Robotic prefabrication of timber structures: towards automated large-scale spatial assembly

Article *in* Construction Robotics · December 2017

DOI: 10.1007/s41693-017-0006-2

Philipp Eversmann
Universität Kassel

Constr Robot (2017) 1:49–60
https://doi.org/10.1007/s41693-017-0006-2

ORIGINAL PAPER

Robotic prefabrication of timber structures: towards automated large-scale spatial assembly

Philipp Eversmann[1] · Fabio Gramazio[2] · Matthias Kohler[2]

Received: 30 December 2016 / Accepted: 31 July 2017 / Published online: 14 August 2017

Abstract Despite modern timber construction being on the forefront of digital technology in construction, subtractive CNC—fabrication technologies are still predominantly used in the industry. An important break in the digital chain occurs when prefabricated small building parts have to be assembled manually into functional modules. This can result in a loss of digital information in the process. Therefore, a robotic setup for timber construction was specifically developed by the authors enabling large-scale spatial fabrication possibilities using a combination of subtractive external tools for cutting and drilling and additive robotic operations. Through automatization techniques and innovative feedback processes, the system can minimize material waste by reacting to different material sizes even during the construction process. In a case study, which was undertaken in the course of the Master of Advanced Studies program in Digital Fabrication at ETH Zurich, a complete digital workflow using additive robotic fabrication processes in timber construction was realized. We demonstrate the conception of the worldwide first double-story robotically assembled timber structure, explain its fabrication processes including an integrated envelope, and conclude by analyzing the robotic fabrication technologies in terms of their efficiency and structural and functional capabilities and limits.

Keywords Robotic fabrication · Digital design · Timber construction · Prefabrication · Additive fabrication · Feedback process

1 Introduction

1.1 Prefabrication

Modern timber construction is already highly integrated and digitally mastered (Internationale Konferenz 2006; Jeska and Pascha 2015). An automated prefabrication of singular timber elements has been demonstrated on various research studies and projects in the last decades (Sass 2007; Beyer 1991; Scheurer 2011). The degree of prefabrication describes the size and complexity of prefabricated components, which is directly related to the amount of on-site construction labor, material use, construction quality, and, therefore, sustainability performance (Boafo et al. 2016). Even today, CNC technologies are used predominantly for subtractive processes in the industry (Popovic et al. 2016), which can also be noted in the available manufacturing techniques of current timber production lines (Hans Hundegger 2016). These machines are used to precisely manufacture small components like beams and plates, which are later assembled manually into larger components. A break of the digital chain occurs exactly before spatial and functional building parts are assembled. This can result in a loss of information and precision in the digital process, but also in unexplored spatial, constructive, and fabrication potentials. Through robotic prefabrication, an extremely

✉ Philipp Eversmann
studio@eversmann.fr

Fabio Gramazio
gramazio@arch.ethz.ch

Matthias Kohler
kohler@arch.ethz.ch

[1] Eversmann Studio, Ohmstr.13, 80802 Munich, Germany

[2] Gramazio Kohler Research, Professur für Architektur und Digitale Fabrikation, ETH Zürich HIB E 43, Stefano-Franscini-Platz 1, 8093 Zurich, Switzerland

high global assembly precision[1] can be realized. Since fabrication is directly connected to a precisely planned virtual model, the danger of mistakes in construction is very low and global precision extremely high, resulting in a cost and construction efficient system.

1.2 Previous studies in digital timber construction

Subtractive digital fabrication and structural design for timber construction have been extensively researched at EPF Lausanne (Weinand 2009; Robeller et al. 2014; Robeller and Weinand 2016), while the fabrication of timber plate structures through robotic milling in combination with manual assembly has been studied on various research projects at the ICD Stuttgart (Knippers and Menges 2013; Menges 2012). Additive assembly processes have been investigated notably by Gramazio Kohler Research at the ETH Zurich, involving horizontal stacking of simple linear wood slats to create complex geometry as for the realisation of the roof of a new faculty building (Apolinarska 2016a, b), and also the robotic assembly of single-joint spatial structures in combination with gluing technology (Zock et al. 2014; Helm 2016). A recent collaborative research project by Søndergaard and the authors of this paper (Søndergaard 2016) investigated robotic timber fabrication for topology optimized structures. Real-time control and interaction during assembling wood sticks of random geometry were explored by Dőrfler (2012) at TU Vienna. Algorithmic techniques for using irregular wood components to design non-standard structures were explored by Monier et al. (2013), while scanning and processing technologies for natural wood branches were researched by Schindler et al. (2014) at CITA.[2] Techniques for assembling wood slats autonomously using feedback processes were recently experimented by Jeffers (2016) at Carnegie Mellon University.

1.3 Large-scale robotic spatial assembly

The work presented in this paper builds on this development, extending the scope to functional volumetric prefabrication on an architectural scale. In Sect. 2, a new robotic fabrication cell is explained, which was specifically conceived for the involved fabrication technologies. We demonstrate the spatial, structural, and functional possibilities of highly diverse and customized timber frame volumetric modules. For the implementation of these goals in the 1:1 scale, a prototypical demonstrator was built during a Masters program[3] in Digital Fabrication. In Sect. 3, we compare and analyze the robotic fabrication technologies in terms of their efficiency, as well as their structural and functional capabilities and limits. Material tolerances and variability are discussed with respect to adaptive robotic processes. We conclude in Sect. 4 by showing potentials for future developments and comparing spatial robotic prefabrication to on-site fabrication.

2 Methods

This section contains a detailed description of the robotic technologies and their spatial arrangement necessary for additive timber construction processes (Sect. 2.1). We focus on four major subjects to demonstrate the construction capacities of the robotic cell with a large-scale case-study fabrication project: the architectural prototype design (Sect. 2.2), structure fabrication (Sect. 2.3), envelope design and fabrication (Sect. 2.4), and on-site assembly (Sect. 2.5). The goal of the case-study was to realize a completely customized production in a continuous digital workflow, with a robotic setup similar to ones used in repetitive industrial applications.

2.1 Design of robotic setup

General setup The robotic cell was designed as a multi-functional robotic tool for additive timber construction. It was conceived to handle fairly unprocessed material of various sizes as solid, slender timber beams of variable cross section, and wood panels of variable dimensions. Therefore, the installation of scanning devices and a real-time connection of an external PC to the robot controller for adaptive feedback control were necessary. The robots were able to communicate with a range of external tooling and also with each other for coordinated or synchronous movements. The robotic setup was built on a movable platform, so that the complete cell can be transported and reconfigured in a matter of days.

Cell components Two industrial robots[4] were mounted on a double carriage linear axis[5] of 5 m length. The cell features a material feeding station configured for 5 m long wood slats, a parallel pneumatic gripper[6] for centering and fixing material during the saw cutting procedure, a CNC saw equipped with servo motors for three controllable axes,

[1] Global precision refers to an industrial robots capability and precision of reaching coordinates and orientations in his workspace (<1 mm).

[2] Centre for Information Technology and Architecture, The Royal Danish Academy of Fine Arts.

[3] Master of Advanced Studies in Architecture and Digital Fabrication of the NCCR Digital Fabrication at ETH Zurich.

[4] ABB IRB 4600, reach: 2.55 m, payload: 40 kg.

[5] ABB IRBT 2005.

[6] Schunk PEH 30.

and a custom designed worktable of 6 m × 2.2 m with integrated aluminum rails used for fixating wood structures during build-up (see Fig. 1). A material feeding/scanning table for wood panels was mounted on the left side of the worktable. Robot 1's (left) endeffector was equipped with a measurement, scanning, vacuum gripping, and automatic nailing tool. Robot 2 (right) was equipped with two parallel electronic grippers controlled via a serial connection. They could open and close on programmed distances, which was especially important when performing movements while releasing the work object in narrow parts of the structure. All external tools were controlled directly through the robot controller using a bus coupler[7] over a profinet connection. Complex control routines were stored in system modules (e.g., saw control/gripper control) and could be accessed by simple functions in the programming interface of Robotstudio.[8]

Security concept In scientific studies, direct interaction of the operators with the robots and the building process is often needed to allow fast and continuous progress. Therefore, a robust security protocol is necessary to limit risks. Therefore, the main operating risks as the saw were protected locally with polycarbonate shields, the maximum speed was limited to manual mode (250 mm/s), and a security distance to the robots during operation was defined outside their maximum reach. Each building process was precisely defined in a number of repetitive steps as described later in detail in Sects. 2.3 and 2.4. These steps were initiated and precisely controlled before full operation mode by a professional operator. In addition, a precise protocol was defined for operator interaction with the cell especially for the saw operations and manual structural fixation of the structure. In addition, each robot had its own security workspace and some of the axes were limited in range to limit collision potential between the robots and tool heads.

2.2 Case study: architectural design

The aim of the prototype was to develop a design and robotic fabrication system for a two-story structure with a basic envelope. A complete digital workflow using additive robotic fabrication processes was developed.

Programming workflow The general programming workflow was defined in four steps. A set of input curves controlled the overall geometry. The geometric detailing occurred within a C# programming routine which was directly connected with the structural calculation, enabling optimization related to structural performance. All fabrication data were generated in a Python routine. The actual control, procedures, and operations of the robots were written in rapid code within Robotstudio. In addition, data acquired by the robots could be directly accessed within the Python routines and could also be written on the controller in real-time, enabling feedback loops during construction. The set up as depicted in Fig. 2 was used for the envelope fabrication process explained in detail in Sect. 2.4.

Geometry An adjustable cuboid is the basis for the geometry generation. When multiplied, the cuboids create a spatially formed braced structure, which is capable of translating seamlessly between different functions as wall, slab, staircase, balustrade, etc. (Fig. 3).

The size and form of the modules were generated regarding to functional, fabrication, and assembly constraints (Fig. 4).

2.3 Case study: structural design and fabrication process

The geometry generation was directly linked to the structural design (FEM 2016) and optimisation of the structure. Custom routines for multiple optimisations were integrated to optimize for the defining load cases. We used the standard values from Swiss building code[9] for live loads, snow and wind loads, and employed safety factors for the calculation.

Optimization of bracings and cross sections We used two strategies for general structural optimization: first by adapting the overall bracing geometry and second by allowing a range of different cross sections. As shown in Fig. 3, each cuboids' bracing orientations can be adapted on its six faces and two diagonals. To use the bracings mainly on compression, we developed an algorithm to orient the bracings on the external shell-like faces following the principal stress lines (Fig. 5 right). We also performed a custom-scripted cross section optimization, resulting in four different cross sections (4, 6, 8, and 10 cm), reducing the amount of material by more than 30% while maintaining visual integrity within the structure.

Structural connections Since each joint acts in a combination between shear and axial forces, we used full-threaded carbon steel screws. Considering the beam's thickness and the angle between the screw axis and the directions of the beams' fibres, we calculated the length and orientation of the screw for each joint. We optimized for four different sizes with similar diameter (Fig. 6). The computational model also allowed us to deconstruct the vectors of the forces that act on the screws in both the shear

[7] Beckhoff EK9300 PROFINET-IO-Buskoppler for EtherCAT.

[8] ABB controller specific programming environment in Rapid language.

[9] Self-weight, Safety Factor SF: 1.35; Live loads: 2 kN/m^2 (SF: 1.5); Snow: 1 kN/m^2 (SF: 1.35) Wind: 1 kN/m^2 (SF: 1,5).

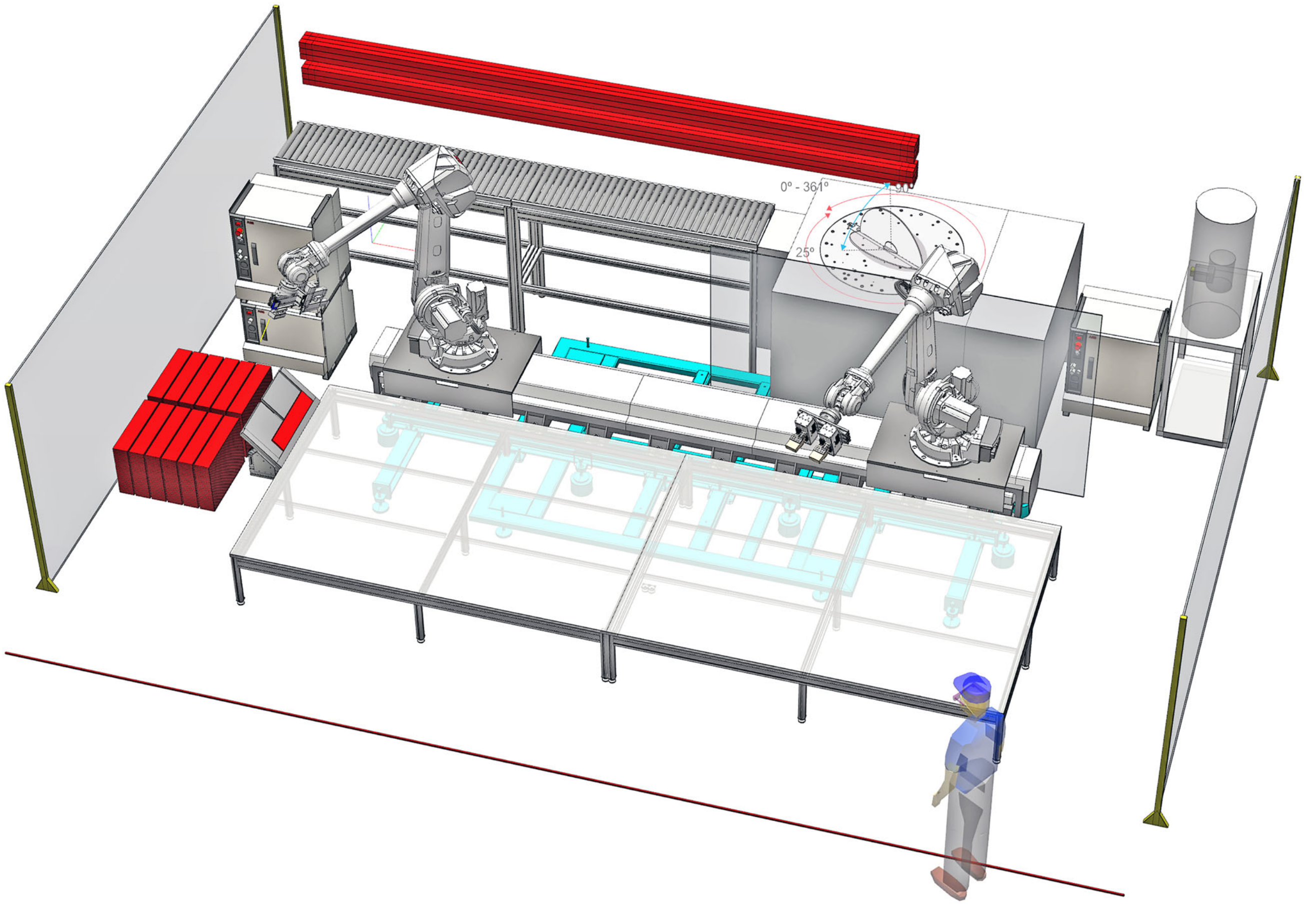


Fig. 1 Design of a robotic setup featuring two robot arms and a 5 m linear axis sitting on a mobile steel platform, a feeding station for 5 m long wood slats equipped with a pneumatic gripper for centralizing and holding slats during cutting procedure, a CNC saw of 600 mm diameter with three controllable axes (360 horizontal orientation, 25–90 tilt, up/down 0–300 mm). Robot 1 (*left*) is provided with a custom gripping and scanning tool and feeding station. Robot 2 (*right*) is equipped with two parallel electric grippers. A custom working table was designed with rails for variable fixation of elements of different sizes and scales

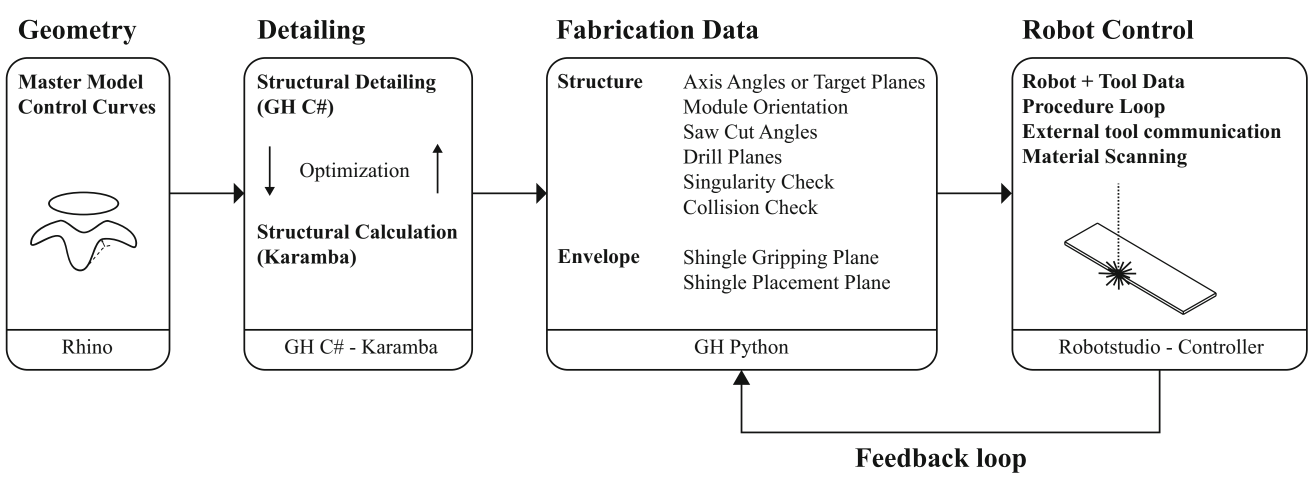


Fig. 2 Programming Workflow: using provided design input curves, all fabrication related geometry is generated in Rhino through a C# script. Structural calculation and cross-section optimization are done through the FEM software Karamba. A Python script organizes fabrication data and calculates the assembly toolpath. In ABB Robotstudio, the fabrication data are then used to drive all robotic operations and control of external tools. Through direct computational access to the controller, feedback is enabled during fabrication

and axial components to check whether the load capacity of the screws was not overreached. To avoid brittle fracture behavior of the connections, all minimal distances between the screw holes and the beams' faces were verified.

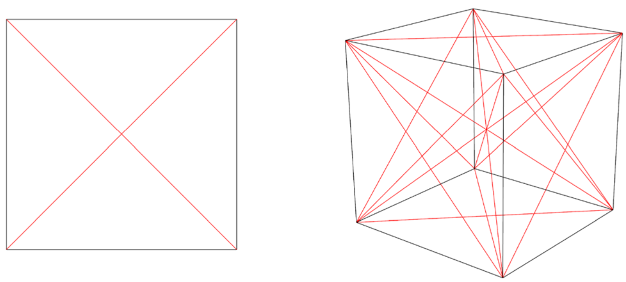


Fig. 3 Geometry generation: a cuboid serves as basic element multiple geometrical connections and permutations are possible within its faces

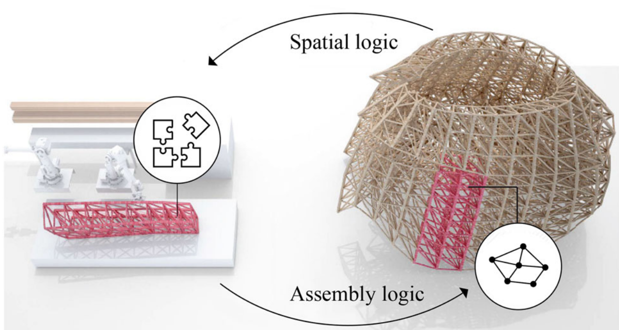


Fig. 4 Spatial module design: size, form, and sequential order of the spatial modules produced by the robotic setup have to correspond to functional, fabrication and assembly constraints. In our case study, the complete structure was composed out of 46 separate modules of maximum dimensions of 5 × 2 × 1.5 m

Robotic Fabrication The large number of sub-procedures integrating a range of external tooling of the structures fabrication processes makes it necessary to have an extremely robust computational and robotic protocol (Fig. 7). Information on each beam is stored in a general array defining whether a fabrication procedure like cutting, drilling, etc. will be performed (1) or not (0). Separate arrays deliver the specific information on saw angles, approach planes, and movement data. First, a wood slat is placed on the roller rack, and centred by closing the saw gripper to the reference position for robotic gripping. Next, the saw gripper releases, allowing the robot to move to the beam's first programmed cutting position. During the saw rotates axes 1 and 2 in position, the beam is held 5 mm above the table, then the robot presses the slat on the table, the saw gripper closes for additional stability, and the cutting procedure is performed through moving axis 3 up and down a programmed height depending on the saw's inclination and the beam size. For the second cut, the last steps are repeated (Fig. 8). The robot can then lift the workpiece to perform additional operations such as pre-drilling or mount the beam directly on the structure. We developed a path planning algorithm organizing the positions to grip, move, approach and place each element. The algorithm sorted the beams depending on orientation, type, and position of the beam in the structure. Since the structure is based on a simple geometric principle, as described in Sect. 2.2, we were able to generate the approach movements towards the final assembly positions in the structure based on topological features (orientation, length, position) rather than having to solve path planning for each single element to avoid collisions with the already assembled parts. In its final mounting position, the fixation screws are attached manually (Fig. 8).

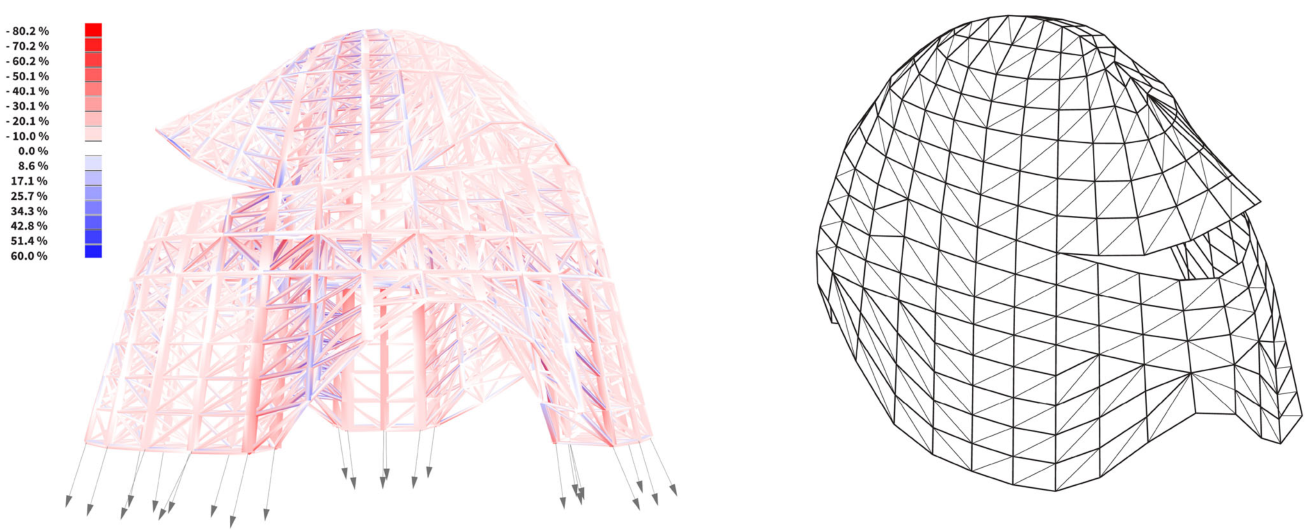


Fig. 5 Structural design of double-story structure of dimensions of around 8.5 × 5 × 7 m (h). *Left* FE analysis showing resulting maximum utilisation of members in relation with wall openings. *Right* Orientation of bracings following stress lines

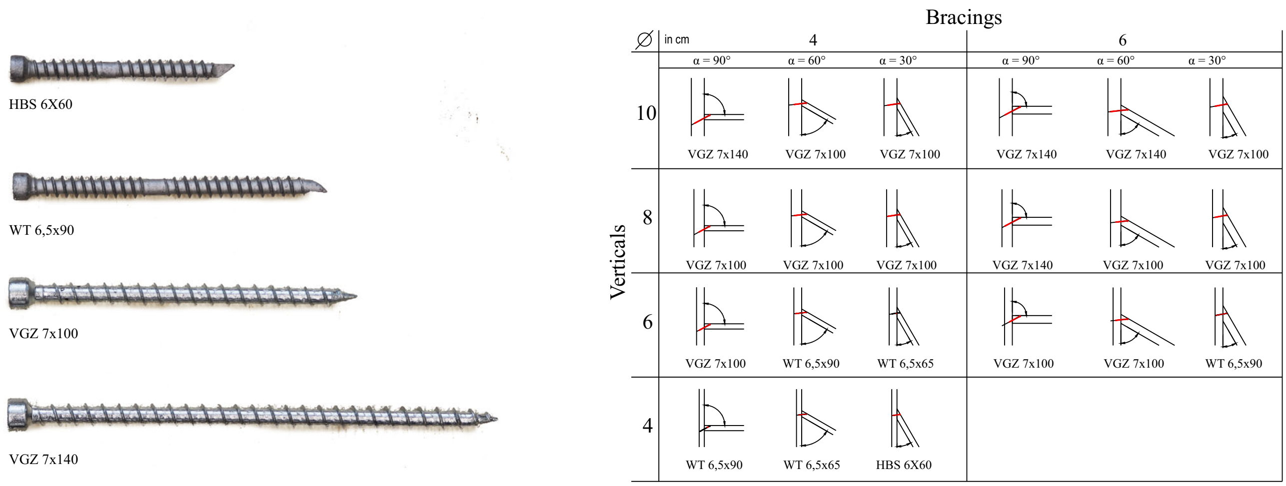


Fig. 6 *Left* Different types of full-threaded screws used for the joints. *Right* Calculation of screw type, length, and angle depending on corresponding geometry and material thickness

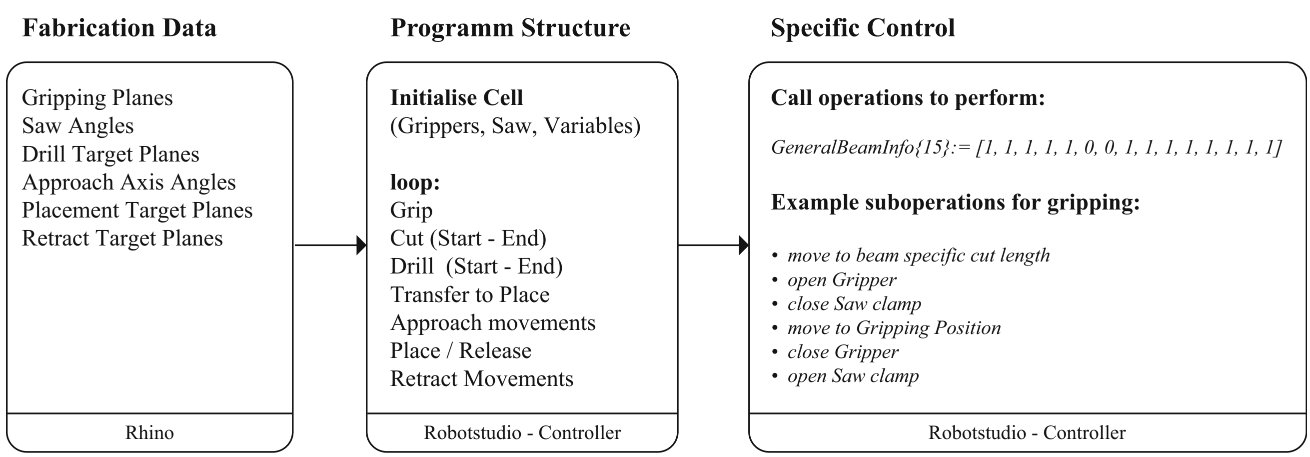


Fig. 7 Data workflow for structure fabrication. Data for each procedure are read in data modules. The robotic procedures are standardized in code and are repeated, even though movements and orientations are specific and customized for each element

2.4 Case study: envelope design and fabrication process

The design project was conceived as a minimal experimental space, in which the envelope served primarily as weather protection without consideration for thermal comfort (Fig. 9). The idea was to use the maximum of material from the natural form of a tree, resulting in variable widths of the timber panels (shingles). Their exterior side got a rough and rich texture through manual splitting, having the advantage of being much more durable than machine sawn, since the material can dry more easily (Niemiec and Brown 1993). We excluded any pre-sorting into width categories, but instead used the intelligence of the computational system to scan the shingle and calculate and place each element according to its size. The final facade geometry appeared only after a unique fabrication procedure.

For material and fabrication efficiency, we integrated the envelope and primary structure in one system without the need for substructure. This resulted in less material usage and less fabrication time but also in a more distinct and visible logic between envelope and structure: the primary structure responds to the structural requirements of the envelope, leading to a denser vertical span to the exterior side of the trusses (max. 45 cm vertical span of bracings corresponding to 60 cm shingle height). The facade directly reflects the distribution of main stresses in the primary structure, resulting in multi-layer cover of shingles in areas, where the bracings are densely concentrated. The robotic setup consists of four different components: (1) a sensor that allows scanning the different widths of the shingles; (2) a scanning table; (3) a vacuum gripper; (4) two nail guns that are activated by an air compressed trigger (Fig. 10). The computational workflow for

(a) (b)

Fig. 8 Assembly sequence of wooden slat in truss element. **a** 5 m long solid spruce slats are placed on the assembly table and the robot moves in its home position. **b** The robot grips the beam and moves it towards the saw, where it gets cut the programmed number of times

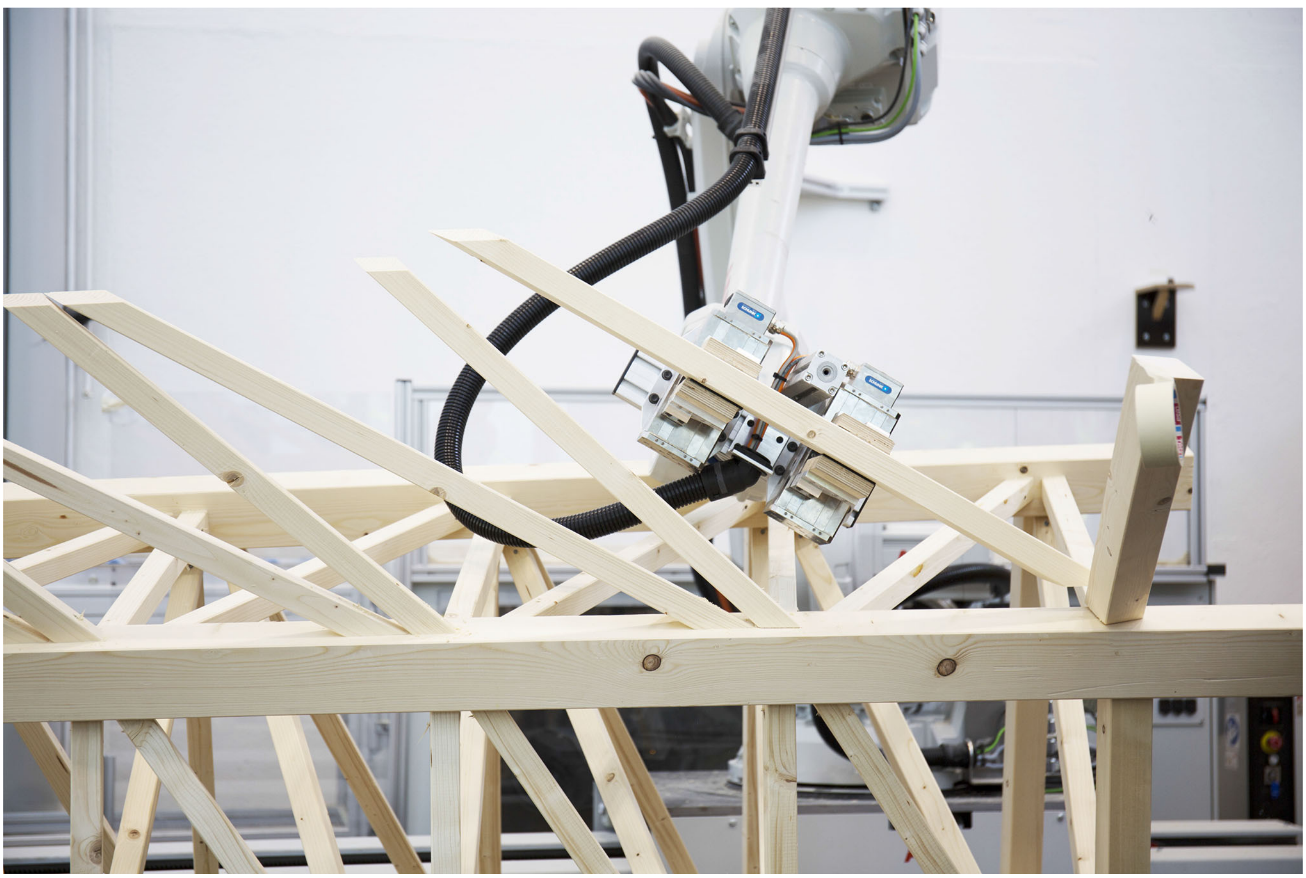


Fig. 9 Assembly sequence of wooden slat in truss element: the beam gets placed in the truss, where it is fixated manually

the envelope consists of the following steps which will be subsequently explained in more detail: acquiring the measurement and reference data of the structure, getting the geometry from shingle scanning, calculating custom gripping and placing positions, and sending the data to the controller for execution. Measurement data were necessary due to the high precision requirements of the envelope process, and was acquired through reference points of the robotically built module of the primary structure. The scanning process using a photoelectric proximity sensor works in the following way: the robot moves linearly along a specific coordinate system relative to the shingle-feeding station (Fig. 10b) until a signal is triggered by sensor. The width of the shingle can be deducted by the position coordinates. The width information is sent to an external computer to calculate the new placement and also the gripping position through a GH Python procedure.

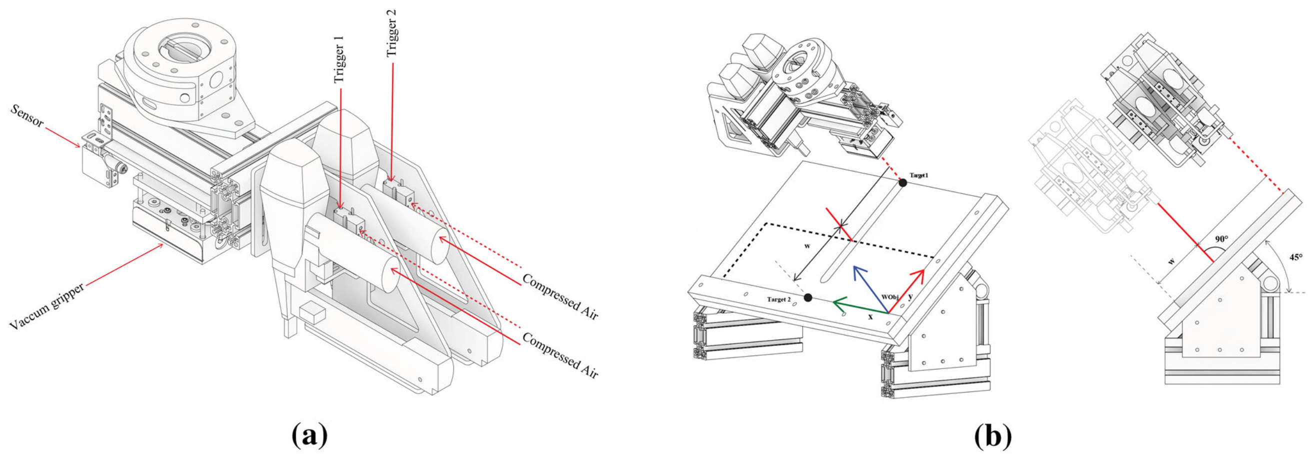


Fig. 10 **a** Shingle tool is equipped with a light-reflex sensor, a vacuum gripper fixated with additional springs and a soft gripping form of the shingle, and two standard nailguns. **b** Feeding table used for the robotic scanning process. During the scanning process, the robot moves in relation with a specific coordinate system until reaching the shingle edge

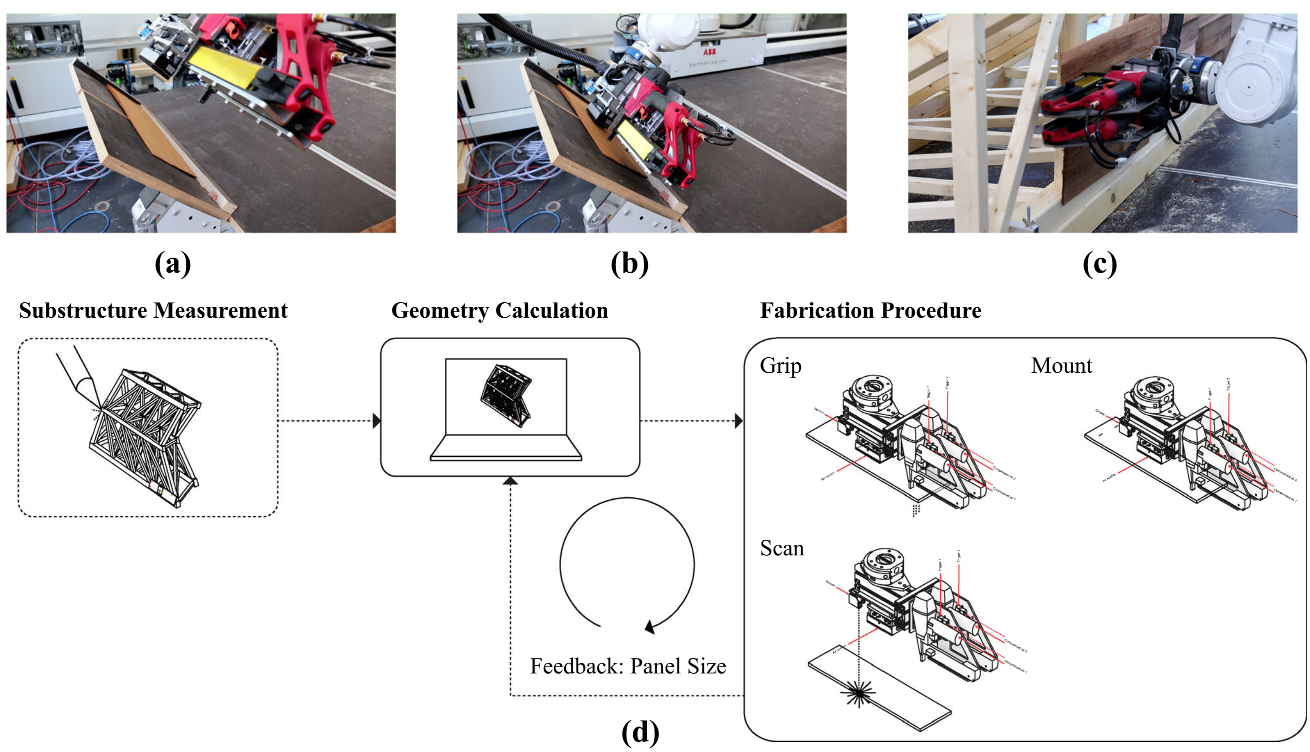


Fig. 11 Robotic fabrication process of shingle facade of unknown geometry: first, the shingle is scanned (**a**), the geometry is processed and assembly information sent back to the controller, then the robot grips the shingle at a specified position (**b**) and finally mounted and fixated on the structure (**c**). **d** Overall procedure

Once the data are sent back to the controller, the robot grips the shingle on its newly defined position, orients it to the final placement position, moves along the linear axis to the placement position, presses the shingle on the structure, and actuates the two nailguns for shooting the fixation staples (Fig. 11).

2.5 Case study: on-site assembly

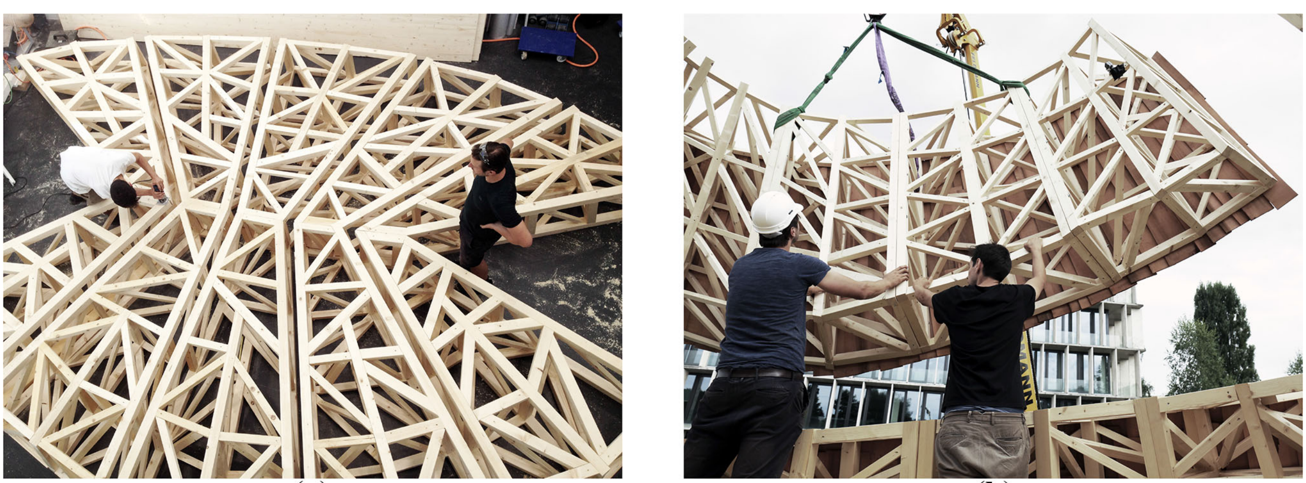
The modules arrived on site as described in the previous Sects. 2.3 and 2.4 completely prefabricated with structure and envelope. Only at the joints, there was a space left uncovered for easier access for on-site hoovering and joining. For the foundations, we used removable earth screws of 1.6 m length with footings for wood columns adjustable in three dimensions. Steel bolts were used to clamp the modules structurally together. The precise prefabrication of a large number of highly unique modules allowed us to refrain from producing a large number of paper plans normally being necessary for on-site construction. Since the manual connections were extremely simple and the specific geometry of each part could only fit at one place in the building, assembly errors were practically impossible (Fig. 12). A simple three-dimensional view of the numbering and form of parts and their connections provided sufficient information on the construction site.

3 Results

The robotic system allows fabrication of customized three-dimensional volumetric elements of complex geometry, integrating functional and architectural requirements. Adaptive robotic processes can be used in combination with fairly unprocessed material of naturally variable sizes to limit material waste. In our case-study project, over 4000 differently shaped elements could be assembled in only 5 weeks including testing and on-site assembly (Fig. 13).

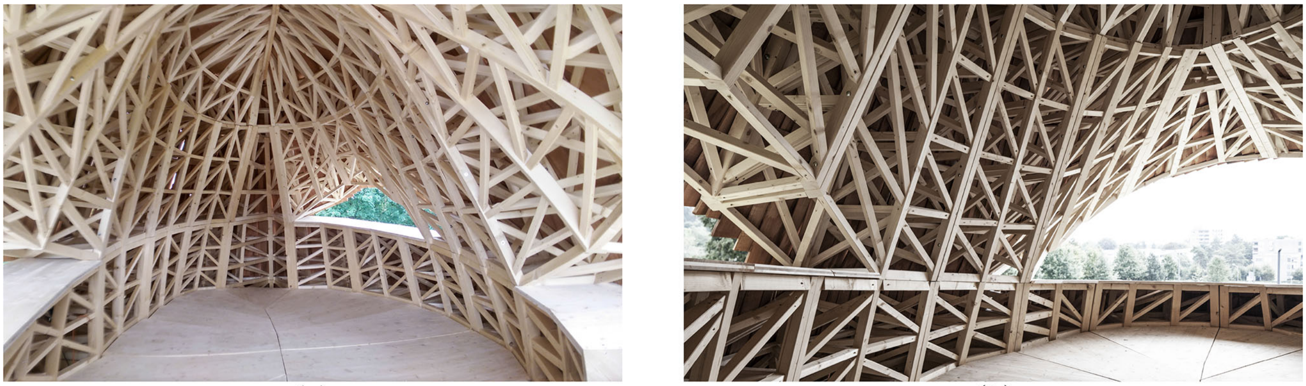
3.1 Structure

Structural and fabrication constraints were negotiated in optimizing the overall geometry, length, and orientation of bracings. Even with 30 people on the top floor, the structure easily stayed within calculated maximal deflections. With the current setup, the most efficient fabrication length of timber slats was between 400 and 1500 mm. Shorter elements were challenging to cut and assemble, while longer elements led to tolerance issues. Since the robotic mounting precision is consistently high (<1 mm), the global assembly tolerance in the joints performs better when using short slats and, therefore, small tolerance. The performance of connections with full threaded screws is directly related to the angle between the screw and the fibre direction of the beams. Since, in the case-study project, all angles are different, the effectiveness of each joint is varying over the whole geometry. A spatial truss being braced in all directions, therefore, assumes a certain structural redundancy. Further research in connection technology is needed to eliminate these redundancies and safety factors for the structural detailing. Another important topic was the definition of the robotic approach and assembly movements in a densely populated structure. There, the classification of beams by topological features proved to be a simple way to avoid custom iterative path planning for each element which is computationally expensive. For a complete industrial process, the structure would have to be either more regular and within the above-mentioned beam size limits, or each assembly path has to be computed separately, which is also subject to current



(a) **(b)**

Fig. 12 **a** Pre-assembly of floor elements for tolerance control and beam connections for site assembly; **b** On-site assembly of a large prefabricated module using a small construction crane



(a) (b)

Fig. 13 Interior images of final structure on the upper floor, showing seamless integration of balustrade, floor elements, walls, roof structure, and staircase (**a**). The size of the prefabricated chunks is still visible through the doubling of structural elements **b** image courtesy of Kasia Jackowska

Fig. 14 Exterior image showing the shingle pattern and opening sequence of the structure

research in multi-robotic applications (Parascho and Gandia 2017).

3.2 Envelope

The envelope fabrication of the case-study project demonstrates the use of robotic feedback processes on large-scale applications with thousands of different elements. The adaptability of these processes even allows the use of highly imprecise material in a continuous fabrication process. Accompanying computation, a physical robotic "softness" was also necessary. We used flexible elements such as gripping foam and holding springs for this purpose. Orientation tolerances can, however, still cause failures.

Therefore, either a general physical flexibility of the end-effector or computationally-induced soft robotic movements can improve the general robustness of the robotic process. Since we used a double overlay of the shingles in the vertical and horizontal directions, we could also apply fixation staples on the lower shingle edge. In traditional shingle facades, a triple overlay in only the vertical direction is usually applied (HOLZBAU 2017). For the doubly curved base geometry, the additional bottom fixation greatly improved the stability of the shingles and also their geometrical positioning, since the shingles are all slightly cold-bent through the fixation procedure. Even during heavy rain, the envelope remained waterproof (Fig. 14).

4 Conclusion

Experimental results show that robotic fabrication of unique, highly complex volumetric modules for on-site assembly has significant potential. The modules can be produced and integrated with all architectural, technical, and functional parameters. Off-site prefabrication has the advantage of a controlled and predictable fabrication environment, resulting in high precision and high general building quality. Even though transportation is less efficient compared to on-site fabrication due to the abundance of hollow forms, sustainability performance is still higher compared to the conventional fabrication (Chao 2013). Form and size of modules are also dependent on transportation, which may affect structural and assembly requirements. The current robotic setup is semi-mobile and partly spatially configurable. Like in our case-study project, the full spatial potential can be realized when using it as an on-site prefabrication facility, liberated from transportation constraints. This also provides the possibility of integrating continuous adjustments and optimization even during the building process. In terms of automation, it still remains a large challenge to find efficient robotic processes capable of integrating all functional requirements such as thermal insulation, air-tightness, and technical systems in continuous fabrication logic.

Acknowledgements The case study project was realized in the framework of a Master of Advanced Studies class on digital fabrication with the students Jay Chenault, Alessandro Dell'Endice, Matthias Helmreich, Nicholas Hoban, Jesús Medina, Pietro Odaglia, Federico Salvalaio, and Stavroula Tsafou. This study was supported by the NCCR Digital Fabrication, Funded by the Swiss National Science Foundation SNSF. (Agreement # 51NF40-141853), and builds directly on research findings and developments from the NRP-66/ SNSF research project "Additive Robotic Fabrication of Complex Timber Structures", established in collaboration between ETH Zurich, Bern University of Applied Science and Nolax AG. We would like to thank the companies Schilliger Holz AG, Rothoblaas, Krinner Ag, ABB, and BAWO Befestigungstechnik AG for their generous support. We would also like to thank P. Fleischmann and M. Lyrenmann for their advice and continuous efforts for the robotic setup and V. Helm and E. Schling for reviewing this article.

References

Apolinarska A et al (2016) The sequential roof. In: Menges A et al (eds), Advancing wood architecture, Routledge, London

Apolinarska A et al (2016) Mastering the Sequential Roof. In: Advances in Architectural Geometry 2016, vdf Hochschulverlag AG an der ETH Zurich. doi:10.3218/3778-4_17

Beyer P-H (1991) Technologie von CNC-Holzbearbeitungsmaschinen, 2nd edn. Cornelsen/Schwann-Girardet, Dusseldorf

Boafo F, Kim J-H, Kim J-T (2016) Performance of modular prefabricated architecture: case study-based review and future pathways. Sustainability 8:558. doi:10.3390/su8060558

Chao M et al (2013) Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: two case studies of residential projects. Energy Build 66:165–176

Dőrfler K et al (2012) Interlacing, an experimental approach to integrating digital and physical design methods. In: Robotic fabrication in architecture, art and design, Springer, New York, pp 82–91

FEM - software (2016) Karamba. www.karamba3d.com. Accessed 25 Nov 2016

Hans Hundegger AG (2016). Products. www.hundegger.de. Accessed 25 Nov 2016

Helm V et al (2016) Additive robotic fabrication of complex timber structures. In: Menges A et al (eds), Advancing wood architecture, Routledge, London

Holzbau Entwicklungsgemeinschaft (2017) Regeln für die Verwendung von Holzschindeln für Auenwandbekleidungen. Bauten mit Holz, 6 Jg, S 86

Internationale Konferenz zur Automation in der Holzwirtschaft (2006) 12. und 13. Oktober 2006, Biel, Schweiz, Biel : Berner Fachhochschule - Architektur, Holz und Bau

Jeffers M (2013) Autonomous robotic assembly with variable material properties, robotic fabrication in architecture, art and design. Springer, New York, pp 48–61

Jeska S, Pascha KS (2015) Emergent timber technologies materials, structures, engineering, projects. Birkhuser, Basel

Knippers J, Menges A (2013) ICD/ITKE research pavilion 2011. In: Hu C (ed), Architectural material and Texture I, pp 266–273 (2013). ISBN 978-7-214-08683-9

Menges A (2012) Material computation higher integration in morphogenetic design. Archit Des Vol 82, No 2, Wiley Academy, London (2012). ISBN: 978 0470973301

Monier V, Bignon J-C, Duchanois G (2013) Use of irregular wood components to design non-standard structures. Adv Mater Res 671–674:2337–2343. ISSN: 1662-8985

Niemiec SS, Brown TD (1993) Care and maintenance of wood shingle and shake roofs. Oregon State University Extension Service, EC 1271

Parascho S, Gandia A et al (2017) Cooperative fabrication of spatial metal structures. In: Menges A, Sheil B, Glynn R, Skavara M (eds), Fabricate 2017, UCL Press, London, pp 24–29

Popovic D, Fast-Berglund A, Winroth M (2016) Production of customized and standardized single family timber houses A comparative study on levels of automation. 7th Swedish Production Symposium, vol 1

Robeller C, Hahn B, Mayencourt P, Weinand Y (2014) CNC-fabricated dovetails for joints of prefabricated CLT components. Bauingenieur 89:487–490

Robeller C, Weinand Y (2016) Integrale Verbindungen fr Faltwerke aus Holzwerkstoffplatten. Detail -Munchen 1:68–74

Sass L (2007) Synthesis of design production with integrated digital fabrication. Automation in construction 16, Elsevier, Amsterdam, pp 298–310

Scheurer F (2011) Digitaler Workflow im Freiform-Holzbau. Forum Bois Construction Beaune, Biel, Forum Holzbau

Schindler C, Tamke M, Tabatabai A, Bereuter M, Yoshida H (2014) Processing branches: reactivating the performativity of natural wooden form with contemporary information technology. Int J Archit Comput 12(2):101–115. doi:10.1260/1475-472X.12.2.101

Søndergaard A et al (2016) Topology optimization and robotic fabrication of advanced timber space-frame structures. Robotic fabrication in architecture, art and design, Springer, New York, pp 190–203

Weinand Y (2009) Innovative timber constructions. J Int Assoc Shell Spatial Struct 50(2):111–120

Zock P, Bachmann E, Gramazio F, Kohler M, Kohlhammer T, Knauss M, Sigrist C, Sitzmann S (2014) Additive robotergestützte Herstellung komplexer Holzstrukturen, 46. Tagungsband Fortbildungskurs Holzverbindungen mit Klebstoffen fr die Bauanwendung, pp 197–208