Non_standard Wood

Tamke, Martin

Publication date:
2009

Document Version:
Publisher's PDF, also known as Version of record

Non_standard Wood

A practice based design research in the fabrication of complex wood construction

Martin Tamke
CITA Centre for IT and Architecture, The Royal Danish Academy of Fine Arts, School of Architecture, Denmarkk
http: //cita.karch.dk
martin.tamke@karch.dk

Non-Standard elements in architecture bear the promise of a better more specific performance (Oosterhuis 2003). A new understanding of design evolves, which is focusing on open ended approaches, able to negotiate between shifting requirements and to integrate knowledge on

process and material. Using parametric design tools and computer controlled production facilities Copenhagens Centre for IT and Architecture undertook a practice based research into performance based non-standard element design and mass customization techniques. In close cooperation with wood construction software- and machine industry we fabricated a 1:1 demonstrator show casing the potential for performance due to digital fabrication in this sustainable material.
The production of a custom made design tool helped not only to explore design variations while keeping up the link to digital production machinery, but the integration of traditional wood craft techniques. The extensive use of self adjusting, load bearing wood-wood joints contributed to ease in production and assembly of a performance based architecture.

1. Performance and the wicked problem

Architecture is the result of a negotiation between outer and inner necessities, between initial demands and the process of its becoming. The overall quality is therefore hardly made of the sum of entities with optimized performance summed into one large formula. The engineer Chris Williams stressed this in 2002 as he said that rules of design are very unlikely to be bound into an algorithm, as they are “vague, incomplete, contradictory, open to dispute and require a great deal of intelligence to interpret”. Yet as he stats further on “parts of design of objects” can well be described by rules described in algorithms and thereafter optimized according to one or several criteria. So it can be concluded that performative criteria may be applied to single entities of a design object. The overall performance is informed by the individual performances, which might be greater or smaller than the sum of its parts, if they can be compared in any way due to a potential difference in their nature.
A successful demonstration of this was done within Frei Otto’s and Gaudi’s formfinding processes, which took their point of departure in the optimization of one design criteria: the tectonic behavior of physical models. Work by Killian (2004) or Williams (2003) demonstrate that the principles of hanging chain models can be transferred into the digital realm, making this into an evenly intuitive place for design investigation, as the former physical environment allowing to approach a final solution in an open ended iterative process.

This experiences show that the opposition between engineering as rational and architecture as intuitive is simplistic. Yet architectural design practice is shaped by its facility to leap between problem spaces (Thomsen, Tamke 2009). Architecture as practice is characterized by being highly involved in many different, and often contradictory, levels of inquiry. The design proposal leaps between different modes of rationality relating its concerns with for instance the scale of the city, sociality, program, construction, material and environment. Architectural practice is to construct meaningful relationships between these concerns, and allow the solution to “find its form” as a particular and unique answer. Rather than being general, architectural practice is always concerned with the specific. In this way architectural practice is concerned with a wicked problem which is creatively solved. Here, “information needed understand the problem depends on ones idea for solving it” (Rittel, Webber 73) and investigation, rather than concluding the project, propels new lines of inquiry. Performance is contextualized and solutions are not defined absolutely as true or false, but rather qualitatively as better or worse.

This demands design strategies and tools that are able integrate new findings, shift design rules and allow a gradual transformation into another state. Within the process knowledge is continuously gathered. An integration of this into the design tool itself is of high value as this codification allows sharing and keeping information alive along the process. Hereby the contemporary interfaces between spheres of hermetic iterative gathering and adding of knowledge as in the steps from predesign to design to construction to production could be overcome.

2. Adding performative capabilities to parametric systems

Computation is best at the two key features mentioned above: memory and behavior within a set of rules. Therefore computational approaches are determined to perform well in the process of gathering and evaluating the design stream against a set of ever enlarging codified knowledge such as that of fabrication and material.

Parametric design systems allow the intuitive exploration of architectural solution space (Burry 2005). This not in an absolute manner but open manner further design parameters can be added, rules changed. The integration of conditional statements allows the embedding of limits (as that of tools, tectonic, assembly). Those conditions can be exclusive, prioritizing just one possibility at a given point, overlaying several parameters by giving them certain weights or using solving algorithms to iterate and negotiate even between contradicting parameters.

Those methods have in common that their range can be scaled from a general level, which might be the mean value of all of the systems parameters, to a local level, where single elements are affected. This local level is of highest interest as it allows answering local conditions in a precise way, thus raising the local performance. It can be furthermore assumed that the systems computed performance requirements will not be met by the performance of the standard elements, i.e. provided by the building industry, in an ideal way. In order to meet this requirements non standard systems, elements and design strategies are needed.

Herein non standard practice and mass customizing techniques can be understood in a range from material level to building elements to urban design (Kieran Timberlake, 2003).

3. Digital tools non standard practice

The requirements of a non-standard practice are met by today’s digital toolset used in design and production. As Catherine Slessor observed in 1993, “the notion that uniqueness is now as economic and easy to achieve as repetition challenges the simplifying assumptions of Modernism and suggests the potential of a new, post-industrial paradigm based on the enhanced, creative capabilities of electronics rather than mechanics.” The notion of non-standard production challenges the traditional building practice, which was oriented on the paradigm of Henry Ford’s industrial mass production. (Holm 2006). In fact the model of mass customization seems to describe the building sector with its often singular outputs in a much better way.

Fig.2: CNC wood joinery machinery are widespread within the European timber industry and allow the fast fabrication of mass customized beams. Pictures by Hundegger Maschinenbau GmbH

As discussed architectural design based on computational methods allow per se mass customization approaches. Herein the focus of design shifts from the constitution of a solution (i.e. single elements), that already has the final overall output in terms of geometry and internal distribution of functions imbedded in its form, towards the definition of relationships between the elements in play. Herein the difference between the elements informs a possible final geometry. As the constitution of every element may vary the formulated overall geometry is just one out of many – solely defined by the given parameters and the setup of the internal rules of interaction, which becomes the main design task (Burry 2005). The evolving systems oriented on a Deleuzian (Ansell Pearson 1999) understanding allow new ways to think design. It allows for the easy exploration of a multitude of design solutions.
The system is thereby driven by outer parameters. This might result in a gradually or sudden change in local performance criteria, resulting in huge or small difference within the elements phenotype. This allows mass customization, to overcome the solely slight changes in appearance (i.e. color, material or embroidery) as seen nowadays in customer products, such as sneakers (Reebok 2008), but introduce dramatic shifts. In addition to the examination of change over time, represented in a diagrammatic linear alignment as seen in the mapping of different states of an object due to movement of its parts, first examined by Eadweard Muybridge and Étienne-Jules Marey in 1890, topological change and its infliction with the designs overall appearance can become a driver design exploration, as the introduction of shift, rupture, definition of internal and external spaces, poche and openings to appear within series.

4. Practice based research project

Whereas the story of the creative use of mass customization and the capabilities of a (re)integration of material properties are quickly told, the actual facilitation of these techniques bears a lot of unresolved questions. These range from technical questions, as the identification of the relevant tools and the possible interfacing between them, over questions of management of production and assembly, to conceptual ones, as modes of integration of feedback loops in the process to include knowledge about later steps into the design.
In order to generate insights in the relation, dependencies and chances between and within the different parts of the process we started an practice based research project. Herein the role of material evidence and its making can is an as integral part as in architectural practice. The evidence acts as material research inquiries by which the concepts, technologies and applications of the project can be tested and evaluated (Thomsen, Tamke 2009).

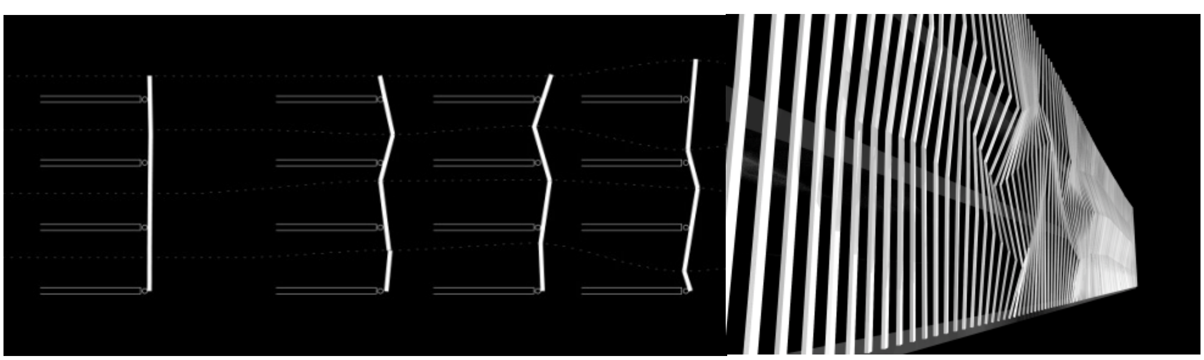

Fig.3: Initial Design Concept: a series of kinked beams create an overall surface

5. Architecture of performance

The research took its point of departure from a real building project – the façade of a large scale multi storey Parking lot, wherein a parametric concept using CNC wood manufacturing processes was proposed (Design: Blunck and Morgen Architects Hamburg with Martin Tamke). The changing transparency of the façade follows an understanding of performative architecture that is hardly computable and measurable in numbers as it is not bound to fixed criteria, but to process (Kolarevic, 2005). It can be evaluated by its socio-economic impact. It is an understanding of performance in a way, wherein design performs. It challenges the spectator or inhabitant, as an actor does on stage. Therefore change and movement are its main characters. The motion of transition leads to an architecture of performance.

The character of performance was first introduced in the basic model design, as shown in fig.3. It consisted of evenly divided but differently kinked beams. Looking at the appearance of the overall series wavelike patterns with changing transparencies and densities appear, making the public spectators of a buildings performance, whenever it moves along the facade.

RESEARCH IN THE PARAMETRICS POTENTIAL

In the following research project looked in a speculative mode at the link and cross breeding between design intent, formal and special expression and realization process. We investigated the systems inherent potential by probing the link of its performance with higher design complexity and inherent aesthetics on one side and the performance in terms of fabrication and assembly on the other, two fields with high difference in their nature and accountability?

Fig.4: Rendering of the third generation within the design series showing the variation of the elements due to creasing and the introduction of internal spaces

Parametric software allowed the programming of a customized tool that enabled us to explore endless variations in the design until certain predefined or from the process evolving performance parameters were met. As every element was defined on its own the appearance could transit from one state into another, allowing for change in topology, as well as typology.

Furthermore the customization process allowed the introduction of fabrication parameters in the very first design process. The tools input parameters were linked to issues of tectonics, material, fabrication, formal concept as well as to a general idea of aesthetics and expression. The exploration was conducted in an iterative process, wherein we built several generations of design probes. By building these wood models the initial idea of a direct as possible link between design tool and fabrication could as well be examined as the parallel emergence of effects in the physical models as in the virtual design space.

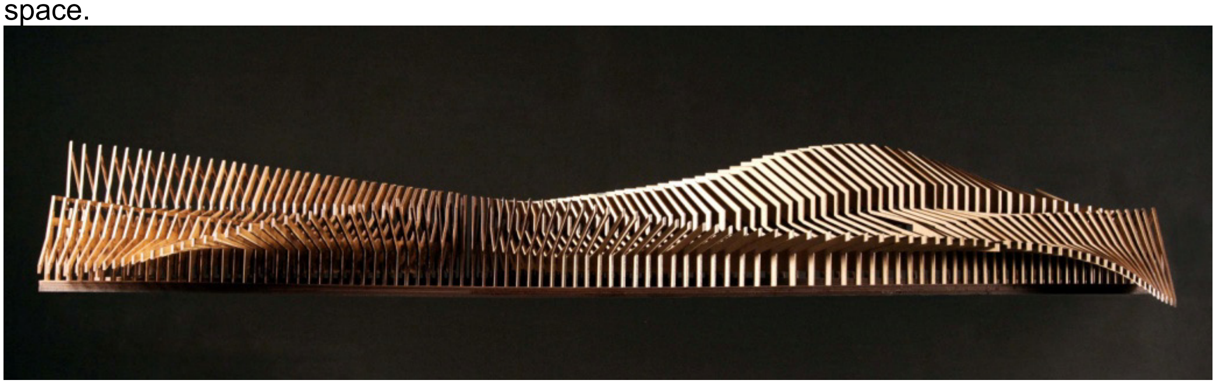

Fig.5: Physical model of the third generation within the design series showing the variation of the elements due to density and topology

SERIES AND REPETITION

The idea of a series was not only met within the setup of the design, but as well in the design process. The notion of series allowed us to individually examine the output of a level of design, discuss its constituting elements and the emerging nature and its effects. In addition the structures level of complexity was raised for each generations design probe, ending in a models with enormous geometrical degree freedom. These would be distilled and emphasized in the next generation of models. By doing so an individual design language could be established. The final scaling of the model into large scale probed not only the custom made tool but as well the coherence of the established design language.

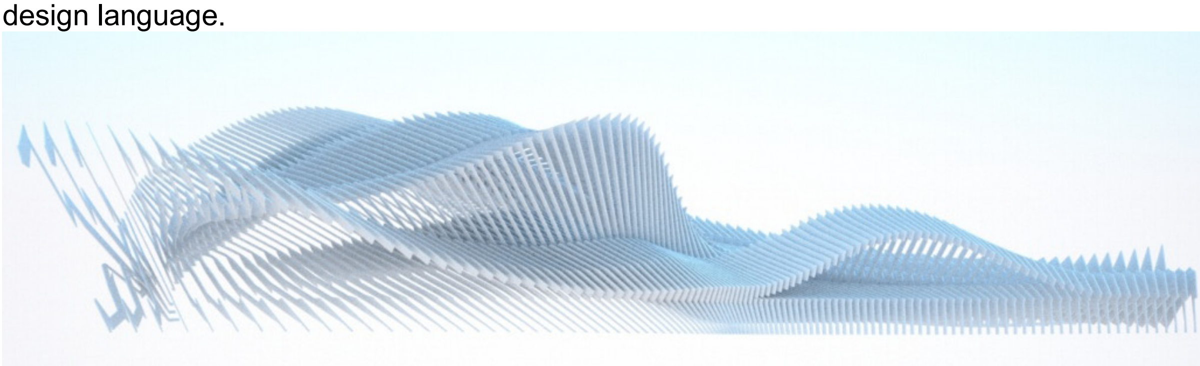

Fig.6: Physical model of the fourth generation within the design series showing high degree of geometrical freedom within the beams movement and variation

6. Wood as construction material

Wood is generally considered as having a high performance in terms of sustainability. It is as well connected to an enormous range of different ways of processing and joining. Especially the ability to easily process the joint directly from the material itself is remarkable. "The benefits of components with integrated attachments geometry are that the attachments can be designed and controlled as part of the generative process" as Larry Sass states in 2006. Based on a long tradition in the crafts wood-wood joints, especially those based on friction as dovetail joints, have advantages:

- Can be specific to certain geometrical and tectonic requirements

- parallel behavior of the joints part if exposed to changing temperature or moisture conditions due to the monolithic setup of the joints
- High level of prefabrication
- Inherit tolerance
- Efficiency in assembly due to self registering joints and little or less secondary elements, as screws or bolts

Precedent research has shown the advantage of implementing self registering joints that can adapt geometrically to specific local requirements in the construction. The required production capacity is given in the highly flexible CNC wood joinery machines, introduced in the typically mid sized wood manufacturing companies. They enable not only the very fast production of individualized wooden beams but as well the rational production of geometrical complex individual joints that fit with little tolerances.

Taking into account that the material and production costs are usually not the main factor in the fabrication of constructions- labor, production and transport are at most equally important (Guthrie 2003, Westney 1997). The interplay of high precision and almost total prefabrication due to CNC manufacturing and the easy assembly of elements with self registering joints should reduce the costs for complex constructions in wood. Geometrical almost unrestricted joints should furthermore enable new ways of design, as the traditional restrictions in fabrication and assembly are softened (Larsen 2007).

7. Demonstrator - introducing a bottom up design approach

Taking a point of departure in the linkage of the parametric system used in the design probes and traditional wood craft techniques the final part of the research project was taking into account the whole process of digital design to production of a complex shaped geometry. In close cooperation with wood construction software- and machine industry we developed a design and fabrication approach, which combined the knowledge about the sustainable materials properties, processing and joinery. The interplay of these attributes produced an intelligent system that could pose answers to complex situations in the spatial construction system of a 1:1 demonstrator.

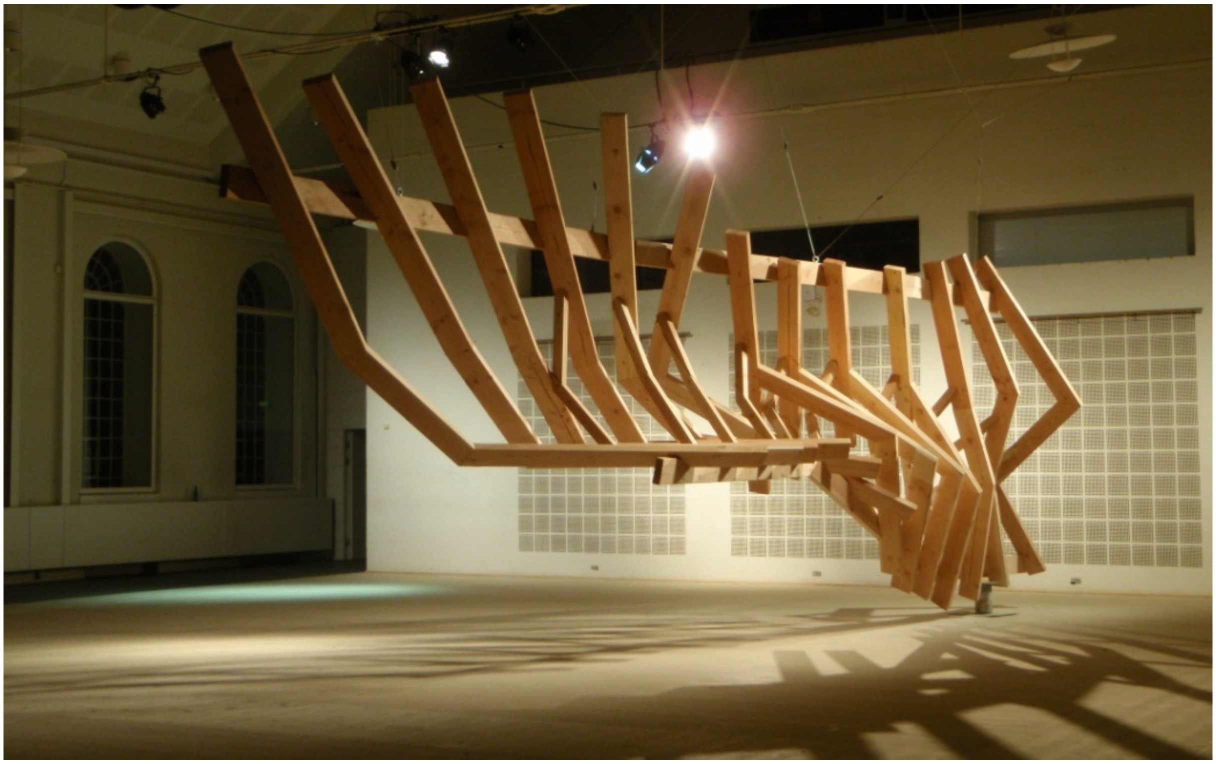

Fig7: Demonstrator build up at the eaae exhibition – July 2008 Copenhagen

We knew already from the design probes that the key to design, fabrication and assembly of complex geometrical situations lied with the process of geometry generation. Within the series of design probes a tool was already developed that could handle design intent, material, processing and assembling properties an give instant feedback to the designer. These allowed to optimize the emerging complex spatial structure design on quantitative as well as on qualitative level. Within the making in real building size the ability to scale developed method and technique was tested

6.1 ACCOMPLISH PERFORMANCE IN A PARAMETRIC DESIGN SYSTEM

The demonstrator aimed as well at testing the production limits of the wood joinery machines provided by our industrial partner and if these restraints could be implemented into our customized design tool. In order to increase the complexity and as well raise the structures stability of diagonal beams were introduced connecting two respective beams. Which members met where and under which angle could be adjusted parametrically, whereas the precise meeting geometries were derived from the given local status of the diagonal. The exact positioning of this element could not be easily calculated from their start and endpoint, instead the diagonal beams were measuring their and their neighbors dimensions, position and orientation and where adjusting themselves automatically in order to avoid intersection and fulfil the constructive needs of the chosen dovetail connectors. The creation of an autonomously operating second order geometry was interesting, as it was based purely on conditional statements and allowed design wise the introduction of spatial pockets in the structure.

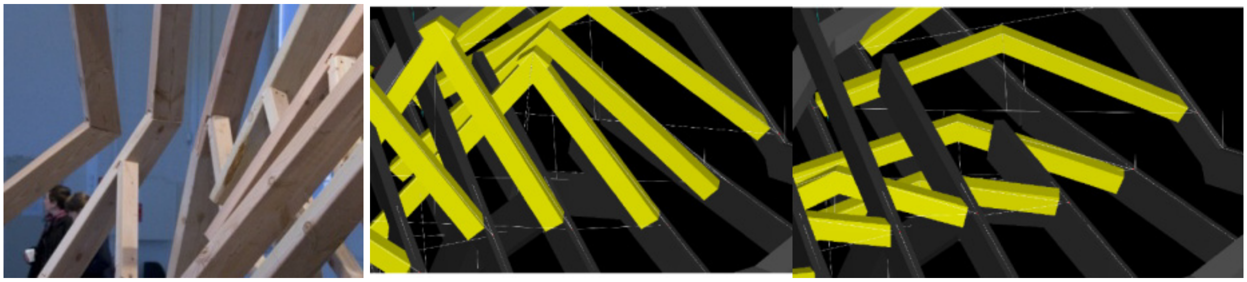

Fig 8: The dovetail connectors posed high requirements on the geometrical setup of the wood construction, which was met by the autonomous generation of diagonals by scripted functions

At other position solver algorithms were integrated into the structure to solve contradicting parameters. This as the underlying abstract parametric model was based on a representation of the axis system. While constructing the data for fabrication the implications coming with material thickness had to be taken into account. In the case of the joint between the rail and the beam – depending on the geometric situation a double rafter cut or a notch – a solver algorithm, courtesy provided by Axel Kilian, was used to limit the depth of the cut out to 30% of the materials dimension in order to keep enough tectonic strength.

6.2 LOCAL INTELLIGENS ALLOWS GLOBAL DESIGN COMPLEXITY

Whereas the overall structural system inherits a high degree of complexity, it was necessary to find ways to easily assembly the overall structure. We found that traditional wood joints were able to create a simple assembly due to their self registering properties. This as a high degree of geometrical complexity is already bound in their making. (Holzner 1999, Schindler 2007)
The quiet complicated fabrication of local complex joints resulted in a high degree of planning, but allowed to avoid on construction site measuring and adjustment. Besides friction based joints, classical tenon joints with wood pegs have been used in the construction which are as well geometrically defined in position. Solely the junctions between the beams and rails were not self registering as they were carried out as double cuts or notches. In order to provide a guidance for assembly the insertion points were marked within the machine, as this joints did not have an build in locking systems, metal connectors where needed –the only place in the construction.

In contrast to traditional modular structure, where joints are easy to assemble but not flexible in their geometrical setup (Wachsmann1959 and Herzog 1988) mass customization design strategies allowed variations within joints that allowed them to fit to a diverse range of geometrical scenarios.
The combination of highly flexible CNC wood joinery machinery with parametric design tool allowed the production of individualized wooden beams and the rational production of geometrical complex individual joints that fit with little tolerances. The complex joint itself is thereby sculptured by a combination of simple cuts, drilling and milling operations out of the massive material allowing a fast production.

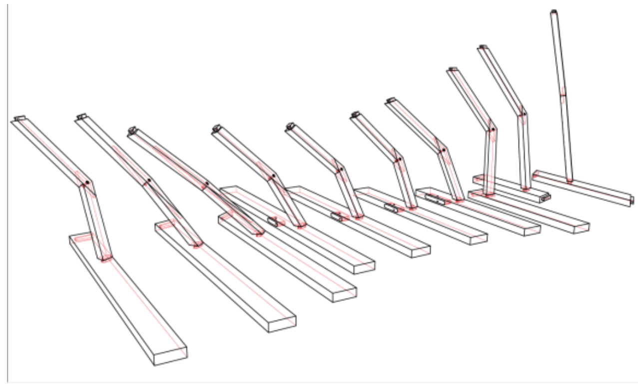

Fig 9. As a monolithic wood joint dovetail connections provide self registering properties in a construction and can be fit into diverse local conditions as shown in Fig.10 on the left, which illustrates their application in diverse local scenarios in the demonstrators structure

6.3 INTEGRATING WORKFLOW AND PRODUCTION PARAMETERS

The process development focused on the setup of a smooth functioning and seamless workflow. We tried to use as much existing tool as possible and test their capacity before writing proprietary tools. As our parametric tools data could be read flawlessly within, we used the Wood CAM tool HSB Cad. Its function was to define the different wood-joints on the predefined beam structure and write the instructions to the wood joinery machine. A color-code, generated in the parametric modeler eased the identification of the single beams and the application of the different types of craft based joints, as notches, cuts, dovetails and rafter joints.

In contrast to CNC mills wood joinery machines can execute a series of different operations, as cutting, milling, drilling and more. Therefore the code send from the CAM program to the machine consist merely of a set of operations send and a special machine driving program is checking the plausibility of operations in between. As the CAM program used has no build in plausibility check – not producible wood operations could be send from the parametric modeler to the machine driving program. As this included two many steps in between it was necessary to integrate the machines limitations into the parametric model. As the limitations could be easily implemented in the constructions design and the parametric model this process took just a few hours at the actual production facility with the operating staff on side.

The machines requirements were introduced within the parametric model in two ways:

- either by algorithms limiting certain values
- by the real-time updating and observation of measured values in an excel sheet during the design process.

The last served i.e. well for the control of the minimal length of beams, as too many interacting factors influenced their dimension during the design process to find a formula covering all occurrences. An iterative process triggering the influencing factors manually helped to find quickly a design solution that complied with aesthetic and production requirements.

The reading of certain parameters into an excel sheet helped as well to figure out further parameters as the overall weight and the center of gravity. Those were defined by the given exhibition space and the fact that the demonstrator was to be suspended from the ceiling and should not tilt. Therefore an algorithm was integrated checking the center of gravity. The resulting point could thereafter be displayed within the parametric modeler and give valuable advice in which way to adjust the design.

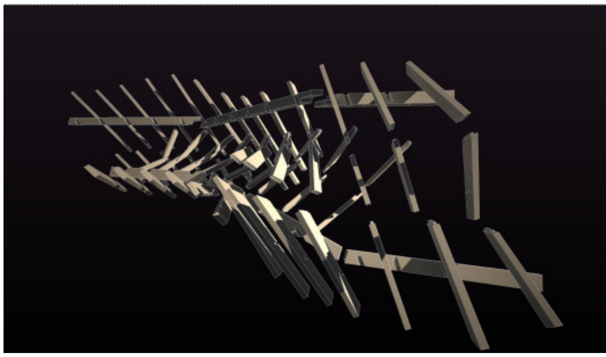


Fig 10. , Fig 11. Modern wood joinery machinery still inherits the basic tooling processes of traditional wood craft: cutting drilling and milling. This allows the production of a geometrical versatile monolithic wood joints as shown in the explosion diagram of the projects demonstrator on the left

6.4 PRODUCTION AND ASSEMBLY

The fabrication of the 65 individual wood beams on the wood joinery machine took 4 hours. As the pieces were not placed in order on the transport and due to an imprecise assembly plan and schedule was sorting and discussion of assembly strategies took some time. In the end the assembly of the construction with 4 inexperienced students, which had no insights of the project beforehand and no background in crafts, took 10 hours. The careful tilting of the construction from its lying first state into the suspension took a great amount of this time. Some tolerances had been set to small, which required force to make the pieces join. In general the joints fit well. Therefore the assembly went well. Especially the mounting on three points, due to the introduction of the diagonal beams, established a structural self centering system, which led to self fitting structural elements.

8. Observation

The successful integration of knowledge about material and fabrication in the design tool and the observation that this allowed a higher performance was the key experiences made in the project. The ability to produce a customized tool allowed the combination of design intend with the possibility to realize it, as the limitations of the machinery and material (i.e. tolerances) where weaved into. In our example this process did actually took not long (1 day), bearing in mind the result of a customized tool. The precise creation of geometry can be identified as the key feature within the process. Geometrical information hold the knowledge of material and process. This precise definition and not additional information added as meta data, formed the basis of the following process. Information as the position and direction in space for tectonic calculation, dimension, material and type of joint for the highly precise fabrication and the position within the structure for the assembly could be extracted from this very data. This allows the developed techniques to be used within structural wood system in building size.

9. Computational aspects of geometry generation in wood craft

The focus of our ongoing research reflects the raise of performance if parametric approaches are introduced in the generation of geometry and the effect on production and assembly.
The ability to create automatic drawing processes enables designers to create higher complexity and better adaptability on local level, but as well a higher precision in the planning process. Elements that

can position themselves by measuring their position and negotiating their placement and orientation (fig. 8, 9, 12) with their neighbors through functions and solver algorithms can be observed as a start into the design of systems that autonomously structure themselves, negotiating between a wide range of outer performance criteria while still allowing a rigid design intent.

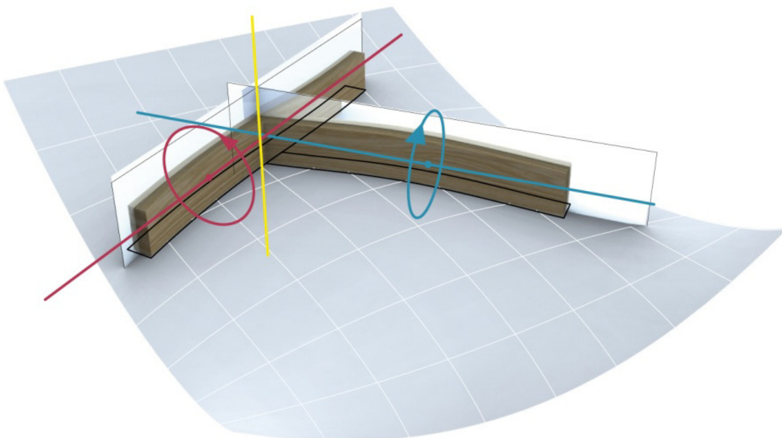

Fig 12. Computation allows designers to include autonomous behavior into single elements within a structure - by doing so elements can automatically negotiate their position and orientation according to measured properties of the adjacent neighbors. These principles were used for the constructed demonstrator as in ongoing research.

Computational processes allow a novel understanding of a buildings setup for design. For instance the ability to describe a structure as a matrix allows the application of computational operations in its design. Matrix operations as the transformation of data between a three-dimensional and two-dimensional representation allows for instance the introduction of attractors and positions that repel on the structure. This operation allows the link of structural, programmatic or aesthetic performance in a design process.

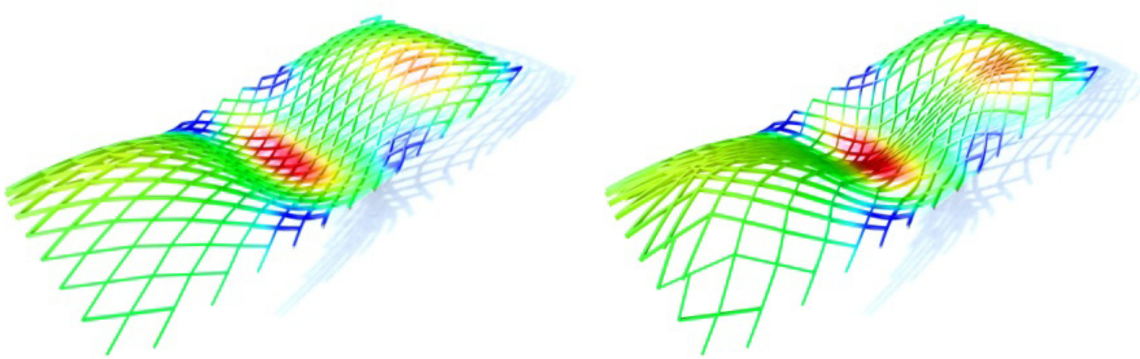

Fig 12. Computation allows structures to adapt to external data. In this example from ongoing research work beams are agglomerated in areas of high curvature. These properties are measured and used for attracting and repelling points identified within the given surfaces. The derived structure provides improved construction performance, as it can follow better the predefined surface.

Computation allows the integration of the knowledge of matter and it’s processing into the design phase and by adding the possibilities of computation novel ways of design emerge.

Reference:

Burry, Mark, Kolarevic, Branko (Ed): 2005, Between intuition and Process: Parametric Design and Rapid Prototyping, in Architecture in the Digital Age: Design and Manufacturing, Washington, DC: Taylor & Francis.

Clegg, Brian, C.: 2007, The Man Who Stopped Time. Joseph Henry Press. ISBN 0-309-10112-3.

Guthrie, P.: 2003, Architect's Portable Handbook : First-Step Rules of Thumb for Building Design, McGraw-Hill Professional Publishing, p 369

Herzog T.: 1988, Vom Sinn des Details. Zum Gesamtwerk Konrad Wachsmanns. Müller, Köln

Holzner H.:1999, Entwicklung eines Nachweisverfahrens zur Bemessung von speziellen (maschinell gefertigten) Zapfenverbindungen, Diplomthesis at Institut für Tragwerksbau - Fachgebiet Holzbau Univ.- Prof. Dr.- Ing. H.Kreuzinger - Dipl.-Ing. Patricia Hamm - Dr.- Ing. R. Spengler, TU Munich

Holm, Ivar: 2006, Ideas and Beliefs in Architecture and Industrial design: How attitudes, orentations, and underlying assumptions shape the build environment. Oslo School of Architecture and Design. ISBN 8254701741

Kilian, Axel: 2003, Fabrication of Partially Double-Curved Surfaces out of Flat Sheet Material Through a 3D Puzzle Approach, Connecting >> Crossroads of Digital Discourse [Proceedings of the 2003 Annual Conference of the Association for Computer Aided Design In Architecture / ISBN 1-880250-12-8] Indianapolis (Indiana) 24-27 October 2003, pp. 75-83

Kilian, A.: 2004, Linking Digital Hanging Chain Models to Fabrication, Fabrication: Examining the Digital Practice of Architecture, in Proceedings of the 23rd Annual Conference of the Association for Computer Aided Design in Architecture and the 2004 Conference of the AIA Technology in Architectural Practice Knowledge Community, Cambridge (Ontario) 8-14 November, 2004, pp. 110-125

Kolarevic, B.: 2005, Towards the performative in architetcure, Kolarevic, B., Malkawi, A. (eds.) Performative Architecture, Routledge Chapman & Hall, pp. 205-211

Kolarevic, B.: 2005, “Information master builders” Architecture in Architecture in the Digital Age: Design and Manufacturing, Washington, DC: Taylor & Francis. pp. 56 – 62

Larsen, K, Scheurer, F.; Schindler, C., Stori, S.: 2007, The Trondheim Camera Obscura, in Predicting the Future [25th eCAADe Conference Proceedings / ISBN 978-0-9541183-6-5] Frankfurt am Main (Germany) 26-29 September 2007, pp. 51-58

Marey, EJ: 1890, Le vol des oiseaux- 1890 - Masson, G., Paris

Oosterhuis, K.: 2003 Oosterhuis.nl, Architectures non standard 12/2003

Pearson, K.A.: Germinal Life: 1999, The Difference and Repetition of Deleuze, Routledge, London

Reebok: 2008, custom sport shoes, http://www.rbkcustom.com

Rittel, H., and Melvin W.:1984, "Dilemmas in a General Theory of Planning," pp. 155-169, Policy Sciences, Vol. 4, Elsevier Scientific Publishing Company, Inc., Amsterdam, 1973.

Sass, L.: 2006, A wood frame grammar: A generative system for digital fabrication, International Journal of Architectural Computing vol. 4 - no. 1, 51-67.

Schindler, C.: 2007, Information-Tool-Technology: Contemporary digital fabrication as part of a continuous development of process technology as illustrated with the example of timber construction. Presented at: ACADIA Conference 2007 Nova Scotia, and on http://www.archplus.net/archiv_ausgaben.php?show=188

Slessor, C.: 1993 in Pine, B. J.: Mass Customization: The New Frontier in Business Competition. Boston: Harvard Business School Press.

Thomsen, M; Tamke, M: 2009, Narratives of Making: thinking practice led research in architecture, to be published in the proceedings of the conference "COMMUNICATING (BY) DESIGN" 15. – 17. April 2009, Brussels, Belgium

Timberlake, J., Kieran, S.: 2003, refabricating ARCHITECTURE, McGraw Hill, pp. 133-

Wachsmann, K: 1959,Wendepunkt im Bauen. Wiesbaden: Krausskopf Verlag, 1959

Westney R.: 1997, 1 Engineer's Cost Handbook: Tools for Managing Project Costs, Marcel Dekker Incorporated, p 146pp

Williams, C, 2003: Design by Algorithm, in Leach, N., Turnbull, D., Williams, C. (eds.) Digital Tectonics, John Wiley & Sons