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Advancing Timber for the Future Built Environment

ENHANCING DESIGN AND PRODUCTION IN MODULAR TIMBER ARCHITECTURE WITH COMPUTATIONAL DESIGN TOOLS

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ABSTRACT: This research explores integrating computational design tools to enhance design and production in modular timber architecture. It focuses on two main aspects: 1) integrating existing analysis tools for better-informed decisions and 2) automating modeling, analysis, and CNC fabrication of various design variations. Computational tools in modular timber construction can improve quality and productivity while allowing for architectural uniqueness. This flexibility enables creating unique solutions with the same effort as standardized ones. The research aims at developing a computational design system with tools for structural analysis, energy simulations, cost evaluation, weight assessment, and design-to-production processes, all integrated into a parametric planning platform. The project "àDisposition" exemplifies this approach, aiming to develop a modular timber construction kit optimized for easy transport and temporary use of vacant buildings. Outcomes are showcased by a user-friendly configurator for planning, visualizing, analyzing, and preparing production files.

KEYWORDS: integrative design, modular architecture, BTL automation, informed design, digital planning

1 – INTRODUCTION

Off-site construction and modular building systems both lead to fast production, economic solutions regarding material and processes, more accuracy and higher overall quality [1, p13]. This research investigates the integration of computational design tools to evaluate to what extent the design process and production methods can be enhanced within the context of modular timber architecture.

The focus is specifically on two aspects. Firstly, the integration of various existing analysis tools into the design process to achieve a more informed design. Secondly, automating the modelling, analysis, and CNC fabrication of different architectural design variations (geometry, shape, materials, etc) using a range of bespoke computational tools.

1.1 PROJECT INTRODUCTION

The transformation of existing buildings and areas plays a significant role in the sustainable development of societies [2]. Often, due to extended planning periods, vacant spaces offer substantial potential for temporary uses, where innovative and dynamic work environments, along with creative spaces, contribute to identity creation. Just in Switzerland there is around 1000 unused commercial halls within urban areas, which stay vacant [3].

Repurposing fallow land allows for the development and sustainable enhancement of existing resources, resulting in ecological, economic, and social benefits. However, it is not always easy to convince owners, authorities or local communities of these potential benefits. This is precisely the challenge that the “àDisposition” project addresses.

The main goal of the project is to temporarily transform unused industrial warehouses into useful and flexible spaces. For this purpose, the research project aims to develop a rentable modular system that can be adapted to different activities and space requirements.

The modular building system is available to the owner or end user through an online configurator to easily test and present project ideas for the temporary use of their vacant buildings and sites, and to implement them in a time and resource efficient manner, demonstrating the viability of their projects.

The modular system is based on the principle of do-it-yourself assembly, using prefabricated lightweight

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timber components with dismountable yet robust joints to create adaptable modules that can be assembled quickly and easily by non-professionals builders using minimal tools. The aim of the project is to provide comfortable spaces for many different usage scenarios. For this reason, the modular system allows for multiple configurations with different dimensions, features and finishes.

To achieve this goal, the project has two main developments (Figure 1). On the one hand, the development of a parametrically defined modular building system that can be easily transported, assembled, adjusted and dismantled. On the other hand, the development of an integrative planning and visualization tool that will allow the rapid design and analysis of the modular building system and, at the final stage, the preparation of files for production.

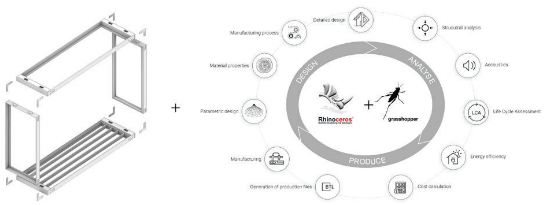

Figure 1. Two project developments: modular building system (left) and integrative planning tool (right).

2 – MODULAR BUILDING SYSTEM

The first development of this project is the design of a modular building system that offers an optimized approach to constructing temporary and adaptable spaces, with simplicity and efficiency at its core (Figure 2). It is mainly made up of two parts: components and layers. The components act as the main structure providing the global stability while also defining the architectural morphology and aesthetics, while the layers define the bioclimatic performance and the finishes. Engineered for non-professional assembly, the building system employs lightweight components and layers, limited to a maximum of 25 kg of weight carried per one person, to ensure safety and ease of handling during the assembly

The assembly process is straightforward and intuitive, utilizing a plug-and-play concept. No adjustments are necessary, making it simple for anyone to put the components together quickly and efficiently.

Figure 2. Image of the simple module 3,60 x 3,60 m.

Grid and reference surface

The modular building system is organized into segments that form a virtual grid (Figure 3). The grid size is based on the width of a wall, a parameter that can be adjusted. The standard width the wall is 1200 mm for its architectural versatility, but many others could be used. The segments can adopt different shapes, like a flat roof or different kinds of double pitch roofs, combining always the same rectangular components with different sizes.

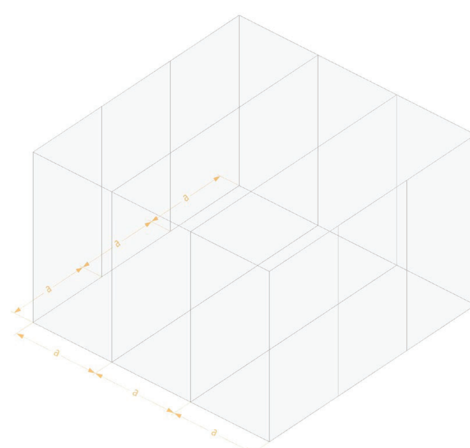

Figure 3. The virtual grid forming a base for generation of elements, segments and modules.

A group of components forms a segment, and a group of segments constitutes a module. Segments are assembled using L-shaped metal brackets, providing sufficient stiffness during erection and usage (Figure 4). The gable walls use special components for horizontal and vertical corners that allows closing the module using the same wall components. The connection between the segments

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and the gable walls is guaranteed by the adjustable toggle clamps.

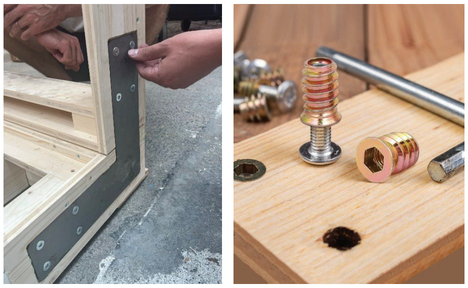

Figure 4. Metal L-shape brackets connected with removable screws

The segment parameters determine the reference surface used to model all the components allowing the same parametric definition for any given rectangular reference surface from a segment (Figure 5).

Figure 5. All components use a rectangular reference surface as a reference (left). From the reference surface many variants can be modelled (right).

Material

This modular building system uses for the main structure a cross-laminated timber board, like a 3-layer panel, produced from reclaimed and joined small soft wood sticks. The final thickness of this panel can be chosen but the 19mm standard product is used.

Based on this type of product, it was decided as a starting point for the design that all parts in a component of the modular building system had to be cut from the same panel with the same thickness. All the components are glued without using any kind of mechanical fasteners.

Components

A component is the basic part of the modular building system. A minimal number of different components is used to keep it as simple as possible. They are parametrically defined so, for any given rectangular reference surface, any component can automatically be modelled. A group of components forms a segment (Figure 6), and a group of segments constitutes a module (Figure 7). The minimal module is a 3x3 walls configuration (or three segments). There are two main components, the vertical ones or wall components, and the horizontal ones, the floor or roof components. Both components can be filled with different layers. Walls can be filled from both sides and floors and roof from one side.

Figure 6. Minimum two walls and two horizontal components are needed to create a segment.

They are completely symmetrical so they can be flipped. All this prevents errors, facilitates assembly allowing for more flexibility. The same horizontal component is used for the floor or the roof, they are completely exchangeable. Just by adding a load bearing layer in it, it becomes a floor with structural capacity.

With a minimum of four components, two walls and two horizontals, connected with the L-shaped metal brackets, a segment can be assembled (Figure 4). As many segments as needed can be placed side by side. Finally, to close the module, the same wall elements are used, together with the horizontal and vertical corners.

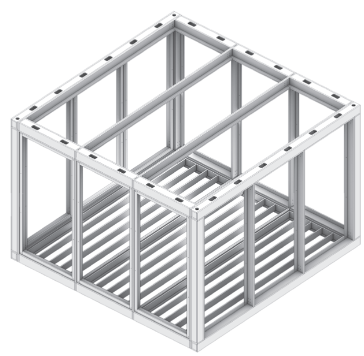

Figure 7. Three segments, 4 corner elements and 6 wall components in the gable wall constitute the minimum module.

Layers

The layers enclose the inhabited space and provide the module with varying performance based on their properties and combinations (Figure 8). To ensure maximum flexibility and adaptability to different demands, different layers can be easily added or removed as needed. They can consist of single or composite materials, and multiple single layers or composites can be combined in the same wall component for enhanced performance.

Figure 8. Interior view of a full-scale prototype showing different layers.

The wall layers are attached to the wall components through matching holes in both with an easy to install and yet robust connection (Figure 9). For the floor and roof, the layers are simply supported and held in place by their self-weight.

Figure 9. Matching holes between the wall and the layer in a mock-up wall.

3 – INTEGRATIVE PLANNING AND DESIGN TOOL

The second development of this project is an integrative planning and design tool that allows the rapid design and analysis of the modular building system, and at the final stage for the preparation of files for production (Figure 10).

From the early phases of the design process, computational design tools were used to explore design options and produce prototypes. Small algorithms were developed to model the first modular systems. Following an iterative design process, they were extended, adding more design options, new features, like the connection to the data base, the visualization, and the different measurements. Finally, these small algorithms bacame the computational design system that enables the integrative design-to-production methodology.

Different disciplines were combined in a single platform to increase interoperability. For this reason, the main tool used is the geometry modeller Rhinoceros by McNeel and its addon Grasshopper. Other Grasshopper plugins like Karamba 3D, Ladybug tools and Woodpecker were used together with some custom python components.

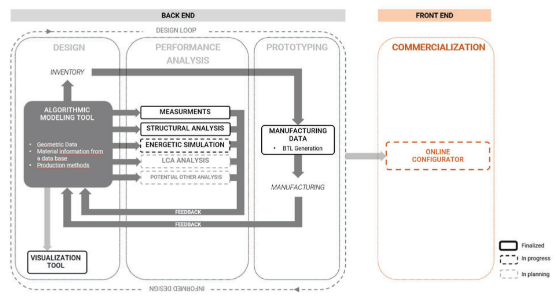

Figure 10. The diagram showing the functionality of the integrative planning and design tool

The integrative planning and design tool is divided into two parts. The first one, also called the "back end", refers to the tool used during the research for the development of the project. It includes all the tools used for the design, analysis and manufacturing of the modular building system. It is called back end because it is exclusively accessible to these researchers who at the same time use it and expand its possibilities and refine the design of the modular building system.

On the other hand, there is the configurator or "front-end". The aim of this tool is to make the modular building system accessible to end users, allowing them to design their temporary modules according to their needs within clearly defined rules. The configurator, based on ShapeDiver, is fed by the results of the integrative planning and design tool and presents them in a user-friendly way to potential customers interested in buying or renting the modular building system.

The tool development strategy was distributed in 4 main modules that at the same time were divided into parts. These were 1) the algorithmic modelling and visualization tool, 2) a set of different performance analysis tools, 3) the design-to-production tool and 4) the configurator. (Figure 11)

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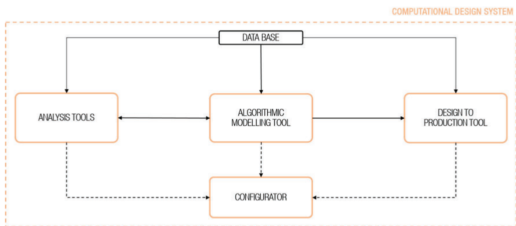

Figure 11. Computational design system.

3.1 ALGORITHMIC MODELLING TOOL

The primary goal of this tool is to model the geometry of all the components needed for the assembly of the modular building system. It incorporates all the design decisions of the modular building system for all available components of the construction kit.

These design decisions are translated into parametric design rules, allowing for the automatic modelling of all possible parameter combinations within the defined design boundaries. The process begins with defining the global parameters that establish the grid of the modular system and the reference surface. From this reference surface and the parametrically defined design rules, all components, along with their geometrical, material, and fabrication information, are modeled and stored in the inventory.

Import database and defining parameters

First, the materials are imported from the data file based on a .csv file that includes all the material information required for the computational design system. For the design tool, the density and the texture of the materials are used.

Components modelling

The following part of the script is the most extensive one. For each component of the modular building, a parametric definition of the design decisions is developed, all following the same structure. There are as many parametric definitions as components in the modular building system. First, the appropriate reference surface is chosen, such as for defining a wall or a floor element. All parts of the component use this reference surface as the reference for all geometrical operations. Simultaneously, all the necessary parameters are placed. The result is a complete set of geometric operations specific to each component.

The raw components are then modified using Boolean operations for drillings and pockets and other features. Finally, the components are positioned at the global coordinates (0,0,0) before being stored in the inventory.

Store in the inventory

The inventory stores all the components that will later be used by other modules of the computational design system, such as the configurator and the design-to-production tool.

The saved file not only contains the geometry of the component but also the raw parts, the fabrication features, like drillings or pockets. Each one is stored in different layers making it easier to sort later (Figure 12).

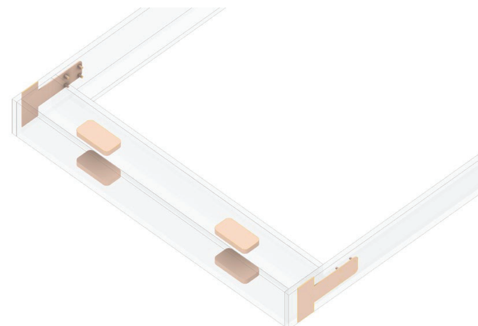

Figure 12. In grey, the raw volumes of the component. Highlighted in orange all the fabrications features.

3.2 PERFORMANCE ANALYSIS TOOL

The second module of the computational design system handles the performance analysis and evaluation of the proposed modular system from various aspects like the weight and cost measurement, the structural analysis and the energy balance.

Measurements

The measurement tool is used in two different parts of the computational design system. On the one hand, it is incorporated into an algorithmic modelling tool. It serves to inform the designer of the implications of his design with respect to the weight of the components and their cost with the goal to inform the decision-making process. On the other hand, it is incorporated in the configurator and serves to inform the end user of the number and type of components and layers that he is using in his configuration. It also gives information regarding rental or sales cost.

The measurement tool uses geometric information from Rhino to analyze the volume of each component and combines it with the information from the data file. This information is visualized in live in the viewport using the plugin Human (Figure 13).

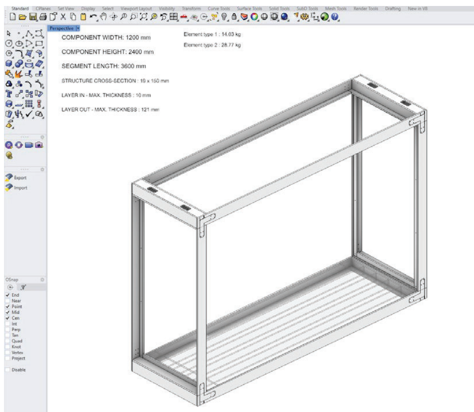

Figure 13. Real-time weight assessment of the components

Structural analysis

The structural analysis tool is used to evaluate the structural performance of the modular building system and provides quantitative feedback on the design considerations. The structural analysis is approached as a series of small problems to be solved during the design of the modular system. This approach made it easier to isolate specific issues and provide simpler but more reliable feedback. To study many variations parametrically, Karamba 3D was used. Karamba 3D is an interactive, parametric engineering tool that allows for fast and quite accurate Finite Element Analysis (FEA) embedded within Grasshopper, keeping the entire process within the same parametric platform.

Two types of structural analysis have been conducted: one to check the structural behavior in the plane of the component (analysis 1) and the other to assess its behavior in the plane of the segment (analysis 2).

<u>Analysis 1</u>

In the first analysis the goal was to study the influence of the cross-section of the modular building system on the in-plane stiffness of the component. More specifically, the influence of using a T- or L-section (Figure 14) instead of a rectangular cross-section was to be studied.

Figure 14. Top view with a clipping plane of a wall. The non-symmetric T or L cross-section can be seen on both sides

In this case an FE analysis was used. The main challenge of FE analysis is the correct modelling of the mesh to be used. To address this, a small parametric remeshing routine was developed ensuring a high-quality mesh and allowing for automatic testing of different configurations easily (Figure 15). The material used was orthotropic material so that all the meshes must be in their correct orientation.

A testing point load of 0.80kN acting horizontally at the middle of the component was used as a plausible approximation of real-life conditions. However, the aim of this analysis is to understand the order of magnitude of the effect rather than the exact displacement result (Figure 16).

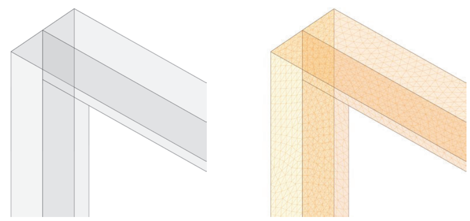

Figure 15. Surface of wall element (left). Remeshed surface for the FE analysis (right)

To determine the most appropriate depth of the T-section for a given wall type, a series of trials was conducted. The results of three typical cases are presented below:

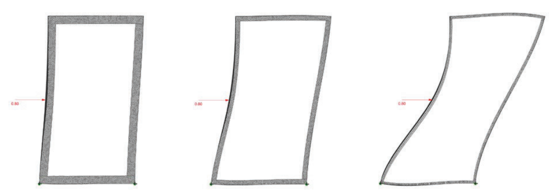

Figure 16. Lateral displacement of a single wall using different length of the T.

<u>Analysis 2</u>

The goal of the second analysis was to study the influence of the L-shape metal bracket, as shown in Figure 4, on the stiffness of the frame. In this plane the stability only relays on this connection. The analysis has two main goals: to verify the lateral displacement of the frame and to evaluate the timber sizes required according to EC5 standards. For this verification, the results obtained from the calculations are used to visually indicate the percentage of utilization of strength of the timber members.

In this case, a beam model is used. To properly model the segment, the connections are modeled as semi-stiff. The

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stiffness of the connection can be derived based on the dowel diameter and arrangement according to EC5. The translational and rotational stiffness of the connection with the timber beam is automatically calculated and assigned to the joint for any combination of parameters used.

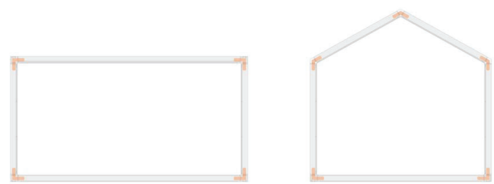

Figure 17. Highlighted in orange the L-shape metal brackets of two segments.

The tool was able to analyse more than 1,200 possible combinations of segments and plot the results based on their compliance with EC5 standards. By color-coding the structure, it was possible to automatically determine the degree of utilization of the segments (Figure 18). Segments coloured in red indicated a utilization exceeding 100%, thereby not complying with EC5 standards. The picture below shows four examples depicting the bending moments in the cross-sections and the percentage of utilization of design stress.

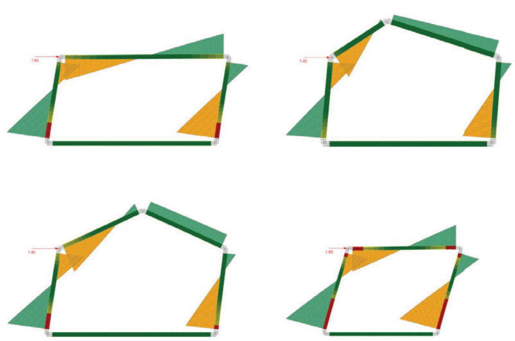

Figure 18. Example of four analysed segments four different parameters combinations

3.3 DESIGN-TO-PRODUCTION TOOL

The aim of the design-to-production tool is to transform geometry data into BTL operations in preparation for CNC machining. BTL is an open standard created by Design2machine organization [4] whose primary purpose is to provide a standardized interface for transferring data from design software to CNC machines in the woodworking industry. It provides a set of parametric operations covering all major woodworking operations. It represents machine parts using a geometry format that is independent of any specific machine or system. It bridges the gap between CAD and CAM, incorporating manufacturing features into its models while leaving machine-specific settings, such as milling strategies and machine code generation, to the fabricator. Licensed software such as Cadwork can automatically generate BTL instructions based on geometry by recognizing features and deciding what machining operation is required to achieve the final shape. This has been proven to work for simple geometry, but as soon as the geometry becomes more complex with parametric dependencies, this process is unsuccessful and must be done manually in the CAM software [5].

To bridge this gap the Woodpecker plug-in for Grasshopper is used. This plugin enables to extend the parametric models seamlessly into fabrication directly defining from the cad model what features are used for the fabrication. It offers several GH components that can turn input geometry into fabrication data in BTL format.

Design-to-production steps

First, the components that are to be produced are imported from the inventory. The imported file includes the final parts of the components but also other geometry that helps to the define the BTL operations. All this is organized by layers so it's easy to sort them by type.

This geometry is then sorted and used to extract the necessary information, including points, lines, thicknesses and lengths to define all the BTL operations using the Woodpecker plugin[6].

Woodpecker's native components facilitate the definition of the most common BTL operations but do not cover all possible operations. Additionally, they offer limited control over their parameters (P) to simplify usage. While this strategy can be helpful, it posed a limitation in this case as it did not allow for complete control over operations. Therefore, when the native components are insufficient, the user-defined operation is utilized, allowing for the complete specification of all parameters (P) available in the BTL manual (Figure 19).

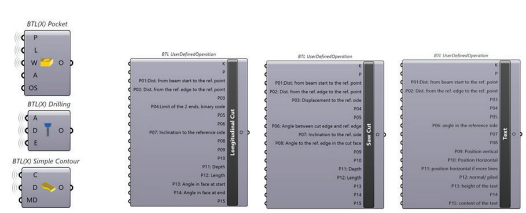

Figure 19. Woodpecker native components (left). UserDefinedOperation (right)

Finally, all the Woodpecker components are merged into one list of operations and exported to BTL (Figure 20). The order of this list is important as it defines the sequence of execution in the machine.

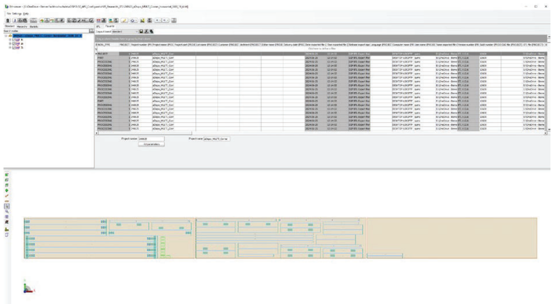

Figure 20. View of BTL file of a segment.

To conclude the process, the BTL file was imported into Lignocam to create the G-code used by the HOMAG CENTATEQ P-500/600 CNC Machining Center. Before fabrication, the tool priority macros need to be reviewed to ensure they match those defined previously.

Figure 21. Cut parts in the CNC.

3.4 CONFIGURATOR

The aim of the configurator is to make the modular building system accessible to end users, allowing them to design their temporary modules according to their needs within clearly defined limits. The configurator is fed by the results of the integrative planning and design tool and presents them in a user-friendly way to potential customers interested in buying or renting the modular building system.

The configurator is composed of several parts. With the components available in the inventory and the parameters defined by the end user, the configurator presents the proposed module. This proposal is displayed graphically, always accompanied by a set of metrics that makes it easier for the user to decide which configuration to choose. These metrics include cost, number of components, embedded CO2 and energy consumption.

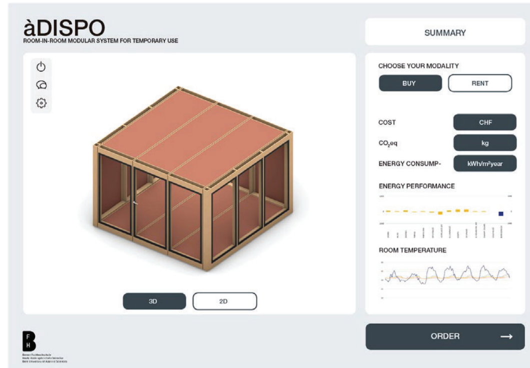

Figure 22. Illustration of how the configuration could look in a web-based application

So far, ShapeDiver has been explored as a potential platform for implementing the online configurator. ShapeDiver is an online platform designed for users to upload and interact with parametric 3D models created using Grasshopper. The platform transforms these models into interactive cloud applications accessible through web browsers. This allows users to manipulate model parameters in real-time, facilitating the exploration of multiple design iterations without the need for specialized software.

ShapeDiver integrates seamlessly with various eCommerce and ERP systems via APIs and SDKs, enabling the automation of tasks such as generating production data and technical drawings based on custom user configurations. This capability makes it particularly useful for creating sophisticated online product configurators and enhancing business processes through automation and collaboration, as it is intended to do in the àDisposition project.

4 – RESULTS

The results of the application of this methodology were showcased in different series of prototypes during the last two years. Early prototypes prioritized design validation over production techniques (Figure 23), while the final segment fully utilized a digital design-to-production workflow. In this case, only 3D information was transferred between the designers and to fabrication tools (Figure 24 and 25). The results confirmed an exceptional level of precision, with errors remaining below a tenth of a millimeter.

Despite being glued together by individuals without carpentry expertise, the components maintained a high level of accuracy. However, gluing time remains a challenge, as gluing one segment required a full day for

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two people. Future research should focus on optimizing this process to improve efficiency. Additionally, the transition from screws to glued joints significantly enhanced the frame's stiffness, demonstrating the potential advantages of this method.

Figure 23. Image of the second round of prototypes. Simple module 3,60 x 3,60 m.

Furthermore, the precision of the digital workflow enabled rapid assembly and disassembly, with a segment being built in under 10 minutes and dismantled in less than 5. These results highlight the effectiveness of the methodology presented in this paper.

Figure 24. Image of the last segment produced, following a complete design-to-production digital chain.

Figure 25. Details of the last segment produced.

5 – CONCLUSION

This research had the goal to evaluate to what extent the design and production of modular timber architecture can be enhanced by computational design tools. Based on the case study àDisposition, it was possible to test all the methods and to evaluate their impact. The results show that the implementation of computational design tools has, under certain conditions, significantly aided the design and manufacturing processes of the propose modular building system.

The modular building system presented in the case study is based on the repetitive use of components to generate modules. However, not only the components are repeated (such as walls or roofs) but also their design rules. The modular building system does not have specific dimensions but relies on design rules applied to reference surfaces instead.

It is clear from this baseline that the parametric definition of the modular building system is highly beneficial. Once the parametric definition is set, all variants within the set limits can be modelled automatically.

Essentially, the design improvements were achieved by extending the parametric approach of the modelling to the analysis phase, allowing for near real-time feedback. This approach informed the design process, making it easier to validate or discard options compared to traditional methods, leading to better decision-making.

Implementing these methods has significantly benefited production. The primary advantage arose from extending algorithmic modelling to facilitate the automatic generation of manufacturing information in BTL format. For any proposed module dimensions within design boundaries, manufacturing instructions were automatically generated.

As a result, the digital manufacturing of parts became highly efficient, enabling mass customization. Simultaneously, precision improved due to the use of CNC technology, allowing greater freedom and complexity in detailing without increasing costs.

Finally, all these computational tools could be integrated into an online configurator, making them accessible to end users and further reinforcing the implementation of mass customization.

However, in both design and production, the proposed methods also had several disadvantages. Most significantly was the time-consuming process of implementing design updates or modifications into the computational design system. This was primarily due to the complexity of translating each design feature into its corresponding BTL definition. Additionally, frequent debugging was required throughout the computational system to accommodate potential changes in the data structure.

Furthermore, the BTL-to-CAM process always required minor adjustments. While the CAD-to-BTL bridge worked effectively, small adjustments to the CAM software macros were required to reflect preferred tools or other BTL parameters that were not accessible through the Woodpecker plugin.

In conclusion, while the methods proposed in this research may not be universally suitable for all types of modular timber architecture, they offer significant advantages for product-based modular building systems such as the one presented in this research. This type of architecture is consistent with the findings of this research, as its clearly defined design boundaries help to maximize the benefits, minimize the drawbacks and ensure the robustness of the computational design system. The repetitive nature and controlled customization of these product-based kits make them highly compatible with the computational design methods demonstrated in this research.

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