Individualizing Wood Production – new design and production decision support systems

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1. Motivation

In recent years, a rising number of technical solutions encountered the field of production and manufacturing. In architecture such novel possibilities led to an advanced level of diversity and individuality. Hence, various traditional manufacturing methods have to be rethought under the aspect of cost-efficiency as well as flexibility during production processes. In this context, the new Chair for Individualized Production at RWTH Aachen University establishes fundamental technical development in wood and stone processing combining the advantages of traditional methods and newest technology.
The research agenda for machine supported processing of naturally grown and inhomogeneous building materials includes the following aspects:

- Utilizing methods of manual as well as automated wood/stone processing
- Transfer of expert knowledge in machine supported processing of inhomogeneous materials to CAD and BIM
- Identification of analogies between wood and stone processing procedures and their automation potential
- New human-machine-interfaces for intuitive processing of inhomogeneous building materials

Since wood allows for simple processing procedures, it plays an important role in architectural construction from the early construction history - e.g. traditional temple construction of Greeks and Romans - up to now (Affentranger 2001). Nevertheless, wood as high value building material almost disappeared from European building sites during early periods of industrialization. Instead, high quality material processing for example creating ornaments for representative stone buildings remained in the portfolio of architectural creation and therefore a wide range of processing methods was developed. However, tendencies of purism of the early 20th century supported by A. Loos subsequently threw ornamentation in stone just as well into crisis. Therefore, high quality material processing of wood and stone became more or less obsolete in Europe.
In order to maintain and add onto the long history of wood and stone processing, working methods of both fields need to be adjusted to meet the demand of current working procedures and digital processes. Therefore, research effort is put into analysis and synthesis of diverse processing procedures in wood and stone and the evaluation of possible transformations to generate (semi-)automated machine-driven processing. Additionally, focus lays on the *robotic* processing of inhomogeneous materials promoting the general aim of digitalization and automation of small and medium enterprises in the building and manufacturing sector.
In the following sections, an overview on the current research progress for individualizing material processing is presented. The first set of project highlights the integration of new technology for the creation of automated processing procedures in the context of robotic production. Subsequently, the factor of materiality for process development on the example of wood is described.

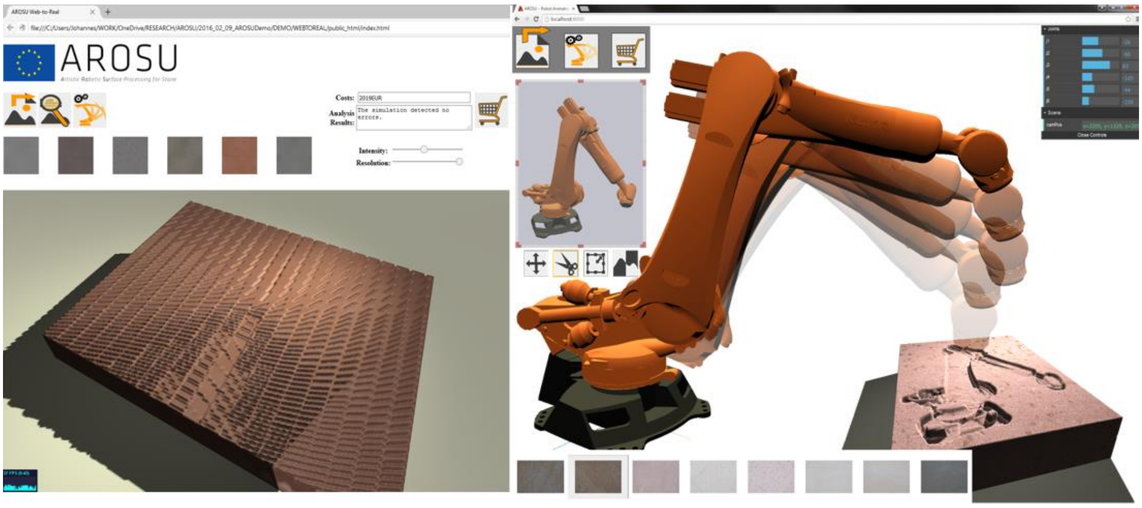
2. Technology as production parameter

2.1. Cloud robotics & decentralized production

The project AROSU "Artistic Robotic Surface Processing for Stone" is an example for raising traditional handcraft to the 21st century with the help of newest technology. Via analyzing the manual procedure, a robotic chiseling process was developed for surface processing of stone blocks. But instead of only transferring the process one by one, the new procedures were tested with the possibilities of the new machinery. Overcoming the limitations of human power and movement controllability, new aesthetics through robotic processing were created.

Manual chiseling equipment and surface design (left), robotically chiseled surface design

Developing robotic processes and therefore implementing digital production planning allows for further interconnection with other state-of-the art technology. In the course of the AROSU project a web-to-real interface was created (Stumm, 2016) that allows to link customers of individualized objects with manufacturers on a new level using cloud robotics. Such interfaces in turn provide the opportunity of new business models for decentralized production which might be able to increase the efficiency of the building sector and its component suppliers.

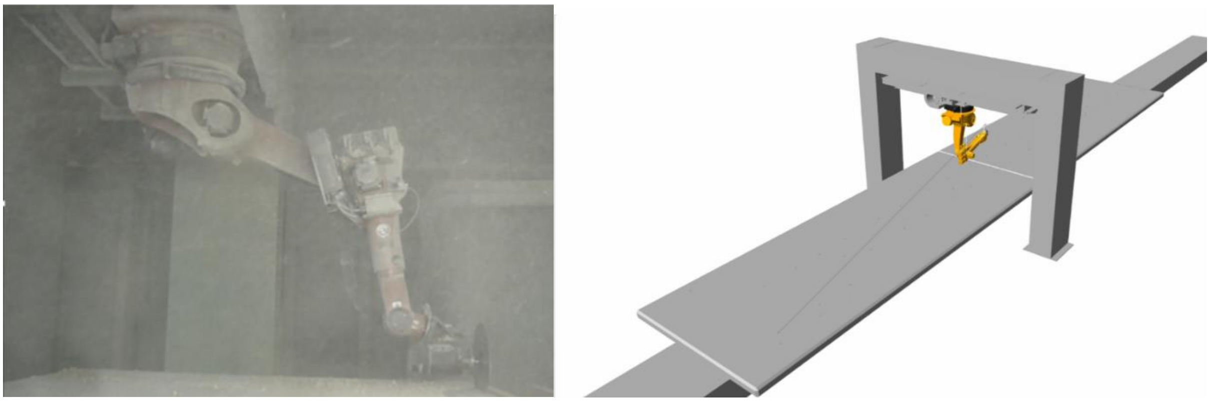


Costs: 2019EUR
Analysis Results: The simulation detected no errors.

Web-to-real interface for robotic chiseling process

2.2. Process development

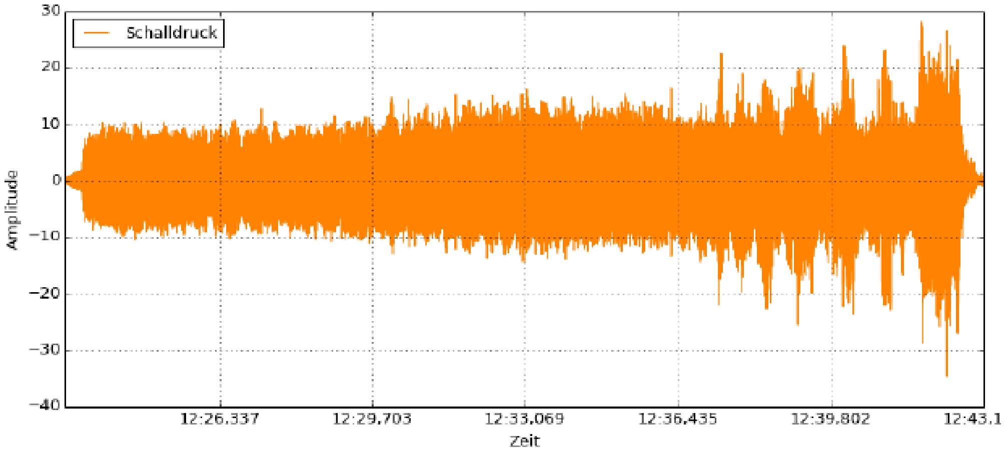
Concerning the efficiency of new robotic process for small and medium enterprises as dominant in woodworking industry also expresses the need for intelligent connection of given hardware, new technology and software implementation. Ordering given hardware and software does not fulfill small enterprises demands for specialized and individualized production of building elements. The depicted setup below shows that through the integration of flexible software such as KUKA|prc given hardware and new robot technology can be combined to create a highly configurable working environment.



Large scale robotic system with splitable 50m table setup and portale robot in reality (left) and in KUKA|prc (right)

2.1. Material adaptive processes

Currently, automation of surface processing of wood elements is applied mainly implementing milling techniques. However, milling strategies are not able to react properly to anisotropic behavior and varying material characteristics of wood. Path planning strategies for milling devices are generated independent of information about the material being processed. Depending on the fiber direction of given wood elements, the outcome of such paths greatly varies and therefore not allows specific nor consistent surface design. The lack of configurability and adaptability of milling processes according to material characteristics has already been researched for other materials e.g. steel. One approach in this context is the integration of sound sensoring and analysis for local adjustment of machine parameters *during* processing.



Sound pressure during metal processing for adaptive milling (Neuhaus, 2016)

This approach of adaptive milling can easily be transferred to wood processing. According to the density of the wood material including also knotholes, different amplitudes of noise can be sensored which than influence the machine parameter of e.g. speed to guarantee the same material subtraction amount throughout the whole wood element.

3. Wood as production parameter

3.1. Adapting CNC Technologies for a Virtual to Physical Design-Transfer

A student project experimented with an intelligent strategy for creating an elaborate 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 inspired by Kirigami and shows the transfer between digital to physical design informed by machinic cutting conditions in combination with a flexible joint system. In this design the definition of the joint system has to be accurate, the cutting angles exactly defined beforehand, requiring accurate CNC machining with a multi-axis machine that can process cuts that are tilted by -45 to +45 degrees in a workspace of at least the width of the panel, in that case about 1 by 1 meters. The only available CNC machine capable of fulfilling these requirements was a KUKA KR16 robot with an attached milling spindle. In a common workflow, the students would have had 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. 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 (parametric robot control). This plugin for Grasshopper provides an interfaces that converts parametric toolpaths into a format that the robot can understand and also simulates the robot’s kinematic movements. Due to the large space 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. However, after each cut, the robot would stop and indicate the users by how much to advance the wood panel, 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.

Flexible joint system with laminated plywood panels (left) and milling of angled connection parts (right).

3.2. Materializing the Fabrication Process

As soon as the scale changes from small scale or objects to large scale free-form structures as seen in the following Düzce Teknopark project, the data flow from digital design to fabrication gains even greater importance. Comparable, realized large scale wooden constructions such as the Centre Pompidou in Metz by Shigeru Ban (Scheurer 2010) or Metropol Parasol in Sevilla (Mayer 2011) have in common that CNC fabrication was excessively used for the overall production process. But what is 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 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 the wooden lattice structure which was inserted into a steel and concrete structure as seen in the Metropol parasol project is not a different process to usual steel constructions as seen at e.g. the Hungerburgbahn by Zaha Hadid, with the only difference, 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 replaced 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.

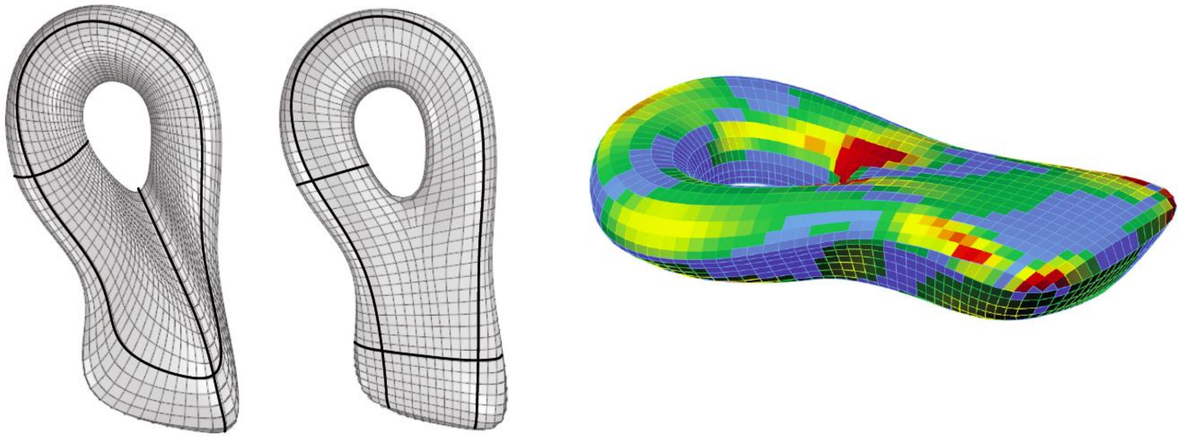
3.3. Activating material tolerances in the digital design to fabrication process

Another way of 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 to process a digital surface is not enough to design a prototypical full scale architectural project, requiring additional, custom plugins, specifically for that project. The resulting applied research into analysing and informing material specific requirements, as well as the digital 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 deeply nourished by having the material inform the fabrication of the physical output.

Scale- model of the free-form Düzce Teknopark design

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 tools, the CAD software 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 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 5 times as much transformation.



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.

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 within Grasshopper, we analysed the mesh that was 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 architectural requirements such as interior lightening, heat load, and aesthetics.

Interior view of the wooden construction of Düzce Teknopark

3.4. Conclusion on large scale wood projects

The Düzce Teknopark project confronted us with the highly complex problem of segmenting a double-curved surface into constructible elements. In our research projects, we explored the possibilities of taking 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 a performance-based design where geometric properties can be read from the outside.

4. References

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