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ORIGINAL PAPER

Towards digital automation flexibility in large-scale timber construction: integrative robotic prefabrication and co-design of the BUGA Wood Pavilion

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Abstract

This paper discusses the digital automation workflows and co-design methods that made possible the comprehensive robotic prefabrication of the BUGA Wood Pavilion—a large-scale production case study of robotic timber construction. Latest research in architectural robotics often focuses on the advancement of singular aspects of integrated digital fabrication and computational design techniques. Few researchers discuss how a multitude of different robotic processes can come together into seamless, collaborative robotic fabrication workflows and how a high level of interaction within larger teams of computational design and robotic fabrication experts can be achieved. It will be increasingly important to discuss suitable methods for the management of robotics and computational design in construction for the successful implementation of robotic fabrication systems in the context of the industry. We present here how a co-design approach enabled the organization of computational design decisions in reciprocal feedback with the fabrication planning, simulation and robotic code generation. We demonstrate how this approach can implement direct and curated reciprocal feedback between all planning domains—paving the way for fast-paced integrative project development. Furthermore, we discuss how the modularization of computational routines simplify the management and computational control of complex robotic construction efforts on a per-project basis and open the door for the flexible reutilization of developed digital technologies across projects and building systems.

Keywords Robotic timber construction · Computational design · Construction automation · Robotic construction management

1 Introduction

1.1 Novel responsibilities of computational design in architecture

For more than 10 years, the architectural research community has been exploring the reciprocal relationships and tectonic potentials of integrative computational design and robotic fabrication for advanced building artefacts. These focused investigations of digital fabrication technologies created a new sets of rules within the architectural discourse (Menges 2012a)—reintroducing the physical logics of materialization into the realm of generative digital design (Willmann et al. 2014; Menges 2012b). This both augments the power and expands the responsibility of the architectural profession and reconnects designers with the practical laws of construction through interdisciplinary collaboration and co-design. This method brought forward remarkable results that are mostly worked out in laboratories around the world.

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As research results are successfully expanding in scale and complexity, questions of how these technologies can be introduced into the wider context of the construction industry arise.

In order to have a sustainable impact in construction on a broad scale, protagonists of this discourse might need to intensify the conversation with actors from within the production networks of the built environment. Few efforts are currently undertaken to think beyond the scale of individual projects and secluded technical innovations in this regard. For the further advancement and rapid implementation of more performative construction methods it is imperative to study how computational methods and digital fabrication technologies facilitate but also necessitate novel and more suitable organizational relationships within larger planning teams of designers, engineers, builders and developers. This is of fundamental importance to start bringing integrative computational design workflows closer to the complex industrial production networks of construction firms that constitute one of architecture's most important collaborator.

1.2 Automation in construction vs. manufacturing

A common scheme within the architectural research community (as well as the management consulting industry) is to a priori set the construction industry in direct comparison with manufacturing. When researchers in the field of architectural technology describe its 'innovation resistance' and low levels of productivity gains, they tend to disregard the unique modalities of construction (Ishak and Newton 2016). It is evident that manufacturing industries have largely advanced to interconnected and sensor-armed (Monostori 2014), self-configuring (Friedrich et al. 2015) and self-organizing (Balta et al. 2017) production systems, while construction companies have made little fundamental advancements. But while manufacturing might be a reliable source of inspiration, it is probably unproductive to take it as a blueprint for construction efforts, as not only the two industries' fundamental economic principles but also cultural, social and political factors are of an entirely different nature.

Construction companies may not get enough credit for their achievements that lie outside the manufacturing paradigms of automation and strict organization. The disapproved 'innovation resistance' may actually have been a critical survival factor for construction firms. To stay competitive across various projects within a volatile and agile market environment the majority of companies follows project-based engineer-to-order principles. This creates an intrinsic necessity to keep their business management, organizational structure and modes of production flexible. This is rather easy for the majority of the industries' small and medium sized companies but their size often is too small for ground-breaking innovation (Hampson et al. 2014). Bigger construction companies struggle with similar problems, as the importance of agile modes of organization increases with the size of the construction firm (Taghizadeh Khamesi 2016). Throughout the last century, in most automation innovation was directly connected to standardization, globalization and strict organization of manufacturing workflows, flexibility has remained a hidden primary success-factor of construction companies and prevented the adoption of similar technologies for a rather long time.

A consistent continuation of digital materialization efforts within the architectural research discourse should include the understanding and development of highly performative construction-production networks. The main features of robotic fabrication can be expected to continue playing a major role: Generic and robust, application agnostic and inexpensive (Bechthold 2010) industrial manipulators are a good foundation for agile automation that can evolvable over time.

1.3 Towards project-based automation flexibility

Strict hierarchical organization of production networks is increasingly seen as detrimental even in the manufacturing industries in the light of the paradigm of the fourth industrial revolution and increasing speed of global development (Kagermann et al. 2013). Protagonists within the construction industry repeatedly tried to imitate automation principles from within manufacturing during the last century, with transferred approaches ranging from Fordist organization, industrialized production and robotic automation (Bock and Linner 2015; Herbert 1984; Knaack et al. 2012; Sawhney et al. 2020). After these approaches failed to leave a sustainable impact, there is little doubt that methods of digital automation that aim for a broad impact on the industry will be ultimately judged based on their level of achieved organizational flexibility. A successful implementation of flexible automation technologies is not only of great relevance for the economic viability of digital technologies in construction on a broad scale but also for the architectural discourse, as only flexible robotic fabrication and computational design methods will have a better chance to enrich the spatial and cultural qualities of the built environment. Although other strategies are still repeatedly proposed (c.f. Johnston 2018; Blanco et al. 2020) their underlying organizational principle is based on productification and standardization. Such approaches drastically ignore the socio-cultural value of building.

In an effort to conceive of an approach to automation that is rooted within the modalities of construction, the authors recently proposed a reconfigurable, transportable and changeable robotic construction platform that can be rapidly set up for a specific project in local construction environments (Wagner et al. 2020). But project-based construction automation depends not only on flexible physical machinery but also on intuitive, interactive and reusable digital computation workflows.

1.4 Advancing building systems

Advanced timber construction is an ideal field to implement these new production approaches. Not only did the timber construction sector already heavily invest in various sets of digital technologies, but it is also becoming the main exponent in sustainable and futureproof construction techniques (Ramage 2017). Wood architecture can not only provide advanced spatial qualities for the built environment but also has the potential to become the largest carbon sink on earth (Churkina et al. 2020). To allow timber construction to gain global leadership within the industry, it is necessary to innovate not only on the level of production processes but also within the field of material tectonics. Wood has a great stiffness to weight ratio, but does not match the strength and stiffness of steel and concrete in absolute numbers (Ramage 2017). However, its easy machinability allows for the integration of geometry as main structural driver on a level that is hard to match on large scale with other major construction materials and comparable energy use and costs. These complex tectonics require computational tools with a level of integration that goes beyond known frameworks within construction but can play a vital role towards reduced climatic impact of construction (Agustí-Juan and Habert 2017).

The computational design and robotic fabrication of segmented wood shells is well suited to demonstrate the performative potential at the intersection of complex geometry, as the geometric variation between components can be readily perceived (Krieg et al. 2014). Segmented wood shell structures can act as clear communicative tool and as ambassadors of advanced technologies in construction. As such they expand the vocabulary of how architectural systems can be discussed in research as well as in industry.

2 State of the art

A comprehensive set of well-documented state-of-the-art projects recently demonstrated how computational design and robotic fabrication can be integrated for the new architectural possibilities. First studies revolved around potential novel aesthetics and fabrication concepts that became possible with digital technologies (Gramazio et al. 2014). Later structural performance potentials were included into the focus of endeavors (Menges et al. 2017). Novel structural systems such as reciprocal (Apolinarska 2018) and folded plate structures were investigated (Robeller and Weinand 2015) and showcase potentials that arise at the intersection of computational design and construction. Further studies investigated the robotic construction of building-scale projects: demonstrators were constructed with robotically nailed timber slats (Willmann et al. 2016), scanned and milled natural tree forks (Self et al. 2017) and robotically milled planar shell segments (Krieg et al. 2014). Fabrication setups include large-scale gantry robots (Chai et al. 2019), stationary robot cells (Eversmann et al. 2017) and mobile robotic in-situ fabricators (Helm et al. 2012). Most of these projects deliberately have a finely defined scope and focus to develop solutions for specific (often mainly procedural) challenges within robotic fabrication. While this is necessary to further push the boundaries of what robots can produce, questions of effective digital robotic fabrication management for comprehensive timber construction workflows remain largely undiscussed.

3 Aim and research questions

In this paper we will discuss the digital workflows that made possible the fabrication of a 500 m^2 segmented wood shell. The successful realization of this demonstrator building within only little more than one year from contract to opening showcases the potential of the underlying digital automation methods and planning frameworks that were inductively explored during its planning and fabrication phase.

The aim of this work is to portray the employed methods and describe challenges and possible solutions concerning the integration of multiple digitally controlled robotic fabrication processes into cohesive, reliable and effectively automated workflows that are planned in parallel with- and directly generated from a central computational model.

Advanced modes of organization needed to be conceived in order to handle comprehensive, multi-scalar robotic process complexities in which pneumatic gripping, vacuum clamping, vacuum gripping, nailing, gluing, planing, drilling, rough-milling and finishing form a continuous workflow in near-industrial production boundary conditions. A major focus during the design and fabrication planning of the case study was set on the effective and reliable data composition and translation of geometric parameters from the computational model into various robotic instructions. Fail-safe mechanisms needed to be devised and integrated to avoid unintentional changes in low-level programs during the automated generation of robotic source code. Furthermore, parameter-hierarchies needed to be defined that ensure geometrical accuracy of the final building assemblies but at the same time allow for quick adaptation of robotic instructions during fabrication—in case of eventual schedule interruptions. Finally, protective measures need to be integrated to ensure data consistency, while preserving the possibility of digital feedback loops between design and fabrication domains.

We will first describe the setting of the demonstrator building project in chapter 4. In chapter 5 we introduce the underlying computational co-design approach that was employed during the integrative planning of the segmented wood shell. Chapter 6 then will describe the computational implementation. In Chapter 7 we discuss the achieved levels of computational performance and interactive planning flexibility on the basis of three peculiar integrative design challenges that occurred as a result of project-specific boundary settings and made necessary tight conversations between planners in the realms of design, fabrication and construction.

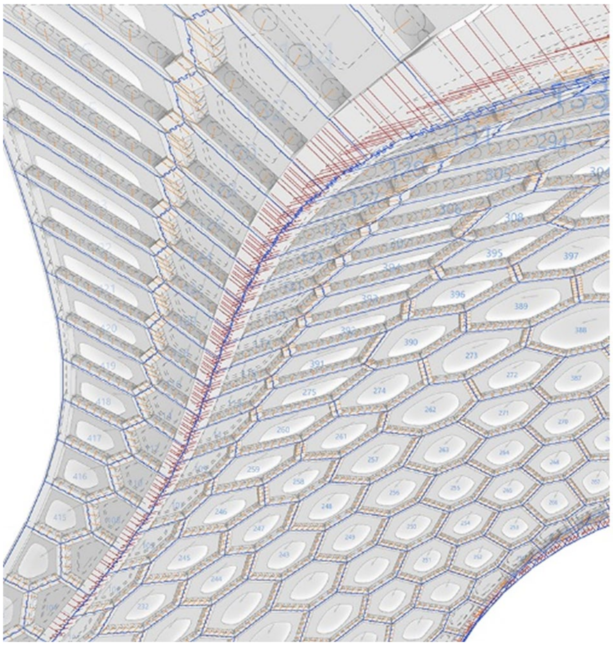


Fig. 2 All geometrical data necessary for fabrication is generated in a computational model

4 Setting

The BUGA Wood Pavilion has its origins in continuous research efforts on segmented timber shell structures at the ICD that started in 2011. It is a direct descendant of the 2014 Landesgartenschau Exhibition Hall (Krieg et al. 2014). With triple the span but the same weight per shell surface area (38 kg/m^2), the BUGA Wood Pavilion leverages a more structurally effective hollow cassette system (Krieg et al. 2018) for further improved structural performance (Sonntag, et al. 2019). While this allows the 500 m^2 shell (Fig. 1) to span up to 30 m, the fabrication complexity is increased significantly (Fig. 2). Each shell segment needs to be created from an average of eight custom timber elements that are glued together (Fig. 3). Apart from accurate subtractive fabrication of Finger Joints (Krieg et al. 2012) and bolted connections, this necessitates the additive placement of beams and plates, preparation of glue joints and fixation of elements with beech nails.

The project was realized in collaboration between the Institute for Computational Design and Construction (ICD), the Institute for Building Structures and Structural Design (ITKE)—both at the University of Stuttgart, the BUGA Heilbronn GmbH, Müller Blaustein Holzbauwerke and the BEC GmbH. As the pavilion spans over a central event space that was visited by more than two million visitors during the summer of 2019, the structure needed to fully comply with building code regulations and building

Fig. 1 The BUGA Wood Pavilion spans 30 m over a central event area on the ‘summer island’ in Heilbronn

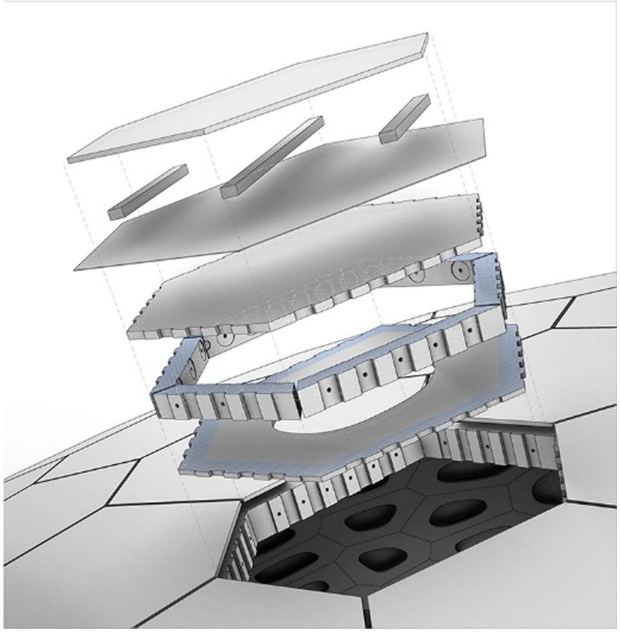


Fig. 3 Each cassette is preassembled from two LVL plates and a ring of LVL edge beams

authority procedures. A transportable robotic timber construction platform was developed in order to bring flexible robotic fabrication capabilities directly to the local prefabrication hall of the timber construction company (Wagner et al. 2020). The robotic fabrication workflow integrated locally available CNC machining capabilities, human craft as well as the certified expertise in adhesive gluing of the construction company. As the production schedule was therefore codependent with the organization of the craftsmen, reliable robotic workflows were crucial to establish—notwithstanding the complex geometry of the 376 bespoke hollow cassette building assemblies of sizes varying between 1.5 and 2.7 m diameter.

The craftsmen checked the quality (dimensional accuracy, moisture content, and visual quality) before supplying the robotic platform with the correct raw element batches by filling beam- and plate input carts. By rolling the carts into the cell and docking them to the platform, a quick exchange sequence was devised. After the robots assembled the raw cassettes and placed them in the press, the craftsmen closed the press and checked conformity with adhesive open- and pressing times. After the pressing, the cassettes were placed into the input cart by the craftsmen. The cassettes were then placed consecutively onto the central work table and machined to sub-millimeter precision. After milling of all four cassettes of one batch the craftsmen again entered the cell to take out the finished palette for finishing work and supply the new batch.

The cassettes finally were transported to the building site, where they were assembled like a three-dimensional puzzle by 2 workers within 10 working days. The structure was than outfitted with light installations, waterproofing layer and a wooden façade layer.

5 Computational workflow organization and co-design methods

5.1 Interactive co-design method

Throughout the last 20 years, computational design methods demonstrated the underlying potentials of generative design for architecture (Menges 2007). This approach allows the direct computational integration of system intrinsic material capacities and external environmental influences and forces. In order to advance this digital design methodology towards large-scale project applicability, new methods of human machine interaction need to be employed. As multiple stakeholders, planning teams and unknown parameters are involved in such projects, the flexible interaction between planning teams and computational models become a primary factor for success. The proposed method of Co-Design integrates the human into the processes of computational form generation and therefore obtains the agency to address project-specific challenges and embed the computational planning process within a wider communicative effort between various stakeholders (Fig. 4).

The integrative digital automation planning of the BUGA Wood Pavilion served as a unique chance to inductively develop and test this framework. As multiple planners with varying expertise collaborated on the same project, an effective coordination of different computational developments was necessary in order to allow for effective progress in a limited project timeframe. The workflows between the computational model and the fabrication automation two parallel modelling environments were set up using Rhinoceros3D's Grasshopper plugin and custom code in C# and Python: (1) the computational design model and (2) the fabrication simulation and robotic code generation model (Fig. 5).

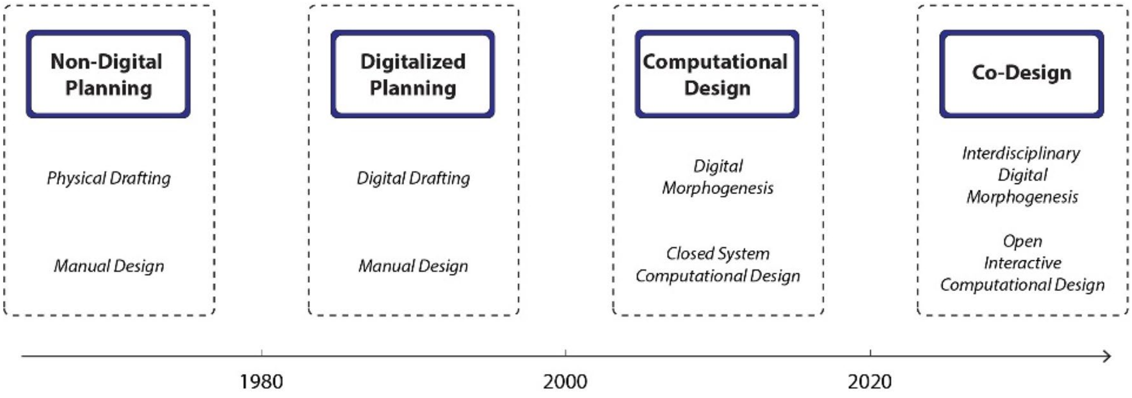


Fig. 4 Schematic overview of emerging digital design frameworks of the last decades

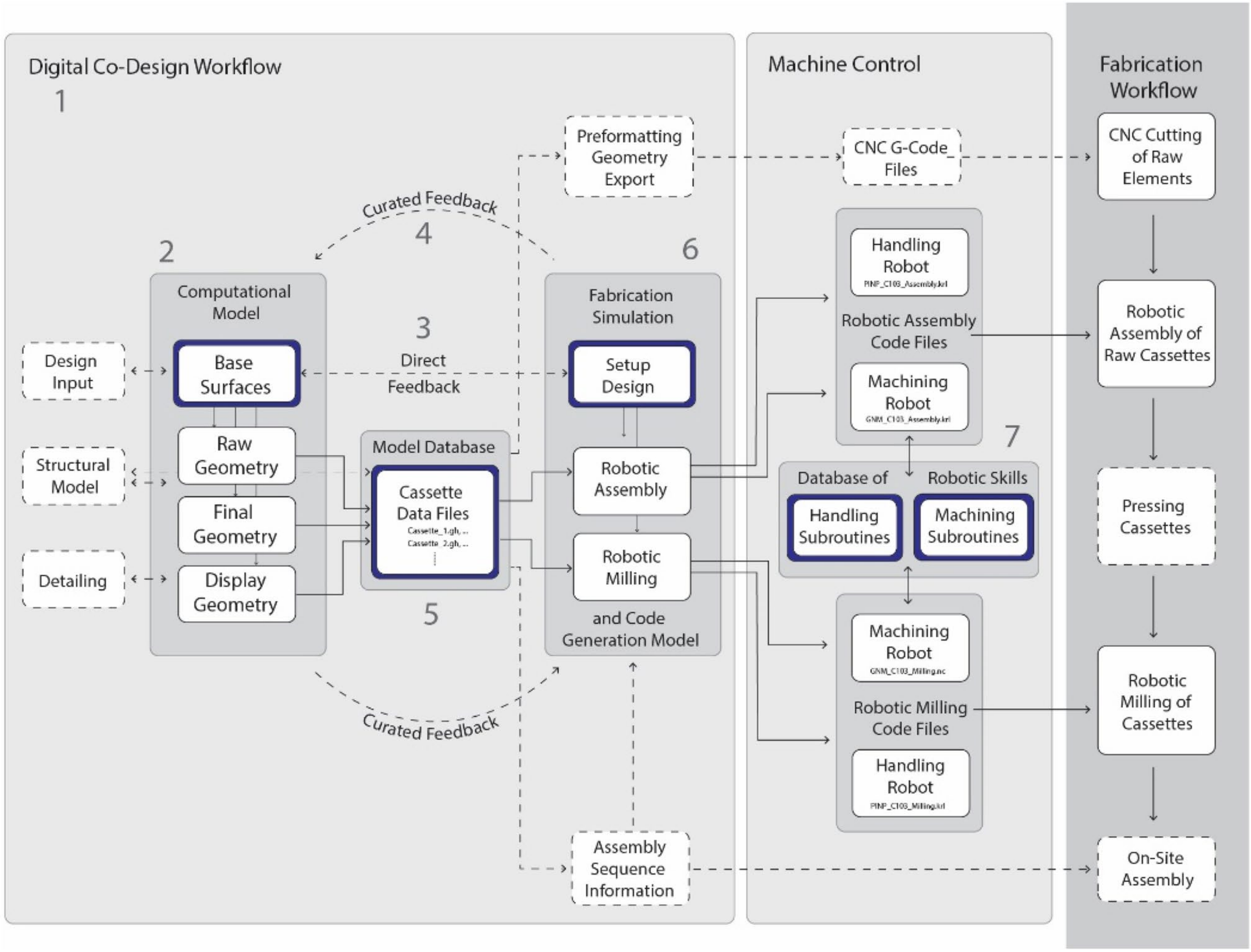


Fig. 5 Computational design to fabrication interrelations of different models: direct digital feedback at initial design stages allowed tight integration of main fabrication parameters. At later stages the underlying building and setup design was frozen and a central model database served as information exchange platform. It can be read by all planning partners but is only updated upon mutual agreement following coordinated feedback loops based on collective decision processes. A collection of robotic skills is used throughout the whole fabrication without being impacted by adaptations of model parameters and to flexibly integrate process control logistics. This enables the effective generation of comprehensive robotic fabrication routines directly from the fabrication simulation and code generation model based on the simple composition of fabrication tasks

5.2 Computational design model

A computational design model was used as the central planning file that generated and stored all necessary data that unambiguously defined design and fabrication geometry of the pavilion down to the smallest detail. The model also acted as communication platform for further models (e.g. site model, structural engineering computation, etc.).

5.3 Direct digital feedback

To coordinate the developments between the models, different feedback strategies were applied throughout the project phase. This allows for reciprocal dependencies between the domains and helps to achieve highest levels of integration. On the other hand, it also poses a challenge on the computational project management. The initial design of the structure's base surface geometry as well as the robotic fabrication setup design can be tightly digitally linked based on main geometric parameters (e.g. plate diameter, edge lengths, edge count, etc.) (c.f. Menges 2012b; Schwinn et al. 2012). The generative design of the base surface model therefore directly included the feedback from the fabrication setup model and therefore was able to come up with design solutions within the machinic morphospace.

5.4 Curated feedback

Whereas the use of main geometric parameters to build a multi-dimensional design morphospace and enable direct digital feedback loop, can be a powerful design approach, this approach is not effective for many other parameters that would explode the design solution space into unnecessarily high dimensions. Given the tectonic complexity of the BUGA Wood Pavilion there appeared to be multiple additional parameters that had direct effect on the generated design geometry, but where a computational implementation across their complete domains seemed unnecessary and would have resulted in rather extensive computation processes. Typically, these parameters were more effectively addressed in a round-table meeting with all planners present. Only after a collective strategy is found, the decisions are integrated into the computational models—either as singular parameters or as an extension of computational routines.

As the quantity of parameters that need to be collectively defined can be rather extensive it can become difficult to keep track of their mutual influences along the project. Although this proved possible within the attentive project team of the BUGA Wood Pavilion, outside the research context a reliable framework for keeping track the parameter interactions might be useful for greater reliability and minimization of risks of disintegration of system developments. Retrospective investigations of the authors suggest that a design-structure matrix (Browning 2016) as coordination tool together with axiomatic design principles (Suh 2001) could be helpful for the effective management and tracking of all parameters and their respective dependencies.

5.5 Model database

After the conclusion of initial, tightly integrated design of the basic building design, more and more detailed planning parameters need to be included. As the building model becomes rather excessive at that point and re-computation times start to need considerable processing time, the data is stored in a model database with a single file for each hollow cassette building assembly each time it is regenerated and updated within the computational design model. All cassettes could then be flexibly used in various other planning environments independently of the computation state of the central model. The database acts as a central information hub similar to what is known as a "single source of truth" within Building Information Modelling. This measure is important as soon as considerable amount of geometry is collected within the model and the re-computation of the whole building model starts to take up considerable processing time. The implementation of the data base aides the transition from a direct feedback to curated feedback loops as it provides a reliable framework for the flexible and immediate integration of (collective) human decisions and enables fluid design interaction also at a later stage of the project development when direct computational feedback cannot effectively be employed anymore.

5.6 Robotic fabrication simulation and code generation model

During the initial project phases the basic fabrication setup parameters are defined in direct feedback with the computational design of the building artefact. This allows a smooth consideration of the most important geometric parameters for successful fabrication. As soon as the geometric dependencies of the fabrication setup were defined, the setup model built the basis for the simulation of the assembly as well as milling processes. As the robotic assembly and milling processes of the cassettes were interrupted by the glue-pressing, it was possible to simulate the procedures in different code generation and simulation environments that were both prepared in Grasshopper. This simplified the code structure of each part significantly and facilitated organizational flexibility during production (e.g. ad hoc milling production schedule changes). Still, both environments used the same building information data as provided by the model data base.

5.7 Robotic skills database

Similarly, both code generation models use the same set of robotic skills that were programmed as separate modules as KRL (KUKA Robot Language) files and stored in a database of robotic skills directly on the robot controllers. The robotic programs were organized as task-based choreographies of collaborative robotic process sequences. Comprehensive fabrication sequences and complex robotic interactions could therefore be simplified into singular process blocks that were composed into larger process assemblies.

6 Development

6.1 Computational setup development

The computational design setup of the BUGA Wood Pavilion is based on a tailor-made agent based computational environment (Groenewolt et al. 2018) that was further extended with the aim of going beyond the current industry practices and enabling synergy between the realms of wood material science, engineering, fabrication and construction. With the exception of the plates on the cantilevers, the plate geometry has been defined using agent behaviors that among others ensure that all plates fit within the available material dimensions and robotic morphospace (Menges 2012b; Schwinn et al. 2012). Each plate corresponds to an agent object; for this project, a specific C# object type containing all necessary geometric and fabrication information has been derived from the agent object type present in the environment. In contrast to the plates on the central part of the shell, the contours of the plates on the cantilever were modeled parametrically and converted to the same custom object type. As the design of this project is a trivalent polyhedral, an exact offset can be made and joint surfaces can be defined as planar surfaces containing the average of the normal vector of two neighboring plates. While all components have the same total thickness, the material thickness of layers within the components varies depending on structural requirements. Structural requirements also govern the arrangement of edge beams within the cassettes: in areas where high forces are anticipated, edge elements are arranged in such a way that there are no gaps in the main stress direction.

After the integrative computational design of the global shell structure (Alvarez et al. 2019), simple planar polygons represented the core input for the generation of all further geometric data and the structural detailing (Sonntag et al. 2019). This allowed for systematic coherence from schematic to detail design (Figs. 3, 6). Multiple versions of three-dimensional parts of the assemblies were constructed. The resulting layers of information allowed the extraction of all fabrication data from the same model.

Finger joint details and bolt positions were parametrically generated, based on available edge length and structural requirements. These details were stored within the plate objects as series of planes, not as geometric objects; this has the benefits that posterior adjustments can be made relatively easily (for example to adjust bolt positions in situations with limited reachability). Based on the stored planes, geometry can be exported in mesh format for visual inspection. In addition to the geometric definition of the components, series of planes with information relevant for fabrication and assembly (such as picking positions for grippers and the position marking the center of the turntable) were generated and stored within the plate object. To generate this information, detailed information about the fabrication processes was necessary: for example, when picking and placing edge elements, the decision to pick up an edge with one or two grippers depends on the spacing between grippers on the effector. While all required information could in principle be generated dynamically each time the file is opened, this process started taking inconveniently long after implementing more and more information in the objects. Because of this and to ensure that no accidental changes could be made to the geometry, each plate object was serialized and stored as a file. In the model data base each file could then be opened to simulate and check the fabrication process of each plate. Programs for the industrial robots were produced based on these files, whereas data for the timber contractor was stored and exported as geometry in a conventional file format.

6.2 Pre-fabrication data, formats and interfaces

The custom agent-based model developed in C# allowed for specific arrangements when designing how to store and compute the pre-fabrication data, enabling feedback between design and fabrication simulation and ultimately connecting the design with the machining tasks (Fig. 6). Each agent represented a Cassette and stored all its features and elements by using different types of data, designed for specific

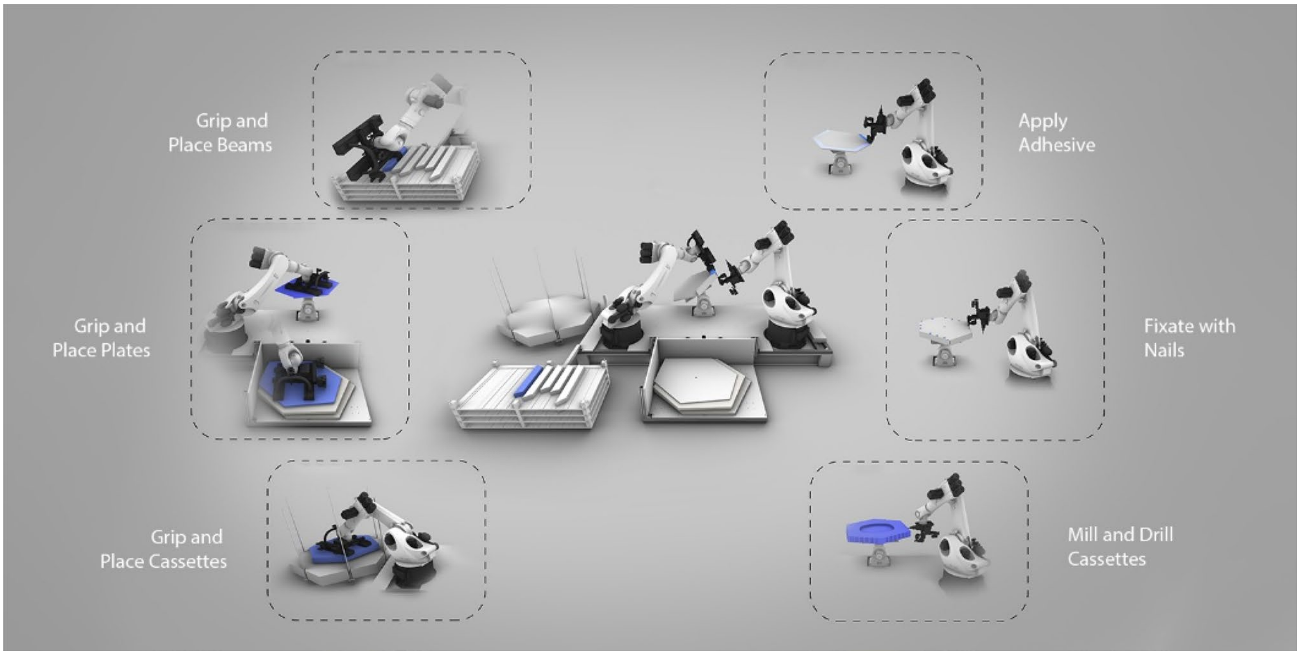


Fig. 6 A compound robotic timber construction setup integrates a comprehensive set of common woodworking processes such as gripping, placing, gluing, nailing, milling and drilling

steps of the generative process that generated the robotic codes. The ‘Cassette Data Files’ were created by serializing and writing all the properties and geometry of each cassette into one file. Therefore, the ‘Fabrication and simulation’ tool could use that information to generate all the codes for the handling and machining routines. This step fundamentally replaces the generation of architectural drawings that mediate between the designer, the contractor, and the produced part. As well as architects and engineers need to define the ontology of architectural drawings, the data needs to be composed in a structure and format that all parties agree on. The necessary information needed to generate the robotic fabrication tasks within the Fabrication and Simulation Model is then automatically generated within the computational model. Thus the cassette data file acts as the direct and curated interface between design and fabrication (Figs. 7, 8).

The types of data stored in the cassette data file that is relevant for the robotic fabrication were as follows: (1) Explicit three-dimensional meshes. (2) Explicit three-dimensional solids represented as Boundary Representation objects (BREPs), available in the CAD Rhinoceros software. (3) NURBS Curves. (4) Geometrically defined planes, structured as single objects or lists, depending on what they represent. (5) Basic numeric data and strings of text.

By storing layers of abstract data (planes, numeric data and text) in relation to the physical description of the elements, the ‘Fabrication and Simulation’ tool worked with information that was reliable, verifiable and contextualized.

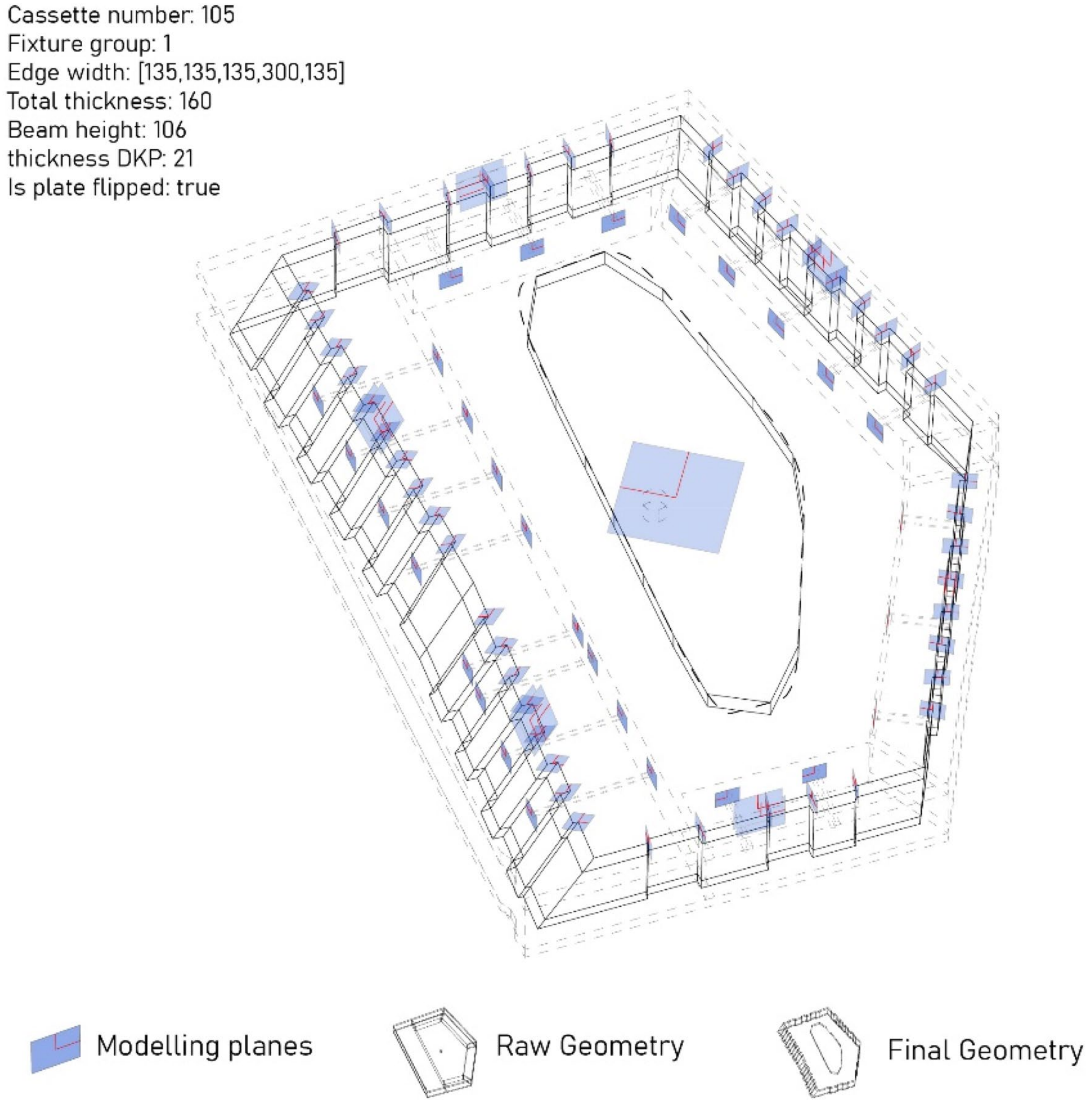


Fig. 7 Exemplary computed geometry and data as stored in the cassette data file. It forms the base input for the robotic milling of cassettes, including raw mesh for simulation visualization and frames and curve objects for accurate fabrication routine generation

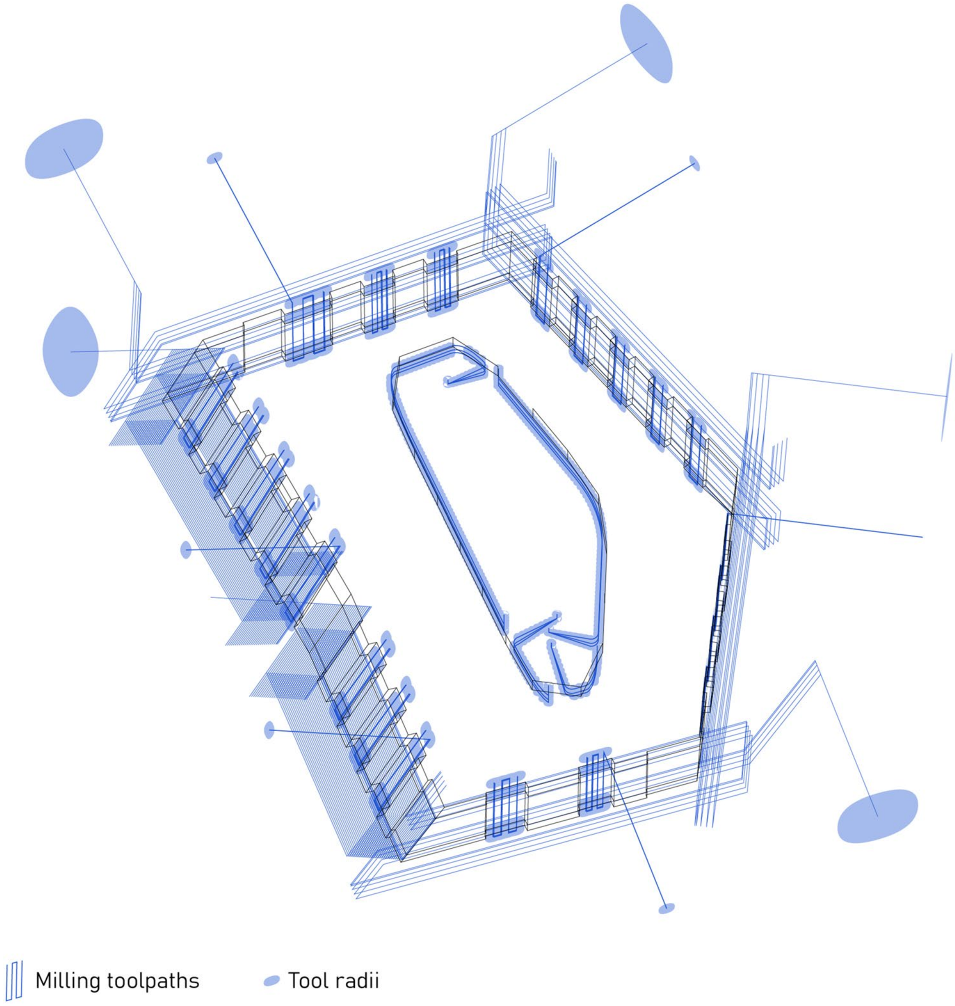


Fig. 8 Cassette milling toolpaths as generated with the geometry information as provided by the central data model

This makes a direct coupling and loss-less information-transition possible and therefore stands in contrast to deriving codes from solids or meshes, which is computationally intensive, creates error prone information tautologies and disintegrated workflows. Solids and meshes were only used as visual guidance and for collision detection procedures. Complementarily, geometrical planes offer intrinsic functionality when working with three dimensional robotic paths. Ultimately, since two parallel modelling tools were developed simultaneously, agreeing on data protocols become more important than focusing on the shape of the parts.

6.3 Robotic fabrication integration, simulation and code generation

The automated generation of the robot command files for cassette assembly and milling workflows is based on the modular composition of singular process blocks (Fig. 5). These process blocks are organized as subroutines that take the necessary geometric parameters as input so that they are usable for various cassette geometries and across multiple projects. This organization within subroutines allows to pack all low-level signal programming, process quality checks, repeating motions and safety routines within a reliable package. This makes possible in-depth optimization of individual robotic routines. An example of robotic skill parameters that are highly relevant for the performance of an individual process step, but do not need to be adapted over the course of the production is the application of the adhesive (Fig. 9).

The modular nature of the code composition enables a clean and human readable generation of robotic command files. Duplicate or co-dependent data is avoided as only the essential geometric parameters are passed on to the robots.

The computational fabrication simulation and robotic code generation model defines three topics: Over-defined axis values are automatically computed, critical robotic positions are simulated for a visual check and geometric data is fed into a predefined code structure. The calculation of additional axis values is based on a compound algorithm taking into account both a target effector orientation and target effector position. Unsatisfying results were automatically flagged, so that they could be checked by the user within the

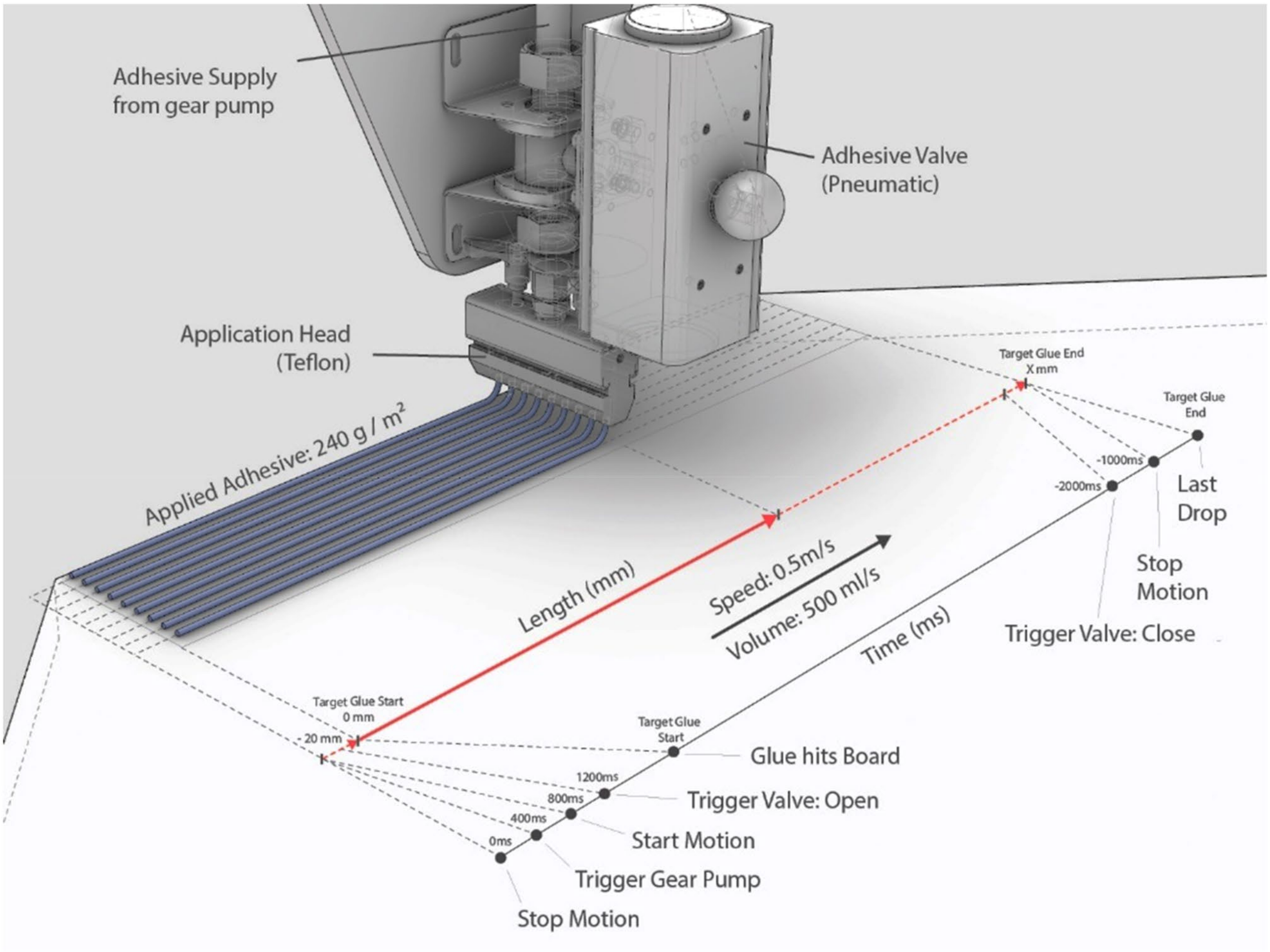


Fig. 9 The robotic adhesive application routine takes only two frames for start- and endpoint as input. Within the routine, a multitude of parameters that are constant across all application processes or directly dependent on the frame inputs are computed. As the adhesive application is strictly regulated by the building code (in terms of application accuracy, volume and homogeneity), the routine was tested using comprehensive parameter testing. An unintended change in core parameters is avoided by wrapping the routine in a subprogram

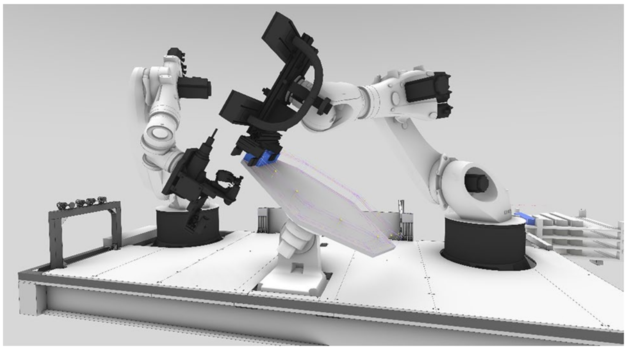


Fig. 10 Digital simulation of the robotic fabrication, used for visual inspection of the generated machine code before fabrication

simulation environment (Fig. 10). Through direct interaction with the parameters, a solution could then be manually found for special cases.

For the chronological coordination of robotic processes between handling and machining robot (c.f. Fig. 11), the simplest solution of sending sequence integers between the robots was used. This allowed an intuitive and clear sequencing and the optimization of fabrication times. Tasks of both robots were numbered consecutively. The structure of tasks was conceived manually and stayed constant for each cassette, except repeating parts that looped according to beam numbers. Fabrication process dependencies were defined in order to allow smooth robotic process choreographies. The dependencies were defined through simple inequations based on task numbers which especially defined coordination sequences for processes that are interdependent on each other (e.g. placing and fixation of beams).

Fig. 11 The coordination of fabrication steps is conceived via enumeration of tasks and the setting of co-dependencies. This enables the effective cooperation of both robots. (Wagner et al. 2020)

7 Instances of curated feedback and interactive computation

Computational design teams of largescale building projects need to be able to address project-specific boundary conditions that might arise at any moment during a fast paced integrative design process. The project teams then need to derive at and implement custom solutions in the planning models upholding reciprocal feedback with all stakeholders. In the following chapters we will discuss three instances of bespoke 'curated' intelligence that was integrated into the computational models of the BUGA Wood Pavilion—focusing on tight curated feedback between design, fabrication and construction.

7.1 Beam assembly sequence

Defining in which order to place edge beams when assembling a component required collision checks that depend on the specific design of the robotic handling effector, the dimension of the beams and the shape of the cassette. A specific robotic fabrication setup might need a specific logic for defining a solid beam assembly sequence in order to avoid collisions between effector geometries during pickup and placement.

Long edge beams were picked with two pneumatic grippers whereas short edges were picked up with just one of the grippers. In either case, collisions between the grippers and edge beams could occur. The number of possible assembly orders equals the factorial of the number of edges; for most plates, this resulted in 720 possible assembly orders. For each plate, all of these were checked for collisions and from the valid orders, the order that resulted in the lowest total rotation of the turntable was chosen.

7.2 Construction assembly sequencing

The order in which components are prefabricated is based on a number of requirements that follow from the on-site assembly process. Components are pressed, stored and transported in stacks and during the on-site assembly process, components are lifted from these stacks and moved to the right location by a crane. As space on the construction site was limited, the number of stacks that were needed at any point during on-site assembly needed to be minimized. Within a stack, the components should be arranged according to the assembly order and in order to ensure that the stacks are stable, there should be only limited variation in component shape per stack. During prefabrication, the components were built and processed on a turntable. In order to support the components on an area that is as large as possible, fixtures with vacuum clamps were fixed on this turntable. In order to better match the different sizes and shapes of components, a number of different fixtures were used. The shape of these fixtures was defined by grouping the component outlines using a sorting algorithm similar to the k means method (Fig. 12).

Based on the geometry of the design, a fabrication sequence consisting of four groups of components was devised, with the first group consisting of components bordering the kinks in the shell, the second group consisting of components in the lower half of the main shell, the third group consisting of components in the central area of the main shell and the fourth group consisting of the outer plates on the cantilevers (Fig. 13). As plates with similar features thus end up in a single group, it turned out that each group could be produced with just two or three different fixtures; consequently, at most three stacks of components would need to be accessible on-site at any given moment.

The method used to sort the component shapes consists of an iterative process starting by randomly dividing the component contours into eight groups. For each group, the average shapes of the contours are defined. After this, all contours are compared to the eight average shapes and regrouped based on the geometric similarity; for this step, various rotations were tested but the contours are not moved. In case any groups are empty, they are removed and the group with the least similar plates is split. The average shapes are updated after the regrouping and the procedure is repeated until the geometric similarity no longer increases (Fig. 14).

After this, the size of the open area in the centre of the groups of contours is increased using an iterative process in which the position and rotation of each contour are adjusted. Finally, the resulting inner shapes of the eight groups can be visually compared, so that groups that are

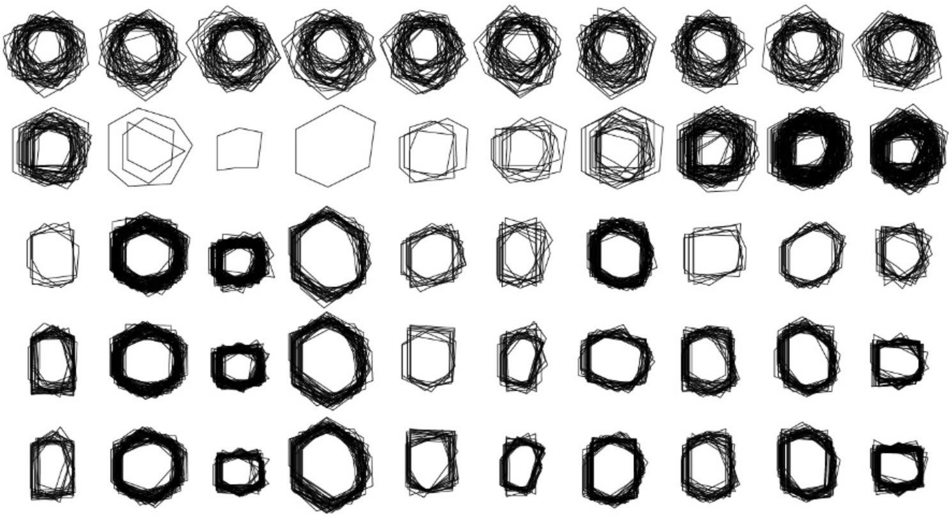


Fig. 12 Five iterations of a grouping process of component contours

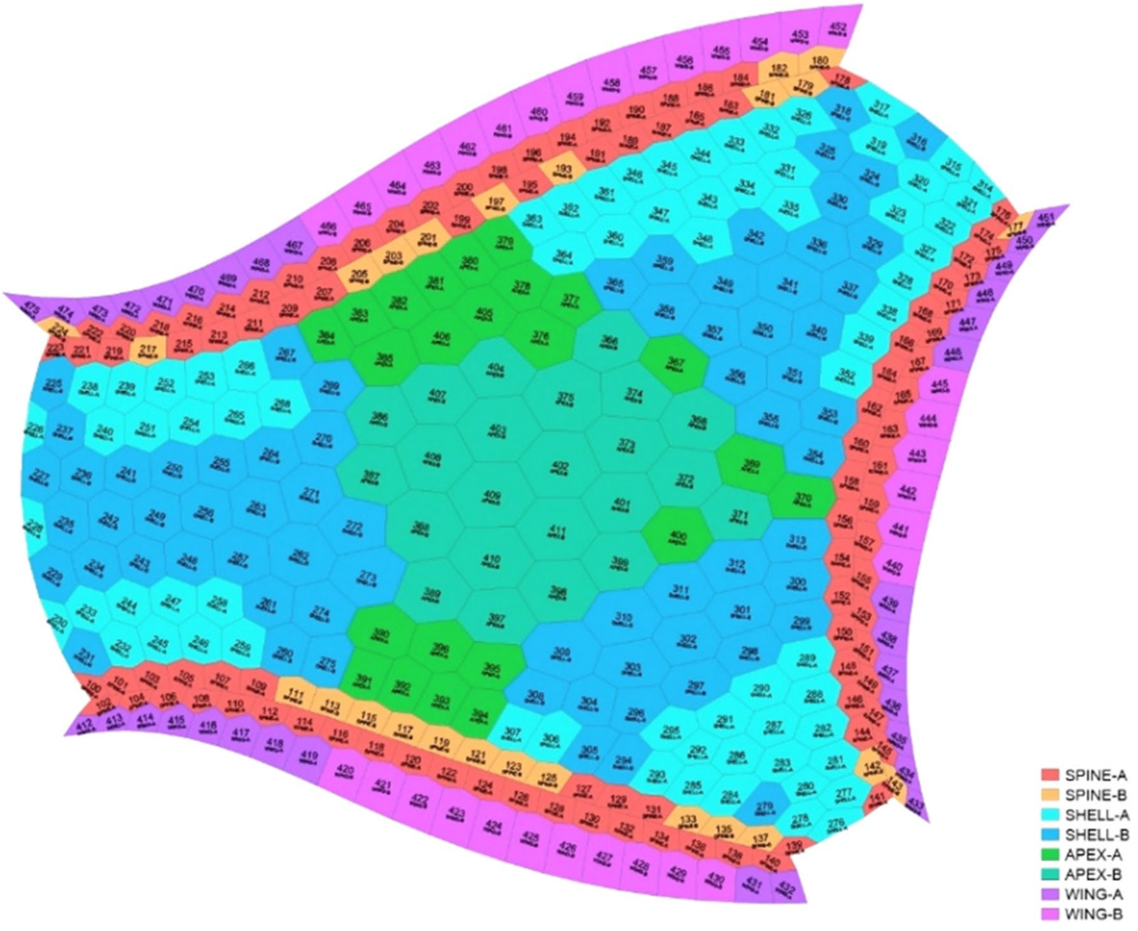


Fig. 13 Each section of the pavilion is divided in pairs of cassette groups. This allows the scheduling of prefabrication following both similar cassette shapes and assembly sequence on site

Fig. 14 Due to detailed sequencing, no sorting was necessary on site. Each cassettes were iteratively taken off the stacks and directly mounted in the shell

similar can be merged. For this project, this last step meant that the number of fixtures could be reduced from eight to five.

7.3 Finger joint directions

In the central area of the shell, the assembly directions of cassettes are hardly constrained: as all side surfaces of a plate point slightly outwards and a plate can be inserted along the normal vector to its surface. This is not the case at the spine cassettes, as neighboring plates might block this insertion direction. As the finger joints put further restriction on the assembly directions, some of the plates at the spines could not be assembled using any assembly order. In these cases, the assembly order was predefined and finger joints were rotated by a couple of degrees using a visualization method of assembly directions based on spherical maps (Gan et al. 1994).

When no finger joints would be present, each joint surface limits the insertion directions to a hemisphere; the shared area of these semi-spheres represents valid insertion directions (Fig. 15, left). When finger joints are present, no shared area may be present and the third plate cannot be placed (Fig. 15, centre). This can be resolved by adjusting the joint geometry, for example by rotating some of the finger joint surfaces (Fig. 15, right). As the latter diagram indicates, the third plate can only be inserted from below.

The discussed changes in cassette design geometry not only need to be brought in accordance with the milling path generation algorithm but also with the construction planning. As the insertion of cassettes from underneath is impossible on-site, it was decided in accordance with the timber construction firm, that the spine cassettes would

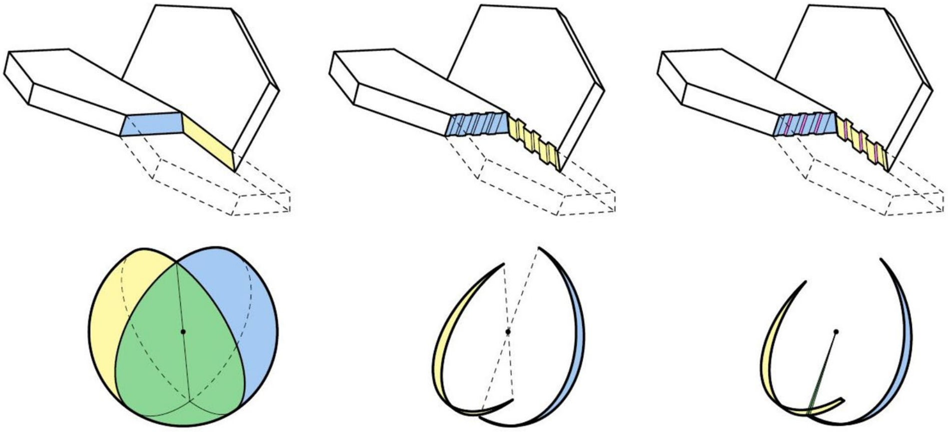


Fig. 15 Visualization of possible insertion directions. The joint geometry in the center image prevents placement of the third component

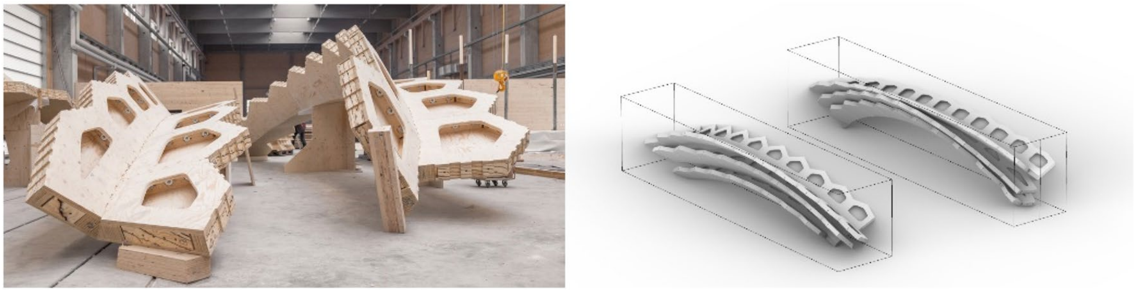


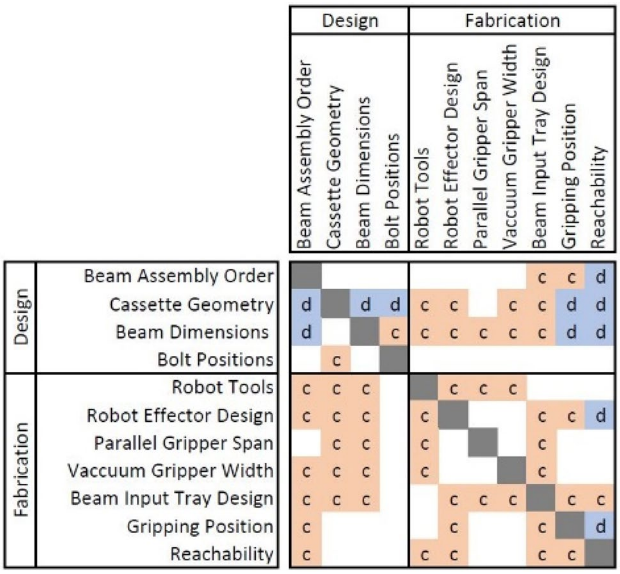
Fig. 16 The ‘spine’ cassette groups were pre-assembled in the fabricators hall forming halves of each spine. The spine halves were transported on two trucks and were assembled on site with a connecting keystone

be assembled in the fabrication hall in flipped orientation. The preassembled spine segments were then transported to the site (Fig. 16).

The changes in Finger Joint geometry therefore had implications not only on robotic fabrication code generation, but also on the production plan and schedule and the overall construction sequence of the pavilion.

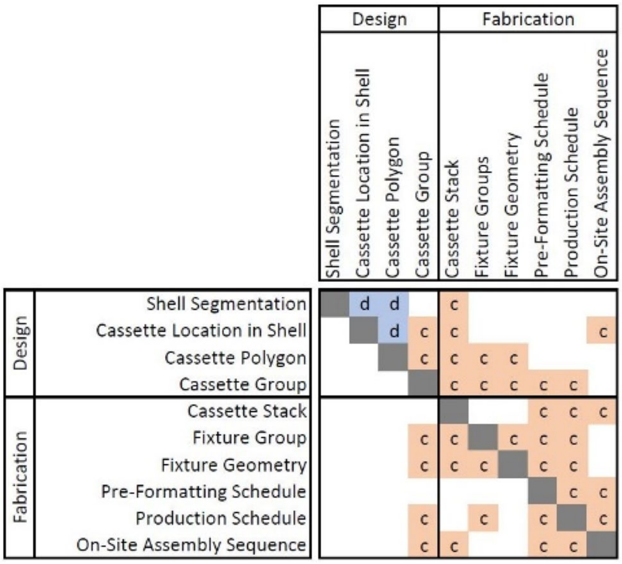
7.4 Reciprocal parameter dependencies

Addressing and integrating various parameter dependencies of the abovementioned topics into the general computational design and fabrication models were key factors for the successful realization of the BUGA Wood Pavilion. Figures 17, 18 and 19 show schematic overviews of the main reciprocal feedback loops in the form of a design structure matrix. As only a minor subsection of feedback loops in these topics can be efficiently formulated as a general relationship (i.e. 'd'—direct computational feedback), the interaction between human planning teams with the employed computational strategies became a highly relevant design method. Employing curated feedback loops ('c') the planning teams either implemented data that resulted from round-table meetings or the added special strategies to the computational models that were collectively devised in the face of emerging project-specific challenges.



		Design				Fabrication						
		Beam Assembly Order	Cassette Geometry	Beam Dimensions	Bolt Positions	Robot Tools	Robot Effector Design	Parallel Gripper Span	Vaccuum Gripper Width	Beam Input Tray Design	Gripping Position	Reachability
Design	Beam Assembly Order	■								c	c	d
	Cassette Geometry	d	■	d	d	c	c		c	c	d	d
	Beam Dimensions	d		■	c	c	c	c	c	c	d	d
	Bolt Positions		c		■							
Fabrication	Robot Tools	c	c	c		■	c	c	c			
	Robot Effector Design	c	c	c		c	■			c	c	d
	Parallel Gripper Span		c	c		c		■		c		
	Vaccuum Gripper Width	c	c	c		c			■	c		
	Beam Input Tray Design	c	c	c			c	c	c	■	c	c
	Gripping Position	c					c			c	■	d
	Reachability	c				c	c			c	c	■

Fig. 17 Schematic Design Structure Matrix depicting the relevant parameter dependencies for the co-design of the beam assembly sequence (Chapter 7.1)

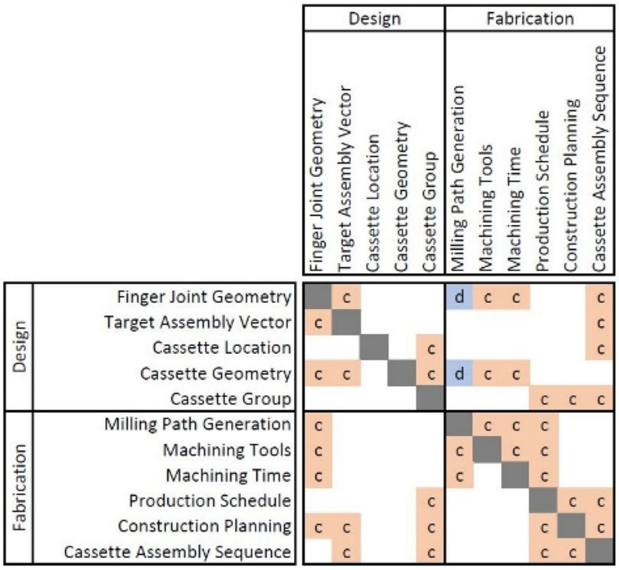


		Design				Fabrication					
		Shell Segmentation	Cassette Location in Shell	Cassette Polygon	Cassette Group	Cassette Stack	Fixture Groups	Fixture Geometry	Pre-Formatting Schedule	Production Schedule	On-Site Assembly Sequence
Design	Shell Segmentation	■	d	d		c					
	Cassette Location in Shell		■	d	c	c					c
	Cassette Polygon			■	c	c	c	c			
	Cassette Group				■	c	c	c	c	c	
Fabrication	Cassette Stack					■			c	c	c
	Fixture Group				c	c	■	c	c	c	
	Fixture Geometry				c	c	c	■	c	c	
	Pre-Formatting Schedule								■	c	c
	Production Schedule				c		c		c	■	c
	On-Site Assembly Sequence				c	c			c	c	■

Fig. 18 Schematic Design Structure Matrix depicting the relevant parameter dependencies for the co-design of the cassette grouping and construction assembly sequence (Chapter 7.2)

8 Conclusion and contributions

The integrative design for the robotic prefabrication of the BUGA Wood Pavilion (Fig. 20) proved highly successful. New co-design methods enabled the parallel development of design and fabrication computation and hence a new level of comprehensive robotic timber construction. The applied



		Design					Fabrication					
		Finger Joint Geometry	Target Assembly Vector	Cassette Location	Cassette Geometry	Cassette Group	Milling Path Generation	Machining Tools	Machining Time	Production Schedule	Construction Planning	Cassette Assembly Sequence
Design	Finger Joint Geometry	■	c				d	c	c			c
	Target Assembly Vector	c	■									c
	Cassette Location			■		c						c
	Cassette Geometry	c	c		■	c	d	c	c			
	Cassette Group					■				c	c	c
Fabrication	Milling Path Generation	c					■	c	c	c		
	Machining Tools	c					c	■	c	c		
	Machining Time	c					c		■	c		
	Production Schedule					c				■	c	c
	Construction Planning	c	c			c				c	■	c
	Cassette Assembly Sequence		c			c				c	c	■

Fig. 19 Schematic Design Structure Matrix depicting the relevant parameter dependencies for the co-design of the finger joints of the spine cassettes and the resulting construction strategy (Chapter 7.3)

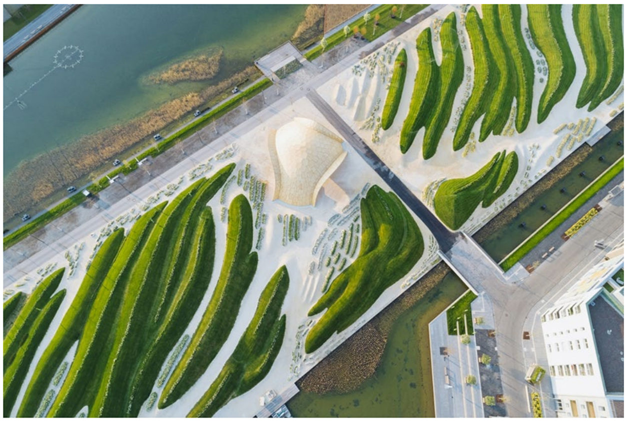


Fig. 20 The BUGA Wood Pavilion in the undulating landscape on the BUGA Wood Pavilion

methods made possible the fast paced development of the project in little more than one year from project commission to the opening of the pavilion. We show that digital robotic fabrication workflows can be conceptualized, developed, tested and put into use at the local timber manufacturer in reciprocal feedback with the digital development of fabrication programming and pavilion detailing. The integration of the human into the generative design loop was fundamental for the tight integration of various domains—especially on largescale, comprehensively automated construction projects.

The consequent, curated implementation of all strategies and decision processes into the design and robotic code generation models rendered printed plans unnecessary and allowed the assembly of the shell by the carpenters with only a single A3-paper in hand, that depicted the assembly sequence.

9 Discussion and further research

Although the employed co-design method between design and fabrication computation proved successful, several points can be further improved. The coordination of all parameters of the project and their mutual dependencies still relied on a highly capable project team and ad-hoc judgements. For the implementation of such methods in the industry, the organizational framework needs to be further developed and a tool implemented that helps to keep track of curated and direct feedback dependencies and interfaces smoothly with the computational models.

The approach of organizing the generation of robotic instructions for the automated fabrication of building assemblies on the basis of tasks and reusable robotic skills needs to be further enhanced. As both tasks and skills represent highly repetitive routines that mostly differ only in their geometric variation they could provide a good basis for a standardized interface between computational design and robotic fabrication.

Further research is also necessary to provide principles of how computational developments can not only be flexibly extended but also transferred across projects. For the further upscaling of the discussed co-design method interfaces with conventional design tools will be of great importance. Although multiple developments are underway in this regard, the main challenge of how such tools can continuously evolve and adapt according to further advances in construction and design technology remains unclear.

The presented approach constitutes the point of departure for multiple research agendas at the newly founded Cluster of Excellence at the University of Stuttgart. A subset of the authors will address the abovementioned topics. We further invite the researchers from academia and practice to further develop integrative and interactive computational design methods and collaboratively work towards a rapid advance of productivity and quality in architectural construction.

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Availability of data and material Selected Data is available upon reasonable request.

Compliance with ethical standards

Conflict of interest The authors do not declare a known conflict of interest.

Code availability Selected Code is available upon reasonable request.

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