OPEN ROOM 03

PERSPECTIVES ON

DIGITAL FABRICATION IN *TOMORROW'S* ARCHITECTURE

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OPEN ROOM

Will wireless networks and virtual worlds make us placeless, will robots destroy craftsmanship, can we solve climate change with more technology, have we become strangers in our own cities, and will exporting welfare architecture challenge our ethical position?

Although it is tempting to answer yes to these questions, it seems like we still need places, that robot technology could be a way to reinvent craftsmanship, that technology alone cannot solve climate change, that co-creation is gaining ground in urban development and that our welfare architecture might be capable of adapting to other cultures. The changes and trends seems ambiguous and they affect our built environment. From an architectural perspective the question is: how do we interact with these changes and how can we build in the future?

The Open Room seminars at Aarhus School of Architecture focus on se-lected current topics in society and provide interdisciplinary perspectives on the relation between trends and the role of architecture. The aim is to share knowledge, open up for new understandings and thereby obtain qualified and nuanced discussions and answers. It is a physical and mental open room where researchers and practicing architects and related disciplines meet and present their perspectives on a given topic. Involving a group of people with a broad range of professional backgrounds - philosophers, engineers, lawyers, organizational analysts, professors of pedagogy - the Open Room seminars create new approaches and a broader understanding of the selected topics. The seminars are always open to participants from outside the school. Together we listen, debate and reflect.

The book you are holding brings together contributions from the seminar on digital fabrication in tomorrows architecture. It is for every-one who have an interest in the topic: builders, researchers, practicing architects, politicians, policy-makers or citizens in general who are interested in different perspectives on future chaftmanship and industrial production.

Anne Mette Boye
Editor OPEN ROOM

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DIGITAL FABRICATION IN *TOMORROW'S* ARCHITECTURE

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Industrial production forms are currently undergoing a transition from being standardised to becoming customised. The change is evident for instance in architecture, arts and crafts, and industrial design. The use of robotics in the building industry allows new forms of variation and expression. Furthermore, the production can take place in Denmark. In this Open Room we will discuss: What potentials for development lie in locally based production setups? How can architects and designers become more involved in fabrication? How can other professions become more involved in design processes?

Niels Martin Larsen
Associate professor at Aarhus School of Architecture and organizing the present Open Room seminar

COMPUTATION, ARCHITECTURAL DESIGN AND FABRICATION LOGIC

– POTENTIAL FOR CHANGES

NIELS MARTIN LARSEN, ARCHITECT AND
ASSOCIATE PROFESSOR AT
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Digital fabrication and digital form generation can change the way different professions interact in relation to the development and construction of architecture. The technologies can provide a more integrated design process and expand the architectural vocabulary. At Aarhus School of Architecture we investigate these possibilities in a series of research projects.

Digital design tools as well as digital fabrication facilities have already been around for decades. For these, architects have fully embraced computers as the primary working environment and manufacturers make use of robotic technologies in their production lines. However, these elements have in most cases merely been indirectly linked through information passed on in the form of traditional drawings from architects through engineers to the manufacturer. Feedback information about fabrication is often passed on as technical sheets or verbal communication between architect and contractor. To fully benefit from the technologies, for instance, in order to achieve a larger scope of architectural expression, it is necessary to integrate the different environments much more directly, and because much of the information exists numerically, this can be achieved through computation.

Fondation Louis Vuitton 2015. Designed by Frank Gehry. The related company, Gehry Technologies developed their own software platform, Digital Project, allowing the realisation of projects that makes use of complex geometry.

Integrating fabrication constraints in the initial form generation means on one hand that the design can be synchronised to match with the actual fabrication and montage of building components. This can be utilised for achieving more variation in the architectural expression but also to minimise use of resources. Computational design allows extreme complexity in architectural projects, which for instance is demonstrated in many of Frank Gehry's designs. While, these projects clearly are realised through handling of massive digital information include fabrication processes and material properties as part of their logic, the initial designs are not computationally generated. What we pursue in our research is to use computation as part of the initial form-generation, and thereby achieve a higher level of integration. A concenquense of this could be that not only exclusive projects can demonstrate advanced amorph geometry or large differentation in building parts, thereby enriching our build environment.

Expanding the architectural vocabulary

Digital technologies allow architects to include a higher degree of complexity and variation in project development. Here it is particularly interesting to look at algorithmic form generation, compared to so-called explicit modelling, where a building is designed "manually" through drawing or modelling. With algorithmic design, a set of mathematical rules, defined by the designer, generates the geometry automatically. This allows for a much higher level of complexity in the final design solution, since complex geometries are handled through computation as easily as more simple shapes. More important, the underlying computational logic makes it possible to expand the amount of information, linked to the individual component gradually through the design process, and finally extract this information for production and construction. Besides keeping track of the underlying geometry in such complex de-

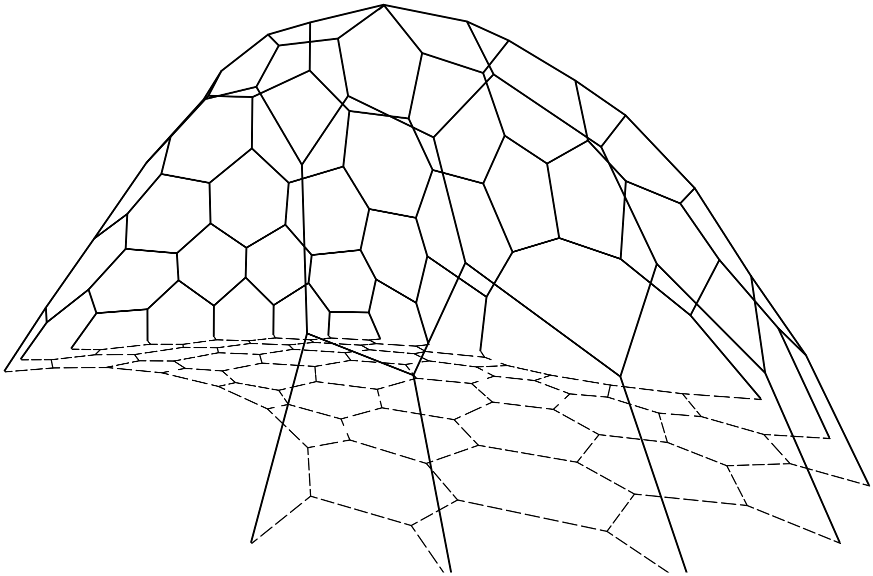
"THE DIGITAL METHODS HAVE THE ADVANTAGE THAT THEY CAN IN MANY CASES BE TRANSLATED DIRECTLY TO SYSTEMS USED BY OTHER PROFESSIONS. THIS GOES PARTICULARLY FOR THE ENGINEERS, WHO, FOR INSTANCE, CAN USE THE DIGITAL MODELS TO CALCULATE STRUCTURAL PROPERTIES."

signs, rule-based form-generation also opens for numerous negotiations of different parameters. For instance, irradiance on different parts of a building or structural analysis can directly influence the way individual components are expressed. The components can 'know' about their neighbours, negotiate dimensions and ensure that they fit together. With use of so-called self-organisation as part of the digital form-generation, it is even possible to transcend the need for an underlying grid. On a more practical level, this integrated negotiation can be directed towards fabrication and montage. For instance, limitations in size of elements that derive from a specific production facility, can be embedded in a script that 'decides' the geometry of building components. In this sense, not only the final result is optimised towards certain criteria, but also the production and realisation processes can be more directly controlled through use of computation. The digital methods have the advantage that they can in many cases be translated directly to systems used by other professions. This goes particularly for the engineers, who, for instance, can use the digital models to calculate structural properties. In more traditional workflows, the engineers would often have to produce separate models, and this is often inefficient, particularly in relation to complex geometry. It is also possible to incorporate methods from other disciplines, such as computer science, physics and biology, into the design methodology.

As part of exploring the potential of the digital technologies, we often make use of case studies that can be denoted as 'proto-architecture'. These studies are framed so they address a particular aspect, such as a tectonic principle, rather than solving a holistic architectural problem. This approach allows the particular subject to be studied in more depth than would be possible if all kinds of general architectural problems had to be resolved at the same time. An example of such a study is the development of a construction system with mass-customised concrete elements.

Concrete gridshell

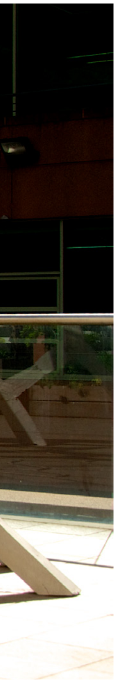
A principle of casting concrete in foldable plastic moulds, developed by Ole Egholm Jackson, formed the starting point for the research, focusing on making a construction system completely directed by digital form generation and produced through digital fabrication technology. The development was initiated at the school in Aarhus, in 2010, in a workshop directed by Ole Egholm Jackson , the author and Dave Pigram from University of Technology in Sydney. Since then, a series of workshops and experiments have been carried out, gradually embedding several challenges concerning structure and assembly. The last case study in this series was the construction of a small pavilion at UTS for the 40th



Utzon40 pavilion. Wireframe model generated with dynamic relaxation.

Utzon40 pavilion assembled at University of Technology in Sydney.

anniversary of the Sydney Opera House. The pavilion was a combination of two different construction systems of respectively concrete and timber, both completely driven by digital form generation and digital fabrication. The overall shape was generated through so-called dynamic relaxation, which is a computational method for simulating particle-spring systems. This is comparable to the analogue methods used by Antoni Gaudi in The Sagrada Familia and other of his famous projects, but here translated to a computer-generated mesh shape. This allows testing of numerous different versions of the shapes in short time, and brings this logic into our present working environment where there is limited time to develop architectural form and often a need to test many different possibilities. As indicated, the concrete elements were fabricated through casting in plastic moulds. The geometries of these components were automatically generated from the wireframe model, created with dynamic relaxation. At the same time, 2D drawings defining the geometries of the templates for casting were generated. These could then be produced through laser cutting and subsequently be folded and riveted. At this stage, the folding and riveting processes are still manual processes that reveal how, even though much is possible using digital fabrication, bottle necks often occur because in many cases the automatized processes need to be paired with manual labour. Anyway, the



"THE FOLDING AND RIVETING PROCESSES ARE STILL MANUAL PROCESSES THAT REVEAL HOW, EVEN THOUGH MUCH IS POSSIBLE USING DIGITAL FABRICATION, BOTTLE NECKS OFTEN OCCUR BECAUSE IN MANY CASES THE AUTOMATIZED PROCESSES NEED TO BE PAIRED WITH MANUAL LABOUR."

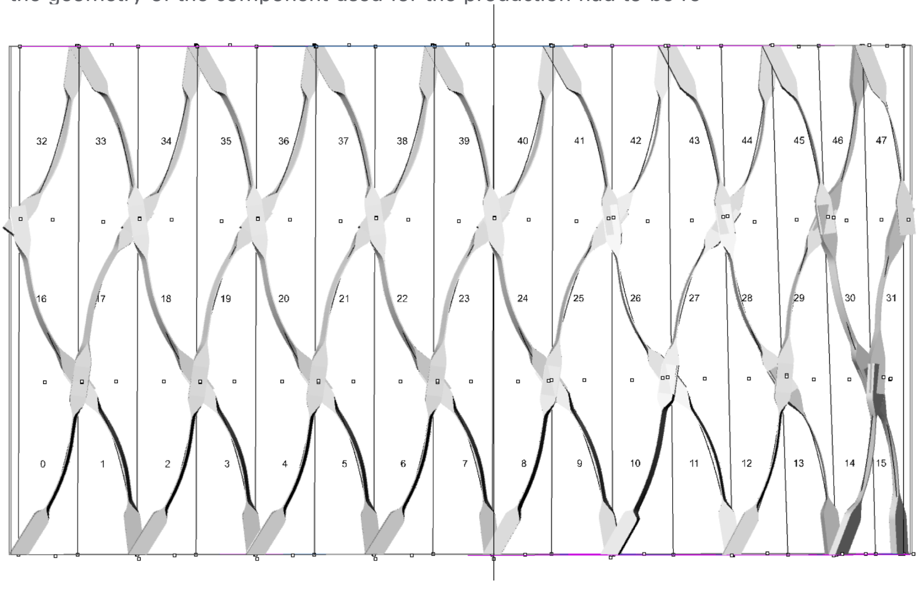
project showed much potential, both in fabrication and construction. One of the improvements that were made in relation to Utzon 40 was the addition of a post-tensioned reinforcement system, which also worked as a principle for joining the components together. This meant that falsework, which is generally used for this type of construction, could be almost completely avoided. The timber system was implemented and improved in a case study by Dave Pigram and Iain Maxwell, based on a method previously developed in collaboration with Wes McGee and Maciej Kaczynski at the University of Michigan. Here, a reciprocal frame principle was produced using 5-axis CNC-milling, also through automatically generating the geometries of the components from the

Utzon40 pavilion. Concrete component with fixture detail.

wireframe model. The system allowed a large variety of asymmetrical shapes and a large differentiation of the individual components. For example, the depth of the timber components can vary automatically, depending on the locally calculated load. This information was extracted from a digital structural analysis model made by Arup Engineers in Sydney, which was again generated from the original wireframe model. All these sets of geometric information derive from the same underlying mesh topology and intertwine to establish the final geometry of the building components.

Timber Curtain

Another case study where fabrication is embedded in the design process is Timber Curtain, which was developed by Maya Lahmy and the author in 2015. It was exhibited as part of the school's exhibition at Ventura Lambrate in Milan the same year. Here, a basic timber component was developed to make possible bending and obtaining shapes within a specific scope of variation. A digital parametric system was created for generating the overall pattern of the structure, defining which parts are connected. The system also controlled the shape of the individual components. What was perhaps unusual in this situation was that two different states of the timber component had to be generated simultaneously. Because, the parts were bent into position when mounted, the geometry of the component used for the production had to be re-

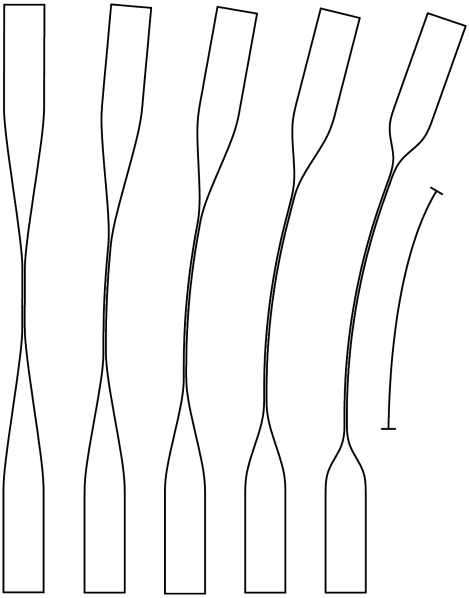


Timber Curtain. Drawing of parametrically generated design.

Timber Curtain installed in Gallery Undai, Ventura Lambrate 2015, Milan.

ding properties. For example, a component sitting relatively straight would be shaped with only a short slim bendable part, whereas a more bent component would have a long slim part. Also, the angle of the bendable part would be automatically adjusted to the particular situation to make the component bend in the right direction. The parametric 3D model would not, as usual, show the abstract image of the requested result, but rather display how the components would behave according to the material properties. This meant that it could be directly ensured that a chosen design proposal would also work in the physical world.

Timber Curtain, joint detail ensuring precise angles between bent components.



Timber Curtain. Diagram showing how the slim bendable part of each component is formed according to its performance in the construction.

Impact on architectural design

Digital design and digital fabrication exist as two different aspects of a realisation process, but in order to fully exploit the potential of both, it is necessary to connect them closely together. The case studies show a development process that relies on an understanding of physical properties and fabrication processes just as much as design intent, allowing more aspects to be directly embedded in the proposed result. Computation is directly used as part of the form-generation, rather than just replacing traditional drawing or modelling techniques. The methods open for new vocabularies

Centre Pompidou-Metz was designed by Shigeru Ban and opened in 2010. The roof construction consists of individually processed glued laminated timber beams that intersect in a hexagonal pattern.

not practically available with traditional methods. The complexity in form variation linked with structural and material properties would be dificult to achieve through explicit modelling and testing of physical models. As such, the projects does not only demonstrate large degree of differentiation of building parts, but also how material properties and fabrication constraints can be embedded in the form genereation.

While the studies cannot be evaluated as architecture as such, they demonstrate potentials that could be refined and adjusted for implementation in other projects and on a larger scale. Hopefully, as more realised examples of these types of architectural projects emerge, the possibilities will become apparent. Already now we see in the architecture scene a number of exclusive projects that clearly rely on digital fabrication, such as Fondation Louis Vuitton (page 7) However, a more integrated and holistic method will allow the principles to be used in projects with more limited budgets, and thereby have an impact on the built environment in a larger scope.

Illustrations

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DIGITAL TIMBER FABRICATION
– DIGITAL CRAFTSMANSHIP

TONI ÖSTERLUND
M.SC. ARCHITECT
GEOMETRIA

As a Finnish architect heavily involved in the design and development of complex timber structures, I stand in awe at the amazing timber fabrication facilities we currently have here in Finland. Though our experiences in building wooden multi storeys are currently at their infancy, we have a very long history building from timber. And the industry to match that, with its hi-tech digital timber machinery capable of fabricating just about anything with speed and unparalleled precision.

It is then quite paradoxical that the most technologically advanced machines are currently used by the manufacturers of log houses, arguably the most traditional branch of the timber building industry. In recent years, these companies have invested in advanced CNC (Computerized Numerical Control) milling machines, which automate and speed up the production of log joinery. Traditional log houses, and their gently modernized versions, are their biggest selling items. The use of sophisticated machines in milling log joinery has created an odd analog/digital hybrid situation, as the machine's database contain the analog history of western and oriental wood joinery in a collection of digitally interpreted details. Each of them ready to be fabricated within minutes. This is an amazing technological feat considering the amount of time and skill it has taken in past to develop and construct them by hand. The skills and work of the carpenter has been digitized and automated by the machine. In this situation, who is the modern craftsman - the machine or the operator? And what about the future of timber structures, as the digital carpenter cannot develop any new solutions or reconsider options. We now have to look in different direction - towards the designers, who challenge and explore the new technological capabilities of timber in construction.

As currently the timber fabrication technologies are used to emulate the past, we should be more focused on the possibilities they have on the

New tools allow for new types of architectural expressions.

future of timber architecture and structures. Even with the introduction of new construction elements, such as the CLT (Cross LaminatedTimber), which necessitate the use of CNC routers, their utilization and exploration in new architectural expressions are scarce.

The capable and fast machines are inevitably here to stay, but instead of emulating and automating the past, we should concern ourselves in exploring and harnessing their capabilities in future architecture. The timber architecture of the digital era should not be just about making the analog more efficient. We can now design and create architecture that has previously been impossible, impractical or just too expensive to make. This provides possibilities to elevate the use of wood in areas where it has lost its footing.

Digital design

Nowadays architects design in a completely digital environment and through the developments in design software, the use of Building Information Modeling (BIM) and information transfer through IFC, we are able to reap the immediate benefits. However, just as in the case of digital fabrication, digital architectural design has mostly been about digitizing the past processes. Efficiency as the leading force for developmental needs.

Technological advances always bring forth new possibilities and in order to break from the chains of the analog traditions, we need design tools and methods that do not just emulate, but take full advantage of the digital environment. Algorithms are the language we can use to translate our design intentions to the form that the computer can understand and compute. And through the use of algorithms we can tap into the processing capabilities of the computer and use it – not just as a glorified drawing pad – but as an integral aid in design. The algorithmic process becomes the design method and tool, which depicts the motivation, actions and outcome. The use of algorithms in design enables us to also embed material and fabrication properties into the design process and produce complex solutions with ease.

On the other side of digital complexity and mass customization are the challenges they create in assembly. Construction of a big puzzle.

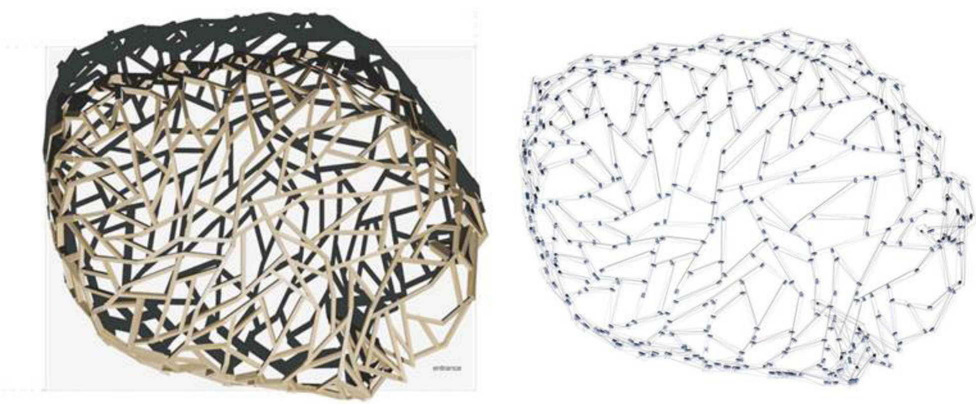
”TECHNOLOGICAL ADVANCES ALWAYS BRING FORTH NEW POSSIBILITIES AND IN ORDER TO BREAK FROM THE CHAINS OF THE ANALOG TRADITIONS, WE NEED DESIGN TOOLS AND METHODS THAT DO NOT JUST EMULATE, BUT TAKE FULL ADVANTAGE OF THE DIGITAL ENVIRONMENT.”

The method of utilizing algorithms and computation as a design aid does not yet have a fixed definition nor a term (including generative design, computational design, algorithmic architecture, etc…). I personally use Algorithm-Aided Design (AAD), as to me it describes the relations of the method to the act of designing, similar as Computer-Aided Design (CAD) does. In addition it translates well into Finnish, retaining its original meaning. The term algorithm-aided design reveals also the additive nature of these methods, as they are design aids, among many others in the tool pack of the designer, and not a strict replacement of any.

Within the digital design environment, we can directly connect ourselves with the computerized fabrication machinery, its possibilities and limitations, and innovate completely new types of digital forms and structures. AAD methods and file-to-factory connections are extending the boundaries of what we can imagine, design and conceive. We are able to manage complex solutions, analyze more quickly and accurately, and fabricate intricate details in mass customized way. This has profound implications to the building industry in whole as we are no longer tied to the use of standardized elements and their rigid rules. Architects become the digital craftsmen, developing new forms, structures and details that are tailored for computerized fabrication.

Explorations in timber

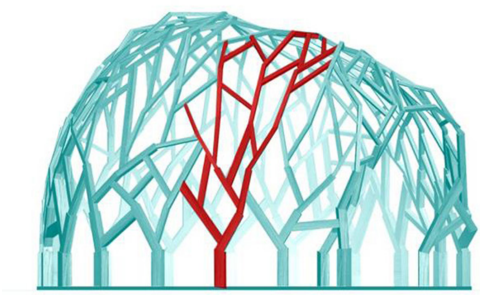
I have been involved in small scale development projects where we have been able to explore the boundaries of contemporary timber design and fabrication. Some projects have been conceived through academia and some through praxis. The common factor in these is that the fabrication has commenced purely through commercial service providers. The lack of available machinery in Finnish universities has pushed us to work with commercial timber production facilities, capable of fabricating digital objects. Here capability refers not only to the technical readiness, but also to the skill and willingness of the machine operator, as unskilled or unwilling operator creates a bigger obstacle than any digital incompatibility could produce. The laborious networking and commercial-sized budgets has limited some possibilities, especially in small-scale studies. But as an added benefit the research seeps from the limited scope of the academia into the real-world processes and realities of the praxis. The knowledge transfer from research into building industry is much more fluent, and for me as a designer and a researcher, it allows the use of the same 'tools' in both ends of the spectrum.



Complex branching mesh and the connections of the Ligna pavilion.

The Ligna pavilion (Lundén & Österlund, 2009) was an exhibition structure for a Finnish company that offers education in timber fabrication and prototyping production facilities. The concept was to design a new type of organic timber structure resembling a forest clearing surrounded by trees. This was achieved by digitally simulating tree growth onto a base form. The digital simulation allowed for a completely new level of complexity and structures inspired by natural processes. The resulting branching mesh was created out of 324 individual timber pieces with 487 wooden connections, fabricated with the same machinery used by log house industry. The pavilion was later erected in the courtyard of the University of Oulu, School of Architecture, for the "Generate –

"THE KNOWLEDGE TRANSFER FROM RESEARCH INTO BUILDING INDUSTRY IS MUCH MORE FLUENT, AND FOR ME AS A DESIGNER AND A RESEARCHER, IT ALLOWS THE USE OF THE SAME 'TOOLS' IN BOTH ENDS OF THE SPECTRUM."



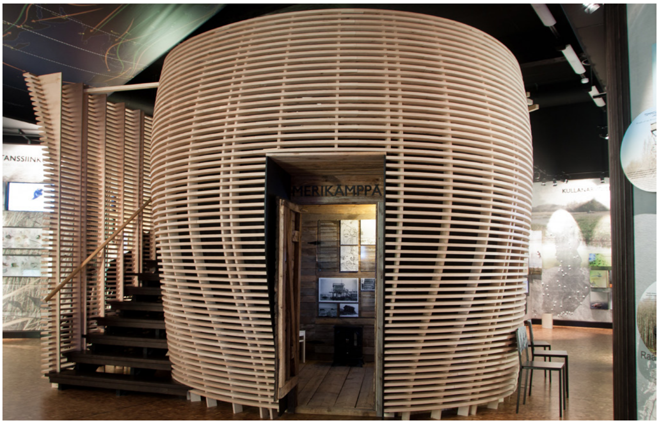
L-system was used to simulate the growth of trees.

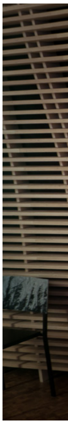
from algorithm to structure" seminar. The exhibition structure for that same seminar was called Kudos (Kosonen, Logren, Metso, Rautiainen, Tanska & Österlund, 2009). It consists of black and white laminated parallel plywood frames, where the individual plywood rows are connected by small hinges. As by itself, a single frame would collapse under its own weight because of the flexible connection of the joint. But by alternating frames that form either an undulating zig-zag or an arch, they form a structurally stiff configuration. This union of two forms help to create a rigid structure, where any two conjoined frames form a free-standing arch. The slight rotation of the undulation of the frames create the appearance of a vortex inside the structure. The lightweight and rigid structure incorporates a simple structural idea with the visual appearance of a kaleidoscopic complexity.


OULU 10

Ligna in the courtyard of the Oulu School of Architecture.

Liminganlahti visitor centre's exhibition pavilion and furniture (Österlund & Architecture Office EST, 2012) was a commission from the exhibition designer. The exhibition itself covers the life of the indigenous birds in Liminganlahti, Finland, and the structure was designed to resemble the smooth curvature of the breast of a bird, and inside of it is a reconstruction of a typical sea man's cabin. On the other side of the pavilion, there is a wall resembling the appearance of cracked egg shell, where children can play games using the recessed interactive screens. The structure is made of lacquered plywood stripes, each different, but which together form the illusion of a smooth and curved form. Innovative use of the flat plywood elements bring out the quality of the wood material in smooth surfaces.





The curved appearance of the Liminganlahti visitor centre's exhibition pavilion is constructed using horizontal plywood strips.

Kudos.

"WE ALREADY WORK IN DIGITAL ENVIRONMENT, SO WE SHOULD EXPLORE ALL THE POSSIBILITIES IT HAS TO OFFER. THE DUALITY OF AN ARCHITECT AS A CREATIVE AND A TECHNICAL PROFESSIONAL IS NOT A NEW IDEA, AND THE ALGORITHM-AIDED DESIGN IS JUST A NEW EMBODIMENT OF THAT."

The wall resembling cracked egg shell. The pieces form together a collage of seasonal nature images.

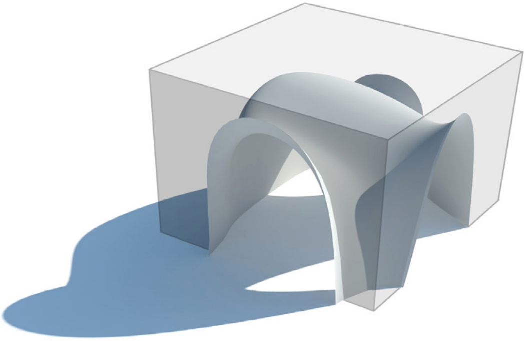
The furniture follow the same form language as the exhibition pavilion.

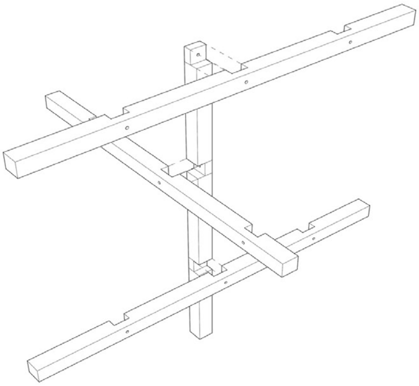
The construction of the HILA pavilion (University of Oulu, DigiWoodLab, 2014) was part of a summer workshop series at the Faculty of architecture, University of Oulu. HILA is located at the Kiikeli island, right in front of the city center. In Finnish 'hila' means lattice, and the pavilion construction is a synthesis of a three-dimensional timber lattice structure and an architectural form. The rectangular outer form is carved by a freeform inner void and the revealed structure inside creates a lace-like appearance. This appearance is amplified by the complex shadows it forms on itself and on the ground. The distribution of the vertical wooden beams is denser on the outer layer in order to have a more solid appearance when viewed from distance. The simple and rigid timber connection brace the structure so no additional diagonal bracing is needed. HILA pavilion consists of 397 prefabricated wooden beams and 1027 joints. The high level of prefabrication allowed for the pavilion be fully assembled without using any power tools. The construction site is more of an assembly site, as the building process resembles solving a huge puzzle.

Embracing the digital

For a designer, the range of possibilities and freedom that the use of AAD methods allow are somewhat overwhelming. The use of algorithms in design allow us to tap into the knowledge of other fields of science, where they communicate and convey ideas through the language of algorithms and code. Because of this, there is no shortage of information or ideas to explore. This also makes collaboration more fluent, as we can work within the same processes utilizing the same language.

Connect that with the highly specific and technical requirements of the digital fabrication machines and their properties, it seems that it is a never ending field of specialization. This is a consuming path, where the idea of an architect as a creative professional is easily blurred against the background of technical know-how. However, it is vital that we as architects get acquainted with that field, and provide our creative view into the mix expanding the collective scientific knowledge. We already work in digital environment, so we should explore all the possibilities it has to offer. The duality of an architect as a creative and a technical professional is not a new idea, and the algorithm-aided design is just a new embodiment of that.





HILA is the synthesis of a three-dimensional wooden lattice structure and a rectangular form carved with a free-form void.

The lattice structure creates a lace-like appearance.

HILA.

Illustrations

All illustrations and phots by the author.

FABRICATING BEHAVIOR

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AALBORG UNIVERSITY AND AREA
&
ANKE PASOLD, AREA

Increasing computer controlled making in architecture has been a clear tendency for some time. Thus, it is difficult to suggest that the application of automated manufacturing processes in architecture and its associated fields, from which the techniques have been adopted from, presents a novel approach of making in architecture.

That stated, the constructs that arrive from these processes appear to approach new formal and functional architectures – also known as performance architectures (Hensel 2013). One such strand is the making of behavioural dynamic constructs through fabrication processes that require high precision in custom and repetitive modes of treating materials into advanced assemblies.

Michael Hensel and Achim Menges has proposed an extended focus on material agency in such processes, integrating potential dynamic properties in the design description (Hensel & Menges 2006). The idea of embedding material dynamics in architecture takes currently two paths – one of plastic transformation (or permanent change) as seen in the work of Phil Ayres (Ayres 2011) among others and one of elastic transformations (or periodic change) as seen in the work of Steffen Reichert (Menges & Reichert 2012) and the authors of this paper (Pasold & Foged 2010; Foged & Pasold 2014), among others. The complexity of dealing with dynamic material agency as part of the manufacturing process offers the advances of embedding or programming the materials response patterns to external stimuli. Such agendas for advanced manufacturing of material properties and their integration into architectural intentions present a set of new architectural possibilities. Two such approaches are discussed below, with concluding remarks and an outlook at the end of the paper.

Two approaches to fabricating behaviour

This text discusses in brief from above orientation in architecture two approaches to fabricating material assemblies, which enable specific environmental behavioural conditions. The first project is based on the construct of acoustic environments through the relations between the musician, the material construction and the sound perceiving occupier. The second project is based on the fabrication of thermal environments through the relation between the solar environment, the material construction and the thermal perceiving occupier.

Fabricating Acoustic Environments

Acoustics in architecture is often determined by the position of the musician in relation to the construct and the listener. More often than not, these three factors are spatially fixed. However, when we start to consider architecture as an extension of the musical instrument, construction becomes literally instrumental through its properties of reflecting, absorbing and transferring sound. The construction therefore shapes acoustic behaviour. If we then consider the spatial positioning of the musician as a design parameter, figure 1, the acoustic behaviour of the construction alters because the sound reflections and absorptions will be different. The project investigates from these conditions how the positioning of the musician can influence the shape and sonic experience, which in turn can inform a design process and a fabrication technique.

The architectural design model is based on a digital parametric model, an acoustic simulation module and an evolutionary algorithmic module. The acoustic module analyses the sound experience, which is modified when the evolutionary algorithm modifies the geometric and material definitions of the parametric model. With an architectural intent to offer two acoustic capacities within the same space, the model searches from the above mentioned group of computational

"WHEN WE START TO CONSIDER ARCHITECTURE AS AN EXTENSION OF THE MUSICAL INSTRUMENT, CONSTRUCTION BECOMES LITERALLY INSTRUMENTAL THROUGH ITS PROPERTIES OF REFLECTING, ABSORBING AND TRANSFERRING SOUND."

techniques. It does so by changing the reflective angles in the space and the absorption of these surfaces through a perforation of the surface layer of a composite structure. The entire structure is created from this sandwich construction of 4mm plywood, 23mm foam and 4 mm plywood, where the perforations of the material's wood surface on the inside of the space/structure alters the surface acoustic properties (see figure 2). The design model is restricted geometrically to maintain the structural integrity of an origami folded surface. The perforations of the plywood layer areas organised in three levels, where each represents a different density of perforations. More perforations equal higher absorption.

From this design process, the acoustic properties of the space are created based on a simple fabrication procedure of plunge routing the wood-foam-wood composite element. To maintain a simple fabrication setup and increase production speed, the same drill can be used for cutting the unique shapes as well as plunging holes in the shapes based on one of the three perforation patterns found by the computational design process. Fabricating behaviour is therefore

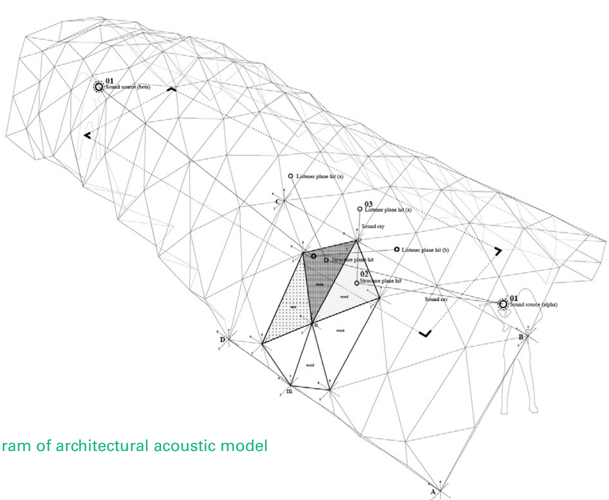


Figure 1. Diagram of architectural acoustic model

Figure 2. Perforations of plywood surface opening the structure to the foam core

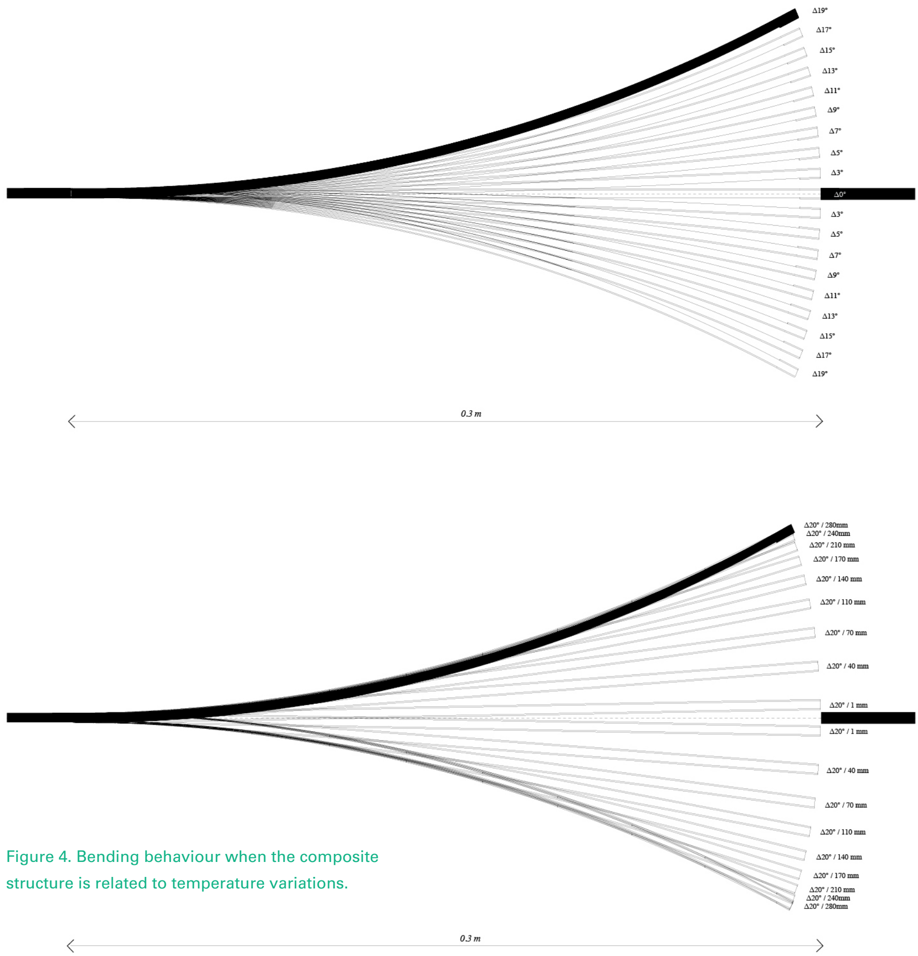


Figure 4. Bending behaviour when the composite structure is related to temperature variations.

pointing both to the fabrication of the material construct and to the 'fabrication' of suggested behaviours by spatial positioning of the musician towards the condition of a specific acoustic environment. While the pavilion appears visually static, the perception of sound is inherently dynamic. This design concept is particularly evident if the musician starts to change position from one end of the pavilion to the other, so that the listeners will perceive the same music differently, as the reverberation time is significantly different due to the fabricated space and material composites. From architectural theorist David Leatherbarrow we also recognize that responsive dynamic behaviour of a construct does not need to be visually expressed (Leatherbarrow 2005) as it passively reacts to the forces that are non-visible. Acoustics, as shown in this project aligns closely with such architectural notions.

Fabricating Thermal Environments

Another approach to fabricating dynamic constructs in architecture is through integrating the thermal related dynamics of a human occupant, the thermal environment and thermal dynamic material properties. Commonly, humans are at thermal comfort around 22 degrees Celsius. But this temperature assumes a particular clothing style, a certain physical level of activity and a set of environmental conditions to be static. In reality, all these are dynamic factors. To address such dynamic conditions, an architectural construction method and design model is developed, based again on a parametric model, a simulation module that calculates the perceived temperature and an evolutionary module, which modifies the geometric and material organisation of

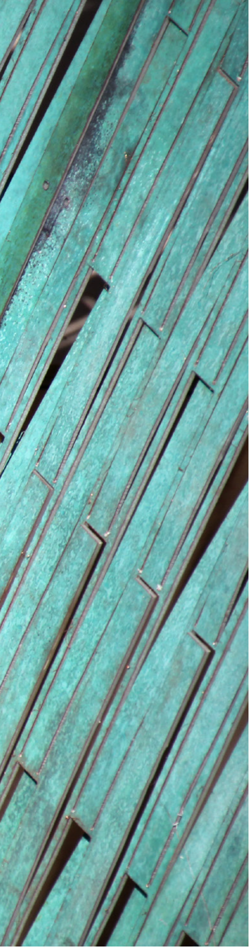
"THROUGH THE INTEGRATED FABRICATION TECHNIQUE, MATERIAL RESPONSE IS EMBEDDED INTO THE STRUCTURE, ALLOWING A FORM OF 'PROGRAMMING' BEHAVIOUR IN AN ARCHITECTURAL ENVELOPE."

Figure 5. Searching fabrication patterns, which result in a behavioural architectural envelope.

Figure 6. Full-scale prototype of the resulting responsive envelope.

the parametric model. In specific, the parametric model combines different materials with different thermal expansion properties. When these are combined as layers in a merged structure, they will start to bend (see figure 4). These composite elements can then be organised as an architectural envelope, which responds to temperature variations through the makeup of the composite structure.

The architectural model allows the designer to prescribe a given thermal environment in a space at a specified time period, and then the architectural design model will start to search for an organisation of different material layers and their different lengths in relation to each other. As the bending element is derived from removing a part of one of the layers from a three-layered copper-polypropylene-copper composite (figure 5), the model effectively searches for a fabrication pattern. In turn, through the integrated fabrication technique,



material response is embedded into the structure, allowing a form of 'programming' behaviour in an architectural envelope. With a similar fabrication method to the one above, the fabrication procedure is based on a simple 3-axis routing technique. As an addition, a tool change is included in the milling procedure that allow a faster removal of the 0.5mm copper material surfaces by a broad flat drill head and a fast cut through the entire composite with a narrow drill, which releases the bending elements and constructs the structural lattice of the module.

The bending elements are then nested in a 1:3 format module, which can be arranged in different organisations as a continuous surface that is easy to assemble on site, figure 6. The fabrication that results in relatively complex composite structures with dynamic response capacities does thus not need to become a complex structural organisations, which often are difficult to install or re-install in case of damage to the system.

The design and complexity of bending behaviour within the module, the elements, is then in contrast to the simple module geometry itself. The project thus also illustrate a way to include advanced performances, but without the complexity of assembling a large set of unique parts, as is very common in current research and practice and as seen in the acoustic project above.

Concluding remarks and future pathways

The resultant architecture of the second project is a dynamic surface derived from the possibilities and constraints of the 3-axis routing technique. In a similar way to the first project, a simple manufacturing technique is able to create advanced acoustic and thermal properties through the use of composite structures. However, despite of the relatively non-complex 3-axis fabrication method, the precision that is necessary (> 0.1mm) for the properties to be embedded correctly points to computer controlled processes over conventional handmade techniques. And in spite of this fabrication precision, flaws in the final prototypes where detected through observation of irregularities in bending behaviour in the second project. As heat is created during the milling process, small variations occur in the material makeup, which appear to have induced the unpredicted properties. From this, it can be suggested that for such fabrication processes, it would be constructive to have a form of sensitivity of the material built into the tooling, which is in direct contact with the material that undergoes treatment. This in turn could offer new possibilities for creating material dynamic constructs in that the fabrication process itself detects and operates according to local material variations during fabrication. An example could be to dynamically analyse fibre organisations in wood, so that the tool path is continuously modified according to the specific material, rather than assuming isotropic properties across the materials treated.

Another path towards future fabrication of behaviour in architectural constructions is the challenge of embedding new behaviour after instalment. This is possible in micro processer based systems, where a system can rewrite its functions. However, if material behaviour could be altered dynamically, new capacities for increased interaction between the material system and the human occupant would be tangible, allowing a more direct and potentially intimate relation between architecture and humans. Today, much sport clothes reacts by allowing vapour to travel through its layers, but it is a linear and predicted response to an increase in humidity. In contrary, as an example, a human hand could touch a building surface, which then would perceive the subjective thermal condition of the specific human and there from modify its behavioural response. Furthermore, in

"IF MATERIAL BEHAVIOUR COULD BE ALTERED DYNAMICALLY, NEW CAPACITIES FOR INCREASED INTERACTION BETWEEN THE MATERIAL SYSTEM AND THE HUMAN OCCUPANT WOULD BE TANGIBLE, ALLOWING A MORE DIRECT AND POTENTIALLY INTIMATE RELATION BETWEEN ARCHITECTURE AND HUMANS."

a space with many occupants, both sensory and actuating material constructions fabricated would require new properties to respond to varying information. A more subtle approach, in terms of connectivity, would be to let the material sense the human on distance, in similarity to thermal cameras. The architectural design process and its products becomes from such ideas not the architectural artefact (alone) but the way in which architecture acts and modifies itself to temporal conditions, such as acoustic, thermal and atmospheric variation over time.

Acknowledgements

The two project prototypes presented have been supported by the Realdania Foundation and published with much greater explanation prior to this paper. Elaborated descriptions of the architectural methods, models, techniques and findings can be found in Foged, I.W., Pasold, A. Brath, M. (2014) Evolution of an Instrumental Architecture, eCAADe2014 Conference Proceedings, Delft, pp. 365-372 and in Foged, I.W., Pasold, A. (2015) Thermal Responsive Envelope – Computational Assembling Behavioural Composites by Additive and Subtractive Processes, Design Modeling Symposium Copenhagen, Springer Verlag. Further theoretical and methodological elaborations can also be found in the PhD thesis by Foged, I.W. (2015) Environmental Tectonics: Matter Based Architectural Computation, Aalborg University Press.

Illustrations

All Illustrations by the Authors

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DIGITAL FABRICATION

SØREN JENSEN,
SØREN JENSEN RÅDGIVENDE INGENIØRFIRMA A/S

Digital fabrication has long been customary in the car industry, among other places. The desired precision and complex geometries are the greatest drivers for the implementation of this technology. When this is paired with a high degree of repetition and a desire for low costs, digital fabrication becomes a necessity. Since the whole process, from concept to fabrication, takes place under the same roof the digital information can be optimised and used throughout the whole project.

The construction industry is a bit different and the projects are seldom alike. However, many parallels can be drawn to the car industry, and as digital design tool are still more developed, building projects become increasingly complex too, both technically and geometrically. It is often in these cases of complex geometries that digital fabrication is usable even though a high degree of repetition can also be a driver in large scale projects. However, the future tendency among leading steel manufacturers is that even the production of the simplest elements is driven by digital information.

There are great potential in, i.a., the exchange of the digital information between the parties involved. One of the greatest obstacles to this development is, among other things, driven by a very tradition-bound industry which does not follow the current trends. The requirement of documentation in 2D is obsolete in the eyes of many manufacturers and highly time-demanding to produce for the advisers. This is due to the fact that many building geometries are now difficult, if not im-

Heimdal, interior photo during construction work.

possible, to reproduce and specify on a 2D drawing and even more difficult to produce without a 3D representation. Therefore in most projects the steel manufacturer builds his own digital 3D model which is then used as direct information to the manufacturing machine.

As a main rule it is not at present possible to apply the same digital model of the building throughout the whole process. Among other things this is due to the fact that the parties involved work with highly different tolerances and the necessary precision in 3D rises as the project progresses. In order for it to be profitable it will require that the

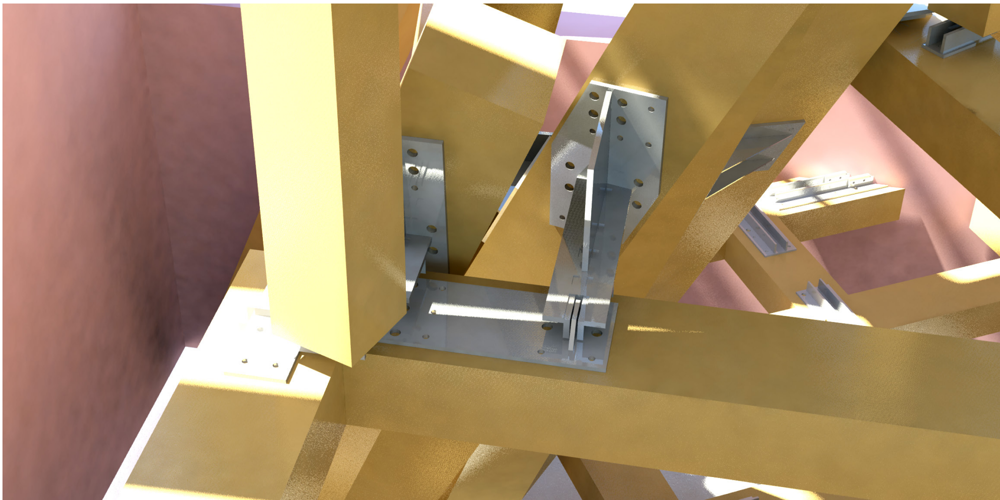
"THIS KIND OF PRODUCTION IS ONLY POSSIBLE WHEN USING DIGITAL MANUFACTURING TOOLS WHERE ONE IS WORKING WITH VERY SMALL TOLERANCES, AND WHERE DATA CAN BE LED ALL THE WAY FROM THE THREE-DIMENSIONAL REPRESENTATION TO THE DIGITAL PRODUCTION."

necessary time is spent to build and maintain a 3D model instead of generating documentation in the shape of 2D drawings. A reaction is required from the whole industry: from authorities, developers, architects, engineers, manufactures to contractors, if this is to be changed into a process where the interfaces between areas of responsibility are erased as the digital information is carried all the way through the project.

If this becomes a reality it opens up to entirely new ways of thinking about form and construction. Traditionally, the building's form is the outer frame of the individual parts which need adjusting and modification in order that the desired form can be obtained. This outer frame is defined by the aid of plans, sections and elevations. Information in the 3D model becomes reduced to a two-dimensional representation and, as a consequence, much information is lost. As a result much resource is often used afterwards to coordinate and answer questions regarding obscurities in the material.

Working with digital fabrication and the small tolerances connected to this opens up the possibility for the form of the individual parts to work together to create the outer frames. This philosophy is evident in for instance Søren Jensen's research project PolyShell, where the geometry is created without two-dimensional representations of the end result. The geometry is created by the individual parts which, together, create the whole. This kind of production is only possible when using digital manufacturing tools where one is working with very small tolerances, and where data can be led all the way from the three-dimensional representation to the digital production. In this case the manufacturing tools work directly from data collected from the 3D model and thereby the whole two-dimensional representation becomes obsolete.

As the complexity in building projects rises, and as new manufacturing techniques are developed, as for instance 3D print in full scale, it becomes still more necessary that the individual parties involved in the process exchange digital data. It would be even better if all parties work on, and share, the same data.



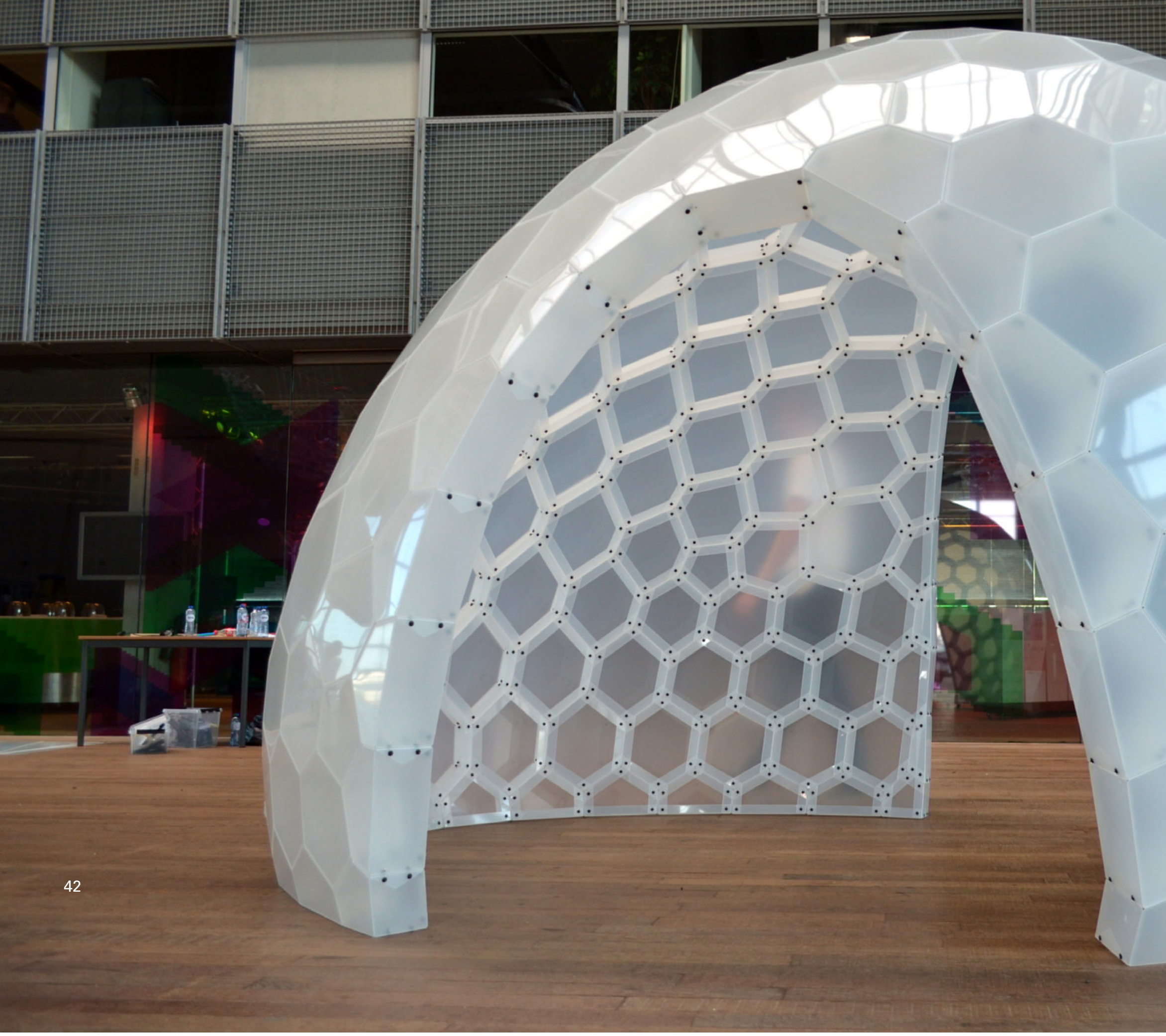
Heimdal, interior photo during construction work

Heimdal.

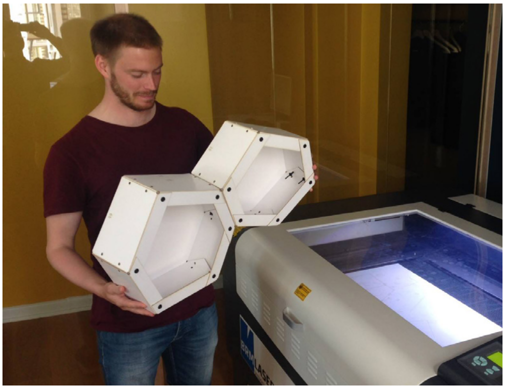
Heimdal

With Frank Gehry as design architect, the partially listed caretaker's building from 1918 has been transformed into a spectacular counselling centre in wood and glass. The old outer walls of the house have been preserved but are no longer bearing, and an impressive interior timber construction now bears a new glass roof and two new floating floors.

The construction's wooden posts measure 45 and has a height up to 14 metres, and combined they create a construction which most of all resembles the sticks in a Mikado game: a highly complex and static structure which is assembled with 500 different specially designed steel fittings, communicated by 8000 manufacturing drawings. Due to the great variation in the individual steel fittings a manual process was far too expensive. The 8000 sheet parts were cut precisely according to a CAD file which was exported from the BIM model. The great challenge with this number of sheet parts was, apart from the production itself, to number each sheet part in a way as to make it clear which fitting and position it belonged to. With the numbering the individual sheet parts could be retrieved in the BIM model and their positions in the building could be determined.



PolyShell exhibited in Amsterdam at IASS 2016.



Digital fabrication at the practice's lasercutter

The individual boxes before the assembling of the construction

PolyShell

The project arose as an answer to the question: “How can a thin sheet material with no bending stiffness be made to enclose a larger volume?” This resulted in a double-curved steel construction made of 1.5 millimetres thick laser-cut folded polypropylene sheets. The folded sheets constitute a total of 205 unique boxes which together create the final form.

For the design and production of the construction a number of digital tools have been applied which are rapidly becoming an integrated part of the modern culture of engineers and architects – parametric geometrical modelling, optimization algorithms and digital fabrication.

The Greenhouses

The Botanical Garden's palm house is shaped according to the sun's trajectory. The dome shape and its orientation according to the corners of the world have been obtained via parametric design with integrated energy analyses. The shape ensures the greatest possible solar radiation during the winter and the least possible during the summer. At the same time the shape has enabled the smallest possible surface in proportion to the largest possible volume, making room for the tall trees in the greenhouse.

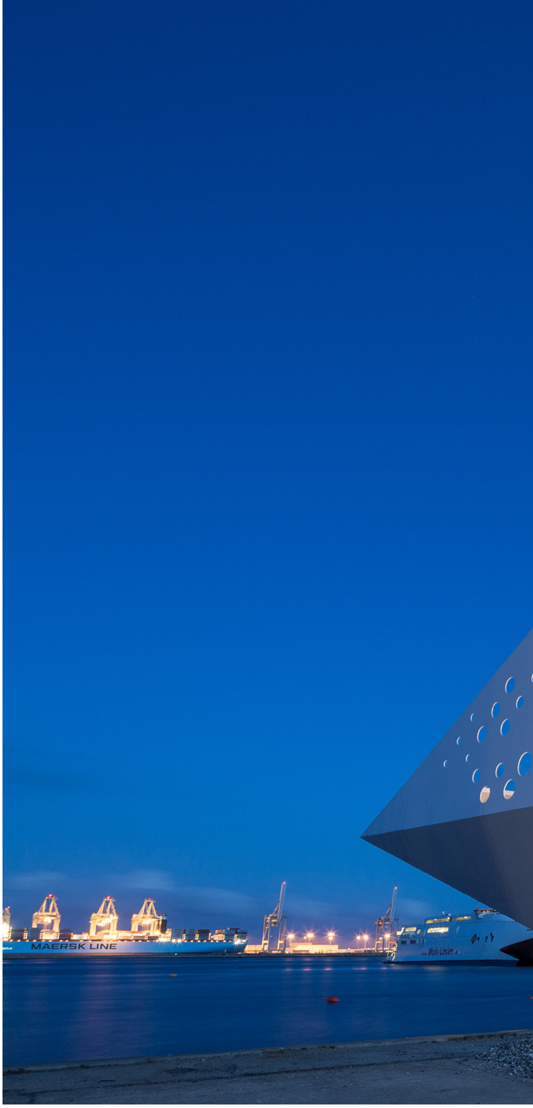
The large steel bows that create the dome's shape were made with the aid of digital production where information from a three-dimensional model was used to directly manage, for instance the rolling radiuses which, due to the complex geometry, vary along the bow's path.

The Green House in the Botanical Garden.

Assemblage of digitally produced steel bows

"A REACTION IS REQUIRED FROM THE WHOLE INDUSTRY: FROM AUTHORITIES, DEVELOPERS, ARCHITECTS, ENGINEERS, MANUFACTURES TO CONTRACTORS, IF THIS IS TO BE CHANGED INTO A PROCESS WHERE THE INTERFACES BETWEEN AREAS OF RESPONSIBILITY ARE ERASED AS THE DIGITAL INFORMATION IS CARRIED ALL THE WAY THROUGH THE PROJECT."

Raw steel plates for the Observation Tower



Observation tower at Aarhus Harbour

Observation tower at Aarhus harbour

The dynamic-looking observation tower at Aarhus harbour is created as a steel construction, standing on its narrow base on the existing quay. The tower's geometry is optimised by parametric analyses. These analyses also contain estimations of the tower's balance in relation to stability and supporting structure.

Digital tools were used in the production of the large steel sheets which together constitute the tower's geometry.

Illustrations

p. 40: Photos: Søren Jensen Rådgivende Ingeniørfirma A/S

p. 41: Photo: Quintin Lake

p. 42: Photos: Søren Jensen Rådgivende Ingeniørfirma A/S

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DIGITAL FABRICATION
– BACK TO THE FUTURE!

KARL CHRISTIANSEN, ARCHITECT
AND PROFESSOR, AARHUS SCHOOL OF
ARCHITECTURE

In contrast to standard products, digital possibilities are able to industrialise a production of building components, which can all have different forms. All in all, the architecture of the future will be given opportunities to expand and renew itself through a richness of form and in a language the world has never seen before.

The straightforward and obvious benefits of using digitally controlled robots in the production of architecture can be seen by everyone: the robots are fast, they don't catch a flu or get their fingers "caught in the machine", also they work night and day, and during weekends. Such things are undoubtedly good for the bottom line.

But there are other benefits, which surpass the pragmatic and rational. We can consequently welcome back the revival of craftsman-like virtues such as a high degree of individuality, albeit now in industrialised version. Similarly, improved possibilities for coherence between drawing and fabrication maximise the interaction between form and content in architecture. The computer's calculation skills can optimise the building process and the use of materials, which is beneficial to sustainability. All in all, the fact that the digital is being incorporated in the production of architecture provides architects with absolutely new and forward-looking architectural possibilities – and, so far, we have only seen the top of the iceberg.

Looking backward

100-150 years ago, when society was characterised by agriculture and craftsmanship, much of what was built we definitely wouldn't like to live with today. Think about moisture, leaks, stove heating and having the john in the backyard, and not least the diseases resulting from this kind of arrangements. However, some things from this era we still appreciate today: craftsmanship is one of those things. At that time one could get a product that was produced the way you wanted it. Each product customised to suit the taste and needs of individuals. This was possible because everything was made by hand. Whether the width of a window needed to be 120 cm, 125 cm or 125.5 cm was all the same to the craftsman. The timber had to be cut in any event, and whether the joiner cut it here or there didn't matter. In that sense one could have a product customised – made individual. At the same time nothing was saved by ordering two or three of a kind. The subsequent copies were also made by hand, and took as long time to make as the first, for which reason the price was consequently almost the same, irrespective of the volume. The architectural idiom at the time mirrored the above-mentioned individuality, and in order to draw things, architects needed to know how they were constructed. Architects without a background in craftsmanship were unthinkable.

In the early 1900s industrialism became dominant. Now components had to be mass produced. Products were stored, and customers could come by and pick up, for instance, a window. Which was now, however, invariably either "a little too small" or "a little too big". On the other hand, significant amounts could be saved by buying larger volumes. Things were produced in a factory, under controlled conditions. Once the machinery was set for a specific product, one had to "exploit" this setup in order to rationalise and produce as many items as possible. And this had a noticeable influence on the price. The watchwords were standardisation and repetition, and the world was in concrete terms shaped by this industrialised way of production, which not least the architectural idiom reflected. At the same time it wasn't really necessary for the architect to know every detail of the mass-produced building elements. The task was limited to picking out and choosing from catalogues, and then assembling the elements. The fact that one doesn't know how things are actually produced, and that one has to settle for the available size, are some of the alienating aspects that have been the target of criticism for about a hundred years.

Experiment from Anders Gammelgaard Nielsen and Karl Christiansen's research project: *"Industrialized Individuality"*

Like the cobblestone pavement below, the concrete elements can be customised individually. Which gives the architect new possibilities to bring some of the craftsman-like virtues back to architecture.

Now - and in the Future

Today it's been a while since we entered the hyper complex era, whose technical tools we already in a variety of areas control and are familiar with. The personal computer is a good example. Nearly everything related to architecture is today drawn, calculated and managed using computers, just as many building elements are fabricated with the aid of digital tools. But there are two categorically different ways of applying these new possibilities:

One is as an actual aid for realising the architecture you have already decided upon. Here the digital becomes a concrete tool in the same way as traditional tools, though the new possibilities are much faster and more rational. But the idiom of the architecture is not significantly changed.

The other way is by inviting 'in' the digital, as an active part of the actual generative process. When the robot is working, it doesn't care whether it has to cut the timber here, there or in a third, entirely different, place. And, consequently, it really doesn't matter whether a given element is exactly similar to or different from the one before or the following. Which means that there is no longer a demand for repetition and standardisation; you can have it the way you want. It looks similar to the individuality we so much liked in the 'old days'. But now the individual has been industrialised – as has been the direct connection between the drawn and how the drawn is fabricated. The generative process no longer necessarily represents a direct line from design to fabrication. The circumstances of the fabrication, which the architect now again carefully has to investigate, can provide 'feedback' for and be included in a redesign, which will result in another, new, fabrication, which again can 'loop back' to yet another design, which again...and so on and so forth to infinity – so to speak. Because of the enormous calculation capacity of the computer, the number of times these iterations can be repeated far exceeds what was earlier humanly possible. And as architecture's coherence between form and content (in this case how architecture is concretely built) has always been a prominent norm of value, we now see that the digital is taking us as close to this objective as we have ever been before.

It is in its genes that the idiom of architecture constantly has to change. The digital breaks with the limiting and final geometry of Euclid, and is becoming infinite – amorphous. That doesn't mean that the amorphous itself is new. What is new is that we now actually, within reasonable limits, including the economic, are able to realise this complex amorphous geometry. And this is where the idiom of architecture now makes a quantum leap, and becomes definitely new.

Let's suppose you wanted a concrete element, predominantly amorphous in shape. The element is generated in a computer program, i.e. topologically optimised. The drawing which represents the geometrical shape of the element is a file, a series of information which, now, taking the same file as a starting point can be used for concretely realising the concrete element in all its phases, since the information from the file can be transferred to, and be used in the different kind of robots which:

- produce the formwork in which the element has to be casted
- process the surface of the formwork to the desired structure
- Mix the aggregates in precise amounts
- Bend and weld the reinforcing steel, to be casted into the concrete
- Finish the surface of the element after dismantling
- Produce the wrapping in which the element will be transported
- And all in all, manage, handle and move the element in between all these many operations, all the way to mounting the element in its final position on site

If we zoom out now to get an overview, we will see a new architecture spread. An architecture that is not limited by standards and repetition, but which contains an individual free richness in geometrical form and adaptability in all thinkable details. Add to this that the sustainability of the whole building process can be optimised in terms of function, fabrication and material consumption. That we are able to build with a precision never seen before, in a shorter span of time, and that dangerous working operations can be solved by ”insensible” robots.

The human aspect

No – the architecture is not to be created by computers and robots - but still by the architect! The computer is still 'stupid' and not poetic at all. But the computer offers an infinite amount of possibilities, which we can draw on. And if we architects learn and understand the scope of all these possibilities, we are equipped to create an almost unlimited architecture which – in all its facets – exceeds even our wildest imaginations... digital fabrication is here to stay!

OPEN ROOMs

OPEN ROOM 01
MODERNE ARBEJDSRUM – FRIHED VS. FRIKTION?

OPEN ROOM 02
TECHNOLOGY IS THE ANSWER, BUT WHAT IS THE QUESTION

OPEN ROOM 03
DIGITAL FABRICATION IN TOMORROW'S ARCHITECTURE

OPEN ROOM 04
KAN BYGGET VELFÆRD EKSPORTERES?

OPEN ROOM 05
SKAB BYEN SAMMEN

OPEN ROOM 03

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