
Latex
Nylon Powder PA2200
Beeswax
EPS foam

Machines

Faro Focus 3D laser scanner
Faro Edge Arm with Laser Line Probe
Nikon D810 DSLR (for photogrammetry)
CMS Antares 5-axis CNC router with various flat end and ball end router bits.
EOS P110 SLS 3D printer

Software

Rhino with Grasshopper plugin
VOLVOX (by CITA) plugin
Geomagic Wrap
Photoscan
AlphaCAM
Faro Scene

Quantity and size

Two concrete castings, 50 cm x 120 cm
Beeswax and latex castings, 50cm x 60 cm
SLS 3D print, 50cm x 60 cm
A series of 1:1 drawings and photos, 50 cm x 120 cm

Comments

Parts of the experiment build upon a research collaboration between Aarhus School of Architecture and CIMS, Carleton University, Ottawa. Espen Lunde Nielsen and Anders Kruse Aagaard hosted a short research workshop in December 2015 in Aarhus. Visiting from CIMS were professor Stephen Fai, PhD-fellow James Hayes, and PhD-fellow Ken Percy. The workshop established the foundation for the experiment 'Alleyway Point' through both production and discussion. The work was finalised by Espen and Anders the beginning of 2016.

The work has been accepted for the 'WORKS+WORDS 2017, Biennale in Artistic Research in Architecture at KADK, The Royal Danish Academy of Fine Arts, Schools of Architecture, Design and Conservation. The work will by presenting by exhibition and paper.

Points as digital substance

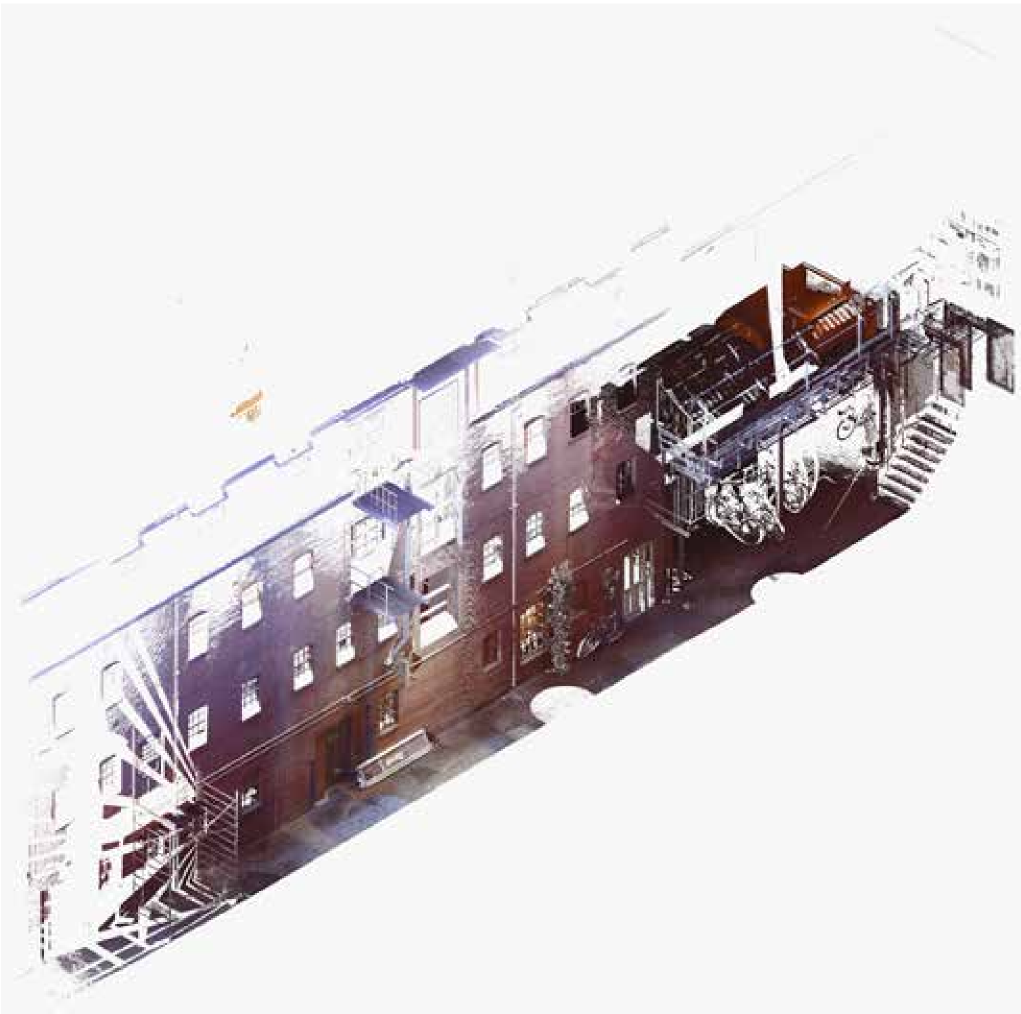
Various forms of 3D capturing and scanning allow the physical world to enter the digital domain. In digitality the representation of the physical is set free from its limitations; there is no solidity or gravity. Manipulations can happen on whatever condition allowed by software and hardware.

Workflows that connect the digital and the physcial are often seen in two versions. Either the physical is a realisation based on abstract, digital data. Or the workflow is quantifying the physical matter into representation through digital survey.

The digitisation of reality has proven useful in many ways. The ability to combine the possibilities of the computer with information from reality creates potentials for interweaving these two coexisting domains. 3D laser scanning is a technology that can establish a unique relationship between real and digital environments. By precise laser surveying, often integrating with photography, a point cloud representation is created. The mass of measured coordinates and series of photographs are post-processed into a coloured point cloud. The point cloud, thereby, provides both accurate and understandable representation of the reality. Unlike traditional surveying the outcome is not notationally based, but is instead visually corresponding with the reality it depicts.

The capturing of reality into the digital seems straightforward at first, but eventually, the created representation holds a major paradox: While being an exact and high-resolution surveying tool and a digital depiction of reality, the data content of the point cloud is the ultimate digital reduction. The point cloud exists of millions of points that are individually placed in three-dimensional space. Each point has an exact position, but no relation to other points, the context or the material from where it was extracted. The real world exists as a complex collage of mutually depending fragments, but the

The point cloud is based on reality and has an immediate visual relationship with the reality. The behavior and nature of the point cloud are, however, far from its source. The point cloud is its own type of substance.



Axonometric section view through the point cloud representation of the scanned alley. The scanning is focused around a series of windows on the ground floor.

digitised version is more like a listing of separate individualities. Materiality, or relation to materiality, is not evident from the points. Only through a parallel understanding of the context is it possible to differentiate the properties behind the measured points. The real world is a virtual composition that will transform as a whole, when exposed to local interruption or engagement. The point cloud is an actualised version of the reality with all immediate potential removed. While initially sounding like a delimiting affirmation the nature of the point cloud instantaneously outlines, at least, two interesting consequences.

First, the point cloud, and the creation of the point cloud, represents a reversed situation in more than one way. The possibility to digitise reality is a highly potential strategy for working back and forth between physical and digital space. Reality can be a starting point equal to that of the representation. The technology flips over the physical-digital directionality, but also changes the relationship between virtuality and actuality. The creation of the point cloud requires a physical context or subject, and someone to handle the scanning of, and to some extent interact with, that context or subject. The kind of equipment, as well as the handling and operation of the equipment, will affect the output. The digitisation is a process involving decision-making, evaluation and judgement in order to create the needed data set. The strategy and physical implementation of the scanning will be present in the point cloud. The local concentration of point will, for instance, be affected by the placements of the scanner, when using a tripod mounted spatial scanner. Or visible 'scan-lines', from the physical hand movements of the operator, will be present when using a handheld scanner type. Thereby, the scanning itself becomes a process open for interaction, editing and manipulation. The outcome, however, is a highly actualised version of the represented reality. Going from real world to digital representation means an instant freeze of alteration and material ability. While being highly descriptive by resolution, the point cloud also results in at high reduction of active information. The digitisation means a passivation of the context or subject and leaves a result that by itself does not initiate any alteration or engagement. The points are solidified and, heavy, computation-wise, to work with. This is contrary to other types of digital data or drawing that have an inherent possibility of action and change. Like NURBS curves, variable

On site: Preparing for digitisation: 3D scanners and computers are brought to the alley to capture space and texture.

datasets or parametric geometry. The point cloud both flips the directionality of the creation of information and produces a descriptive, but actualised, type of digital data.

Secondly, the behaviour of the point cloud produces a kind of digital substance. The points are not relational, or specific, in any other sense than their position in space. The mass of points, the cloud, thereby acts as a mass of substance. Substance is understood as *'a particular kind of matter with uniform properties.'*[1]. While this behaviour causes a dramatic reduction of the potentials of the information compared to the source, the nature of the substance opens up for considering the 3D scan as a pure, but susceptible, matter. This matter can, by utilising its material independence, be employed for either modelling or as a transitional medium. Both scenarios require an involvement of external environments or setups.

The understanding of the point cloud as being a descriptive connection to the real materiality, and its functions as a type of digital substance, became a starting point for the experiment *Alleyway Points*. The understanding and the experiment combined, became a general reflection on the use of 3D scanning throughout the project. Prior to *Alleyway Points* the 3D scanning was mostly functioning as a digitising and analytical layer in the experiments. *Alleyway Points* seeks to put in the 3D scanning forward as a motive force in the experimentation.

Scanning the alley

In the centre of Aarhus an alley, with an unusual high complexity, is found. The alley is squeezed in between an overlap of multiple functions connected by walkways and hanging cables. The architecture is a composition of a series of older factory buildings, now transformed into different purposes. The complex nature of the space makes it difficult to manually survey and therefore an ideal case for 3D scanning.

The alley was scanned using two different strategies. First, a Faro Focus 3D scanner was used to establish an overall representation of the context. The Faro Focus is a LIDAR scanner that, mounted on a tripod, captures a continuous series of points in all directions, while rotating around itself. The Focus scans and photographs everything within line-of-sight, from whatever position it is

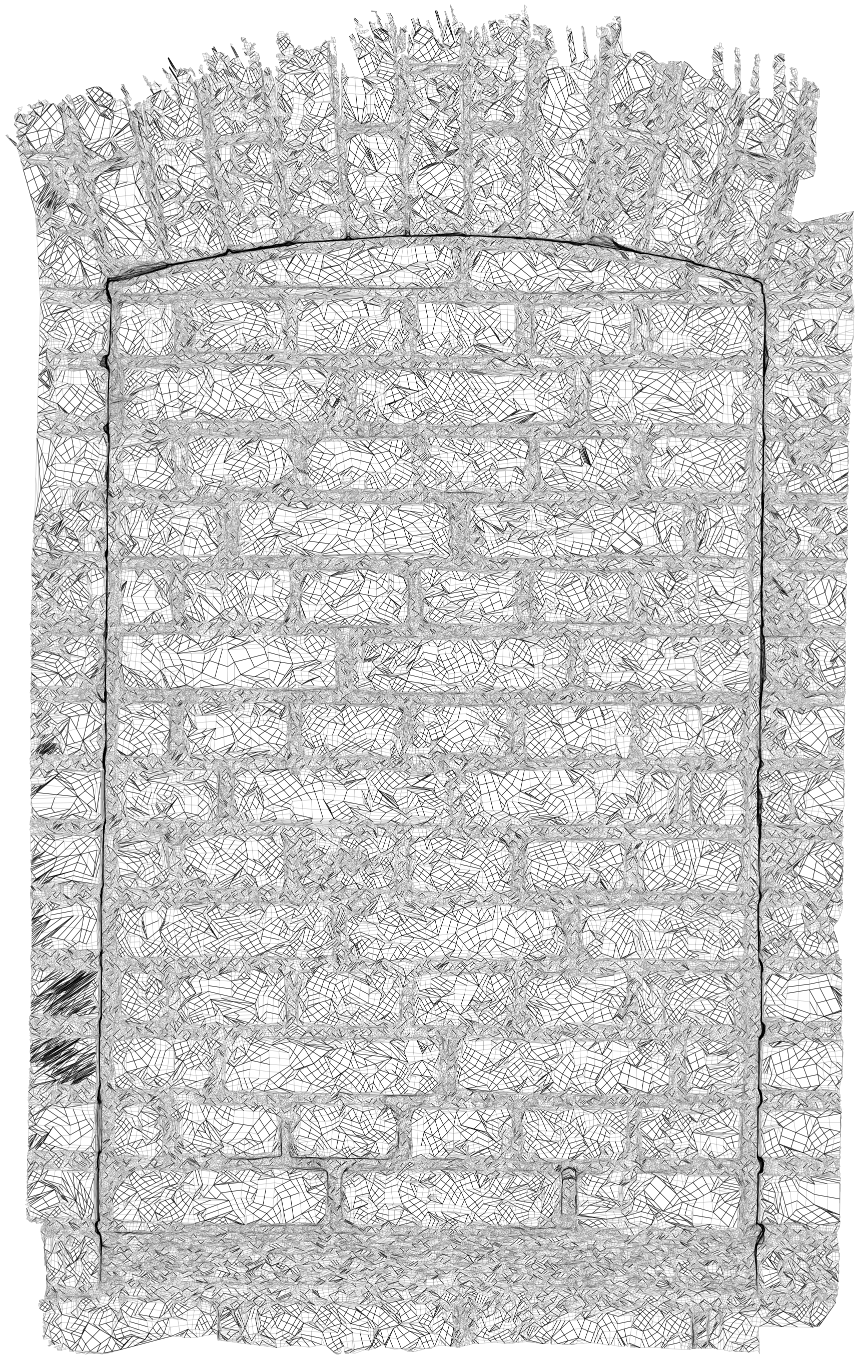
High-resolution detail scanning using the handheld FARO Edge Arm. This type of scanning is a manual process that requires direct engagement with the material and continuous evaluation of the scanning result.

in. In order to create a complete representation of the context, several scans from multiple scanner positions are needed. These scans are then registered into a single, combined point cloud. In this case, the point cloud was created with a handful of scans captured down the alley. This strategy did not capture the alley in its entirety, but established an excerpt with a high local resolution. Secondly, a few picked out locations were scanned using a Faro Edge Arm with a laser probe attached. The Edge Arm with laser probe is using laser scanning like the Focus. Unlike the Focus, the Edge is used by manually moving and orientating the gun-like probe. The probe is recording half a million points per second in a line. The movement of the probe defines not only the covered area, but also the resolution in the direction of the motion. Compared to the Focus, the Edge creates a much more detailed and precise point cloud, and enables the capturing of microscopic textures. The Edge is, however, not using photography, meaning that point cloud will not contain colour. The locations picked out for the Edge were based on a visual screening for context specific architectural elements and textures. Mainly, the detailed scanning was carried out around a series of windows facing the alley. Some were still functioning as windows, others were broken, others blocked.

The complete set of captures from the alley provides an extensive representation of the site. The millions of points produces a comprehensive insight in the composition and detailing of the alley. The created data set is, however, based on the decisions made and actions taken during the process of capturing.

Interpreting, transforming and producing

As outlined earlier, the point cloud itself bears limited ability to perform based on any inherent capability. The raw data set requires an external involvement in order to utilise the 3D scans as a substance in the production of something new. The external involvement often starts by the use of dedicated software and human assessment of the data. To begin with, the point clouds need to be cleaned and often decimated. Advanced tools are able to assist with this part. However, every altering of the point cloud alters the representation at hand. A critical attention is needed, but also a recognition of the consequence of every



The point cloud is translated into a surface mesh, then into NURBS geometry. This representation of the blocked window is a dense, but manoeuvrable, geometry.

step. Just like the capturing of the points, the cleaning and decimating are based on both algorithmic and human interpretation of the data. The interpretation and involved decision-making becomes a transformation of the substance.

Following the post-processing of the points comes the actions needed in order to convert the points to a type of data that can inform a fabrication process. The fabrication was from the beginning intended to embrace the project's material and processing setup. However, instead of departing from the specificities of the materials or the machining, the properties of the points were instead used to inform the materialisation.

The point clouds were processed into triangular mesh geometry. The conversion from point to mesh relies on a process that establishes a relationship between points, thereby creating a surface made of triangles. This conversion is crucial in order to create data that can inform fabrication, but also essential since it establishes a prior non-existent relationship between neighbouring points. The process involves a series of software-specific parameters that can alter or manipulate the interpretation. The triangular mesh opens for new types of transformation and manipulation, compared to the format of the point cloud. A triangular mesh is, however, still limited in possibilities given that the geometry is locked by a dependency on the scale of the origin. For an ultimate manoeuvrable geometry, the mesh can be translated into NURBS surfaces or similar. This translation from point cloud to surfaces is neither non-destructive or unbiased. The creation of surfaces is also a process that often needs reconsideration for every intended use. This was also the case in this experiment. The point clouds were revisited for every type of fabrication initiated. Consequently, a shuttling between different translations and thereby different layers of potential and virtuality became essential.

Fabrication-wise, the materialisation in *Alleyway Points* focused on the material concrete and CNC machining of formwork, but expanded into other techniques and materials. These detours occurred both as a consequence of the experiment being a part of a diverse research collaboration and because of an extensive pursuit of the workflow of 'reality *to* point cloud *to* materialisation' as a series of constantly transformative steps. The process of utilising the digital

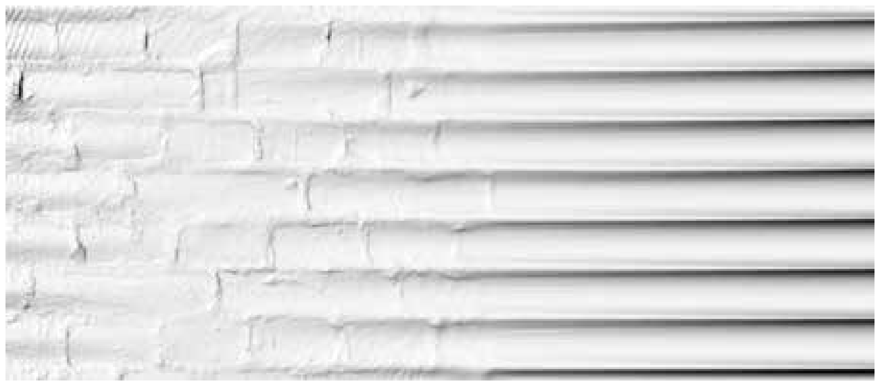
Different fabrications made from scannings of the alley: CNC-milled foam, beeswax casting, SLS 3D print of texture collage and latex casting of the collage.

substance as information for real materials widened into an investigation of the possible collision of the represented reality, and the reality of the materials and fabrications processes.

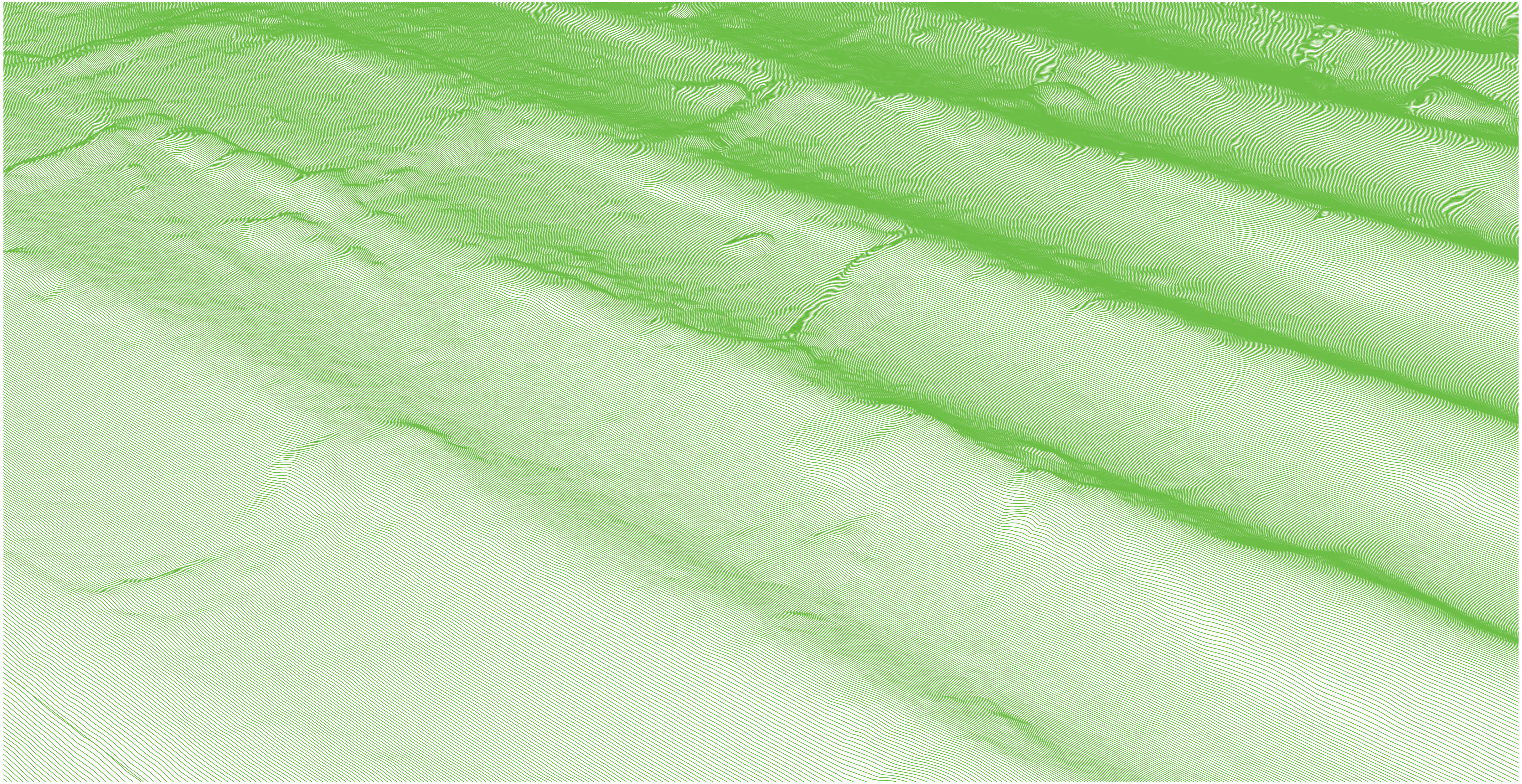
Series of point clouds, representing particular contextual textures or elements, were collaged together, meshed, and 3D printed. This was an attempt to use the points literally as building material. The 3D prints were made using SLS technology featuring a fine nylon powder. The result is a homogeneous and consistent material result with a complicated and wondering mode of expression. The 3D print seems as a material prolongation of the reality of the point cloud. The 3D print was following used as the basis for latex casting. The latex was again used for experiments with concrete casting. The idea was to obtain a more active and agile version of the point based textures through the latex. The latex is stretchable and flexible which makes it possible to adjust and shape by, for instance, formwork or the material forces from the concrete.

With the intention of bringing a form editing process into the workflow prior to materialisation, a point cloud representing a piece of a brick wall was combined with rippled NURBS surfaces. The NURBS surfaces were used to digitally bend and warp the point cloud data and create a gradient shape and texture from the point cloud brick representation to the rippled NURBS surfaces. The new geometry was applied with parallel toolpath for milling. This resulted in the digital surface being just a brief, intermediate step. Instead the high-resolution tool path became the primary drawing set for both visual representation and fabrication instructions. The tool paths were eventually used together with a ball-end router bit in the making of an XPS-based, retarder coated formwork. The conclusive concrete cast both solidifies the textural gradient and underlying processes into an solid object and exposes its own materiality in the piece.

Another, but more direct, translation from point cloud to fabrication can be seen in a concrete replica of a broken window. The point cloud is translated into surfaces and tool paths and then milled in foam. A smooth vaseline coating is used for formwork. The process calls for an investigation of a non-material reproduction. The scanned window consists of both steel and glass. Following the logic of the point clouds those materialities are existing after digitisation. Instead, every point is treated equal, and surface quality is



Left: 3D visualisation of a merge between NURBS geometry created in the computer and texture created using 3D scanning. The visualisation is based on triangulated mesh created from the merge. Right: Formwork milled with ball-end tool. Tool paths created by tracing the merged geometry.



Tool paths created from the merged geometry and texture shown on the previous page. The tool paths become both information for fabrication and a combined visual representation of the source data and the object to be.

The concrete casting of merged computer-made geometry and texture from the digitisation of reality.

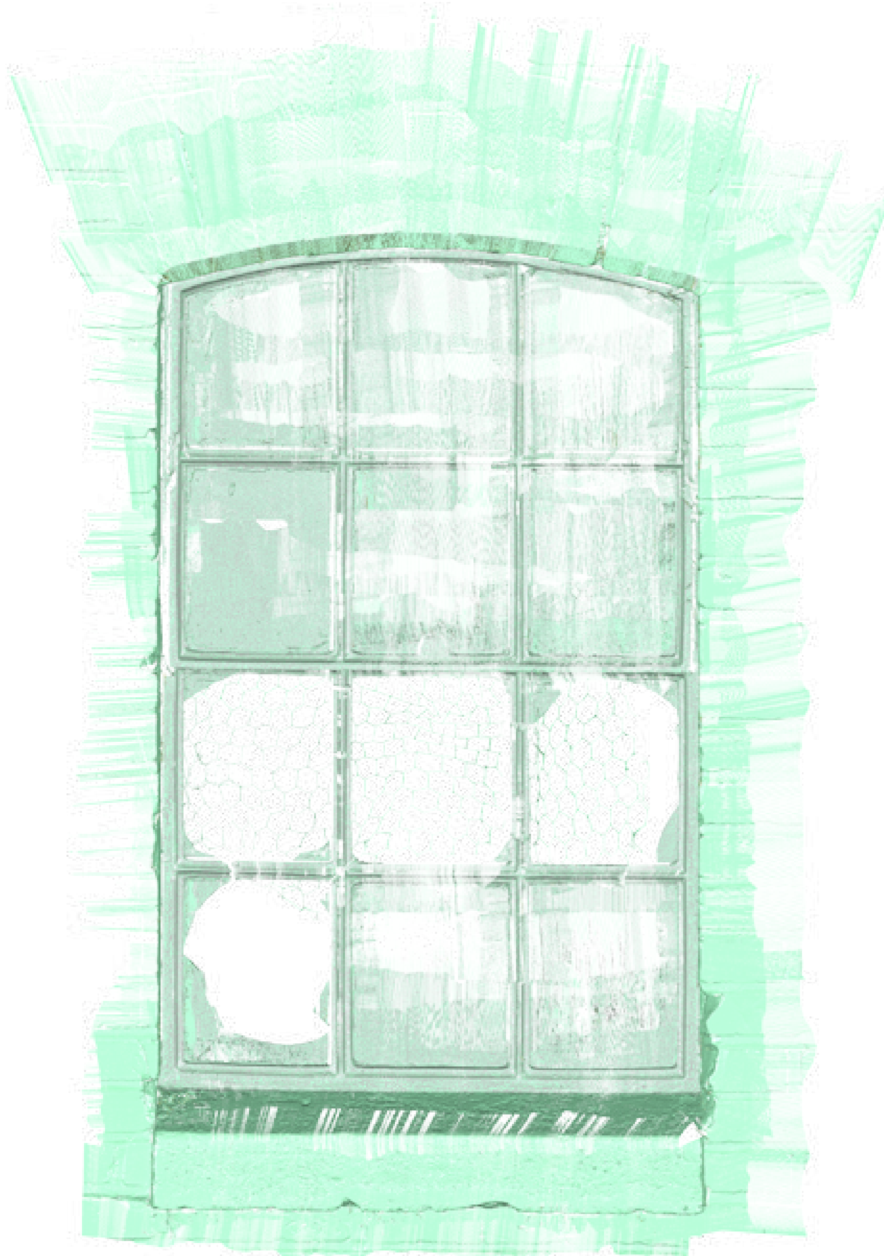
A devastated window in the alley. Multiple materials and textures and the passage of time create a complex scenario.

judged upon its coherent uniformity, both in relation to digital and physical processing. The final concrete cast contains scanning artefacts and distortions. They are visible especially in the 'glass' part of the concrete window. The concrete window is much more a physical representation of a point cloud, than a reproduction of a physical window.

Scanning as architectural tool

The experiment *Alleyway Points* is both partly inspired by and partly created together with CIMS, Carleton University, Ottawa[2]. CIMS is a research leader in the field of 3D scanning. A lot of the work done by CIMS is engaging restoration and cultural heritage. As an extension of their preservation work CIMS is moving in the direction of using their state-of-the-art scanning technologies and knowledge for fabrication purposes. The project *Digitally-Assisted Stone Carving* (Hayes et al., 2015) is based on CIMS' extensive work on the restoration of the Canadian parliament. The project zooms in on a stone relief and establishes a collaboration between the research lab and a traditional stonemason. Thereby, the project brings together new, advanced technologies and traditional craftsmanship. Through 3D scanning of a broken relief, a foam maquette is made and given to the stonemason. The stonemason repairs and rebuilds the relief on top of the maquette in order to bring it as close to its, believed, original state. The corrected maquette is then 3D scanned again. This time, the point cloud is translated into tool paths for a robotic arm. A geometrically offset version of the relief is milled in stone. The stone is then giving back to the stonemason who eventually finishes the piece by applying detailing with traditional tools and methods. As a part of the PhD project, CIMS was visited in Ottawa during the summer of 2015. At the time, the stonemason was in the process of applying the finishing details to the relief. The visit also established a research collaboration between Aarhus School of Architecture and CIMS. CIMS eventually visited Aarhus in December 2015 and took part in the work that eventually became *Alleyway Points*.

Both *Alleyway Points* and *Digitally-Assisted Stone Carving* uses 3D scanning as the basis for fabrication of elements, somehow related to architecture and building. Likewise, both experiments embrace that the transition from scanning to materialisation isn't a direct impartial path but



The raw 3D scan made on site. Millions of points describe the window and its associated textures.

The window cast in concrete. Going from points to concrete requires several steps and translations. Eventually, the casting becomes a representation of the digital point cloud.

Photos taking during visit at CIMS. Here stonemason Phil White is finishing the robotic milled sandstone relief. Close up show the difference between manual finish ans robotic roughening.

a series of transformations and decision-making processes. *Alleyway Points*, however, introduces a more open handling of the points clouds and established an articulation of the points as a type of digital substance. While only just establishing this as a discussion, the intention is to contribute to an emerging field within digital fabrication in architecture. The computational development around digital fabrication is often seen as a way of pushing materials toward new functions or geometries (Gramazio and Kohler, 2008, pp. 7–11; Schröpfer and Carpenter, 2011, pp. 23–25) on the basis of technological improvement and development. In experiment *Alleyway Point*s, the workflow and hierarchy are, conversely, shifted, and the outcome is different of what is usually seen within the field. The production mixes textures and materiality in an unorthodox way, with the intention of looking for relations between the real world and the digital from another perspective. It is the belief that much land is still needed to be uncovered, but the experiments *Alleyway Point*s and *Digitally-Assisted Stone Carving* combined point towards how the existing material condition of architecture can inform digital driven design and development.

Notes

1 (“substance - definition of substance in English from the Oxford dictionary,” n.d.)

2 See http://cims.carleton.ca/ for more information

E5: **INTERMEDIATE FRAGMENT**

E5: **INTERMEDIATE FRAGMENT**

Materials
Wood, ash
Concrete
EPS foam
Surface retarder
Latex, sheets

Machines
CMS 5-axis CNC machining centre with 330 mm saw blade tool

Software
Rhino with Grasshopper plugin
AlphaCAM for 5 axes CNC milling and sawing

Quantity and size
Several tests, 30-200 cm
One large architectural fragment, 150 cm x 240 cm

Comments
'Intermediate Fragment' was exhibited at the 'Engaging Through Architecture' exhibition by Aarhus School of Architecture at the Milan Design Week Ventura Lambrate 2015. Later, the experiment as a whole, included its process and developed thinking, was exhibitied and presented at the Adapt-r conference 'Making Research, Research Making' September 2015. 'Intermediate Fragment' was also partly discussed and presented at the 'NAF 2016 The Production of Knowledge in Architecture by Ph.D. Research in the Nordic Countries'-symposium in Stockholm 2016.

Aagaard, A.K. (2016). Bespoke Fragments: Experiment and experience-driven knowledge production, in: NAF 2016.

Aagaard, A.K. (2015). Intermediate Fragment: Explorative Materials and Machining Driven Design. I Making Research | Researching Making: A publication by ADAPT-r for the Creative Practice Conference. (s. 84-93)

Aagaard, A.K. (2015). Materials Driven Architectural Design and Representation, in: Tangible Means - Experiential Knowledge through Materials. Presented at the EKSIG 2015 - International Conference 2015 of the Design Research Society Special Interest Group on Experiential Knowledge, Design School Kolding, Denmark.

Special thanks to Mathias Ørum Nørgård for the huge amount of help during the final production and assembly of the exhibition piece.

Aiming big

The intention of this experiment is twofold. First, the intention builds directly on the notion of the drawing as a tool for embedding information into the material through fabrication. The materials' properties are seen as the basis for the creation of new capacities in the material. The new capacities of the material are realised through the machining but exist solely as virtual possibilities until actualised in physical space. The expanding of the virtual domain from digital space to physical space is intended to be further tested out in this experiment. In continuation of this, the shuttling between digital and physical through virtualities is seen as a strategy to create a coherent, productive cycle of material investigations, directly connected to the process of drawing.

Secondly, this experiment is aiming for a greater level of wholeness in the concluding production than seen in some of the other experiments. The idea is to create a production that can be seen as a fragment of architecture. The intention is to achieve this through a focusing and refinement of findings – and through scaling. Even though all materials, no matter the sample size or dimension, is seen as being real and 1:1, a certain size is needed in order to perceive an object as a real spatial fragment of architecture.

This aim for a larger, concluding fragment was a combined wish for the overall project and an ambition of ending with a summarising piece that was suitable for display at the Aarhus School of Architecture exhibition at Milan Design Week Ventura Lambrate 2015. The hope was that a building component sized fragment could ignite new perspectives and discussions on material processing and realisation as a design tool, and the produced as a type of real representation or dissemination.

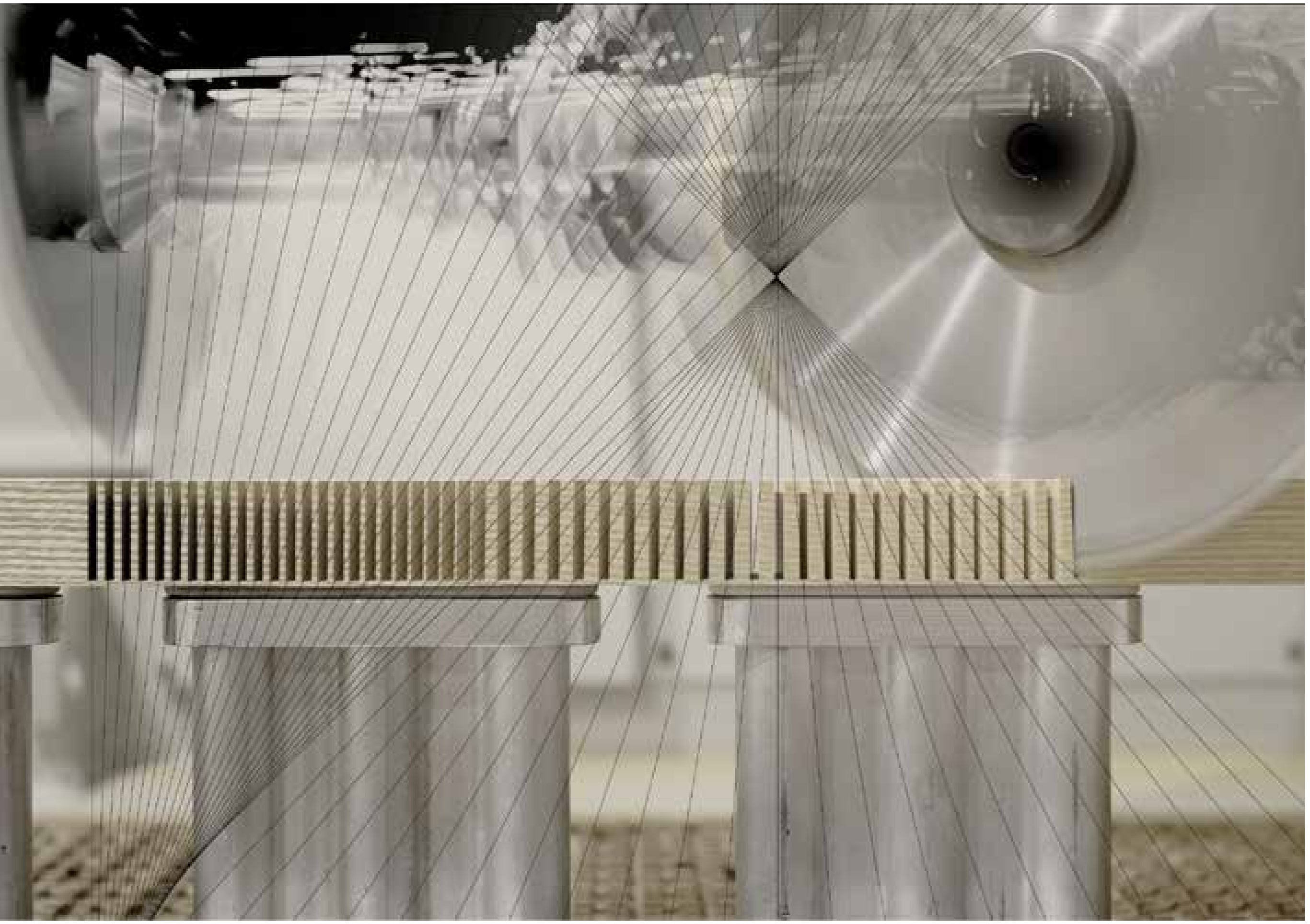
Complex kerf bending: Digital drawing and fabrication combined bring another perspective to the term wood bending.

Exploring the design space

The starting point for this experiment is a group of material tests found in the pool of *Continual Accumulation*. In a series of smaller experiments, different types and species of wood were combined with various types of subtracting or dividing machining. In many cases, the resulting wooden part was attempted transformed. The transformation could either be a simple manual-mechanic procedure or involve steaming or soaking to induce a reaction from the material capacities.

During the preceding material test, different relations between drawing and material were tested out. Some types of machining were based on an exact, modelled drawing set and defined a precise geometry that a tool would eventually have to submit to. Other types of drawing introduced a less form-specific attitude, but instead prepared the ground for the choosing of tool and machine behaviour to influence and inform the outcome.

A focusing was made on a specific kind of drawing and a particular tool. The drawing was developed in its simplest form with no representational intent. The lines of the drawing in digital space were directly translated into paths for the tool. The tool chosen was a 330 mm circular saw attached to a 5-axis CNC-machining system using an HSK tool holder and flange. The simplistic notion and style of drawing combined with a direct translation to G-code provided a short and uncomplicated workflow from 'mouse clicking' to saw blade. This setup gave almost direct access to tool control and, through that, a very flexible, but accurate, way of controlling this subtractive machining. Machining with a circular saw blade is obviously a quite linear procedure, even when to mounted on a 5-axis system. The rotational force in the circular saw sets limits for how sudden or pointy moves can be. Also, the machining is at first perceived as a dividing type of machining. That hold true, but the amount of removed material, 3 mm – the thickness of the blade, is such a considerable amount that the results are perceived as just as much a result of a subtracting process. These consequences related to the particularities of the tool immediately gave a design framework for the drawings. The drawings could be both complex and expressive, as long as they did not exceed the tool limitations or attempted to put the machine and tool combination in a too hazardous situation.

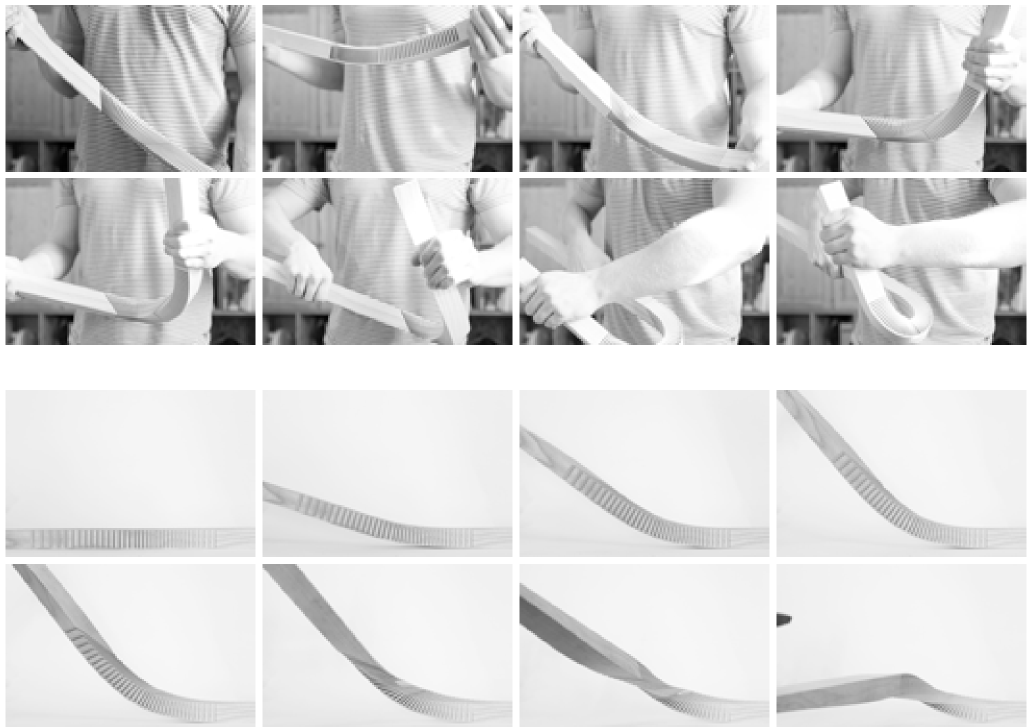


The drawing and the machine: The simple line-based drawing serves as information for the processing. This direct relation between drawing and material brings both terms into a new potential position in architectural design; a deeply rooted form of architectural representation can become the direct interface with the physical world.

While the orientation and direction of the saw blade was luckily fully controled, the machining in wood was, to begin with, a highly uncertain process. Different cuttings of the wood grains result in various reactions. Internal tensions in the wood are released, resulting new distributions of forces being made. Combinations of more, or numerous, cuts quickly created results whose logic was not easily readable. Naturally, this process led to a lot of testing and trial. This initial exploring phase had the primary purpose of establishing an overview of possibilities and preparing for material and machining revelations.

The work became focused on complex variations of traditional kerf-bending techniques, where a piece of wood is cut in order to bend it in a direction perpendicular to the kerf. Understandably this method is dependent on the amount of remaining wood, and the strength and orientation of the fibres in the bent piece. The drawing for these kerf-bending investigations started out as explorative arrangements of lines. In their earliest stages, they had no or very little experiential foundation. Instead, they served as probing instruments in the process of finding relations and defining parameters in the encounter of materials and machining. Through the recurring experiments, the drawings, however, gradually built up experiential knowledge around the investigated procedures. Every iteration gave a material feedback to the drawing loop.

Simultaneously with defining a field of possibilities, iteration by iteration, the experiential gaining increased, taking the drawings from mainly being uncertain catalysts of surprise, to being vessels for obtained know-how. More and more systematic approaches to the fabrication were utilised, creating an overview of decisive parameters, the definition of those, and their impact on the results. Kerf depths, cutting angles, kerf distribution and spacing, overall machining length, as well as the wood type and orientation, all have a definite impact on the bent shape that the machined piece will eventually be able to obtain. This knowledge, listed as parameters, in interplay with the machined result, was considered a combined design space and structural logic from which form and spatial compositions could be retrieved. This material and machining experience created a foundation for creating several versions of kerf patterns that could facilitate the bending of wood into surprisingly agile shapes. The physical shapes were reclaimed into the digital domain using 3D scanning and contact probe metrology. This allowed for a geometrical analysis



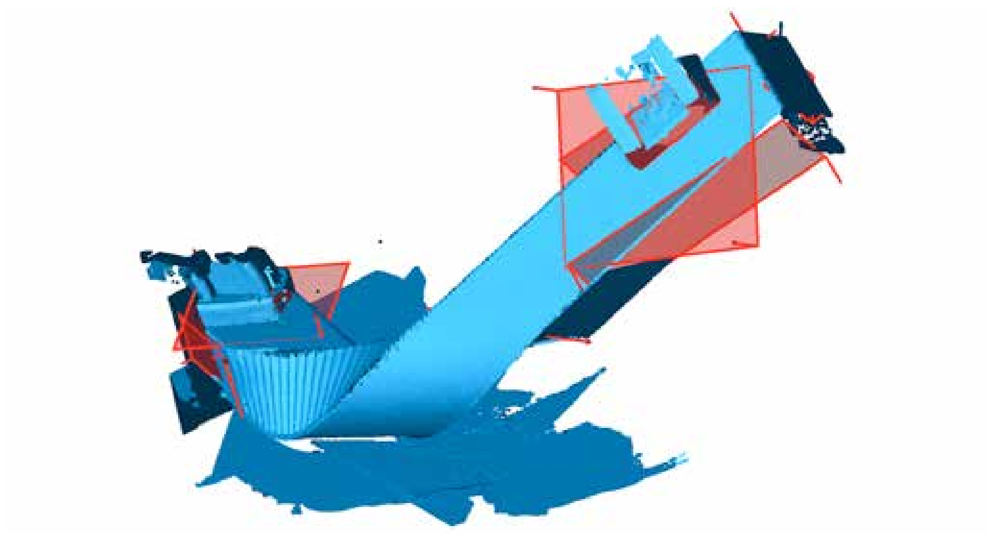
Uncertainty and control / Exploration and systematisation: After spontaneously exploring a field of possibilities, the concept is exposed to a more analytic process.

of the resulting shapes in relations to their preceding machining, as well as a basis for digital compositions and drawings. An experimental space consisting of both the physical objects and their digital representation created a potential, rich grounding for exploring. While being able to gain hands-on experience on the behaviour and structural capabilities of the physical object, the computer's digital drawing space delivered possibilities of testing combinations of objects in more intricate and larger situations. The abilities to copy, rotate and combine with parametric strategies without considering quantities or physics are qualities, provided by the virtualities in a computer's drawing space.

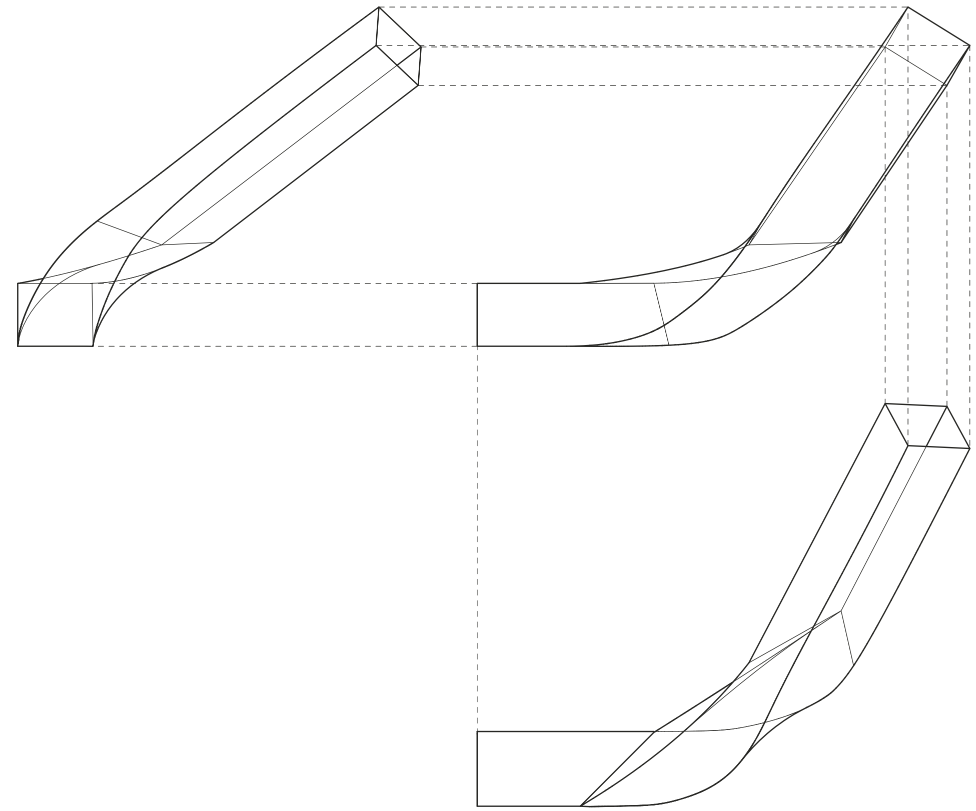
The potential of to actually bending the wood types differently and exploring the spatial transformation gained through combination of those are, in this case, solely based on virtualities found in reality. This joint set of potentials caused the development of this experiment to eventually choose ash wood as the primary material for further exploration. Ash wood has flexible, long, elastic, and strong fibres that enables the wood to be relatively easy to bend. It, therefore, has a wider application than most wood species and is thereby more predisposed for incorporating input from discoveries made both in a physical and digital experimental space.

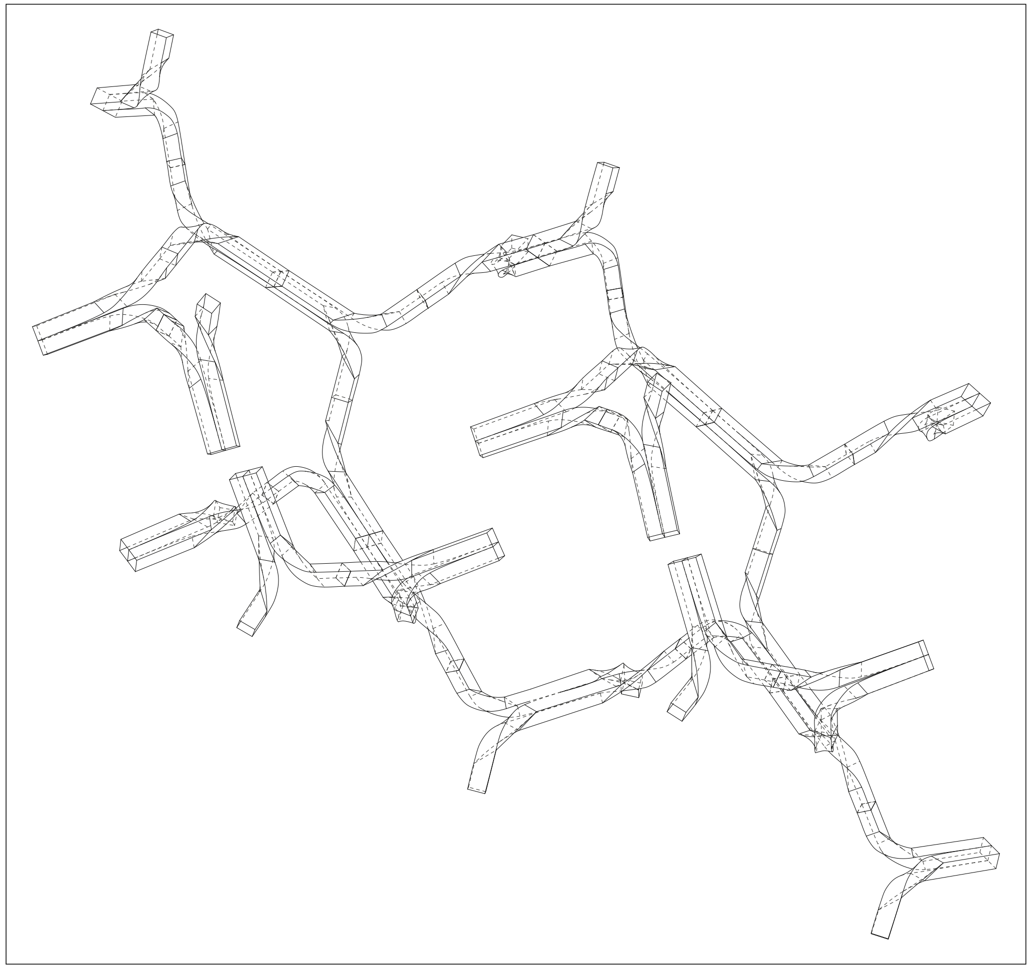
Hierarchic hybrid

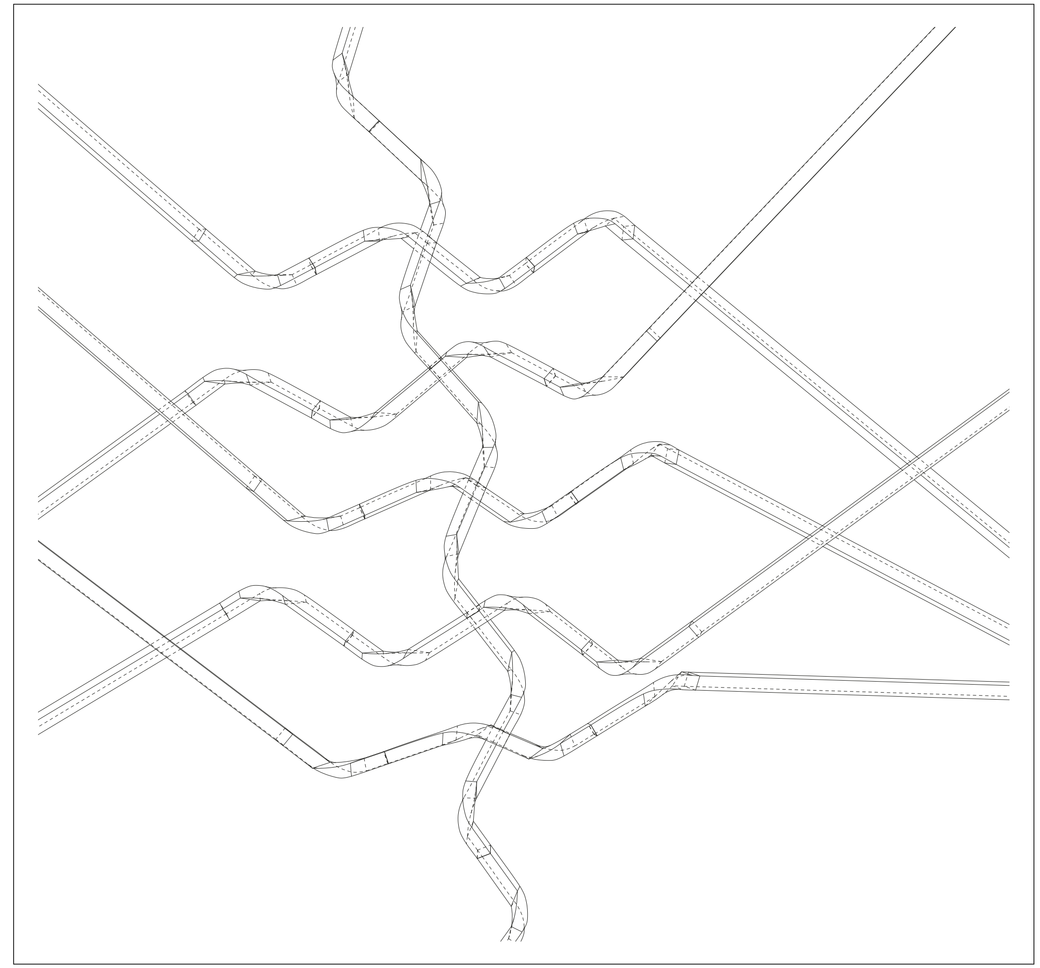
During the process of conducting wood investigations, similar, although less extensive, experiments with concrete and CNC-milled formwork were carried out. This process gained speed in a phase where the wooden experiments were already well developed. This resulted in more focused investigation and design strategy. The studies in concrete eventually acquired an supporting strategy for the design developed through the wooden experiments. While the introduction of a second material was always inteded, the exact type, purpose, or role was not determined beforehand. Concrete has a heft that complements the lighter ash wood well, both in terms of structural foundation and spatial establishment. Concrete also has the ability to adapt to numerous shapes. A quite precise shape and spatial language was built around the bent ash wood. If an investigation in concrete had been carried out independent from the ash wood, the result would have likely been very specific and therefore probably



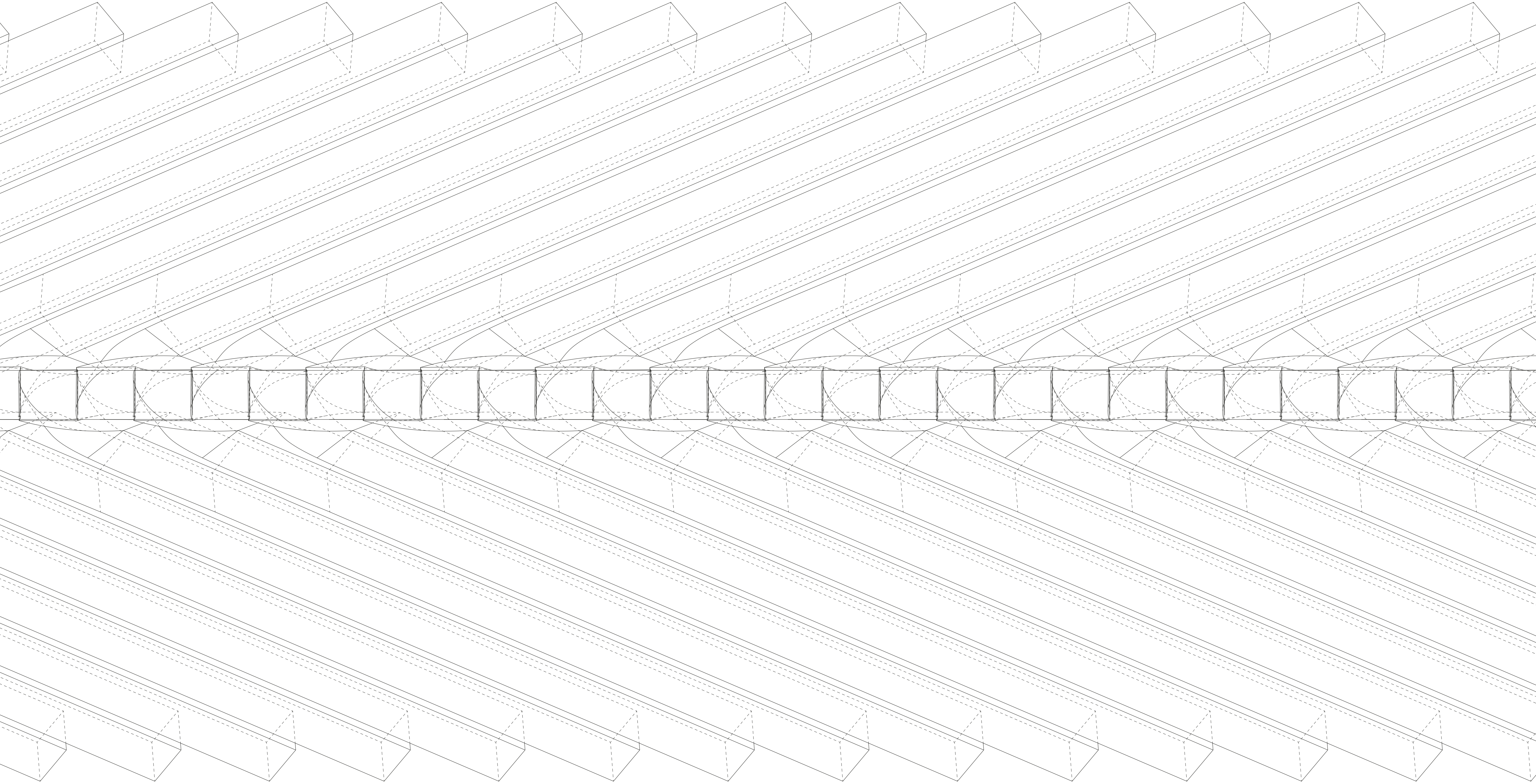
This page: 3D scanning and digital metrology help to understand the curvatures and utilise the physical transformation combined with computational power.
Next page: The digitisation of the bending also lets the findings merge with traditional practices of drawing. Here, the wood has been translated into an orthographic projection.





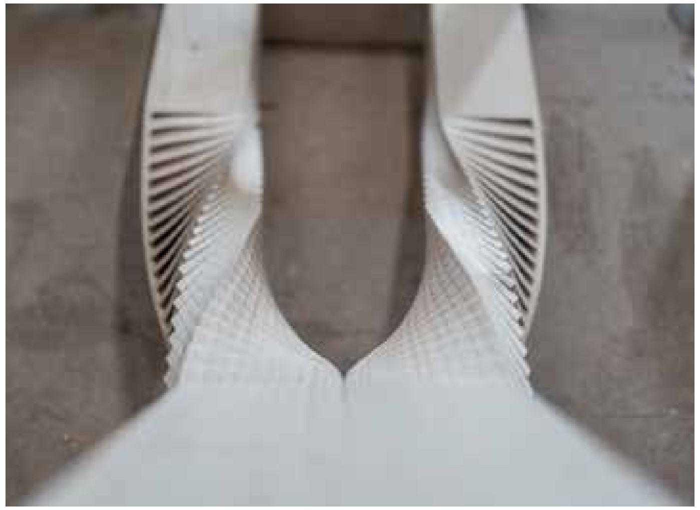


This spread and overleaf: With different types of bends digitised, the investigation can continue using the tools of the computer. Combinations and configuration can be rapidly tested. While not, in this case, providing a tectonic feedback, the spatial potential of the wood elements is examined through multiple strategies.

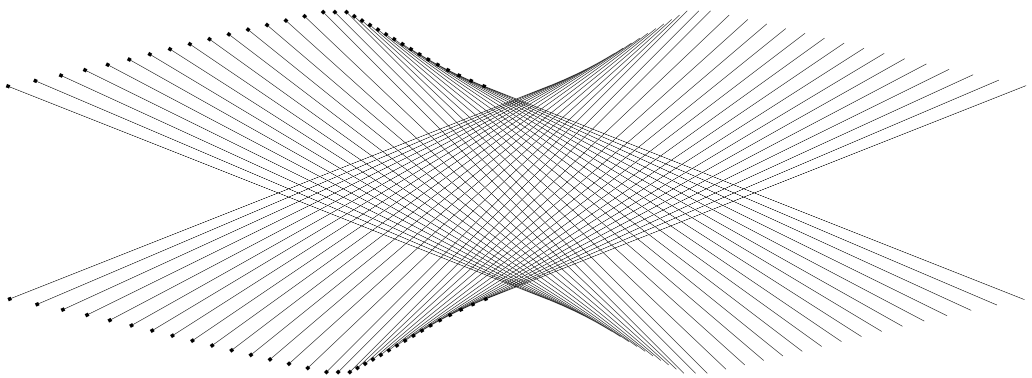




Parallel with the digital exploration of forms, physical tests are continuously created. The physical mockups provide another type of feedback than the digital; forces from the complex torsion are located through hands-on experience and the 'easiness of assembly' is examined. Combined, the digital and physical feedback advances and focuses the experiment.

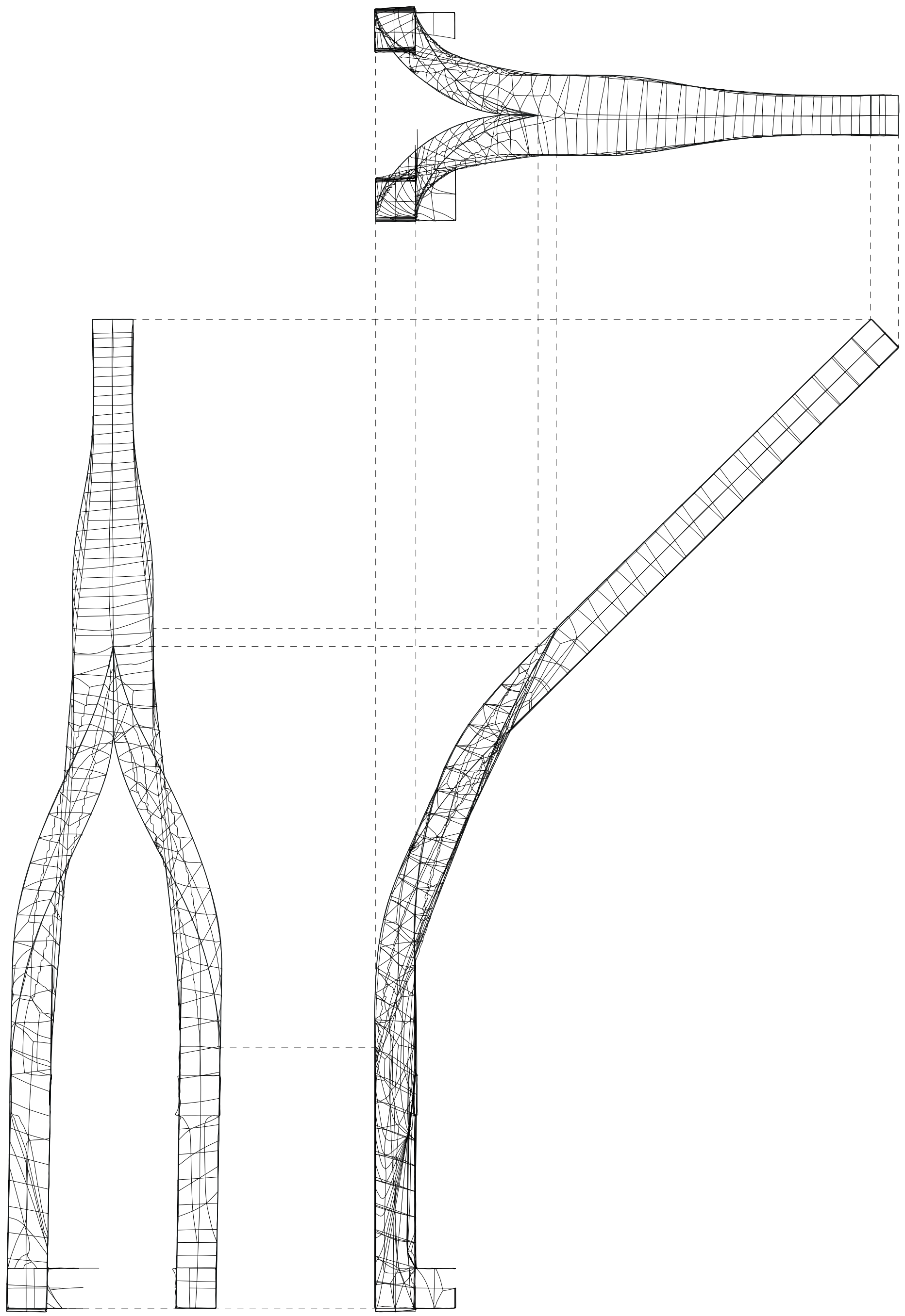



Two symmetrical bends are fixing each other and thereby using the torsion as a supporting force instead of a conflicting one.



Left + right: Even though the drawing does not visually represent the physical outcome, there is an apparent affinity among them.

After several iterations in both digital and physical space a set of forms, drawings and machining strategies are framing the experiments. The conceptually refined objects are digitised once again in preparation for the next phase of the experimentation, which includes an encounter with concrete.



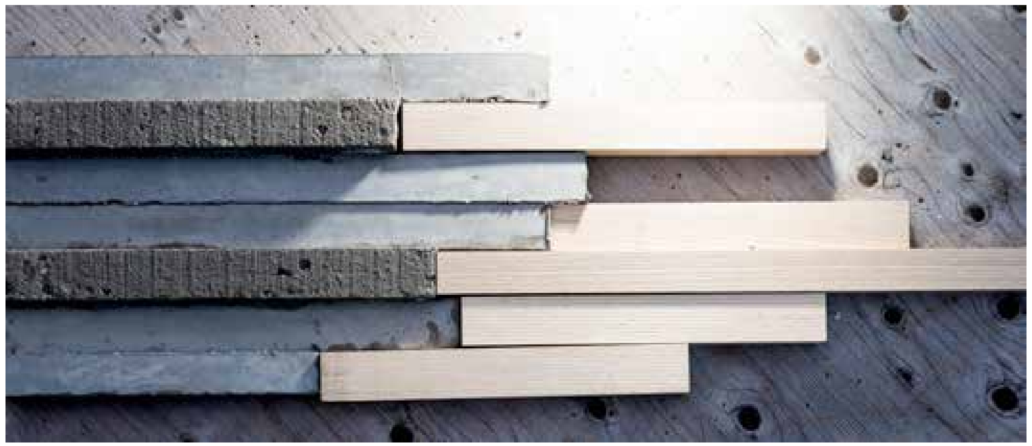
Top view and elevation based on 3D scanning of wood parts. Drawings are used for planning the larger, hybrid material fragment.

too difficult to integrate with the ash wood. Concrete, therefore, served as an essential ingredient in order to bring the work towards being a hybrid fragment, but with a clear hierarchy in terms of form finding.

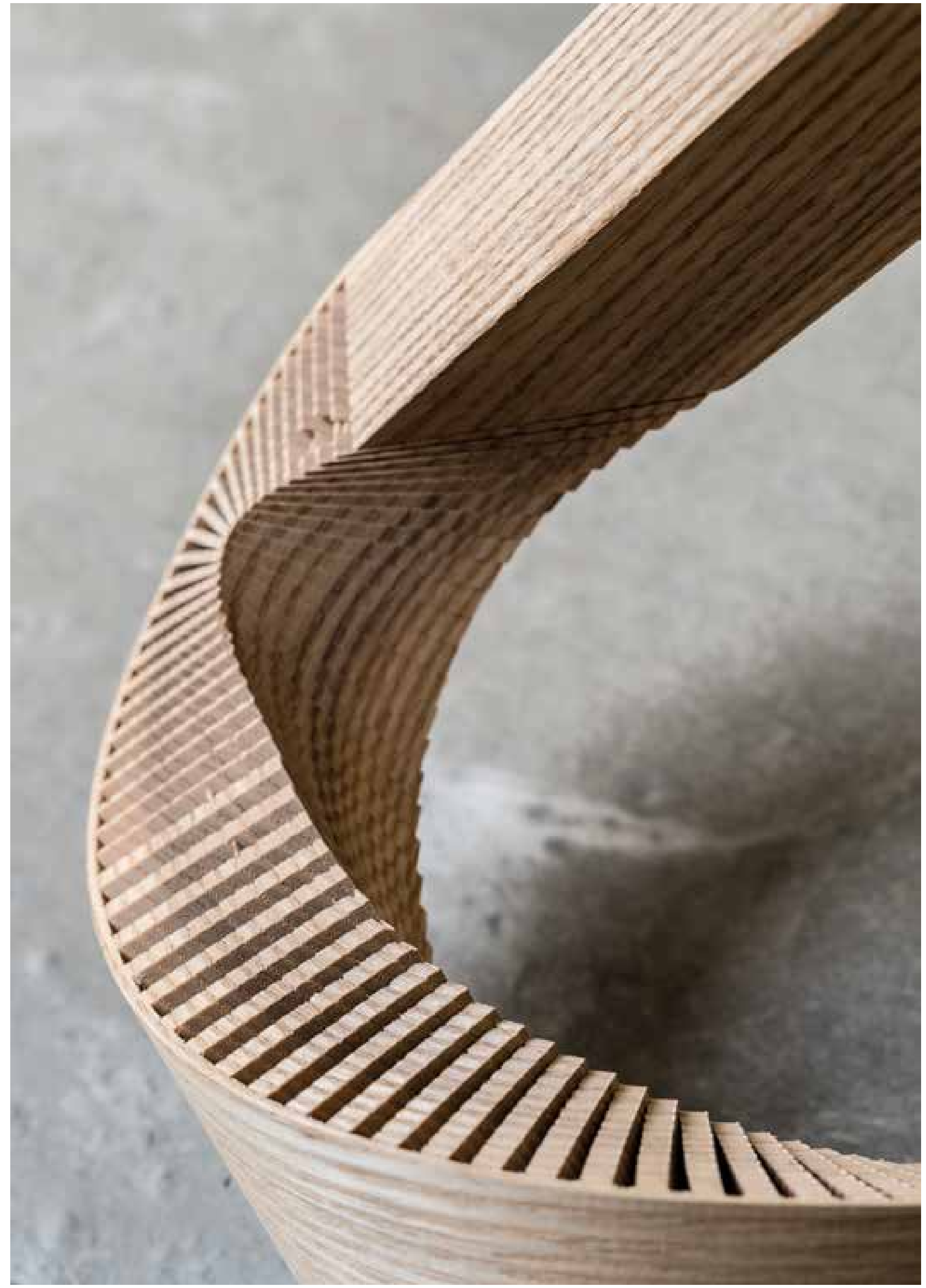
As opposed to the drawings for the wood, the formwork drawings for the concrete were drawn as explicit solid geometries based on shapes passed on from the result of the wooden transformation. The digitisations of the bent shapes and curved contours from the ash were passed on to the design of the concrete. Formwork was routed in expanded polystyrene (EPS). EPS is easy to machine, but the result is miserable for casting due to its open texture. Therefore, surface treatment is needed. Consequently, the EPS negative solids were looked upon as blank, three-dimensional canvases for imposing surface features that could brace the design and in that way extend the active process of designing into the material. Different materials, including acrylics, treated wood, textiles, oils, solutions ,and more, were tested out. A partial lining with sheet latex cut by a digital cutter in combination with areas treated with an acid-based, retarding solution was chosen. This arrangement offered a smooth surface texture where the latex was applied and a rough erosion of the surface where the solution was active. By taking advantage of the capacities of the concrete, the formwork created an inside-out effect to the casting that followed and continued the ribbon-like effect achieved by the machined and transformed ash wood.

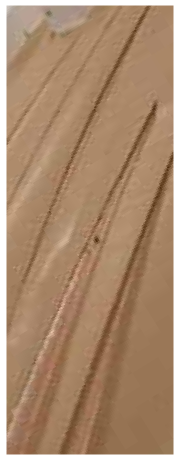
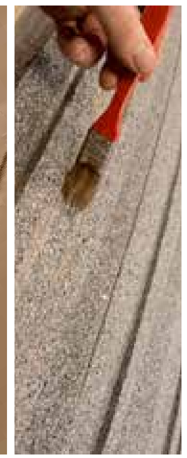
Materials and machining driven design

The result of the extensive testing and prototyping turned into a built bespoke, architectural fragment. The fragment exists as a component of coasleced transition between ash wood construction and concrete base. The structure is an intermediate result based on the quantity of experimental results and the experiential knowledge gained from the research process of combining digital drawing and fabrication tools *and* an investigation in material capacities. While temporarily acting as an exhibition piece, *Intermediate Fragment* is not to be considered a final result. It is to be considered an architectural fragment belonging to a process containing a quantity of informative, actual and representational elements. At the same time, the process also starts to shape a production method and strategy around the designs to be.

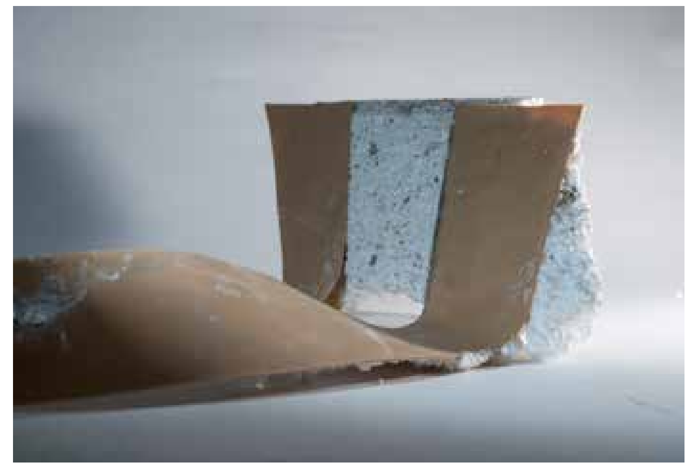


The long grains of the ash wood are sought to be combined with the solidified homogeneity of the concrete. Different surface treatments for the concrete are tested out.



The strategy for the concrete part eventually ended up with a formwork milled in EPS, partly lined with sheet latex and partly treated with retarder. This results in two types of surfaces that can interplay with the curved wood.




Both surface texture and overall form of the concrete element is tested intensly. The complete design for 'Intermediate Fragment' appeared through constant iteration.

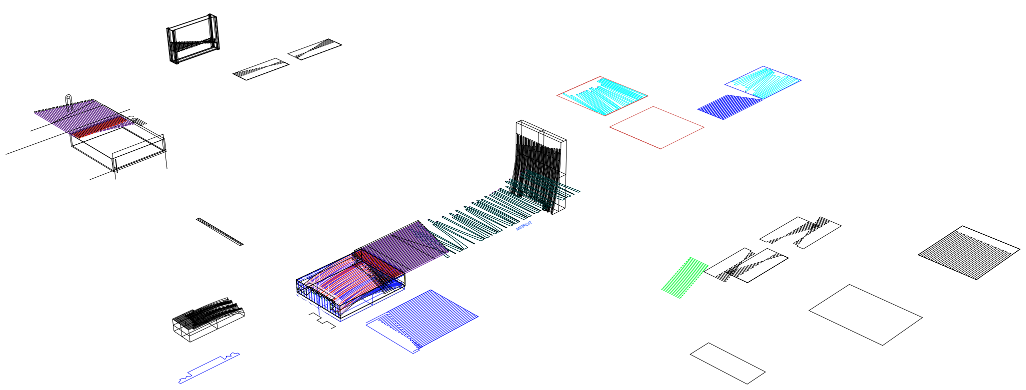
While not being based on, the design process of *Intermediate Fragment* resembles the thoughts of Aart van Bezooyen, described in the text *Materials Driven Design* (van Bezooyen, 2014). Van Bezooyen describes material driven design as being about bringing materials to the beginning of the design process by using material samples to expand the idea generation or use the materials as starting points for exploring different applications. This approach of *materials exploration* is in contrast to that of *materials selection*. Van Bezooyen explains the difference using the *double diamond design model* (Design Council, 2007) where the process of design is described by the phases *discover*, *define*, *develop* ,and *deliver*. In a traditional design process materials selection takes place in the *develop* phase, whereas, in a design process driven by material exploration, materials are introduced in the *discover* phase and thereby utilised to inform the design in a broader way.

The process of creating *Intermediate Fragment* was indeed characterised by being material driven. But equally so characterised as being *machining driven*. The machining of material as a design-driving factor opens up possibilities for material exploration. Without being constrained by trying to realise a predetermined shape, the machining instead becomes a way to initiate a more sketching-like process. At the same time, the process also starts to develop a production method and strategy around the design to be. Potentially, materials and machining driven design will not only be able to suggest new spatial constellations and shapings of materials in architecture, but also suggest the process of manufacturing these in a later construction phase. With this potential in mind, the inclusion of machining of materials in the early design process create a two-fold strategy for a tighter connection between design and realisation.

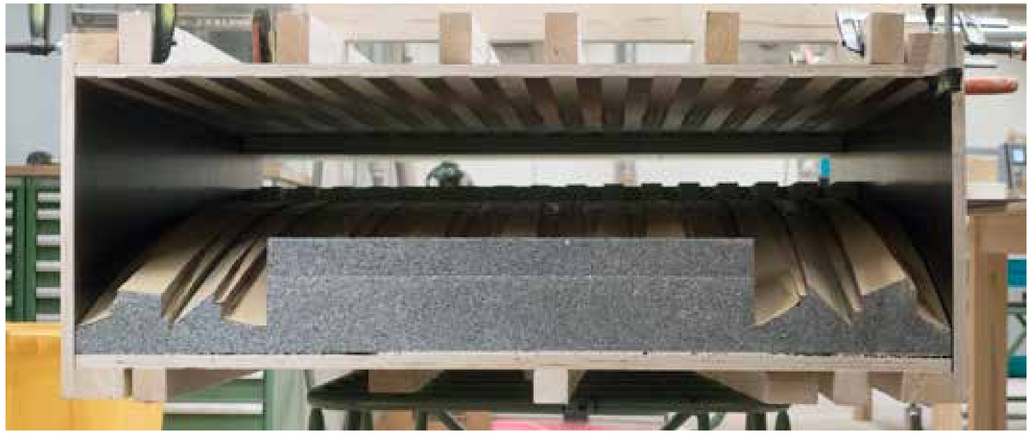
Expanding representation

Many of the techniques, methods, and tools used in the designing and the fabrication of *Intermediate Fragment* and its preceding phase of material research are well known and established as either architectural tools or manufacturing methods. Nonetheless, the project, and proposal of a material and machining driven design method, suggest both an expansion of the architect's toolbox as well as an extended idea of architectural representation.

The creation of the first elements for the fragment also means the creation of assembly methods and workshop procedures. Here, the wood is being fixed by an articulated arm while waiting for the next assembly step.



Shuttling between digital and physical: Sketching, development, and production are happening simultaneously in two types of workshop-like environments.



Upper: Formwork almost ready for casting. Different surface treatments are applied.
Lower: Formwork removal reveals the different surface textures.

Architectural production is traditionally characterised by a number of different representational pieces which altogether brings forth a collective explanation and understanding of a coherent idea (Leatherbarrow, 2001). Architectural representation is often multifaceted, engaging the project through different mediums and from different perspectives. Scale models, section drawings, artistic visualisations, detail drawings, conceptual diagrams, material samples – they all try to form a notion of what the particular architecture and architectural idea are about. Individually, every piece of representation in this set can be of artistic, professional, or technical value, but alone do they not deliver the cohesive understanding behind an architectural project (Leatherbarrow, 2001, pp. 87–92). The architectural set is representational and altogether forms a domain of individual, but relational fragments. Put together; these elements create the context for understanding a proposed architecture, but also an understanding of the architect's underlying work. To sum up, architectural representation often compresses both a conducted work process *and* the idea of a future construction into a complete set.

As earlier noted, the use of digital fabrication tools have proven to bridge digital drawing and materials, enabling the architect to inform production through drawing. Mainly in academia, but also in some office practices, the linkage has resulted in a current era of pavilions and small-scale experimental architecture types. They seem to discuss this coupling while also testing out new materials and construction systems found through these processes (Gramazio et al., 2014). While many of these structures stand on their own and, to some extent, can be regarded as autonomous pieces of architecture, they are not buildings and their existence do not replace the need for buildings - and was never intended to do so. Instead, they propose new spatial possibilities through new ways of designing structures and machining material, that could potentially be implemented in future buildings.

Reflecting on this existing field *and* the experiments carried out in this research project, it can be implied that the discipline sees this new type of architectural production as an expansion of the already existing set of representation types. Tangible, material constructions provide another perspective on both the creation and presentation of an architectural idea, and should in that context be seen alongside drawings, models, diagrams, etc. The

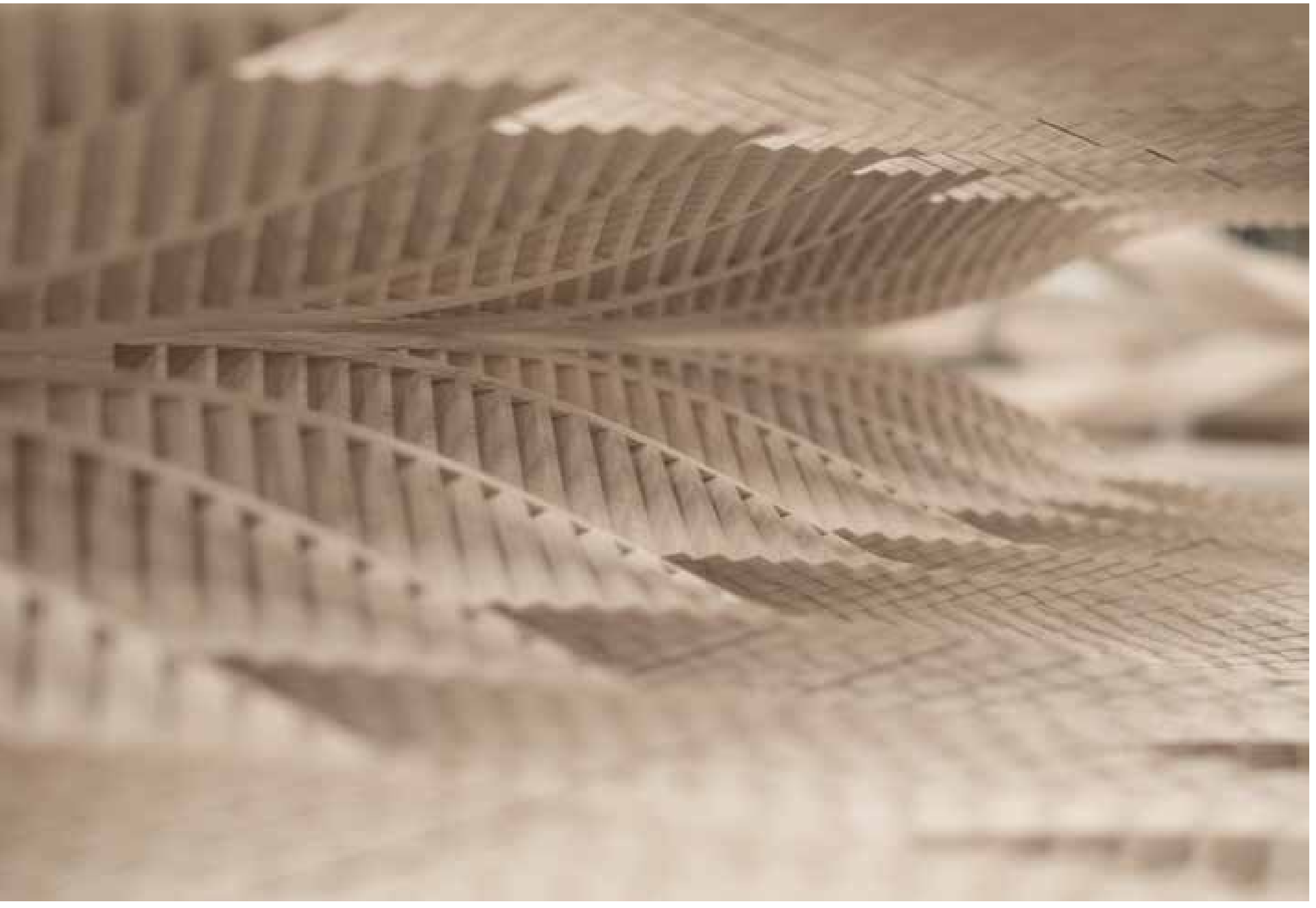
Under construction: Concrete and wood parts are being assembled into 'Intermediate Fragment.'

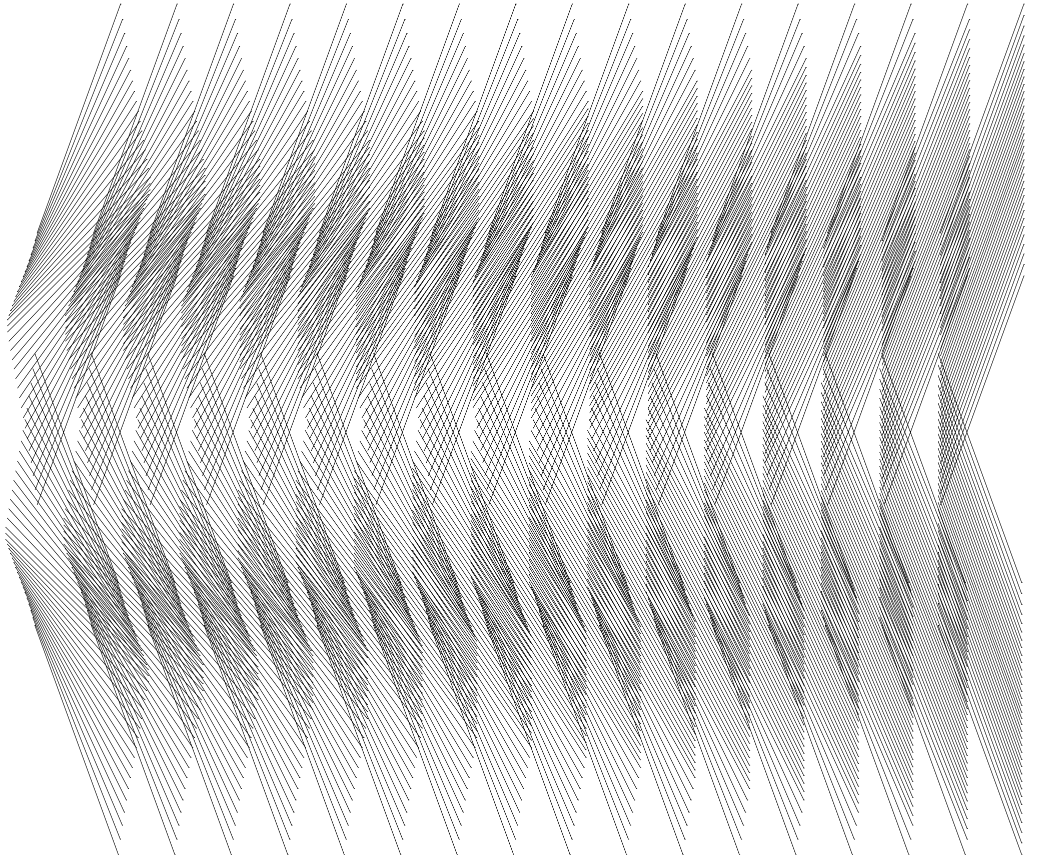
on-going creation of architectural representation will always play a vital role in the designing of architectural space and generation of spatial ideas. Sketching and modelling in any medium will provide a constant, experiential feedback to the design process. Unique for the material representation created through digital fabrication is, however, the ability to be both introduced very early in the process *and* throughout the designing continuously evolve alongside with the development of the associated drawing and the machining method *and* the architectural idea. Phil Ayres articulates this process as *persistent modelling* (2012), meaning a process of constant production and evaluation, shuttling between digital and physical domains and argues that this way of designing is extending the *role* of architectural representation. This type of representation can drive a design, but also evolve into information that is not only picturing, but holds information for the realisation itself.

The thought and the material

"Bringing with me the conviction that architecture and the visual art were closely allied, I was soon struck by what seemed at the time the peculiar disadvantage under which architects labour, never working directly with the object of their thought, always working at it through some intervening medium, almost always the drawing, while painters and sculptors, who might spend some time on preliminary sketches and maquettes, all ended up working on the thing itself which, naturally, absorbed most of their attention and effort" (Evans, 1997, p. 156).

The above quote is taken from the well-known essay *Translation from Drawing to Building* from 1986 by Robin Evans (1997). Evans asserts that a vital function of the architectural drawing or representation is to deliver a 'complete determination in advance' (Evans, 1997, p. 156). While the essay is not 'freshly new', it is a rather modern manifestation of a complication related to the Albertian paradigm (Carpo, 2011, pp. 20–26). Evans is in his essay discussing the functions of the architectural drawing and suggesting the potentials of establishing a closer relationship between architect and the product – the drawing or representation – of the architect, thereby maybe redefining architecture as a discipline and, as a result, approach end up closer





Left: When assembled, the series of wooden parts form a complex, but repetive, spatial constellation.
Right: The drawing set that informed the kerf cutting somehow resembles the material situation.

The fragment is assembled. From being an evolving process, it now undertakes the function of being an exhibition piece at the Milan Design Week.

to the professions of fine art. He also suggest to dissolve the drawing into an even purer abstraction, to disembody it and disengage it (Evans, 1997, p. 160). Evans argues that the *directionality* of the drawing is of great importance to the understanding of its function.

The drawing of an architect is a drawing of something not yet realised and thereby an imaginary projection that is the reverse of the imaginary projection happening in the painting of a landscape or a portrait. Evans explains that the imaginary projection, or the direction of the object to the picture plane, has 'reversed directionality' (Evans, 1997, p. 165) when created of an architectural or design intention. The direction is related to the projection of the object, but Evans also believes that this projection is an active attribute of an object (Zambelli, 2013, p. 364). The projection is not only a vessel for passive images or notations, but is an action that can have intentionality.

Evans' essay provides an excellent discussion and immersive series of analyse on the demeanour of representation in architecture. The essay, and Evans' other writing for that matter, should not be treated as a provider of truth, but as analytic instruments trying to pursue sophisticated understandings.

When focusing on the development and resulting material made in the experiment *Intermediate Fragment* Evans' considerations about drawing directionality become relevant. First, *Intermediate Fragment* offers potential for discussing the type, making, and meaning of architectural drawing in relation to Evans's thinking in a new technological context. Secondly, the process, or mode of process, used and proposed by the experiment can be discussed as possible, future alternative to the issue that is the initiator of the discussion in the referenced essay – namely the separation of the reality of the architect and the reality of the building due to the 'reversed directionality' of the architectural drawing.

Evans's discussions about drawing and representation are clearly angled towards the production that mediates the architectural idea towards a construction phase. Evans is concerned about the production of these representations and maybe less so about the type of drawings and representations made in order to get to the final result. To discuss this thinking in relation to the experiment at hand, the sketching and developing process, however, will have to be taken into consideration.

This page and overleaf: 'Intermediate Fragment' shining at the Aarhus School of Architecture exhibition at Milan Design Week. The 'completness,' size and heaviness of the fragment makes it an independent piece. It got visitors excited but also wondering. What is it? What is the purpose? 'Intermediate Fragment' looks like a building fragment, but let alone it does not explain the full scope of its existence. While being a kind of prototype, it is also a piece of representation.

The factual basis for the work that developed into *Intermediate Fragment* was a 'techno-mechanical' interest in wood bending, but also the investigations of the information needed to do this. Particular processing types and strategies reconfigured the conditions for the wood fibres, thereby allowing the wood to behave differently.

The experiment started out with different kinds of wood, different types of machining, and an investigative manner. A drawing, in the classical sense, was not present at the beginning. The initial sketching was therefore performed in a way more similar to sculpturing or traditional craftsmanship – a process happening directly in the actual materials in the hands of the practitioner, contrary to a process based on a set of blueprints (Carpo, 2011, p. 45). At the very beginning the wood was processed using manual tools – circular saw, hand router, etc. – but very quickly, digital processing was added to the material sketching. In every case, the workflow of drawing, processing and bending characterised this particular finding process. Drawings, either pen on wood or digital drawing, were notations for processing. The processing altered the wood by removing material and the bending or deforming in the hands of the drafter exposed the consequences of the drawing and processing *and*, at the same time, informed the next iteration of those.

This way of modelling and creating drawings differs from both traditional sketching and classical architectural drawing. The drawing is here a carrier of processing information and not a representative of an object. The material at hand concurrently medium for sketching and material of the object. Therefore, the drawings play a double role regarding directionality. They serve as instructions for fabrication to be, but simultaneously they are based on preceding fabrication. They, however, do not project an object to a picture plane, but instead they extract information from an object and note it as a drawing. Likewise, the drawing to follow is not an image of an existing object, but instead a further informed digital instruction set.

With the experiment progressing towards being a fragment, a drawing set of machining instructions were created alongside series of physical objects. These were of an inquisitive nature, but also self-referring in terms of the scale and spatial extent. The produced, material objects were physically arranged and recombined to explore possible relations and configurations. Simultaneously,

the physical constellation was digitised and the digital design domain was used along with the physical explorations. The action of creating a digital drawing based on the physical object introduced yet another shift in the directionality of the drawing. Material, processed on the basis of a digital drawing, became a source for both a new drawing, and a new type of drawing with different potential than the prior.

The technological context of the drawing disperses the directionality of the drawing and the notations associated with it. Instead of being a phenomenon with a fixed direction, the drawing can function both as a design and development tool itself, while being a key to capturing actual materials and materials' processing into the drawing process.

The making of *Intermediate Fragment* was an experimental process performed in a closed, controlled environment. Therefore, the course is not a representative or replacement for a practise based situation. It is a research exercise that has potential to eventually inform a practise-based situation. The split between the type of work done by architects – the drawings, the representations – and the intention and purpose of this work – the buildings, the constructions – is usually a reality in practice. Designing and making do not currently mix. This is true both on a general level, as per Alberti's distribution of roles (Carpo, 2011) and on Evans' (1997) more specific and drawing-based level. The growing overlap of digital technologies shows that a rethinking or shift from this paradigm can unleash a number of new possibilities.

It is clear that an abandonment of fixed drawing directionality can result in a digital drawing that can quickly transform into and function in many different forms. One of them being as both carrier of machining information and the interface to interact with the production equipment. An apparent benefit of establishing this interface is the integration of the machining of materials into the creation of the drawing, thereby letting the means of construction be a part of the production of architectural representation and the following architectural realisation. The benefit of doing so is, as a minimum, twofold. First, the use of machining equipment and materials in an early design phase will unfold new ways of designing and thereby new spatial designs, not conceivable without this approach. In itself, this is a great expanding beyond the classical limits of the drawing. Secondly, the construction and material knowledge will have the

At the Adapt-r conference 'Making Research, Research Making' September 2015 the experiment 'Intermediate Fragment' had another chance to be exhibited. This time in a more casual setting and together with elements, tools, and drawings from the full process. The presentation of this collective set gave visitor and audience insight and produced discussion around the experiment's perspective on materials and digital machining as tools for architectural designing.

potential to embed directly as part of a drawing set. With unique fabrication data being developed through the process, this information could be established as an unbroken link. This would allow architectural production to contain a level of specificity not seen before. Elements of a drawing set could be machining instructions for very specific processes essential for unique or custom designs. Instead of taking on the role of being images that need to be interpreted and rationalised into building components, architectural production could be the information necessary to construct the images and the object of the architects' thoughts.

Intermediate Fragment was created by a combined research, design and construction process. Everything from the early material investigation, machining principles, design decisions and actual construction of the architectural fragment was carried by the author and supporting collegues. Thereby the architect took on almost all possible roles of the building-like process. The execution of this performance should not be seen as a desireable model. Instead, this should be viewed as a function and temporal interface set up to test several phases of the process. Taking a material and machining based workflow into a practice context would not contain this egocentric division of labour. The experiment is proposing to establish a closer relation to material and making through the inclusion of these as part of the architect's tool set and awareness. In the context of reality, this would need a serious intermingling of disciplines and industries, following the proposed idea of a non-fixed directionality of drawing. If architectural drawing interfaces could gain access to actual production facilities through industrial partnerships, a wide and powerful set of design tools would suddenly be in the hand of architects. Concurrently, a mixing of design and making could demystify, facilitate, and even obviate the translation from drawing to construction. Doing so could prioritise the aspiration for the built intention and downplay the postulate of the image.

While this project suggests that the type of fragment presented by *Intermediate Fragment* could be a type of production that can both belong to the general architectural production and reach out towards a built reality, it is also clear that this type of materialisation cannot replace the existing set of architectural representation. The creation of *Intermediate Fragment* resulted in a huge amount of literacy and know-how. The process was, however also extremely troublesome and time-consuming. The use of a bespoke fragment like this in a real architectural context do provide many possibilities, but equally as many challenges. Of course, one cannot construct the entire building prior to actually construction the actual building. There is a reason behind the existing use of drawing and scale models in architectural production and the discipline in general. The ability to hold complex organising information concerning construction and design is not within the scope of the fragment. This job is better done through the process of drawing. However, the use of fragment in specific and carefully selected scenarios can provide an in-depth process that will be able to inform a design on an otherwise unobtainable material level.

E6: **REBAR INSIDE OUT**

E6: **REBAR INSIDE OUT**

Materials

Steel, rods, cold rolled - 3/8 inch
Concrete, Aalborg Portland RAPID, grey

EPS foam
Surface retarder
Plywood, film faced

Machines

Kuka KR100 robotic arm on linear track with custom made steel rod bending equipment at the FABLab, University of Michigan, Ann Arbor.
ABB IRB 6620 robotic arm with hot wire cutter at Aarhus School of Architecture.

Software

Rhino with Grasshopper plug-in.
FABLab made python code for simulation and Kuka KRL code generation for steel rod bending, plugged into Grasshopper definition.
Mussel for Grasshopper for generation of ABB RAPID code for hot wire cutting.
AlphaCAM for 5 axes CNC milling and drilling.

Quantity and size

Several test, 30-200 cm
One medium steel construction, 40 cm x 40 cm x 140 cm.
One larger steel construction, 115 cm x 385 cm x 75 cm.
One larger steel and concrete construction, 1550 cm x 1500 cm x 125 cm.

Comments

This experiment is conducted in collaboration with Wes McGee, director of the FABLab at Taubman College School of Architecture, University of Michigan, Ann Arbor. Many thanks to Wes McGee, Dustin Brugmann, Asa Peller and John Cross for letting me use the FABLab facilities and helping me out with everything during my stay in Ann Arbor.
Special thanks to Ryan Hughes for great help and assistance with the hot wire cutting.

Composite rethinking

Rebar Inside Out is an experiment derived from the context of the other experiments and events carried out through *Bespoke Fragments*. While some experiments are quite conceptual regarding what they investigate, others utilise more tangible approaches.

In this experiment, the idea is to expand the architectural possibilities around a well-known composite by applying new material and fabrication approaches and knowledge.

Reinforced concrete is a widely used composite in building construction. The interplay between the properties of steel and concrete makes it a reliable approach to many challenges in the realisation of buildings, but also an obvious case within the framework of this project. Traditionally, reinforced concrete components are cast slabs, columns, or walls that together create a basic structure for a building. These components are often defined by planar concrete surfaces with an internal grid of reinforcing steel.

It is in this experiment the idea to rethink the possibilities of the reinforced concrete composite starting from the inside out. This means starting with the reinforcing steel, the production and shaping of this, and then through that process build a workflow for the production of the composite.

The rethinking of steel reinforcement in terms of production can also lead to an opening of a discussion regarding the relationship between steel and concrete in the composite. Currently, while highly internally dependent, the concrete is the material visible in the result. It is the ambition to widen the relation beyond the existing composite bring it and into a more spatial thinking. The steel and concrete could be seen as not only a twosome where the one is living inside the other, but maybe more like a symbiosis of the two materials. It is the intention to reimagine a combined steel-and-concrete construction

Robotic steel rod bending, assembly, and welding at SuperFlex workshop at RobArch 2014 conference, University of Michigan, Ann Arbor. This experience initiated the idea for the Rebar Inside Out experiment.

type, where the steel is sometimes acting on its own and sometimes coalesced with concrete. Thereby, the role of the steel could change throughout a larger structure, but constantly be in a composed situation with the concrete.

The focus of this experiment is targeted towards the interplay of steel and concrete. It will take its starting point from a reimagining of the steel reinforcement, but will aim to suggest a whole process that embraces the joint possibilities of the material composite. Choices regarding technologies and processes will, at some point, need to be balanced, in order to create a coherent workflow. The techniques will need to play together in order to create a combined design space for the experiment.

Building on existing

The initial foundation for the experiment was established during the 'RobArch 2014' conference at Taubman College School of Architecture in Ann Arbor, Michigan at a workshop held by the experimental architectural office *supermanouvre*[1]. The workshop was utilising the unique robotic setup in Ann Arbor to explore workflows for bending, assembling, and welding steel rods. While the processes around the steel bending did not include concrete or rebar, the idea of taking the technology in that direction was established during this event.

The robotic steel rod bending setup in Ann Arbor has already been widely used in both research and education. One of the more substantial and novel uses of the setup was shown at the 2012 Venice Architecture Biennale. The *Clouds of Venice* installation by *supermanouvre* and *Matter Design Studio* combined an algorithmic approach to the creation of spatial configuration with a thorough understanding and utilisation of both material properties and the limitation of the processing. 1000 unique steel rod components constituated the installation (Aiello, 2014, p. 193).

Building on top of an already established collaboration between Taubman College and Aarhus School of Architecture[2] this rebar experiment was initiated in the fall of 2015. Following the idea originating from the novel robot technologies created in Michigan and the academic partnership between the two institutions, the experiment was set up as a continuation of established technologies and partnerships. Quite literally, this meant that the experimental

Left + right: The Clouds of Venice installation by supermanoeuvre studio was made with the robot setup at FABLab, University of Michigan, Ann Arbor.

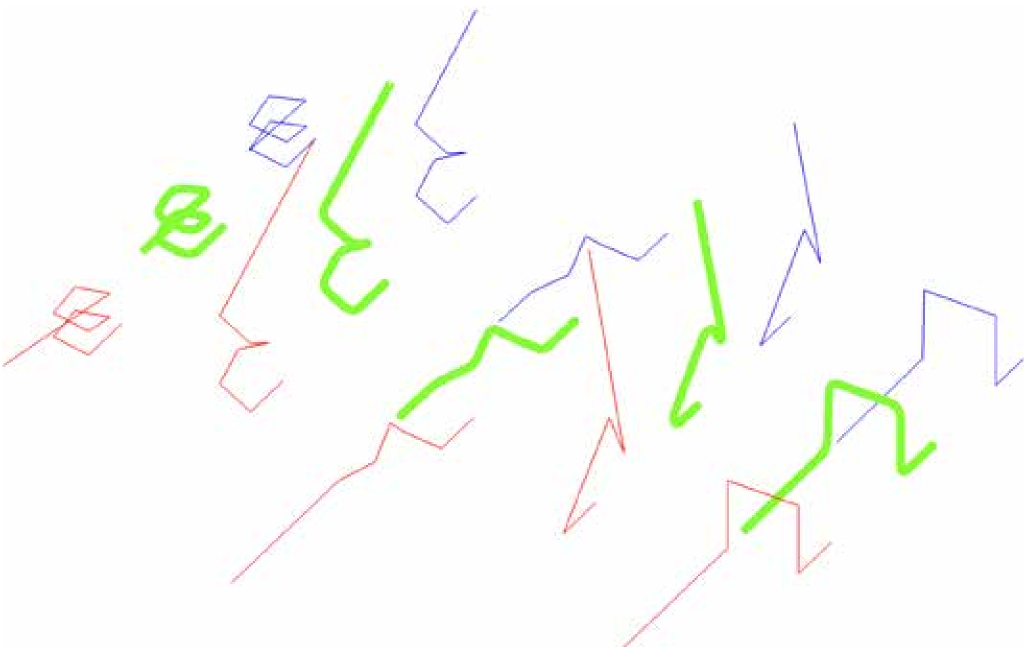
Close-up of the robot's end effector and the external axis with the bender die. The final bent angle is the cobined result of the bending angle and the material springback. The bending setup is a custom installation made by FABLab Director Wes McGee et al.

approach of this project was framed around specific, already existing, expertise of the two institutions. The FABLab at Taubman College holds vast knowledge in the machinery for robotic bending of steel. Aarhus School of Architecture holds knowledge and tradition of concrete component casting as well as a newly setup 3D Lab that includes high-precision 3D scanning facilities. As a consequence of this shared setup, the experiment was planned as a shuttling process between the two facilities. Bending of steel was, naturally, planned to be carried out in Michigan, while 3D scanning, assembling, and concrete casting was scheduled in Aarhus. This workflow utilises the specific knowledge and machinery in both locations, but also requires both data and physical material to be sent or shipped across the Atlantic.

Possibilities of control

Seen in the context of the overall project *Bespoke Fragments* this experiment takes its starting point in a more advanced phase than some of the other experiments. While the robotic bending of steel rods is still on an experimental research level and the use of the steel in the function of rebar is untested, general knowledge does exist around both the material properties and the technologies involved. Surprising material behavior and uncertainty as a consequence of the processing is thereby delimited, although not fully controlled. The objective of the experiment is similarly well defined, and a specific type of output – a steel reinforced concrete component – is planned. While not digging into the fundamentals of steel and concrete, this experiment is instead implemented in a way that takes advantage of already outlined parameters and creates new ones by overlapping those.

Bending the steel is done through a cold forming process where a robotic arm is positioning a steel rod precisely into a rod bender. The bender is controlled through the same set of code as the robot, thereby functioning as an external axis in the system. The bender performs a bend at a specific angle at a given time. The robot then repositions the rod, and a new bend is done at a different length and orientation. This process enables full control of the course of bending. The plastic deformation creating the actual bend is, however, not final after the bending is performed. The material properties of steel will cause a springback giving a final angle that is smaller than the actual bending angle. The



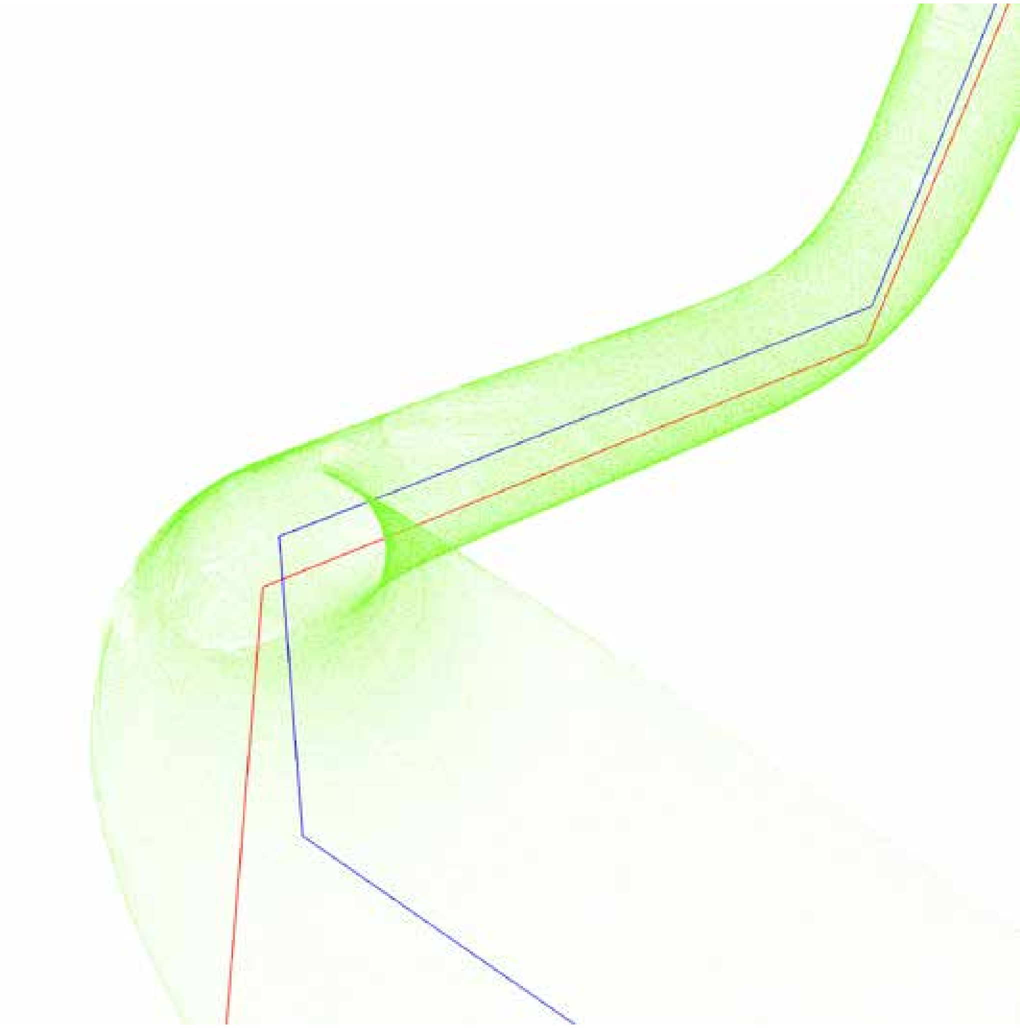
A lineup of digital data and representation. The red curve is the original input geometry for bending. Green is a 3D scanned point cloud of the bent steel. Blue is a 'best fit' calculation based on the point cloud. Differences between red and blue curves help understand deviation caused by the bending and springback.

high level of control of the machinery allows for the compensation of this in the coding. Some knowledge about springback and compensation already exists within the setup. A deviation of around one or two degrees has previously been accepted. Each combination of bends is, however, unique and with deviation building up in longer, more complex rods the total overview of the outcome versus expected geometry is not precisely predictable. In order to create a better insight into this matter, it was decided to bend a series of test rods in Ann Arbor, ship them to Aarhus and perform high-resolution 3D scanning of the objects. Through the digitisation of the curved rods, specific insight and understanding were made. Obviously, bending the rods will create a curved and not a absolute angle. The curving is done through a redistribution of material when the plastic deformation is happening. This operation is changing the profile of the rod at a given place and strengthening the steel through the deformation process ("Deformation (engineering)," 2014; Lubliner, 1990, pp. 76–78). Both of these factors depend on the bending angle and will in combination with the springback create a new situation for the next bend. The length between each bend will determine how significant these consequences are. Fresh steel will behave more or less similarly each time whereas steel that has been hardened through the bending process will react with a different springback. The 3D scanning of a series of rods bent in various combinations sheds light on the behaviour and deviation of the bent steel in comparison with the drawing input provided.

A relatively high level of control of the bending process, in combination with the inspection and insight from the 3D scan, frames the starting point for exploring the robotic bending of steel rods.

Exploring geometries and processes

The steel rod bending setup in Ann Arbor is a homemade, custom system – both regarding hardware and software. The heart of the system is a Kuka KR100 industrial robotic arm mounted on a linear track. Parallel to the track is a bending setup that includes feeder, shear, and rod bender also in a linear setup. The robot is handling the rod in order to rotate and place the point of bending accurately. The steel rods can be bent at several points. This creates a situation where the rod is 'growing' out from the bender. The bending point is



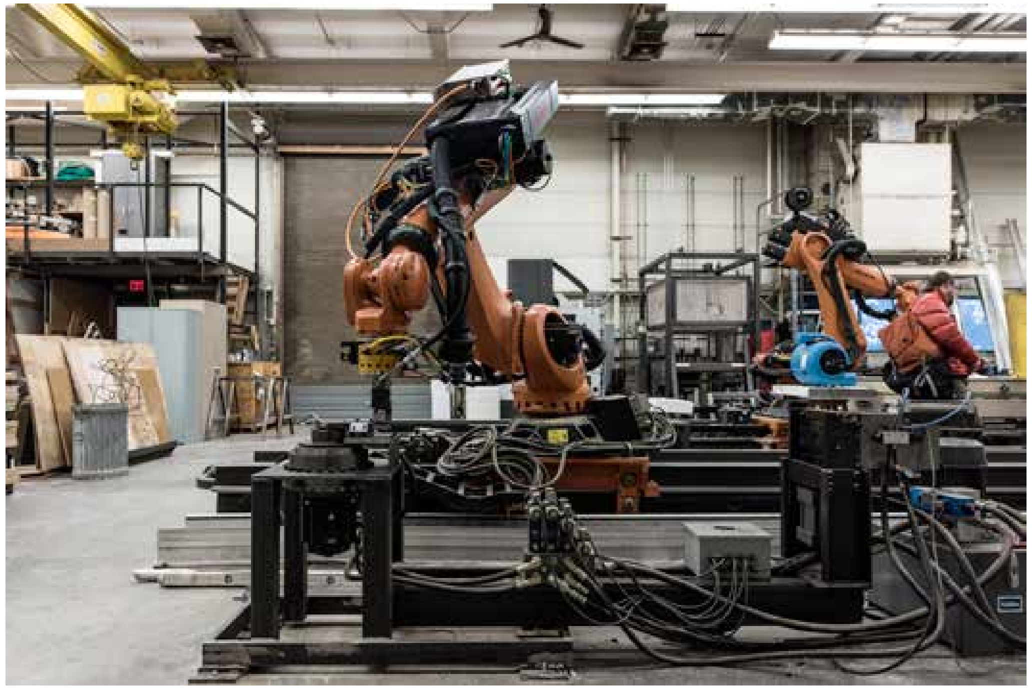
Understanding deviation: Red curve is the input geometry fed to the robot bending script. Green dots are the millions of point from 3D scan of the actual bent steel rod. The blue curve is a software-calculated 'best fit' based on the point cloud data. The deviation is analysed by the comparison of the red and the blue curve. This is useful both for design and calibration purposes.

located at a height of around 80 cm from the floor. When encountering several, following bends with changing internal angles, the setup can easily create a situation where the steel rod will either hit the floor, the robot, or the bender during operation. This a is a limiting factor specific to this setup.

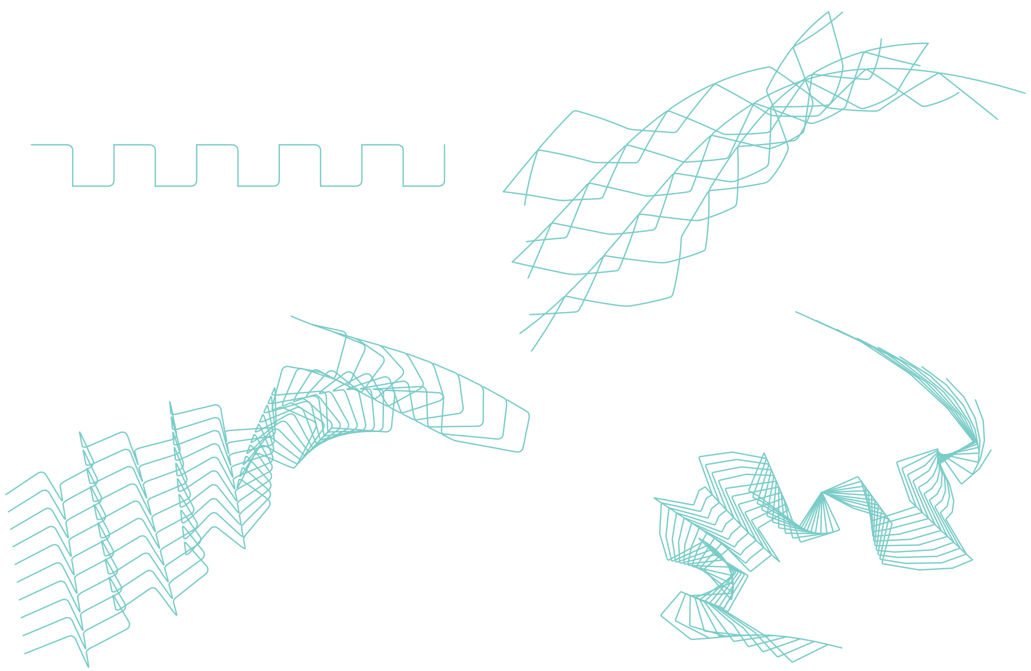
The setup is instructed by code executed by the robot controller. The code is Kuka KRL language made from a custom set of scripts unique to the bending configuration. A series of programs, mainly consisting of Python code, refined over several years of research and teaching in Ann Arbor, are consolidated in a Grasshopper definition that allows polyline geometry to be used as a source for data generation. The definition also includes simulation options that provide a visual feedback of the expected appearance of the bent rod and an actual simulation of the bending process. The latter provides insight in whether or not the input geometry will cause physical collision during the bending, but do not take into account springback or deviations.

While the well-developed software components of the bending setup provide a good insight into potential troubles with the digital geometry of the actual bending, it does not provide any framework for actual designing. The code generation and simulation software are code preparations and troubleshooting toolkits.

To initiate the creation of a design space based on the possibilities of the material and the technology involved, a series of digital only experiments were made. The series was based primarily on experiences made through the simulated response from the software. A key aim was to define the degrees of freedom possible in the designing of bending geometry, without always running into collisions. By a combination of trial and error and reflections on different types of geometries, a set of potentially interesting geometries were made. These geometries were not verified in this phase but functioned more as inspirational kickstarters in the progress of converting the possibilities of the processing into a design space. The geometries were 3D printed in model scale to provide a better understanding of the spatial potentials. At the same time, some of the geometries were wrapped with offset surfaces in order to give them appearances as if the line-based structures were a type of rebar inside a cast concrete component. The resulting solids had fascinating spatial exteriors but also revealed considerable complexity if they were to be realised. Many



Left + right: The robotic steel rod bending setup at FABLab, University of Michigan. The installation comprises an industrial robotic arm that feeds and orients the steel rod through a linear configuration of a shear, a collar, a gripper, and a rod bender. Every component is controlled through I/O commands in the robotic code. The robotic arm's ability to flip and feed the rod in custom and constantly unique positions and lengths makes the setup very flexible.



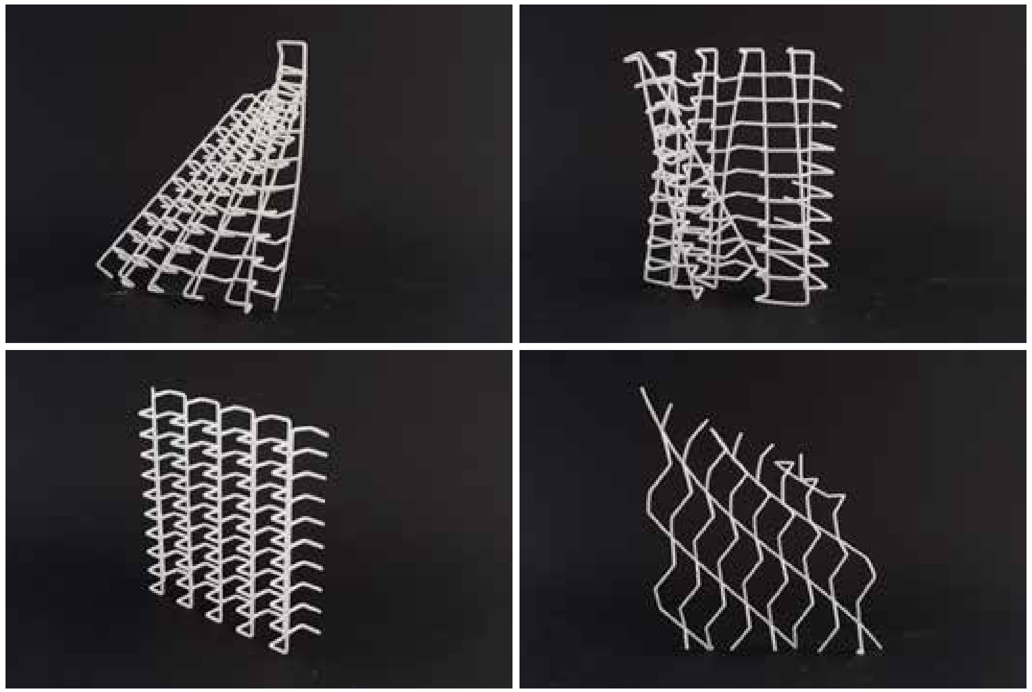
Polylines ready to serve as information for robotic rod bending. A simple, regular system is distorted within the limitations of the bending setup.

would require very troublesome and time-consuming CNC milling. As a result, a series of solids based on ruled surfaces were created in equal scale. These were all geometries that can be realised by hot wire cutting. Together, the series of 3D prints functioned as a narrowed down design space. The delimitation of the design space became the intersection of geometries from which polylines that fulfill the limitation of the bending setup can be extracted, as well as geometries whose outer surfaces can be described as ruled surface and are therefore manufacturable by robotic hot wire cutting (Burry, 2011). From this design, space steel constructions were designed and prepared for bending in Michigan.

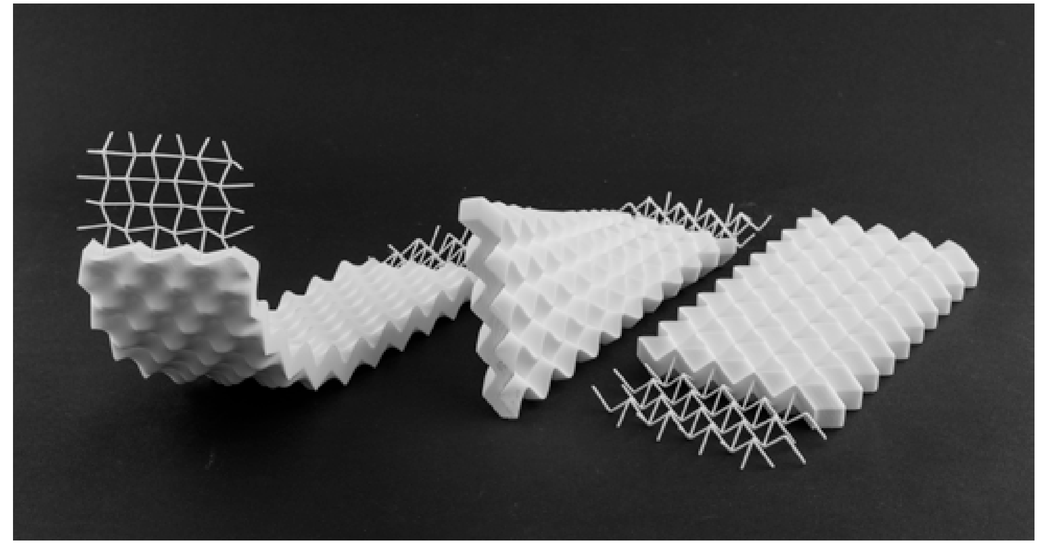
Re-evaluating the design space

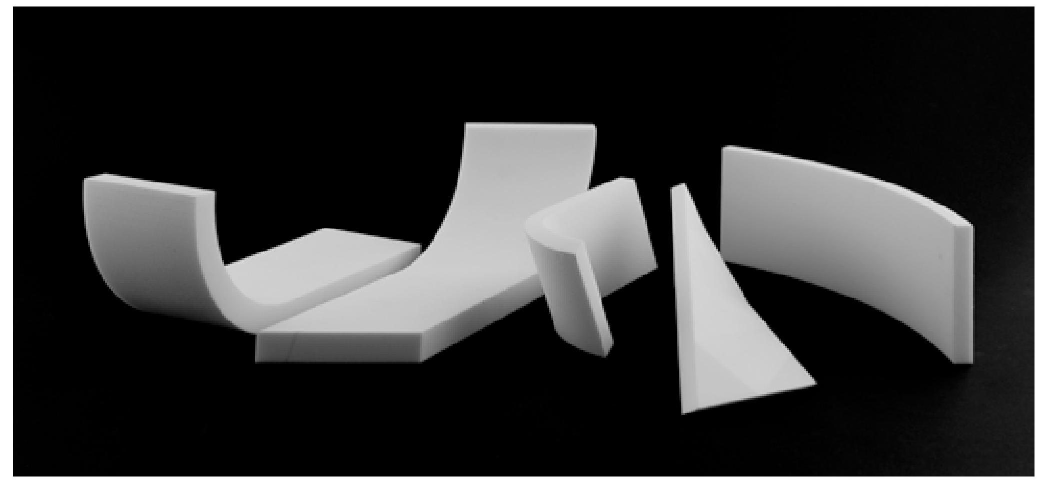
The manufacturing setup was confronted with a handful of qualified designs. While all files were theoretically ready for fabrication, it was expected that a closer hands-on experience with the robot setup could result in a revising or altering of the production files or strategy. Therefore series of samples from different models were tried out. As expected, this gave another perspective on the manufacturing process.

In order to create a steel rod structure, or rebar construction, a series of steel rods have to be connected. This can either be done by the use of binders or by welding. Both are valid methods for rebar in the building industry. The method of joining the rod was not decided during the digital design phases. The potentials of both binding and welding were therefore tested out during the initial sample runs. In both cases, the steel rods seems to cause more trouble than hoped for during assembly. A combination of a piling up of deviation caused by plenty of bends and the fact that the roundness of the steel rods made alignment difficult resulted in a re-evaluation of the design strategies. Therefore, the prepared structures were revised and adapted to the newfound knowledge. The new geometries were easier to line up and bind or weld together. The valuable, reconfirmed, lesson here is a recognition of the hands-on experiences as being driving parameters in a design phase. While material behaviour and structural capabilities were included in the thinking during the digital analytic and sketching phase, even the in-depth understanding gained through test bending and 3D scanning did not make up for the knowledge gained through direct engagement of materials and machines. This finding was,



3D prints of possible bent rod geometries. The systems are based on the software and hardware limitations of the rod bending setup at FABLab, University of Michigan. Digitally developed to kickoff the 'Rebar Inside Out' experiment.





Upper: Rod based rebar systems used as the basis for the forming of surrounding concrete structure. Rebar is designed based on known fabrication possibilities - rebar design then controls concrete. 3D printed test models.
Lower: Ruled surface geometries. The limitations and opportunities of hot wire cutting are explored through digital modelling and 3D printing.

Test and trials in the workshop. Feedback from the fabrication process informs the design strategy during the early production phase.
The steel used in this experiment is traditional cold rolled steel - not the ribbed tentor steel bar typically used for reinforcement. The bending setup is only supporting smooth surface steel rods. Special steel rod with a roughened, but smooth, surface can, however, be used. This type of steel has a concrete grip similar to tentor bars.

however, highly expected due to many previous experiences, but also as a true consequence of the Atlantic separation of the design phase and manufacturing facility.

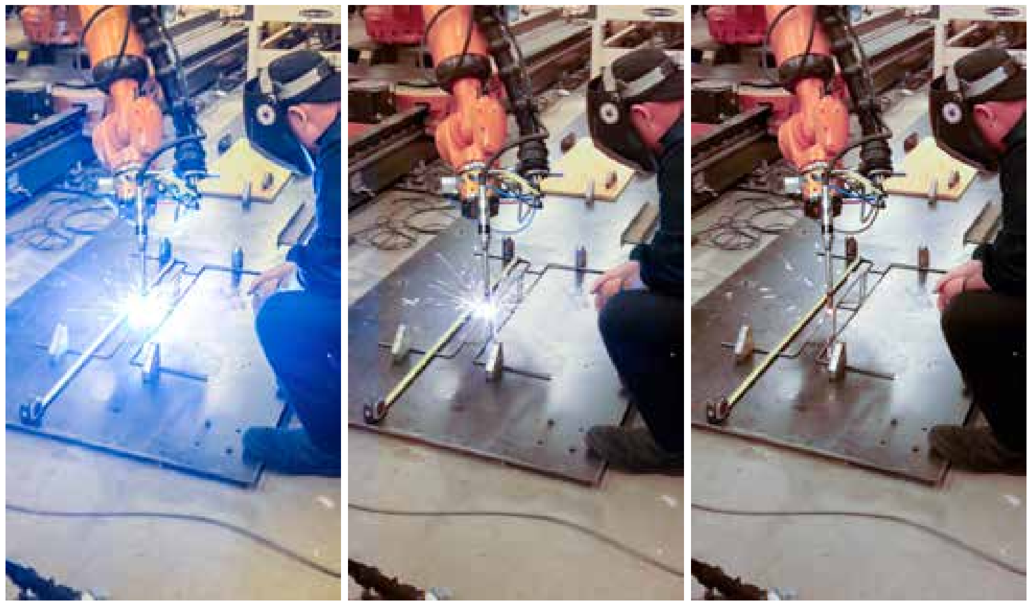
A production of two larger structures and multiple smaller constructions was finalised in Ann Arbor and shipped to Aarhus for assembly and concrete casting. Both larger structure were designed within the found design space. The driving process for the design were the steel process - partly delimited by types of geometries accommodable by the concrete formwork fabrication process. The steel was seen as rebar, but also as construction on its own. The primed steel structures act therefore as twofold. They take on the role as an advanced rebar solution but grows out of the concrete to eventually settle as an independent system. The transition from composite to single-material construction allows a fluidness in the design approach that, instead of stacking different components, calls for a fusion of architectonic and tectonic strategies.

Enriching the framework for production

While the experiments in *Rebar Inside Out* are only at a research stage and highly speculative, the apparent direction of the work is pointing towards components for architecture. Through the studies of materials and experimental manufacturing processes, a setup is delimited to a type of components resulting from a type of geometries. The main data piece – a ruled surface – is supplying infrastructure for both steel rod bending data and data for hot wire cutting formwork. This is done by a distribution of a point grid through the surface. The point grid are is then offset by rod diameter and directionality, then connected by lines that eventually becomes bending information, and a set of edge curves that become guides for the hot wire cutting EPS formwork. This, however, is not enough information to complete a component. The rods will not bind together or weld themselves, and the EPS formwork will not hold the concrete without a supporting structure.

To complete the process in progress and further develop the experiment, speculations of retrieving the mentioned missing data from the very same ruled surface, mentioned earlier began. The FABLab in Ann Arbor already had a good amount of knowledge related to robot welding. This was explored during the RobArch conference from where the idea for this rebar

Hot wire cutting at the robot lab at Aarhus School of Architecture



Robotic welding at the RobArch 2014 conference. Welding with robots is an obvious further development of this experiment.

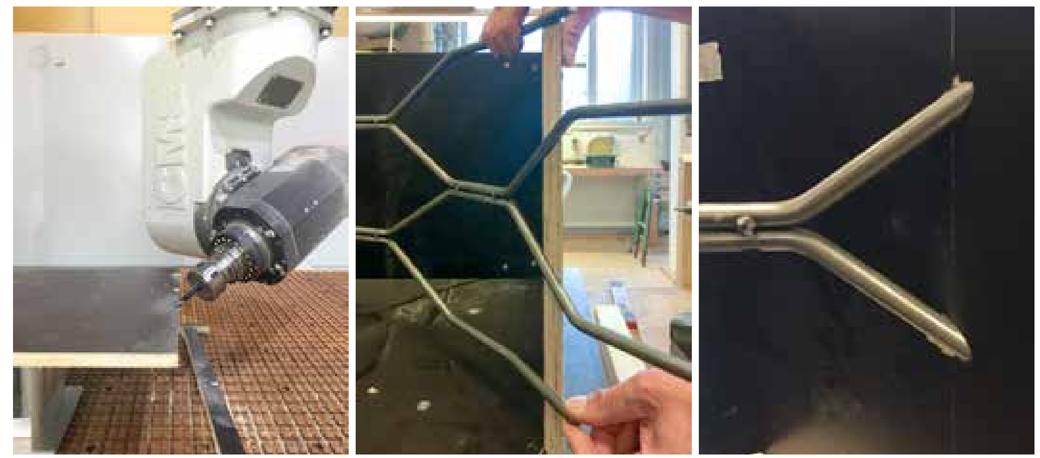
experiment originated. Incorporating tool paths for welding into the geometry is not a problem. Robotic placement of the steel rod and following compensating for deviation and misalignment is solvable with the addition of the 2D scanner and feedback to the robot code and controller (Vasey et al., 2014, pp. 296–300). The planning of motion paths for the robot to orient itself correctly and not collide with the structure in focus seems to be more difficult. Particularly in a more complicated situation where the robot would need to do the welding from awkward positions. While robotic welding in scenarios like this was tested out at the RobArch 2014 conference, robotic welding is not included in this version of the *Rebar Inside Out* experiment. The possibility of implementing welding strategies in both geometry and robotic workflow, however, points toward the potential of an even more integrated process that could be relevant in a case of the rebar workflow being upscaled an industry production.

After formwork for the concrete casting is cut in EPS foam using robotic hot wire cutting ,two problems still need to be solved. The rebar will need to be fixed in the center of the formwork to ensure that it does not move when pushed by the concrete. The EPS will likewise need to have a supporting structure, so it does not move by the forces of the concrete. Both of these matters are solved by using information already existing within the geometry. The boundaries of the EPS formwork is known and can easily be wrapped with board-based geometry for mould support. The orientation and directionality of the rebar inside the formwork are also known, as well as the direction and diameter of each steel rod sticking out from the component. By using the board-based geometry wrapped around the digital representation of the EPS and combining this with extracted line segments from the steel rods, a complete set of data is available. This data can be transferred to a CAM software and used to generate G-code for 5-axis milling of the boards and the to drill uniquely angled holes for fixing the rebar. The result is an enriching of the geometry that can inform a substantial part of the remaining process. With these considerations taken care of, one of the bent rebar structure was cast.

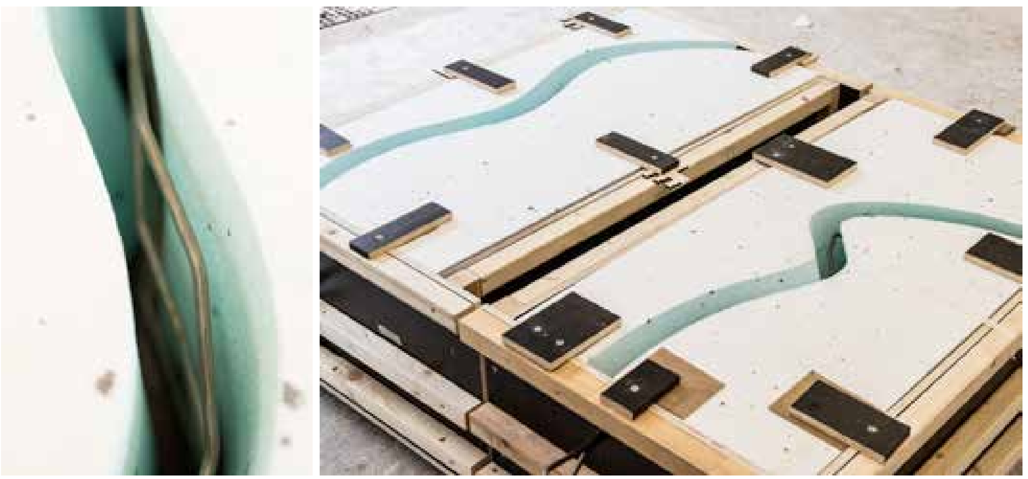
Hybrid structures and integrated processes

Rebar Inside Out suggests a new approach to a popular hybrid. By using the steel in reinforced concrete as a starting point, the creation of rebar is

Assembled rebar steel and EPS formwork. Even though both a bending process and hot wire cutting tolerances can be improved, the formwork surface and steel structure closely follow each other.

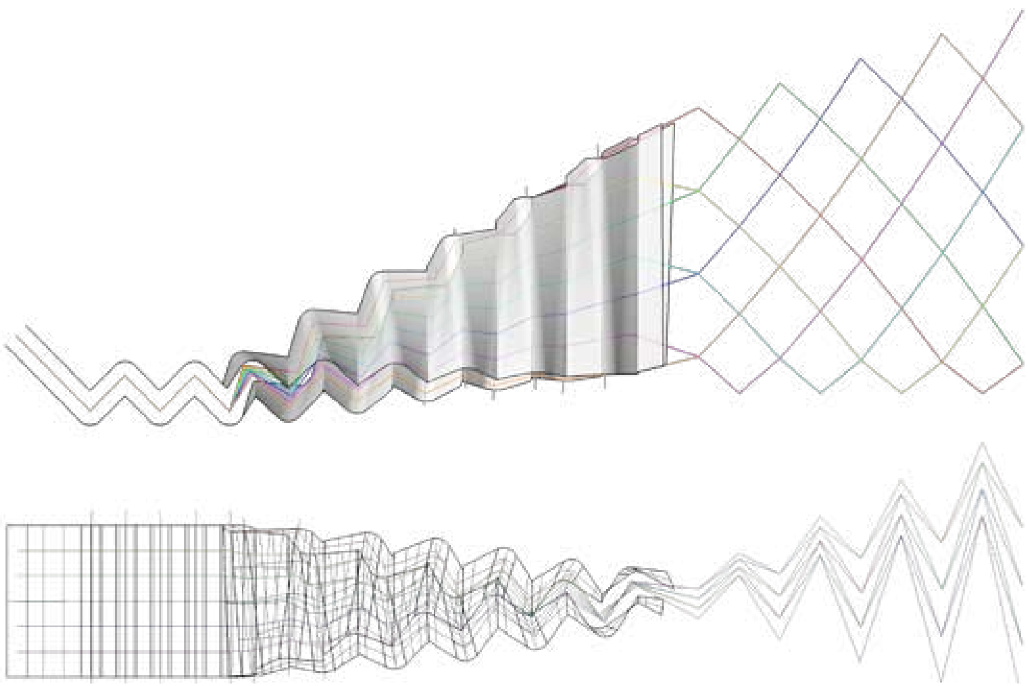


By using the information already existing in the digital file, dimensions and directions for formwork supports structure can be extracted and used for milling and drilling. Here, uniquely oriented holes are drilled with a 5-axis CNC machining center. The holes fix the rebar in the formwork during the casting, ensuring that the steel is correctly placed and thereby utilises its full strength as reinforcement.



Formwork with rebar fixed inside, ready for casting. The formwork surface is treated with retarder to make demoulding easy despite of the curvy shapes.

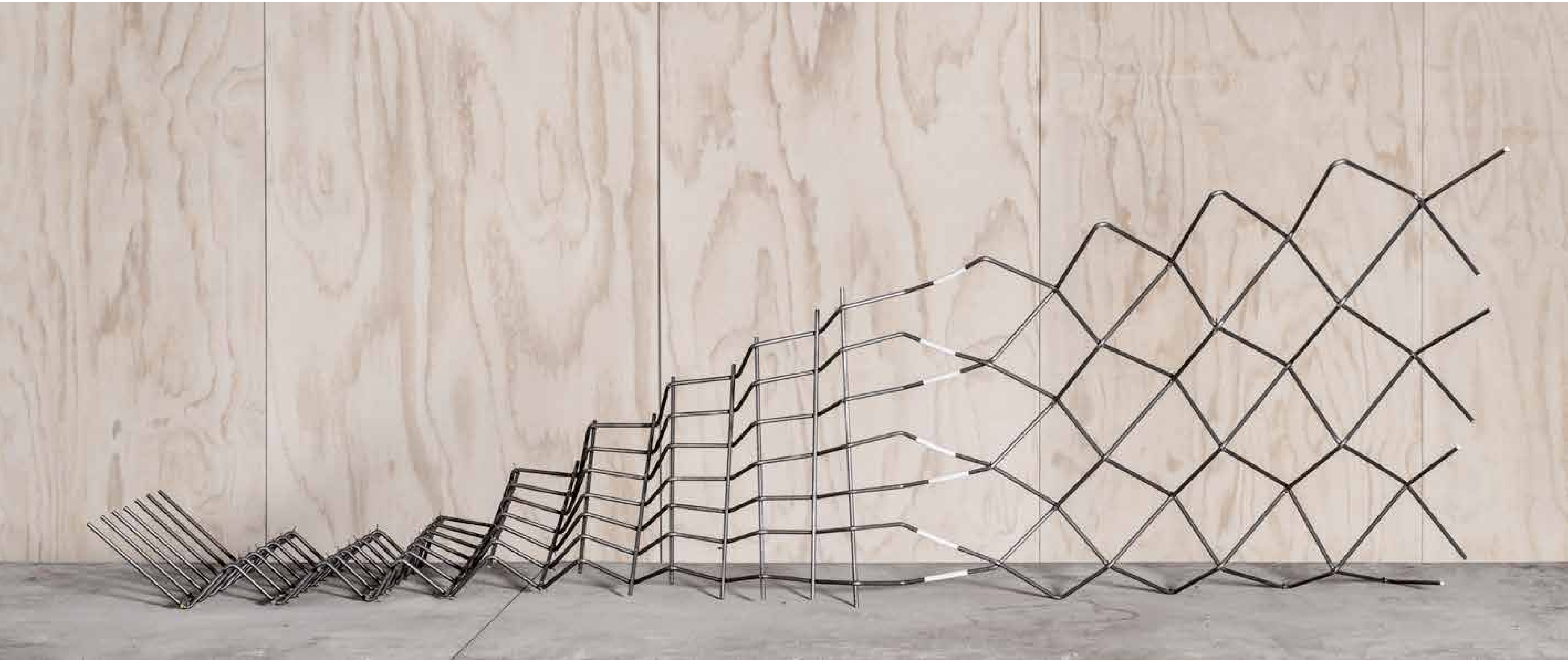
From left to right: Positive EPS shape left over from cutting, rebar element, concrete with rebar element inside, and used formwork. The lineup shows some of the involved processes and how they correspond.



Digital drawing of steel rod pattern and concrete boundary surface. The steel flows through the concrete functioning as rebar, then exits and morphs into a truss wall construction.
Top illustration shows plan view; lower illustration shows elevation view.

rethought. Instead of being a submissive addition to a component, it becomes the generating factor in both design and manufacturing. This starts an open discussion of what roles steel constructions can take on in the complexity of buildings and how these functions can maybe join and merge. By setting up different sets of parameters for various purposes, transitions can be found between the material or structural functions *or* regarded as a material change from one condition to another. In this experiment, the steel takes on a double role of being both rebar and independent structure. While the transitions here are real, their purposes are fictional. The constructed element does not belong to any building or represent any particular tectonic case. They can, however, be looked upon as whatever building part that comes into mind. That could be a situation going from floor to steel grid column, a solid wall-type transitioning to an open steel truss curtain wall or anything else. The exact role for the produced fragments is of little relevance compared to the discussions they can initiate.

The experiment shows an interesting approach for architects and to architectural production. By rethinking the premises of how something is created, new design strategies arise. Suddenly, design becomes a function of new processes. Thereby, the representation and drawn information change perspective. In this case, the drawing becomes a vessel for various types of robotic and machining information that is easily adaptable for a larger variation of shapes and designs. The design space is delimited by an inside-out approach that literally starts with production specification and builds its aesthetic consequences from that. The drawing set, in this case, never looks exactly like the totality of the component to be, but instead more like an overlay of different information deposits each supplying an integrated production process with data. The approach that started this experiment can therefore both be seen as a method that can redefine the scope of existing knowledge by implementing new manufacturing strategies, as well as a design tool that brings production consideration into the architectural design from the earliest stage possible. One could see that the findings of new perspectives on components could affect the overall design concept of buildings.



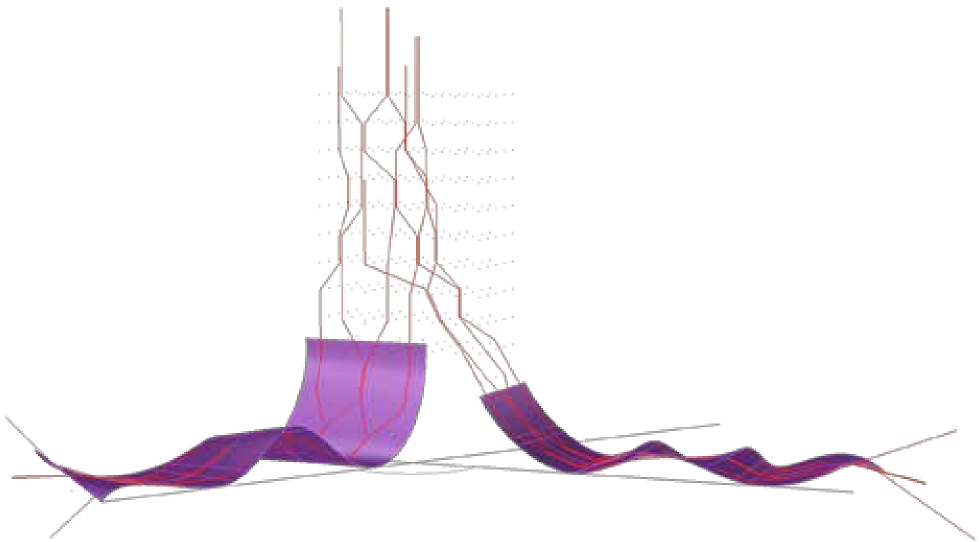
Steel is bent and assembled. Final construction to be partly reinforced concrete, partly steel truss construction.

Combined concrete and steel hybrid construction - before concrete casting. Two reinforced, curved concrete slabs morph into a steel truss beam.

Understanding processes - building or rethinking factories

The experiment can be viewed from two perspectives in relation to the introduction of manufacturing knowledge early in the design development. First, the research shows a new take on reinforced concrete. By implementing novel technologies into successful domain, new architectural potential are created. Importantly, those possibilities are set up on the basis of architectural intention and not solely based on e.g. engineering or cost-efficiency. While both of these are valid and important factors in material processing, their effectiveness will be inefficient if not corresponding with their intended use. Without a doubt, a significant amount of industrial standardised materials could be improved in many areas, including their architectural potential, if the processes behind could be rethought. *Rebar Inside Out* could be an example of a rethinking of an already existing industry, based on an inclusion of architectural thinking.

Secondly, the research could be seen from the perspective of using already established material processing setups to create a new type of component or architectural fragment. In this case, the machinery is based at research facilities and still on a somewhat experimental level. However, the strategy could be applied to more refined industrial manufacturing workflows. In the case of this experiment, the robotic steel rod bending configuration has been used for several amazing projects. This experiment, however, utilises it in a new way in the combination with other machining processes. The bedrock for a project like this to succeed relies on an ample understanding of the material and the processing capabilities. Based on this, the architect can define a design space and a usability. Unlike in the previous perspective, architects might not need to develop new processes fully or build new factories. An understanding of existing possibilities, combined with new thinking or other processes, can pave the way for new types of architectural components and thereby architecture.



Left: Representation of a digital file with several layers of information for both rebar design, robotic bending, hot wire cutting, and formwork construction
Right: The realised fragment is a complex result of multiple processes.

Close-up photo of a concrete surface. The surface is a result of hot wire cutting, EPS material texture, retarder surface treatment, and the concrete casting. All processes are visible in the final result.

Notes

1 http://www.supermanoeuvre.com/#contact for more information

2 Wes McGee, Assistant Professor and Director at the FABLab Taubman College already had an ongoing collaboration with Associate Professor Niels Martin Larsen and Assistant Professor Ole Jackson Egholm. Wes McGee was visiting Aarhus School of Architecture as Velux Guest Professor Fall 2015.

CONCLUSION

Transverse exposition of the experiments

The experiments executed within *Bespoke Fragment* collectively outline a field of interest. The experiments should be seen as different perspectives upon this field of interest but also as probing instruments that seek to make the interest clearer and focus its explanation.

It is important to note that the appearance of the experiments in this dissertation is not organised chronologically. The experiments have been conducted with overlaps, pauses and interruptions and are both collectively and individually formed by the progress of the project. While the project was initiated by a series a investigations that quickly led to the experiment *Stretching the Steel*, the genesis and evolution of the experiments has been an ongoing process, based on the findings within the context of the project and incoming influences.

The experiments are all contributing to the project, but also appear as individual entities. The experiments build upon different processes and have various types of results. The experiments have not been categorised after type or end-result. Instead, they will in the following be compared with regard to their diversities and connections. This evaluation should enable a possible inference or concluding discussion, based on the findings within the experiments and the differences and correlations between the experiments.

Diversity across the experimentation

Some of the experiments have more in common than others, but even though they are articulated individually in the project, they are to be seen as collective body of work. The experiments *Stretching the Steel*, *Concrete Moves* and *Intermediate Fragment* are all anchored in specific material properties and capacities and a specific type of processing or machining. The workshop

Digital Matter is established around a teaching situation and utilises the event of drawing more distinctly than the others but falls into a close kinship with the three above-mentioned experiments. They are all tied closely to the experimental framework established in the 'Introduction'-chapter. The four experiments build directly on the encounters of specific materials and specific types of processing and are thereby easy to align or at least understand as products of the same discussion. They are, however, different regarding their orientation and how the processes affect the outcome.

Stretching the Steel uses the fabrication to prepare the steel for further transformation - this is formulated as an embedding of the drawing information into the material and as a creation of virtualities. The stretching utilises the specificities of the steel and, through transformation and plastic deformation, actualises those virtualities.

In *Concrete Moves,* the material premise is the flowing concrete, but the particular process is here paramount. The manipulation of the concrete using robotic motions becomes the virtualiser that initiates the shaping. The robotic motions and the end-effectors play a significant role in experimentation and the forming of the concrete.

Intermediate Fragment is also processing dependent but largely focuses on and utilises the capacities of the wooden fibres. The experiment centres around findings in wood and integrates these into a constellation together with the material of concrete. The physical output of this experiment seems more refined and concluded than in the other experiments.

Digital Matter uses both findings from drawings, materials properties and capacities, and transformations, but the architectural discussion and exploration was mainly opened up by the contextualisation of the elements and materials, and through an insistence an improvisational and straightforward workflow and attitude in all phases from drawing, through fabrication and transformations, to spatial combining and discussion. In this specific experiment, the sketching-like method was pushed forward as a result of the students' low amount of material and fabrication preknowledge. This limited the potential complexity and development, which is why the focus was intentionally pointed towards the exploratory element of the workflow.

The four experiments are individually situated within the experimental framework of the project, but it is also evident that they collectively both unfold and interlink the field of interest. Their processes differ in focus, and they end with different types of results and discussions. Material properties and capacities might take the leading role in the transverse understanding of the experiments, but the diversity is also reflected in the experimental workflow. The elements of both virtualising and actualising character are different in the experiments, and also differently arranged within the experiments. The four experiments unfold this phenomenon and activates it in connection to the objective of the project: to explore the possibility of using materials and digital machining as methodological elements in architectural designing.

The experiments *Alleyway Point* and *Rebar Inside Out* adopts a different role in the context mentioned above. *Alleyway Points* has the point cloud as a starting point instead of a material. *Rebar Inside Out* becomes a design space defined by specific machining limits and forms a more factory-like type of workflow. The outputs appear, and possibly perform, as something that could be related to the prefabrication industry. *Alleyway Point* and *Rebar Inside Out* seem slightly different in the context of the other experiments. In order to understand this difference, it is important to note that both were established in a somewhat different context than the other experiment and that they play a different role in the positioning of the project. *Alleyway Point* and *Rebar Inside Out* were created in cooperation with other academic partners. *Alleyway Points* was created together with architect and fellow PhD colleague Espen Lunde Nielsen and collaborators from CIMS, Carleton University, Ottawa. *Rebar Inside Out* was a partnership with Wes McGee and his FABlab at the University of Michigan. These partnerships have been arranged during the project to position the project in relation to a larger research context: Where the other four experiments seek to define a core understanding of the project's intention, the experiments *Alleyway Point* and *Rebar Inside Out* seek to test the boundaries of the project. They both attempt to extend the possibilities of the project while bridging elements of the project with other variants of research within the field.

Alleyway Point stands out from the other experiments by being started and highly dominated by a particular type of technology. Even though the point cloud captures a reality and transforms this capture, both digitally and materially into concrete artefacts, the understanding and the discussion within the experiment are very much based on the premises of the 3D scanning technology. This technology is so dominant and the point clouds so substantial that they, combined, almost prevent the material's ability to inform and affect the process. The concrete uses its ability to obtain detailed information from the captured point cloud and transform this digital substance into a materialisation, but does not affect the process to a higher degree. The material properties and capacities barely come into play in this experiment even though the experiment maintains the investigative and reflective attitude, characterising the project as a whole. *Alleyway Point*, however, manages to establish a radically different approach to the relationship between 3D scanning and materials. *Alleyway Point* articulates the point clouds as a digital substance , which thereby reinterprets the perception of materiality. Texture and materiality become the domains of the technology and the material itself becomes the processing element. Thereby, the experiment opens up a trajectory that could be further investigated and potentially calibrated to allow for more material influence.

Rebar Inside Out brings an explorative approach to a steel reinforced concrete production and sets up a fabrication workflow around two robotic operations; one operation allows advanced bending of the steel rods, the other operation is hit wire cutting EPS foam for formwork.

The steel bending process is based on specific material capacities, but the possible types of bending and transformation are constrained by dimensions and machining limits. While the geometrical input can be varied, the results are repetitions of the same kind of bend. The hot wire cutting defines the geometries of the formwork and the rebar eventually has to assign to these geometries. The outcome is material but primarily defined by an integrated digital management of robotic processes that coalesce into a coordination between two sets of geometrical limitations. Exploration of material capacities plays a small role in the conclusive process. Therefore, the experiment seems different than the most other experiments within *Bespoke Fragments*. *Rebar Inside Out* starts with an open approach towards reinforced steel, but ends quite closed due to a design space, heavily defined by maching. Findings within the compound process, however, point towards more materially defined explorations that opens for further investigation and rethinking of the process. Both the operation of steel bending and hot wire cutting contain material challenges and deviations that could be reformulated and regarded as attractive capacities. The plastic deformation of steel rods resists the machining through a spring back, and the hot wire cutting clearly defines the surface character of the cast concrete due to it burning and locally behaving in unforeseeable ways.

Connections and reactions

As earlier mentioned, the experiments are created not once at a time, but sometimes simultaneously and sometimes with overlaps, interruptions and pauses in between. The experiments have therefore been able to communicate, be compared to each other and influence each other ongoing during the project. This project structure also means that experiments in progress could initiate or create the basis for other future experiments. Hence, the experiments are to some extent, connected.

A combination of the continuous production of smaller tests and trials in the *Accumulated Transformation* and the ongoing gaining of insight through the experiments functioned as take-offs for new experiments. Findings or exploration - either material or process oriented - often resulted in perspectives that seemed of relevance for the project. The experiments *Stretching the Steel*, for instance, gained most focus around the material capacities that was actualised in the process of stretching. The drawing and the fabrication became almost preparing processes for this happening. This caused an idea of initiating a type of experiment where the machining could more directly produce a shaping in collaboration with the material specificities. This idea was later grabbed in the experiment *Concrete Moves*. However, the experiment *Stretching the Steel* seemed to reach a standstill at a particular type of shapes and stretchings. The manipulation of slit or cut steel was therefore further explored, together with the machining of plywood, in the student workshop *Digital Matter*.

In preparation for *Digital Matter,* a series of digital files and machined material samples were made to guide the students towards an explorative, material thinking. Those samples and tests became a part of the *Accumulated Transformation*, but also ignited a new series of explorations that later turned into the wood bending principle in *Intermediate Fragment*. The bent plywood test from the workshop gave a basic understanding of the behaviour of wood fibres, and the investigations then swiftly moved to solid wood. Eventually, a circular saw replaced router bits and complexity increased.

Intermediate Fragment combined the two materials of ash wood and concrete. The main findings were, however, done within the ash wood. The curvatures, that were generated by the bending, was inherited by the concrete base of the composite fragment. The experiment, thereby, introduced a kind of material hierarchy derived from the experimental concentration; the ash wood accounted for the primary material investigations and findings in the experiment and the concrete then followed the devised principles. This traditional use of concrete casting in *Intermediate Fragment* was, however, not found as materially exciting as the findings in the wood. Therefore, an eagerness for an experiment that looked deeply into the properties and capacities of concrete was created. In combination with the idea already planted during *Stretching the Steel*, this resulted in concrete tests done by hand and from there developed into *Concrete Moves*. *Intermediate Fragment* also utilised 3D scanning as a tool for digitising the actualised wood and extract its non-simulative shapes. This made a parallel experimentation in the digital domain possible. The experiment thereby built on a workflow already established in *Stretching the Steel,* but refined the process into a scheme where it would inform the experiment directly. Both examples of the use of 3D scanning were, however, similar and showed that it was to some extent a supporting tool. Following this realisation, mixed with a belief in a more integrated and explorative use of the scanning technology, the idea for *Alleyway Points* was born.

The massiveness of the fragment built during *Intermediate Fragment* resulted in a revised expectation on the outcomes of the experiments. Both regarding size and in the form of the discussion of wholeness brought forward by of the combination of the two materials. The material hierarchy initiates a more tectonic discourse within the project, and the combining and meeting of multiple materials becomes a focal point of this discussion. This reflection gave rise to an ambition of a similar type of fragment, built, however, by way of a different kind of process. Where *Intermediate Fragment* was developed directly from the explorations of the strength and elasticity of wooden fibres,

a more machining-oriented workflow was chosen as the starting point for a subsequent experiment. Since steel seemed slightly under-represented in the overview of the project and robotic steel rod bending had been tested out during a conference workshop, this process became the starting point. *Rebar Inside Out* was born and arranged from this thinking.

As it is hopefully clear from the abovementioned brief tour through the landscape of the experiments, *Bespoke Fragments* is a connected unfolding of a field of interest. The experiments are individually anchored in their foci and capabilities but created from an interconnected reflective practice.

The chain of reactions above is, of course, only a limited insight into the elapsed experiments. Many more connections and crossings have been made in between the experiments. However, many important decisions and findings are also caused by internal or external parameters. The experiments' individualities have, in a significant way, been developed through their internal iterative processes. Also, sometimes ideas or inputs from outside the experimental interface of *Bespoke Fragments* have been introduced to the experiments. For instance through discussions or project and literature reviews.

The transverse reading and exposition of the experiments expose a substantial understanding of the connection between the experiments and the project. This connection seems to be a reflection of experiments' the internal events of the experiments, bridged the progress of the series of experiments. The experiments exist of actualisations, but through the creation of those new virtualities arise. These latent potentials of the experiments might not be directly graspable in their materialised extent but exist through their bridging to the other experiments. An actualising condition might sometimes delimit the experimental scope, but concurrently create a foundation for another experimental trajectory. This is discovered through the experiments, but established as a general understanding only when the experiments are collectively and crosswise evaluated.

Elements of influence

The expositions of the diversities and the connections in between the experiments, both point to a series of mutually related investigations. However, they also point to an internal chain of dependencies within the experiments.

Each experiment has a focus or a predominant phase of the process that defines the experiment in the context of the others. The focus in the individual experiment then influences the foci of the other experiments or help articulate their individuality. Combined, they unfold a field and outline a map of influencing elements of the experimental processes. The series of experiments together produce an overview of the constituents of the experimental process and positions the experiments within the context of the project. Some experiments are placed within the central interest of the project, while others seek to scan the outer borders of that interest. The specificities of the individual experiments each develop their attention to the influences of materials and process of fabrication. Collectively, these findings outline a field that informs the project and the research.

Based on the transverse exposition of the experiments, their governing elements can be described as *drawing*, *processing*, *material, transformation* and *contextualisation*. While these elements are not investigated on equal level or depth in each experiment, they appear as a connected set of influencing elements in all workflows set up in *Bespoke Fragments.*

The *drawing* is in *Bespoke Fragments* constantly a digital form of drawing. Therefore, the conception of the element *drawing* is based on this. The digital form of the drawing establishes a link to the digital processing. Drawing is, however, just as much an act as it is an object in the case of architectural designing. The drawing can be created in multiple ways and one could imagine that a type of drawing, detached from the domain of the computer screen, mouse and keyboard could and still be a functioning element in the process. The type of drawing and the thinking established in the drawing, nonetheless, influences the course of the materialisation and the material experimentation. Some experiments offer a more direct or literal form and format of the drawing than others. *Digital Matter*, for instance, is based on a series of actual drawings that the students draw using several computer tools and strategies. Before the drawings are used for fabrication, they are printed, considered and discussed as drawings. In *Concrete Moves* the digital drawing exists as more of an interface. Lines are at first created, but then immediately interpreted into code. The code

then initiates a redrawing through the robotic interpolation. Collectively, the term drawing in *Bespoke Fragment* becomes a container for information, but in particular an interface for involvement in that information.

The *processing* often seems like the bridge in between digital drawing information and the material. However, it becomes evident through the experimentations that the processing is not transparent, but is highly influencing the materialisation. The processing often involves a conversion or translation of digital information into machine and tool specific data. Post-processors or CAM software often do this. The translation impacts the subsequent physical machining as it takes both machine motions, interpolations, and tolerances into account or prepares the data, in order for this to happen in the machining. The machining itself is responsible for the direct contact and processing of the material. The interface between tool and material affects the outcome directly but is based on both the digital and physical handling of the information. The processing – from data input to material contact – profoundly affects the material experimentation (Cannaerts, 2015 pp. 228-230). The possibilities of affecting this element are dependent on the particular type and interface of the processing.

Material is a central element in *Bespoke Fragment*. Even in the early framing of the project, material properties and capacities are articulated as variables and parameters of influence. While material specificities have proven not to be the only influential element in the process of material experimentation, their presence are highly dominant. The presence of materials in an investigative design workflow establishes a direct contact with the physical reality at which the architectural production is eventually aimed. The recognition of the properties and capacities of materials as significant parameters that affect the designing and the realisation also becomes an essential part of utilising those parameters actively as an element in the designing phase.

Transformation means, in the context of this project, the transformation of materials. The element of transformation is usually located as a processing itself or following a processing of materials, where the transformation introduces an influential practice in continuation of the material output. An essential consequence of this is that the material output is not regarded as finished or as a result, but as a preparing element for the transformation.

This consequence then feeds back to the processing and the drawing that can eventually respond with an adapted behaviour: When the material form becomes the result of transformation, the representational similarity with the drawing that informs the processing is often small or even non-existent. The element of transformation, therefore, not only transforms the physical material but the connotation of the elements preceding.

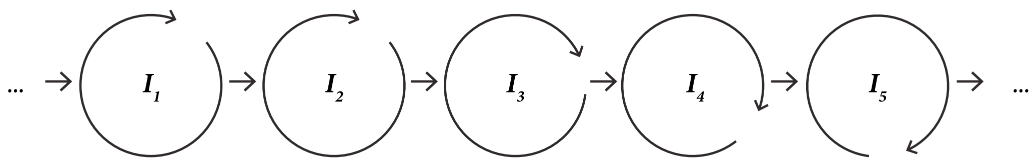
Contextualisation is containing the actions and events of a juxtaposition of physical outputs in conjunction with themselves or external physicalities. In *Bespoke Fragment* some experiments either combine several identical materialisations into larger and more complex fields or compositions, combine different processings or transformations, or combine different material output into hybrid fragments. However, the contextualisation can also involve existing physical context. No matter the type of contextualisation, the element influences the understanding of the experiment output. Instead of considering the output as individual objects, the element of contextualisation relates the output to a larger context or suggests the output as fragments of a more extensive condition. In light of the potentials of material experimentation as a relevant process in architectural design, the element of contextualisation also situates the experimental output as possible, constituent parts that can interact with parallel material experiments or other methods of designing.

The sequence of elements is arranged as a general order derived from the project. It is, however, clear that the order is not limited to this sequence. Elements can shift around during experimentation and establish other interfaces between the elements. For instance, transformed material interfaces with processing or contextualisation can directly relate to the drawing. A shifting of the order can be relevant as an active design tool or as a consequence of the iterative workflow where not all necessary elements are equally developed in every iteration. An actual example of this shifting of the elements is seen in the experiment *Concrete Moves*. Here, the preparation of the concrete before the robotic manipulation becomes a part of the processing. The processing of the concrete with the robotic arm morphs into being the element of transformation, thereby showcasing a very connected interface between the two elements of the experiment.

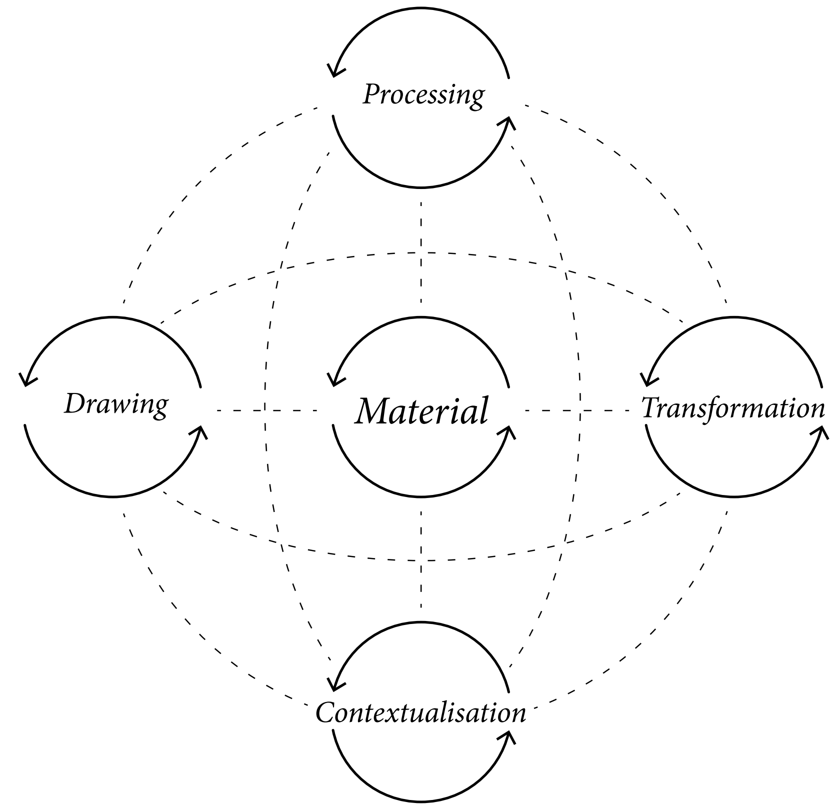
The five described elements are based on the understanding of the experimental workflows that appear across the project. Through the experiments, it has been found that these five elements do more than solely establishing the experiments. The elements clearly affect the combined process of the experiments. They influence and offer resistance on their own terms, but they also have the ability to be affected themselves. They function as influencing constituents that can be modified. The interfering with the elements is a precondition for the experiments to exist. Within the experiments, the focus can be pointed towards one or more elements that become the dominant actor. This results in an introduction of hierarchy or priority within the experiments and is often reflected in the outcome. An important consequence of this seems necessary to explicitly articulate: The elements will affect each other and change the balancing of the experiment. A focusing or prioritising on a particular element will alter the possibilities of the other elements. The altering can result in either strengthened or diminished opportunities for the other elements. This interconnection between the elements influences the experiments and individualises them. This is what comes to surface in the transverse exposition of the experiments. On the underlying methodological level, the individualisation is caused by the orientation of experiments by the mechanics described in the system of orientation. The system of orientation was created through the experimentation as an operative tool to navigate the experiments. The consequence of this navigation appears not only on the experiment level, but as negotiations in-between the elements. When, for instance, a lot of attention is put on the virtualities of a material capacity, other elements will naturally respond to this.

An example is the experiment *Intermediate Fragment*. Here, the central investigation is built around the wooden fibres in ash wood. The terms *material* and *transformation* are central. Therefore the processing and the drawing that control the processing are orientated according to the material feedback. Later in the experiment, the *contextualisation* with concrete becomes determined by the transformed material.

Another example is the experiment *Rebar Inside Out*. The experiment starts with an interest in the coalesced materiality of reinforced concrete and thereby in the joint capacities of steel and concrete. The *processing* becomes



The material experiment is regarded an iterative process. For every incremental progress, an iteration of the experiment is carried out. The iteration, however, does not have to alter or involve all underlying constituents of the experiment.



The material experiments consist of five elements. In between each elements is an interface of negotiation. Because the elements are connected, an altering of one interface will affect the entire experiment. The sequence and relations between the elements can potentially change during experimentation. The material experiment consists of non-transparent elements that will affect the outcome – the process can, however, be affected through the elements.

dominant but also internally aligned, given that the experiment incorporates two robotic workflows. The processing of steel and formwork for the cast hybrid ends up defining a linked set of digital drawing information. The investigations are therefore mostly based on feedback from the *processing*. Even though the output is physical, the level of material investigation within the experiment is minor. The material element adds little uncertainty since it becomes limited by the complex and dominant processing that requires a quite controlled input from the drawing. Seen in the context of *Bespoke Fragments,* the minimal material influence in the experimentation is maybe not satisfactory. However, the experiment points to the influence of the experimental elements and an awareness of their impact on the experimental setup.

A more equal balancing of the elements can maybe be seen in the workshop *Digital Matter*. All five elements influence the experimentation. The digital drawing is the initiator of the workflow, and the sketching attitude of the drawing seems to affect the other elements. *Processing*, *material*, *transformation* and *contextualisation* seem to eventually inherit the exploring and uncertain position that was introduced by the drawing. Following the fabrication, the experiment shifts towards more uncertain transformations of the processed materials. The feedback that is routed to the drawing seems, in this case, to gain more and more control gradually. Soon the *contextualisation* of transformed material appears to set a more controlled agenda for the transformation. The contextualisation becomes the preeminent discovering design principles related to an architectural discussion. The shifting of orientation that occurs as the experiment evolves is, of course, a consequence of focusing – one cannot vary all parameters continually without losing some sort of overview. However, it also points to the iterative nature of the negotiation in between the elements and among the experiments in general.

The concept of gaining feedback through production in an experimental practice is established as a methodological angle of approach. Every experiment within *Bespoke Fragments* consists of a number of iterations that are continuously informed by the output of the elements in the experiments. Some iterations include the experimental workflow in its entirety, while other focus only on parts of the workflow. Both types of iterations influence the experimental construction continuously. Throughout the project, the iterations

have been closely linked to the particular experiments and thereby to both the specific materials, methods of processing and the included discussions within each experiment. Based on the more general, transverse reading of the experiments, the iterations can be expressed as negotiations between two or more elements of the experimental process. The interface between drawing and processing can, for instance, trigger an iterative development wherein progression through incremental explorings and findings can inform both drawing and processing and thereby affect the construction and course of the experiment. By instituting literacy and experiential knowledge as key elements in the interfaces of the elements, a guideline for the experimentation can be established. Since the elements are what is constituting the experiment, every iteration within a part of the investigation will have an influence on the entire workflow. In order to orientate the experiment, the interfaces that exist between the elements become essential. This has become evident through the executing and evaluation of the experiments. The comparing of the different experiments allows for a generalising and concluding articulation of this finding: The elements of the experiments are connected and not transparent. Each element affects other elements and thereby the experimental setup as a whole. The elements can, however, be affected and thus, the experiments can be affected through them. By articulating the experiments as iterative processes, the elements can be incrementally affected and the experiments can be oriented through this course of action. This general reflection addresses the specific character of the described elements of influence.

The material experiment as a design method

Bespoke Fragments is founded in an interest of the potentials and possibilities of including materials in the process of architectural design. The strategy for the research project and associated experimental work takes its departure from a perspective put forward by various scholars in the field: A new relation between design and materialisation, established by the interface of digital drawing and digital fabrication, can bridge the gap that separates the discipline of architecture from realisation (Ayres, 2012; Carpo, 2011; Gramazio and Kohler, 2008; Kieran and Timberlake, 2004; Kolarevic, 2003; Menges et al., 2016; Sheil, 2005). By seizing this potential, *Bespoke Fragment* carries out a series of experiments that aim at being rooted in material properties and capacities without being oppressed by existing material meanings, dogmas or connotations. The project sees the potential of a new, and closer, relationship between design and materialisation as an opportunity to inform designing through material, but also to inform materials through their prospective engagement with designing. Or, as David Leatherbarrow says so fittingly (2009, p. 91): *"Neither stone nor glass possesses any essence or 'truth,' nor is one or the other singularly apposite to our time. The whole matter rests on the ways materials are shaped and transformed, the ways they become what they have not been before, the ways they exceed themselves."*

In the quest to inform new designs through materials or to use the process of designing to discover new findings from materials the act of performing experiments becomes vital. This standpoint has been present since the inception of this project, but has been further detailed and elaborated upon as the project was developed. The project delivers an unfolded perspective on how the material experimentation can affect the discipline and vice versa. This points towards a potential that can eventually be utilised in architectural practice. Further research, possibly done in collaboration with practice, could inform this desirable trajectory.

A notable revelation derived from the series of experiments is the uncovering of the elements of influence that appear in the material experiments and thereby in the relation between designing and materialisation. This distinct articulation is important in the perspective of design integration and design process since it points to the fact that a translation from the mediums of representation to the mediums of realisation are neither straightforward or transparent. While the influence of material behaviour might be easy to concede immediately, an awareness of the full extent of the chain of connected, influential elements in the process is essential to reaching an understanding of the complications and possibilities for the material experiment as a contributor to architectural designing.

As a design method or process of design, the elements of influence become a set of tools to involve the materials. The elements outline potential points of engagement. All elements do not need to be in focus in every experiment or design process, but it is important to acknowledge the influence and complications they cause, whether they are given attention or not. Instead of understanding the relation between designing and materialisation as a one-step conversion that is impervious, the relation should instead be regarded as a multi-faceted process with several possible approaches. The material experiment could then conceivably, become a rewarding and advantageous method of designing.

A benefit of an experiment that is formed around the digital machining of materials, is that it links the digital drawing directly to the realm of materials. The development of designs and findings through the material experiment spurs progress in both the mediums of representation and realisation, and makes it possible to create information that is useable in both domains. Instead of solely picturing through the use of annotations and conventions, the information of the digital drawing can be tweaked and oriented towards specific types of machining and production. In *Intermediate Fragment*, for instance, the digital drawing is first oriented towards CNC machining. As the experiment continues, the focusing is directed towards a circular saw, attached to the CNC machine. The focusing advances the drawing into accommodating the specificities of the circular saw, and promotes a type of drawing that takes into account the behaviour of this adapted tool. This means, that besides an advancement of material invention and exploration, the material experiment can potentially be seen as facilitating the development of information that could be further pushed to instruct manufacturing. The fabrication could eventually leave the experimental setting and utilise its information in a development towards actual construction.

Contribution

The work of this PhD dissertation is diverse both in its content and application. The series of experiments constitute the primary amount of work, both in terms of time consumption and findings. The experiments supply the research project with findings on various levels.

First, the experiments explore materials and machining and through their specific setups contribute with material inventions and machining processes. These tangible materialisations sometimes offer spatial and material discoveries that in their own individualised way. break with tradition While none of these findings are prepared for any specific use, they can maybe trigger a novel perspective in a debate about material informed designs.

Secondly, the experiments have fostered a development of a set of strategies and terms, and associated understandings. These have been developed on a methodological level in close cooperation with the execution of the physical experiments. They consist of an understanding of the term 'bespoke fragment' and the underlying 'system of orientation.' The term bespoke fragment provides an essential anchoring to the physical and the materials in the project, while maintaining an openness regarding function and use. The bespoke fragments take on a role in the extension of an understanding of architectural representation. The bespoke fragments are not dependent on a representational source that depicts their design. Instead, they originate from processes. This type of materialisation is a shift from the traditional architectural representation towards one that is informing materiality through the process of designing. *Bespoke Fragments* as a project provides a suggested approach towards an altering of this traditional division of architectural representation and realisation.

In the experimental creation of the fragments, the orientational system described by the virtual and the actual, and control and uncertainty is used as a strategy for navigation. This strategy provides a constant assessment of the ongoing experimental process. Insight and understanding of the level of control versus uncertainty at a particular given moment in the experimentation benefits a reflective practice during the iterative developments. Similarly, a constant awareness of virtualities and actualising processes can be a strategy for keeping an overview of and involvement in the direction of the experiments. Both the term bespoke fragment and the system of orientation were developed through the specific experiments in the project, but could potentially be used for anchoring and navigation of other experiments and processes.

Lastly, the transverse exposition of the series of experiments as a whole provides an unfolding of the influential elements in processes that connect the domain of digital drawing to the domain of realisation. The elements are understood as connected interfaces that each affect the outcome of the process. The elements can, however, also be individually affected and thereby

provide a set of approaches to utilise and influence the process of the material experiment. This generalisation of the process, done through the cross-reading of the experiments, is seen as a design methodological input and as the main contribution of the project.

Discussion of possible further research

While the project explores and outlines a field within the overlapping of design processes, materials, and digital machining, several paths within and around this field remain uncovered and unexplored. Some of those reaches out into disciplines and types of research not possible within the capability of this project, whereas others could be seen as a prolongation or elaboration of the project.

Designed materials

Through the project and the executed experiments, three existing materials are processed and modified. The involvement is always anchored in the material capacities that become available through the encounters of materials and machining. The project, however, never explicitly answers any questions regarding the level of control that designers could or should apply to the designing of materiality or specific material capacities. Instead of clinging on to the present materials, the discoveries found through the experimentation could potentially inform the invention of entirely new materials. In the reflection of the experiment *Stretching the Steel*, the research done by Sarat Babu (Babu, 2014; Beckett and Babu, 2014) and Skylar Tibbits (Raviv et al., 2014; Tibbits, 2014) is referred to. A possible path to extending the research done in *Bespoke Fragments* into a field of designed material could be through an isolation of specific material findings followed by an iterative reproduction and refining of those. The work of CITA researcher Paul Nicholas (Nicholas, 2013) could be of interest in that perspective. Though the area of designed material still seems too limited in scale, and the outcome is still highly speculative, it could be interesting to initiate a focused awareness of the potentials in the context of an architectural design process.

Feedback through processing

The experiments in this research project, as well in as the concluding, generalising understanding of the material and machining experimentation, utilise dialogues and feedback between their elements. The feedback is often a subjective evaluation, in combination with more analytical appraisal of the outcome. The evaluation is an assessment of the potential of the outcome related to the field of the research interest. The more systematic decipherment involves a technical or physical understanding of the phenomenon and often requires an understanding of materials and tools, testings, and digital metrology. The feedback through the production is a driver for the iterative physical development and can, to some extent, be understood in relation to the idea of 'the craftsmanship of risk' put forward by David Pye (1968) and appliedt in a digital-making perspective by Branko Kolarevic (2008). Unlike the craftsman's consistent response to his working, the iterative experiments in this project do not continuously receive feedback, but are to a greater extent a gradual process. This is not entirely intentional, but simply a consequence of how the steps of digital machining currently work. The involved machines simply do not provide feedback synchronously with the production. This machine limitation could, however, be a thing of the past as the digital fabrication tools evolve. In the project *Augmented Materiality: Modelling with material Indeterminacy* Ryan Luke Johns (2014, pp. 216–231) establishes a continuous robotic heat modelling of wax on the basis of a constant feedback from a interplay of the melting wax and the user. In an interactive workflow, a material scanning done by a Kinect, connects to a robot controller that continually adjust the tool paths accordingly. A user level overlay provides direct manual feedback to the machining. The feedback becomes a direct response of the ongoing processing, instead of a evaluation based on the output of the production.

A similar, but much more limited, approach was introduced at the Superflex workshop at the RobArch 2014 conference. This workshop was based on robotic bending of steel rods and would later on initiate the experiment *Rebar Inside Out*. At the workshop, robotic welding was introduced on a quite experimental level. The welding workflow included a predefined robotic welding instruction and an approximated location of the steel, segment where the welding should be applied. Since the exact location was unknown due to the accumulated deviation from both bending and placement of the steel, a 2D laser attached to the robotic welding device was utilised. The robot searched the approximate location with the laser, found the exact position and orientaion of the steel rods and updated the robotic tool path accordingly (Vasey et al., 2014). This workflow points to a type processing feedback that allows a certain degree of material indeterminacy.

The change of digital fabrication from a closed environment to an interactive setting that allows feedback directly from processing, will indisputably create space for an entirely new set of experiments in continuation of this project. The interfaces of the elements in the experimentation and the iterative design approach could see significant benefit from these emerging technologies. The impact of feedback through processing could also potentially affect the construction of architecture. This aspect is discussed in a conversation between Gramazio Kohler and Mario Carpo in the publication that followed the Fabricate 2014 conference (Gramazio et al., 2014, pp. 12–21). To link this dialogue to the utilised feedback methods of *Bespoke Fragment* and to draw attention to the excitement of this field, a quote from the conversation seems appropriate. Mario Carpo: "*Aha, so an automatic feedback on the material the machine is working on? Fantastic, it is exactly what the hand of a craftsman would always have done*" (Gramazio et al., 2014, p. 16).

Architectural machines and interfaces

The last decade of research in architecture has seen a booming use of digital fabrication tools and especially an increased use of the industrial robotic arm. The field of robots in architectural research have predominantly emerged from the ground-breaking research from Gramazio & Kohler at ETH Zurich (Gramazio and Kohler, 2008). Following their initial findings, robotic laboratories at schools of architecture and polytechnical universities have surfaced around the globe and now collectively define a field of research. The potential of the robot arm is quite comparable to the general potential of digital fabrication tools, only with an increased versatility. Whereas other machines are made for particular uses in industries, the robot arm is born without an end-effector. Instead, the robotic arm is prepared for custom made tools, both physically and through a supporting programming environment. Furthermore, it provides an extra axis compared to most other digital fabrication machines and therefore offers one more degree of freedom. The robotic arm itself might be of little interest, but the interface it defines between architect and production is exciting. The material involved is not limited to existing machinery, but is allowing the architect to step into the domain of machining and invent and define own processes. Thereby, the processes can utilise the potential of digital fabrication tools, but also employ thinking and tools that are distinct to the architectural discipline.

In *Bespoke Fragment,* the robotic arm is utilised in three processes. Two of these are found in the experiment *Rebar Inside Out* and one process in located is *Concrete Moves*. In *Rebar Inside Out,* the robotic processes are set up and created by researchers in architecture but can be described as robotic versions of existing machining technologies. The hot wire cutting is not particular to the robot; neither is the steel rod bending. The use of robots in the respective processes however highly increases the versatility of the processes, especially in relation to interaction with digital geometry. The process in *Concrete Moves* is very simple, but developed specifically through the experiment. The manipulation of fluid concrete is not an existing type of transforming process but a specific utilisation of material capacities and robotic motion. *Concrete Moves* also references the artist Anish Kapoor's *Identity Machine* (Kapoor, 2009). This machine creates a particular type of art informed by the material specificities. As noted, the process of this machining is reminiscent of the process of drawing, and the results seem almost like a type of three-dimensional drawing themselves.

A similar approach is seen in the work by REXLAB at the University of Innsbruck (Tamre et al., 2014). They investigate phase-changing materials by special robotic tools and processing methods. By utilising up to three robots, they obtain synchronous motion with 18 combined axes. In this highly robotic setup, foaming materials are investigated in order to utilise their inherent self-organising capacities. The results become a juxtaposition of precisely controlled parts and highly uncertain forming. The notable contribution is, however, the specificity of the setup that becomes material exploring through a highly customised processing workflow.

The above examples are just a brief mentioning of possible cases of specific machines with specific purposes. The potential is still emerging, and the current field of robots in architecture have merely set up a framework for new types of machines and processes. The revised role of the architect can be to take on the challenge with the creation of specific machining setups with explicit interfaces that are relevant in the world of architecture and architectural design. The potential goes beyond both the established field of robots as automated hands for existing tools and the technological breakthroughs seen so far. Further material research in architecture could hopefully provide architectural machines and interfaces that anchor the processes of digital fabrication close to the future field of architecture. This should include a not solely technological attitude and provide a further critical perspective on architectural machines and interfaces. As pointed to by this project, the processes of both materials and machines, and their interfaces, are not transparent, but influence the realisation. A deeper understanding of these influences may provide a better insight in what the machines can actually provide and not what we as users think they can provide. The individual and influential characters of machines could provide a further bridging between drawing, fabrication, and material, and lead to architectural machines and architectural interfaces that support and advance the exploring quality of an architectural design process.

Materials and machining driven architectural practice

While *Bespoke Fragments* exists as a research project, aimed at the discipline of architecture, it also points to the potentials of the discussed experiments in an architectural practice. *Bespoke Fragments* discusses material and machining driven design as a way to of amending the current division between architectural representation and architectural realisation. The scope of this altering is to potentially overlap explorative designing methods with the mediums of physical materials, thereby connecting the two domains into a conversing design space.

The strategy and degree of implementation of a materials and machining driven design method within an architectural design practice remain to be explored. Further research could provide a look into how this joining of representational and realising practices could potentially function.

The idea of a design practice driven by a material thinking is, however, not unheard-of. Multiple examples could be mentioned. One example could be the Danish architectural office E+N (former Exners tegnestue) that through a partnership with Randers Tegl, developed series of new types of bricks[1].The new types of bricks provide other potentials than the usual brick formats. Those potentials become the initiator of new architectural design. A simple example, but none the less, an example that has managed to bridge a level of material research with actual construction.

Another architectural design practice that should be mentioned is Norwegian Helen & Hard. Helen & Hard has several realised project in which essential material elements of the buildings have been developed by the office. Helen & Hard refers to their design method as 'relational design', meaning a design strategy of conceptual, organisational, structural, and material propositions that allow feedback loops to influence and guide the process (Braathen et al., 2012). The thinking seems parallel to the thinking of material and machining driven design articulated in this project, thus pointing towards a shared interest and objective.

Further research could seek to establish a collaborative effort between research and practice to combine the results made in both fields into new advances and findings. This research could provide a more extensive and in-depth investigation of the design space emerging from studies of the capacities appearing from the encounter of materials and machining.

Notes

1 See http://eplusn.dk/flexstone-1 and http://www.randerstegl.dk/dk/mursten/serier/flexstone for more information.

Ending comments

Bespoke Fragments does not intend to end with a closed conclusion. The investigations made during the project form a group of perspectives that leads to a generalisation of the project and a design methodological proposition. The contribution of the project represents a potential direction and strategy for an inclusion of material experimentation in architectural design. The strategy is anchored in the work and research context. The use of materials and digital machining will to a varying degree require a supplemental knowledge and literacy, as well as a changed attitude towards the architectural production. Thus, the project does not claim to be an immediate answer, but a discourse or input to a, not too distant, future of architecture.

Bespoke Fragments does not end within the format of this dissertation. Even though these writings conclude the formal ending of the project, it leaves behind unfinished experiments, open discussions, unsolved problems and awaiting potentials. The concluding design methodological reflection is derived from the executed experiments and the created results, but with a view towards a possible impact and future progression. While being anchored in intention of the project, the contribution, seen as a type of potential design, thinking is an abstraction made on the basis of the experiments. Consequently, the concluding of *Bespoke Fragments* can be seen as independent regarding further implementation and a future use, but closely connected to the events and discussions that are unfolded within the project and the project experiments.

It is the hope that *Bespoke Fragment* can offer an alternative, but grounded, input to an architectural discourse and an emerging field of potential in the discipline.

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