Performative Wood

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This research builds upon projects from both university and practice to explore new approaches on how the multifunctionality, flexibility, and performance of wood can be utilized to inform new approaches towards both design and fabrication. The following projects use physical prototypes to bend wood just within its tolerances, design with the high precision of multi-axis robotic fabrication in mind, and finally inform the shape of a large free-form structure through material properties.

Keywords: *wood, high-performance material, CNC, robotic fabrication, geometric design*

MOTIVATION

Wood is one of *the* traditional materials in architecture, but has gone through significant developments over the centuries and is now perceived as a high-performance material. It has evolved from being used for dome-like huts at the beginning of mankind to industrialized, pre-fabricated housing, but is still the subject of significant research, resulting e.g. in highly durable wood composite materials, or new strategies for forming wood. In this paper we will focus on the performance of wood in terms of the transfer from digital to physical 3D space in architectural design and education, and its inherent *multi-functionality* - from the "natural" behaviour of bending to the use of high-end CNC (Computer Numeric Control) fabrication methods.

WOOD AS DESIGN PARAMETER

Material has become an important design factor. In our research-based teaching we try to incorporate material properties in the design process by developing plug-ins and add-ons for Computer Aided Design (CAD) systems that approximate behaviour or provide feedback/simulations of the fabrication process. We identified three distinctive ways of approaching materiality as a design driver for complex spatial structures:

- A material-based approach via physical experimentation with material properties, which is a well-established method dating back to the earliest buildings.
- A semi-automated fabrication approach by adapting recent CNC technologies for transferring between virtual and physical space.
- A pure digital approach where material relevant properties are simulated right at the beginning of a design process.

Designing through Material Experimentation

The design studio Bending without Breaking - taught at TU Vienna's Institute for Structural Design and Timber Construction - experimented with a canopy structure of over 5 by 5 metres and a diagonal of 7 metres to span the main entrance of the Künstlerhaus in Vienna (see figure 1). The main challenge was the physical behaviour of a wide-span structure and its complex bending in two directions. A solution was found through the analysis of the industrial process of fabricating glue laminated girders that was adapted by the students to produce a large scale structure. Initially, the plan was to create a rib structure out of precisely CNC-cut wood elements that would control the shape and bending of the form within tight tolerances. However, this would have required more material and resulted in additional weight and increased torsion at the main girder. Therefore, in order to define the three-dimensional spatial structure, the students established a simple design principle by dividing a planar wooden plate into eight strip segments by offsetting a sequence of squares. For the third dimension each second quadratic strip was bent in the opposite direction of the previous strip, resulting in a sequence of positive and negative curvature.

Comparable to the paper cutting tradition of Kirigami (Jackson 2011) the three-dimensional space structure of a manta ray is generated out of a single plane, hovering across the visitors´ heads. The canopy is supported by 2 columns, its spine consisting of a reinforced comb interleaved with the plate strips.

Each strip consists of two layers of plywood, which are glue laminated to control and stabilize the form of the manta strips; additional bolts secure the

Figure 1
Installation "Bending without Breaking" at the entrance of the Künstlerhaus Vienna

form. The compensation of the material bounce back and as such the geometry of the form-giving mould for the cold forming process were explored by the students via trial and error and re-used for all 16 strips. For the bending, a wooden offset form was generated and two layers of plywood strips - each one 5 by 2.5 meters - and placed on top of it. To ensure that the wood bends without breaking, each strip was cut 5mm deep, normal to the bending direction.

Now, it became possible to force the strip into position and to fasten it with screws spaced at a distance of approximately 20cm (see figure 2). The final assembly of all wooden elements was performed onsite at the Künstlerhaus within 36 hours moving from the outside to the inside. For every strip, 4mm tolerance was added to ensure that the central element would fit, despite any tolerances that result from the assembly or the bending.

Adapting CNC Technologies for a Virtual to Physical Design-Transfer

Another project of the design studio experimented with an intelligent strategy for creating a 3D structure by selectively cutting a single, laminated, planar wood panel. The lamination is done by inserting a layer of fibre-glass fabric between the wooden layers. Joints are created by selectively removing wooden material, while leaving the inner fibre-glass layer intact, which would then act as a hinge. By controlling and shaping the amount of removed material, axis limits for each hinge are defined, finally resulting in a complex, self-interlocking system with flexible hinges.

This project was again inspired by Kirigami and relies on a seamless transfer from digital to physical space, informed by machinic cutting conditions in combination with a flexible joint system. In this design, the geometry of the joint system has to be accurate, with the cutting angles precisely defined within the code, requiring accurate CNC machining with a multi-axis machine that can process cuts of -45 to +45 degrees in a workspace of at least the width of the panel, in that case about 1 by 1 metres. The only locally available CNC machine capable of fulfilling these requirements was one of the Association for Robots in Architecture's KUKA KR16 robots with an attached milling spindle. In a common workflow, the students would have to create a threedimensional model in CAD software for every part, calculate the toolpaths using a Computer Aided Manufacturing (CAM) software, and then simulate the robotic fabrication in a special robot-simulation environment (Brell-Cokcan and Braumann 2010). However, we managed to streamline the fabrication process by creating a parametric system in Grasshopper that would generate all necessary cuts and directly connects with KUKA|prc (Braumann and Brell-Cokcan 2011). This plugin for Grasshopper provides a direct interface that converts parametric toolpaths into a format that the robot can understand, while also simulating the robot's kinematic movements. Due to the large extents of the single wood panel, even the robot's large workspace was insufficient to create all cuts. Therefore, we developed a semi-automated workflow that contained all robotic toolpaths. After each cut, a comment in the robot code would instruct the user by how far the panel has to be advanced, before starting the next operation.

This resulted in a complex system of varying, mathematically calculated cut-angles forming a self-interlocking, flexible joint system that allows the transformation of a flat panel to a spatial structure, facilitating both fabrication, transport, and mounting (see figure 3).

Materializing the Fabrication Process

Once the scale changes from small scale canopy structures or objects to large scale free-form structures as below, the data flow from digital design to fabrication gains even greater importance. Realized large scale wooden constructions such as the Centre Pompidou in Metz by Shigeru Ban (Scheurer 2010) or Metropol Parasol in Sevilla (Lepik and Santner 2011) have in common that CNC fabrication was of great importance for the overall production process.

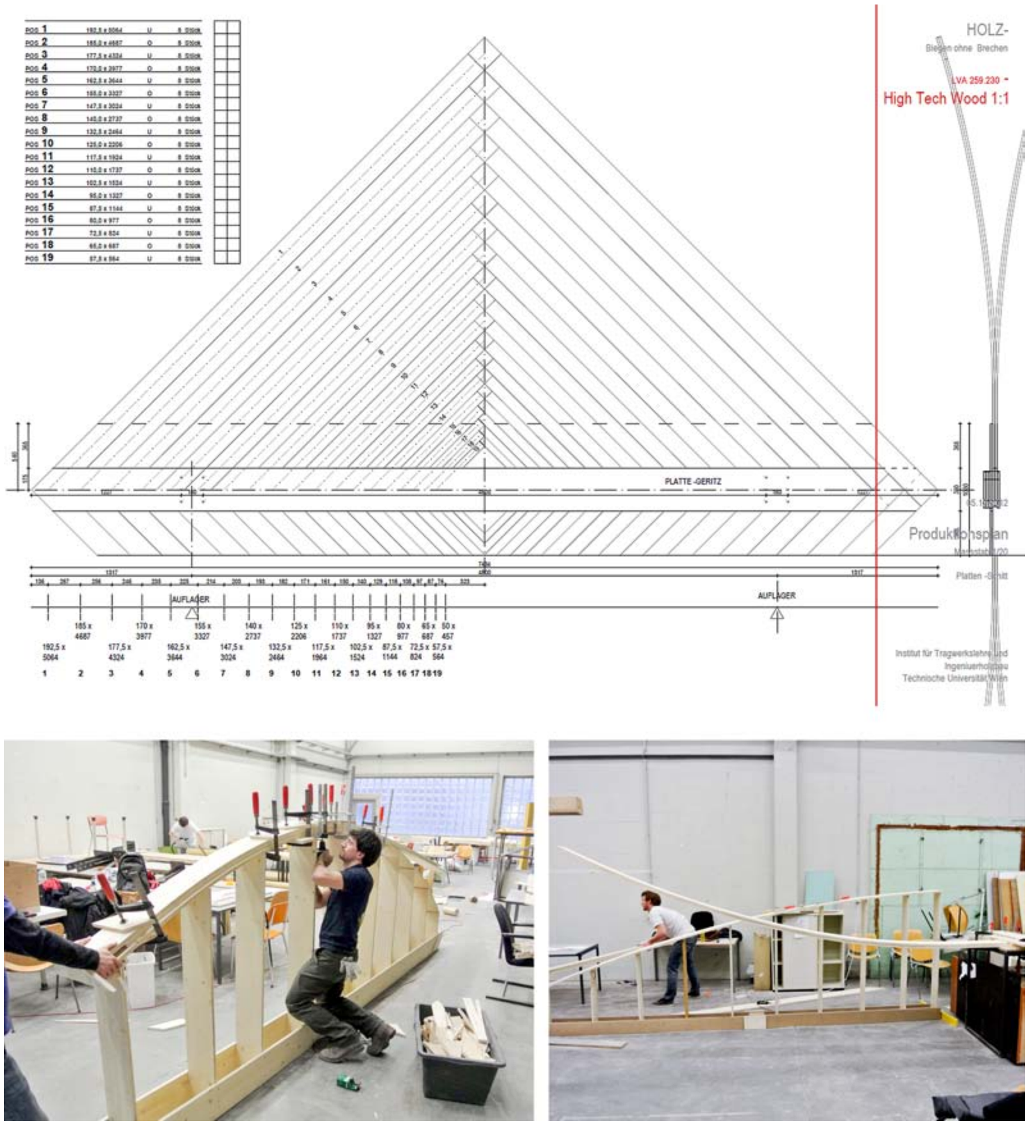

Figure 2
Construction drawings of the two-dimensional cutting pattern (above), material deformation experiments (lower left), layered bending process using glued plywood plates (lower right)

Figure 3
Flexible joint system with laminated plywood panels and milling of angled connection parts

However, what we believe to be still missing in their design to fabrication process are the material properties of wood which have not been considered as an active design parameter.

Both projects show that CNC technology was used to mill the finishing surface of all structural glue laminated girders and to adapt the structure in high precision to the geometrically changing conditions of a freeform surface. The special properties of wood that allow it to be bent (see ""Designing through Material Experimentation") have not yet been encountered in large scale construction. Instead industry is aiming to achieve high precision, even though wood is an inhomogeneous, anisotropic material.

The fabrication process of milling a wooden lattice structure to be inserted into a steel and concrete structure (as seen in the Metropol parasol project) is not too different from common steel construction, with the only difference being that a softer material was milled to overcome the geometric deviations between the structure and the freeform surface. While processes like CNC cutting, milling or waterjet cutting can be interchanged according to the type of material used, wood with its inhomogeneous properties has got the potential of adding a value to the design to production process that is discussed in the Düzce Teknopark large scale project (see figure 4).

ACTIVATING MATERIAL TOLERANCES IN THE DIGITAL DESIGN TO FABRICATION PROCESS

An approach towards informing wooden freeform surfaces with digital tools is the use of mathematical algorithms for "planarizing" a freeform façade. In this project, in contrast to the previous educational projects, the performance of wood has to be virtually prototyped before the building process. However, even state of the art software for processing a digital surface is not enough to design a prototypical full scale architectural project, requiring additional plugins, custom-tailored for that project. The resulting applied research into analysing and informing material specific requirements, as well as the dig-

Figure 4
Scale-model of the free-form Düzce Teknopark design

ital performance of customized CAD will be further discussed in this paper, as our full-scale application of these techniques for a freeform technology centre in Turkey has been greatly influenced by having the material inform the fabrication of the physical output. The core element of the Düzce Teknopark is its outer shell, which was designed and optimized to offer a balanced layout of public and private areas as well as high ecological and environmental performance, while visually representing the dynamic and innovative research that is happening inside. Thus, the shell is geometrically a double-curved freeform geometry. While such surfaces are nowadays easy to construct in CAD software, they are highly complicated to turn into constructible, large-scale geometries, as - unlike single-curved surfaces - they are not developable, requiring threedimensionally shaped façade elements, instead of simple 2D-cut parts. Only triangulation would allow the geometrical "flattening" of such a surface, though at the expense of more complicated knots and connection length.

One of the first challenges in the Düzce Teknopark project was therefore the topological and geometrical optimization of the building's shell. As software tools, the CAD tool Rhinoceros, the parametric modelling plugin Grasshopper, and the geometric optimization software Evolute Tools were used. The latter software was specifically developed for processing complex surfaces (Eigensatz et al. 2010), but does not provide an automated solution for such geometries, instead requiring careful interaction with both the geometry and the software's parameters. Evolute works similar to a physics solver, where different weights are attached to certain properties. The software then performs calculations, until an equilibrium state is achieved where the defined forces are in balance. However, such a process greatly depends on the quality of the initial, rough geometry, which is then refined and adjusted until it best approximates the given freeform surface. We therefore developed customized tools within the parametric modelling environment Grasshopper that allowed us to accurately adjust and fine-tune the generation of the initial mesh. This data was then processed in Evolute, to generate a mesh that would create equilateral elements that are as evenly spaced and as planar as possible. However, these forces work against each other, as evenly spaced elements may sacrifice their planarity and the other way around. As mentioned above, a mathematically exact planarity of such a surface could only be achieved with triangulation. We therefore had to precisely evaluate the physical properties of the materials of the external shell to establish the maximum allowable amount of unplanarity for each material, as e.g. glass can only be bent by 0.8 millimetres per metre, while the wooden components allow up to five times as much transformation (see figure 5). As the double-curved geometry is not symmetrical, the results of the optimization process greatly differ depending on the local geometry, with very planar elements in geometrically nearly single-curved areas, but quite unplanar elements in areas with significant double-curvature. Therefore, the question is not which material to apply to the *whole* structure, but rather where each material could be potentially applied. Using a custom software tool within Grasshopper, we analysed the mesh that was previously optimized within Evolute and assigned zones to each panel that signify the allowable selection of materials. The final choice of all the available materials was finally made according to building requirements such as interior lightening, heat load, and aesthetics (see figure 6).

CONCLUSION

The Düzce Teknopark project confronted us with the highly complex problem of segmenting a double-curved surface into constructible elements. In our previous wooden projects that were made in an educational context, we explored the possibilities of taken advantage of material properties and efficient CNC fabrication. Especially the Manta project shows that complex shapes often do not have to be subtractively fabricated, but can actually be produced by relatively simple means, if one considers the material properties - without even requiring CNC machines. In the case of the Düzce Teknopark, this approach enables us to intelligently assign construction materials over a complex surface according to their material behaviour. As the curvature and geometric properties change fluently along the surface, this process does not lead to an erratic shell, but rather to

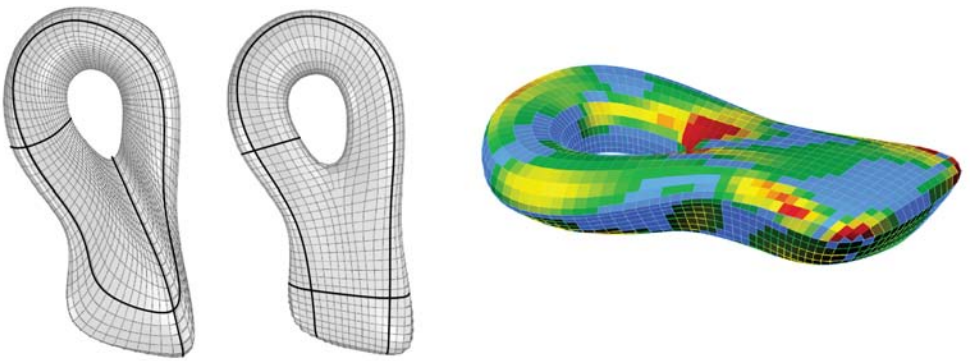

Figure 5
Optimization and Analysis: Top view before (left) and after (middle) mesh optimization in Grasshopper, planarity analysis in Evolute (right): blue is within required glass planarity tolerances

Figure 6
Interior view of the wooden construction of Düzce Teknopark

a performance-based design where geometric properties can be read from the outside.

At the moment, construction of the concrete foundation in Düzce are starting. Once finished, new measurements will be taken and the current digital model adapted to the physical realities of the construction site. Ideally, we will then be able to link the geometric data to a CNC machine for a fluid design to fabrication process that not only takes the geometry, but also the material constraints into account.

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REFERENCES

Braumann, J and Brell-Cokcan, S 2011 'Parametric Robot Control: Integrated CAD/CAM for Architectural Design', *ACADIA 2011 Proceedings*, Banff, pp. 242-251

Brell-Cokcan, S and Braumann, J 2010 'A New Parametric Design Tool for Robot Milling', *ACADIA 2010 Proceedings*, New York, pp. 357-363

Eigensatz, M, Kilian, M, Schiftner, A, Mitra, N, Pottmann, H and Pauly, M 2010 'Paneling Architectural Freeform Surfaces', *Proc. SIGGRAPH 2010*

Jackson, P 2011, *Folding Techniques for Designers*, Laurence King Publishers, London

Lepik, A and Santner, A (eds) 2011, *Metropol Parasol*, Hatje Cantz Verlag, Stuttgart

Scheurer, F 2010, 'Materialising Complexity', *Architectural Design*, 80, pp. 86-93