ABSTRACT: Wood is one of the most traditional materials in architecture, but has gone through significant developments over the centuries and is now perceived as a high-performance material. Before the industrialisation, wooden constructions were planned and produced by carpenters, acting upon the clients’ parameters such as the number of stories, number of rooms and required functions. Most often, the carpenters did their work without plans - all they needed for their work were experience, proficiency and knowledge regarding the traditional joints. Thus, both planning and production happened in real-time on the building site. Using woodworking tools, the joints were fitted “just in time”, without relying on additional metal fasteners. [1]

During the period of industrialisation modularity and mass production dominated the construction industry. Prefabricated panels became the most relevant construction elements, turning connections into undesirable weak points and establishing steel elements as the preferred method for connecting plates. Later on, framework construction became the second stage of modularity, replacing panels with beams and pillars, while steel plates, screws or bolts were used to connect the single components. All steel elements were standardized to simplify the planning and construction process [4]. In recent decades, contemporary architecture has turned away from this kind of modularity, instead utilizing digital design methods, CAD/CAM planning and flexible manufacturing technologies to enable new and different forms of modularity [3]. The module of this digital period is defined by its capability of combining unique forms and elements with dynamic manufacturing strategies. Thus, modern modular constructions can consist of highly individualized elements that are produced with nearly the same efficiency as serial manufacturing.

This paper focuses on the project “Addition” – a Pavilion, which was designed with this new concept of modularity, manufactured automatically with a 6-axis robotic arm. New CAD/CAM interfaces, linking design directly with fabrication, enabled the serial production of 450 individual slab joints with 14 different connection angles.

KEYWORDS: Computational Design, Robotic Production, Digital Fabrication, Wood Joints, Pavilion, Addition

Figure 1: The pavilion after the assembling
1 INTRODUCTION

The aim of the project was to design a pavilion out of wood as a part of the exhibition “Think Global Build Social” at the Az W “Architekturzentrum Wien”. Similar to the nearby “Enzis”, the pavilion was to simultaneously act as a multifunctional furniture piece and a sculptural element. The design of the object emphasizes the innovation, easy process ability and high performance of wood based constructions, while the temporary nature of the event necessitated a quick assembly and disassembly, the reusability of the elements and a versatile usage of the space.

To find a design that incorporated the many constraints, we initiated a student competition at Vienna University of Technology. 17 students took part, resulting in a total of 13 projects at the final review. After eight weeks of planning the project “Addition”, designed by Evelyn Hochegger, was elected by the jury for realisation. The project was chosen due its flexibility in design and the feasibility of a digital production process for developed joint details. The final detail planning and digital data preparation for the production took three further weeks. Finally we started with the production process, which also took three weeks.

Figure 2: Digitally modified “Mitered corner dovetail joint”

2 DESIGN IDEA & PROCESS

Wood was chosen as the building material at the very beginning of the project as we consider it especially suitable for social projects in public spaces due to its good ecological qualities, sustainability and the relative ease of woodworking processes. Another design parameter was the ability to manufacture the structure using digital fabrication methods with a robotic arm. The simple design idea of “Addition” was developed under these requirements.

The dynamic appearance and the multi functionality of the object stems from just four differently shaped frames (referred to as frame, table, bench and lounger), which are stringed together in a single row. The frames were shaped out of individual beams, which were assembled on-site. Thus, the concept allows for many variations through recombination of the differently shaped frames, so that the final geometry of the pavilion can be changed even as late as during assembling.

The pavilion covers an area of 3.5 x 7.0 meters with a height of 2.5 meters, requiring 3.8 cubic meter solid lumber (KVH, spruce) for the whole construction. The cross section of the beams are all the same at 6.0 by 6.0 centimeters.

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3 DETAILING & MATERIALIZING

During the first design stage the material was set to be said wooden beams with a square profile. The design goal was to be able to set up the timber beams to frames without using any screws, nails, steel plates or glue, so that it can be assembled and disassembled multiple times over its lifespan.

Such metal connectors would also make the reuse possible, but incur greater costs. The engineered wood based connections in Europa mostly use steel connectors. So our solution for the connectors followed principles of Japanese wooden joints, which can be designed without using metal connectors as moment resistant frames. We have decided to develop a corner mitre blind tenon joint. This kind of joint is designed as a corner connection and is a modified version of a mortise and tenon joint.

The frames were designed with non-right angles between 77-125°, so the joint details also had to be developed to address this. The proportions of the haunched stub tenon were dimensioned to ensure material integrity at the various angles. Instead of a straight mitred cut the shoulders were cut using a curve. This creates a horizontal shoulder that helps absorb the vertical forces (e.g. from people sitting on the bench).

We intended to use beams with a cross section of 10,0 x10,0 cm. This kind of beam would allow us to use two tenons, so that the frames could resist more moment.

Instead we decided to use beams with a cross section by 6,0 x 6,0 cm, in order to reduce the cost and weight. With the smaller cross sections we saved approximately 3,2 kg per meter. Transport and assembly thereby became much easier. On the other hand it also reduced milling time and wood shavings per joint. Yet with more joints needed to form the whole pavilion (450 milling processes instead of 270) overall milling time would have been similar. The smaller cross section necessitated tighter tolerances which for required more precise manufacturing. Lastly the smaller cross section lowered moment resistance and load bearing capacity of the elements (Figure 2).

As intended we didn’t use glue for joining the beams. The precise manufacturing and unique shape of the joint ensured the required moment resistance of the frames. The beams are fixed with a wooden dowel (diameter 8 mm).

We made several stress tests to establish the moment resistance in the frame corners. The “lounger” element had the lowest stability with 0,466 kNm. This forced us to additionally fix the connection with glue due to its layout as a cantilever arm. This gave the element sufficient stability (Figures 6-8).

The connections between the frame elements were also designed with wood to wood detail principles. Every 16 cm a hole were drilled along the long side of the beams. Then wooden dowels were placed in offset to fix the frames to each other.

4 FABRICATION PROCESS & ASSEMBLY

4.1 DIGITAL DATA

A very common process in computational design is the post processing of shapes for fabrication. This can take a variety of shapes, from rather simple algorithms that ensure that façade-panels conform to given maximum dimensions as dictated by the available material, to highly complex approaches that optimize geometry towards given parameters such as planarity, length equality, and connectivity. Another very common optimization parameter that greatly impacts manufacturing processes is the reduction of variety, aiming to break down a structure.
into a maximum number of identical elements, as larger lot sizes commonly result in a lower costs. While this concept is certainly true in some businesses, it actually does not necessarily apply to many processes involving machines – for a machine, it does not mechanically matter if it performs many identical movements, or completely individual movements. The complexity lies solely in the programming, where ineffective software requires the user to manually process every part, even if the parts are very similar to each other. Thus, programming two elements for fabrication scales linearly to twice the programming time.

We propose that a more direct access to fabrication machines has the potential of greatly reducing costs in the construction industry. Rather than having a fabricator postprocess and redraw the geometry for fabrication, architects and engineers with direct access to machines can integrate the fabrication process as an important parameter into the design process. Thus, the user is not just working with a design, but receiving immediate, parallel feedback regarding the manufacturability of an object. The machine-data file that contains the entire logic to fabricate an object can then be handed over to the fabricator, and after a quick verification sent to the machine for fabrication. We refer to such a process as production-immanent design. [2]

To explore this approach in a prototypical project, we intended to use the University for Applied Arts’ KUKA KR120R2500 robot as the design-driver. As a heavy-payload robot it can move 120kg within a range of 2.5m in each direction, thus also enabling it to mill through denser materials such as hard wood, a fabrication strategy that was to be used for the very complex nodes of the “Addition” pavilion project.

For the development of both design and fabrication, we used the visual programming environment Grasshopper to deal with the geometric complexities. Rather than modelling geometry manually, or writing code for automatically generating geometry, Grasshopper allowed us to define geometric relationships in a very accessible way, by connecting components with each other, thus
forming an acyclic graph that updates whenever any parameters change: When an initial geometric parameter is updated, this change immediately propagates through the graph and is also reflected in the fabrication planning, allowing us to optimize both design and fabrication process in a very accessible way.

For the node design, it was our ambition to define an extremely efficient design that is optimized for the industrial robot and its milling tool, needing a minimum of machine time. Milling tools are available in many different geometries, with cylindrical, spherical, and conical tips. For general-purpose milling, a cylindrical tool is used for roughening – the efficient removal of material – followed by a spherical tool for finishing the surface. In order to optimize machining time, we decided to only use the cylindrical tool. This leads to a series of complications, as a cylindrical tool cannot perfectly create any interior corners – the radius of the tool always remains – and cannot finish free-formed surfaces.

The final node is the result of a series of experimentations towards realizing a structurally sound, aesthetically pleasing and of course functional node design. However, when it came to the fabrication, the milling spindle of the heavy-payload KUKA robot was unavailable due to technical problems, forcing us to use the much smaller KR16 robot – with a 16kg payload instead of 120kg and a very small spindle that could only accommodate 6mm milling tools.

Thanks to the parametric design of the node, we were able to very quickly adapt to the changed tool constraints. Despite our efforts towards optimization, the small diameter and weak spindle of the new setup greatly slowed down the process. To ensure a timely completion of the project, we were able to acquire a second robot, and by doing so doubled the fabrication speed.

4.2 PHYSICAL FABRICATION

For the production of all 450 joints we used two 6-axis KR16 robotic arms from KUKA, with a maximum payload of 16kg and a reach of about 1.5m. The production took place in one step and with the same milling cutter, which is operated by a spindle with a maximum rotational speed of 5000 revolutions per minute. For the production a 6 mm diameter and 86 mm long milling cutter is used to shape the joints.

Before the milling process of the joints, the slabs are cut to the required length and the holes are drilled. These steps are done with standard tools like a drill press and a portable circular saw. Afterwards we started milling the joints with the robotic arms.

A special jig was designed out of wood, to enable processing with two robotic arms. The jig is fixed to the concrete basement in several points and stiffened with additional wooden plates to avoid vibrations. Concrete blocks were put on the bottom of the jig, in order to further stabilize the jig.
Due to the limited facilities the beams had to be inserted into the jig manually. The tool centre point is set on the top corner of the beam. To ensure the exact position of the beams two wooden bars were screwed on the jig. The working pieces are fixed between the two bars using two clamps. Long working pieces are additionally fixed to a third point. To prevent a collision between the robotic arms and the jig, the working pieces are cantilevered out by 30 cm. Both robotic arms worked synchronously. Following the milling process we drilled a hole with a 7,5 mm drill bit across the joint.

The manufacturing of each joint took 12-15 minutes depending on its geometry, resulting in a total fabrication time of 14 days. Finally, all elements were sanded before they were treated with a breathable protective coating.

4.3 CHALLENGES

Digital production with a robotic arm is very precise and can handle extremely small tolerances. Due to its flexibility and elasticity wood can be processed within greater tolerances than steel, glass etc. Wood is an anisotropic and hygroscopic material and it changes its form depending on the humidity. This characteristic of wood can cause problems during such digital production processes, which we also encountered in our project. The delivery was made on a rainy day without protection, and we measured a humidity of more than 50%. The maximum acceptable moisture levels for construction wood lies between 15-18%. After two weeks of drying we could start with the manufacturing process. But we realised that the cross section of beams had shrunk from 6,0 x 6,0 cm to below 5,6 x 5,6 cm. The dimension of the beams varying slightly between these values.

The shrinking caused the following problems for the milling process. Assembly of two beams worked correctly, because the shapes of the mortise and tenon remain identical. The robotic arm milled both sided to precision. We had also included a tolerance of up to 0,5 mm between mortise and tenon in each direction. The shape of the joint for the milling data was computed for an average section (5,9 x 5,9 cm). The zero point of the base coordinate system was located at the right top corner of the beam. This assumption meant that the side walls of the mortise couldn’t be milled symmetrically if the cross section of the beam deviated from the average. The adjacent parts didn’t lie flush when assembled.

To avoid this problem, two different solutions were developed. First we measured all beams manually before the milling process and sorted the beams according to size. Then we redefined the zero point of the base coordinate system. This didn’t lead to satisfactory results, since the shrunk beams didn’t lie centred in the jig. We therefore also adjusted the jig (Figure 11).

A future step will be to build a more flexible jig and a sliding bar to react to the different sizes of working pieces. The zero point of the base coordinate system should then be arranged as the middle point of the working piece. The sliding jig should also automatically bring the working piece into the right position. For further improvement the digital milling path should start from the centre and adapt parametrically to various dimensions. This methodology would also correspond to the manufacturing technology of the Japanese wood joints. Starting the layout from the centre and working towards to outside.

Engineered wood also called composite wood is a range of precise manufactured industrial products, which are very suitable for digital processing. On the other hand solid timber elements are semi-processed products, which continue to work during the lifetime. These characteristics of wood come into conflict with the precise digital manufacturing processes. To avoid such problems the used manufacturing process needs to be understood in depth. For each milling process a thoroughly designed solution should be developed with the help of a carpenter.

The production of the designed mortise-tenon joint is not possible with the common carpenter methods, due to curved shape of side walls. It is possible to produce the traditional corner mitre blind tenon joint with such carpenter tools (e.g. chisel, mortise saw, offset saw and marking tool). This took approximately 30 minutes per connection. By using standard carpentry machines this process still takes no less than 15 minutes. It is therefore more expedient to compare the robotic arms with a 5 axis portal milling machine.

4.4 ASSEMBLY

The pavilion is placed upon a base structure. This structure consist of eight wooden frames of 0,9 x 3,5 meters, which were built in the production area. The basement structure had two advantages. First height adjustable feet can be integrated in this structure, so the pavilion can be adapted to the uneven. We measured up to 10 cm difference on the building site between opposite corners of the pavilion. Secondly the different shaped frames can be easily assembled to a pavilion structure.

At the first stage of assembly the seven frames were put together and fixed to each other in three different points with steel bolts.
At the second stage the beams were transported to the courtyard of the MuseumsQuartier in Vienna. Then the beams were assembled on-site simply by hammering them together. Afterwards they are fixed with a single wooden dowel per joint. Only the “lounger” element had to be fixed with glue due to its layout as a cantilever arm. Finally all elements were aligned behind each other. They were fixed with wooden dowels each 16 cm. The order of the elements was decided at the construction site. The entire assembly took 24 hours, involving a range of participants, between 15-65 years, with different skillsets and backgrounds. Due to the robotic pre-fabrication in the workshop, it was possible to set up to the pavilion without the help of professionals or special equipment. The precise manufacturing process also made it possible to achieve sufficient stability and.

5 RELATED WORK

Industry commonly uses 5 axis joinery machines for wood to wood joints. However, these machines are very voluminous and expensive, so that only large wood fabricators specialized in mass production can afford them. The most frequent industrial use for wood to wood joints are beam to beam connections, which can be produced with different angles by joinery machines, mostly for roof and staircase constructions.

Thus, joinery machines are optimized for the manufacturing methodology of the carpenter, so that standard applications can be programmed rather easily and are then performed with great speed and accuracy. Problems only arise once non-standard solutions are required. The programming of difficult geometry is time consuming and not as flexible as with a robot arm. While robots – due to their kinematic layout – cannot compete with specialized machines with regards to absolute accuracy and speed, these machines represent a new and affordable way towards making complex joinery technologies available to smaller companies and even individual carpenters that were previously only accessible to high-end industry. Apart from other obvious advantages over different CNC machinery and joinery machines, like the cost efficiency it is the manufacturing flexibility of robots that make them valuable to both researches as well as carpenters. Since the robotic arm can manipulate any tool that is mounted on its flange, robots already take on a large variety of tasks [6].

Since 2010 several experimental projects with wooden joints were realized using industrial robots. Most of them were developed and realized by Menges, Schwinn and Robeller. They mostly use dovetail and finger joints for their wood to wood connections. In their approach the edges of the timber panels are milled in order to produce parametrically designed three dimensional finger joint connections. The robotic fabrication allows for performative finger joint connections even at extreme angles.

A project with a similar joint design was developed in Graz University of Technology by Richard Dank and
Christian Freissling 2012. This project was built out of 11 irregular frames mutating along an axis [5]. The connection design was inspired by Japanese wood joints. All slabs are assembled without any metal elements and adhesive. There are some similarities between both projects but the most significant difference is the joint designs. In our AZW Pavilion you can see a much larger additional supporting surface on the side to support greater moment loads. We needed such a sophisticated geometrical design because all four elements we designed, were not a closed framework, unlike the “Framed Pavilion” in Graz.

The results of this project represent the first step of investigation for a research program, which compares digital fabrication techniques with traditional production methods of carpenters.

Figure 12: team

6 CONCLUSION

Wood is being used for larger and larger buildings, even in the urban areas. Multistoried buildings with wood structures are not uncommon in our cities. A seven storied house in Berlin, nine storied in London or eight storied office building in Donbirn are built out of wood. Vienna will be home to the highest wood building with 24 stories and 84 meter height in a couple of years. Beside this development more and more architects and engineers are trying to design the wooden structures without metal connectors. Metal connectors have substantial disadvantages regarding fire safety and can also increase the costs.

Shigeru Ban succeeded in building a spectacular office building (headquarter Tamedia publishing company – seven stories) in the center of Zurich with a structure entirely made from wood, similar to traditional Japanese timber buildings. The connecting elements were produced out of beech using CNC milling technology. The design of joints was inspired by traditional Japanese wood structures but re-interpreted in a unique way by Shigeru Ban [7].

Also the design philosophy is fundamentally changing. Instead of having to rely on mass-fabricated elements, today’s digital and machine tools allow us to create designs that consist of individual, unique building parts. However, to cope with the complexity of the high number of digital shapes, it is not enough to solely draw a 2D plan or even a 3D model. Instead, contemporary architectural design methods require the use of digital parametric design tools and knowledge of programming.

Combining such high-end digital processes with the high-end, ecological material wood can now create new, sustainable designs with the same efficiency as mass-production.

New interfaces enable a direct communication between 3D modelling software and even complex machines such as robotic arms. This allows designers and architects to develop entire manufacturing methods by themselves, and thus have control over all aspects of a design, from sketch to fabrication.

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