A COLLABORATIVE WORKFLOW TO AUTOMATE THE DESIGN, ANALYSIS, AND CONSTRUCTION OF INTEGRALLY-ATTACHED TIMBER PLATE STRUCTURES

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Abstract.   This paper introduces a computational framework that fosters collaboration between architects, engineers, and contractors by bridging the gap between architectural design, structural analysis, and digital construction. The present research is oriented toward the formulation of an automatic design-to-construction pipeline for Integrally-Attached Timber Plate Structures (IATPS). This construction system is based on assembling timber panels through the sole interlocking of wood-wood connections inspired by traditional Japanese joinery. Prior research focused on developing distinct computational workflows and dealt with the automation of 3D modelling, numerical simulation, fabrication, and assembly separately. In the current study, a single and interactive design tool is presented. Its versatility is demonstrated through two case studies, as well as the assembly of a physical prototype with a robotic arm. Results indicate that efficiency in terms of data flow and stakeholder synergy is considerably increased. The proposed approach contributes to the Sustainable Development Goal (SDG) 11 by facilitating the collaborative design of sustainable timber structures. Besides, the research also contributes to SDG 9 as it paves the way for sustainable industrialisation of the timber construction sector through streamlined digital fabrication and robotic assembly processes. This reduces manufacturing time and associated costs while leveraging richer design possibilities.

Keywords. Timber Plate Structures; Timber Joints; Collaborative Design; Interdisciplinary Design; Structural Performance Assessment; Robotic Assembly; SDG 11; SDG 9.

1. Introduction

1.1. INTERDISCIPLINARITY AS A DRIVER OF SUSTAINABILITY

In 2020, the construction sector was responsible for 37% of energy-related C02 emissions. A decrease in economic activities due to the COVID-19 pandemic has led to temporary improvements. However, the decarbonisation of buildings is currently not on track to reach the goals of the Paris Agreement (United Nations Environment Programme, 2021). While there is a clear reduction trend in life cycle greenhouse gas emissions due to improved operational energy performance, researchers have reported an increase in embodied emissions arising from the manufacturing and processing of building materials (Röck et al., 2020) (Zimmermann et al., 2021). Given the high demand for new housing, the entire life cycle of buildings should be taken into consideration during the design phase to mitigate the environmental impact of construction.

Digitisation can enhance the productivity of the construction sector and help deliver the required building stock. However, automating existing workflows without a paradigm shift would only increase the environmental impact of building activities. To reach United Nations Sustainable Development Goal 11 – Making cities and human settlements inclusive, safe, resilient, and sustainable – it is necessary to both rethink standard design workflows and develop more sustainable construction processes. On the one hand, given the increasing complexity of architectural projects, interdisciplinary collaboration needs to be strengthened (Knippers et al., 2021). Physical considerations such as material properties, structural performance, and prefabrication constraints need to be included upstream in the design process. On the other hand, low carbon materials and efficient manufacturing techniques need to be more broadly adopted.

This research focuses on Integrally-Attached Timber Plate Structures (IATPS) – an innovative building system relying on the interlocking of engineered timber panels. Drawing inspiration from traditional Japanese craftsmanship, the elements are connected solely by wooden joints (i.e. mortises and tenons), reducing the need for additional metallic fasteners (Figure 1). The advantages of IATPS are double. Firstly, this construction technique offers the possibility of creating complex shapes out of flat standard wooden panels. It therefore provides a low-carbon alternative for creating architecturally appealing structures, relying mainly on a natural and renewable resource. Secondly, recent advances in digital timber construction allow a high degree of automation for IATPS. Panels can be cut with a Computer Numerical Control (CNC) machine and assembled into larger modules with an industrial robotic arm (Rogeau et al., 2021). The main objective of this research is to ease the design of IATPS by facilitating the data flow from architectural design to structural analysis and automated construction. To enable reciprocal feedback between the different fields of expertise involved in the project (i.e. architecture, engineering, and robotics), a collaborative computational design tool has been developed and is presented in this paper.
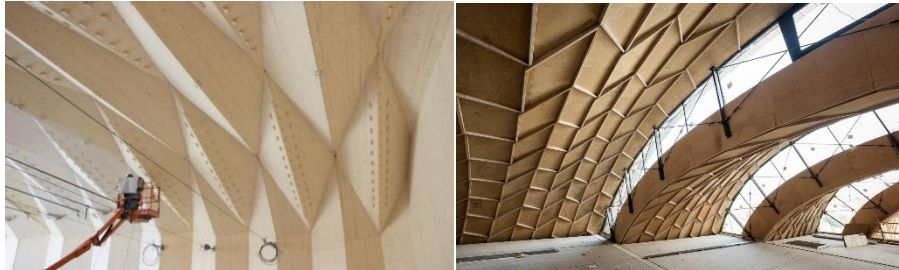
Figure 1. Two examples of IATPS: the theatre of Vidy in Lausanne (left, © Ilka Kramer) and the multipurpose hall of Annen in Manternach (right, © Valentin Bianchi).

1.2. INTERACTIVE COMPUTATIONAL WORKFLOWS

Despite the progressive adoption of Computer-Aided Design (CAD) software that increased drafting productivity in architectural and engineering offices, standard design-to-construction workflows have barely changed and remained very linear (Carpo, 2017). However, as design teams keep getting bigger and their members more and more specialised, collaboration is both more essential and more complex than ever (Dalla Valle, 2021). One major challenge lies in the diversity of digital tools used by architects, engineers, and contractors, as proprietary file formats lack interoperability to enable a real collaborative design workflow (Oti & Tizani, 2010). Indeed, most professional software focuses on one part of the design process (drafting, analysing, manufacturing...) and ensures that its functionalities are generic enough to accommodate all building typologies (Figure 2, left).

As developing custom software, applications, and plugins become more accessible, collaborative design workflows tailored for specific building typologies (Figure 2, right) have been elaborated and tested by different researchers. So-called "Interactive co-design methods" have been used to realise the BUGA wood (Wagner et al., 2020) and fibre (Dambrosio et al., 2019) pavilions. Computational developments consisted notably in integrating physical constraints linked to the robotic prefabrication of the elements into the 3D design model. This was achieved by allowing designers to simulate fabrication toolpath and assembly sequences inside the design interface.
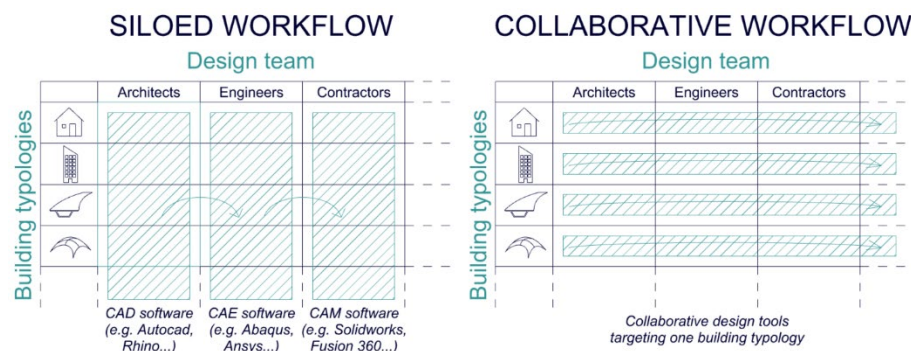

Figure 2. Standard software focuses on one part of the design process leading to siloed workflows. Collaborative design workflows focus instead on one building typology.

2. Method

2.1. DEVELOPING A COLLABORATIVE DESIGN INTERFACE

The methodology builds on previous work on Integrally-Attached Timber Plate Structures (IATPS) conducted at the laboratory for timber constructions (IBOIS, EPFL). An integrated design tool to generate joint geometry, fabrication toolpath, and robot trajectories (Rogeau et al., 2021), as well as a framework for the structural analysis of IATPS (Rezaei Rad et al., 2020), were separately introduced. The novelty of this contribution lies in the integration of the structural engineering feedback directly into the design interface. This is achieved through the systematic conversion of architectural 3D models to Finite Element (FE) meshes and will be further detailed in the next sections.

The collaborative design workflow was implemented in Grasshopper – the parametric interface of Rhinoceros 3D software and released as an open-source plugin named Manis. The algorithm automatically outputs visual information on the structural performance and the construction feasibility of a timber plate structure based on an initial 3D model (Figure 3). Interdisciplinary collaboration is thereby made possible by following an iterative design process. The collection of 3D panels that composes the structure is converted to a *plate model object*. This custom python class instance automatically generates an additional layer of data based on the order of the elements (assembly sequence) and the way they are connected (adjacency graph). A set of components that operate on the plate model is then available to: (1) simulate the computed assembly sequence, (2) generate parametric timber joints between the pieces, (3) generate a FE model and run a FE analysis, (4) generate, simulate, and execute CNC fabrication toolpath, (5) generate, simulate, and execute robotic trajectories.
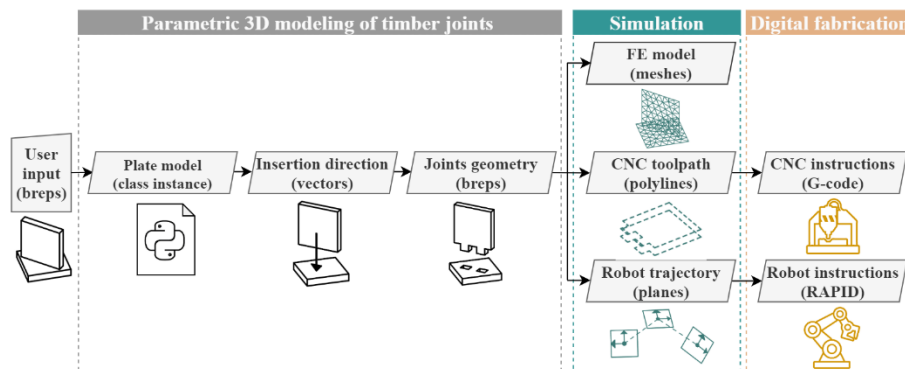

Figure 3. The algorithm enables collaboration by integrating structural performance as well as fabrication and assembly constraints into the design process.

2.2. INTEGRATING NUMERICAL SIMULATION

The integration of the numerical simulation is achieved through COMPAS – an open-source python-based platform developed at the NCCR Digital Fabrication to enhance code reusability and facilitate the development of collaborative design workflows (Van

Mele et al., 2017). The COMPAS_FEA extension aims to provide a smooth interface between CAD and FEA. First, this Python package creates a *structure* object associated with the 3D model. It includes geometric information, element, section, and material properties. Then, it enables the user to specify loads and boundary conditions for structural analysis. The construction of the *structure* object is performed using various modules that exist in the core COMPAS library (i.e., data structure, mesh) and the FEA extension. Accordingly, the majority of the repetitive scripting tasks are eliminated while streamlined data post-processing and visualisation support are provided. Once the *structure* object is constructed, COMPAS_FEA writes the native input file for the FE software. In this case, the model is generated in either ABAQUS or OpenSees. It is then sent to the original solver for analysis. Lastly, the data from the analysis results are extracted and returned to the collaborative design interface (Figure 4).
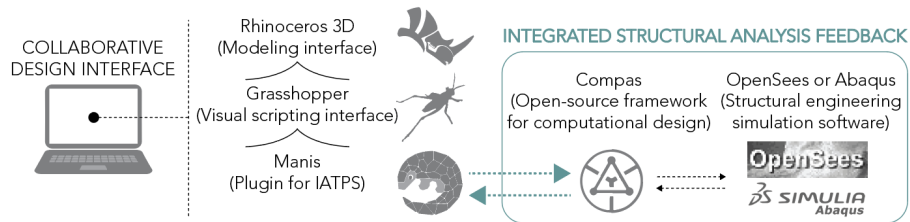

Figure 4. Integrating engineering feedback from Abaqus and OpenSees into the collaborative design plugin "Manis" via COMPAS open-source platform.

In detail, each plate is simulated using a conventional shell element with a homogeneous section property. The thickness, the integration rule (i.e. Simpson's rule), and the number of integration points are also specified in this step. General-purpose thin shell elements are used to account for finite membrane strains, as well as large rotations. In particular, a finite-strain shell element with four nodes (S4R), which uses lower-order integration to compute the element stiffness, is employed. This type of shell element has six degrees of freedom and enables thickness changes, which will lead to a realistic evaluation of the performance of the structure. Also, a free meshing technique is used to convert each plate mid-surface to a triangular mesh while line segments are created to represent the connections between the plates (Figure 5). Those connection links are integrated into the simulation by defining Spring elements between the Shell elements. The algorithm ensures that the nodes of each connection link correspond to vertices of the plate meshes. Finally, mesh data and connection links are added to the *structure* object to perform the analysis.
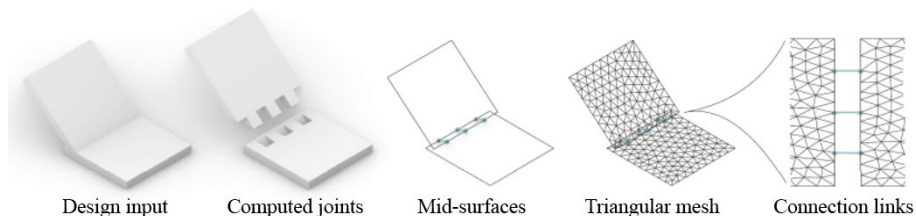

Figure 5. Automated conversion of architectural 3D models to Finite Element models.

3. Results

3.1. FIRST CASE STUDY: ORTHOGONAL TIMBER SLAB

Our collaborative design workflow has first been tested on a piece of timber slab consisting of 4 panels connected by through tenon joints (Figure 6). This construction system was initially developed with the idea of shipping flat packs of timber panels to be assembled on-site (Gamerro et al, 2020). Using our parametric tool, timber joints are automatically generated between the panels. The influence of the number of tenons, their dimensions, and spacing on the structural performance is systematically visualised through the integrated numerical simulation module. Load and support points for the analysis are parametrically defined through a complementary script. The deformation of the structure is displayed in the design interface. In addition, von Mises stresses are computed to evaluate yield and failure states near the connections. The simulation of the CNC toolpath, as well as the robotic trajectory, is performed in the same environment. This allows modifying the design at any time while ensuring compliance with fabrication and assembly constraints.
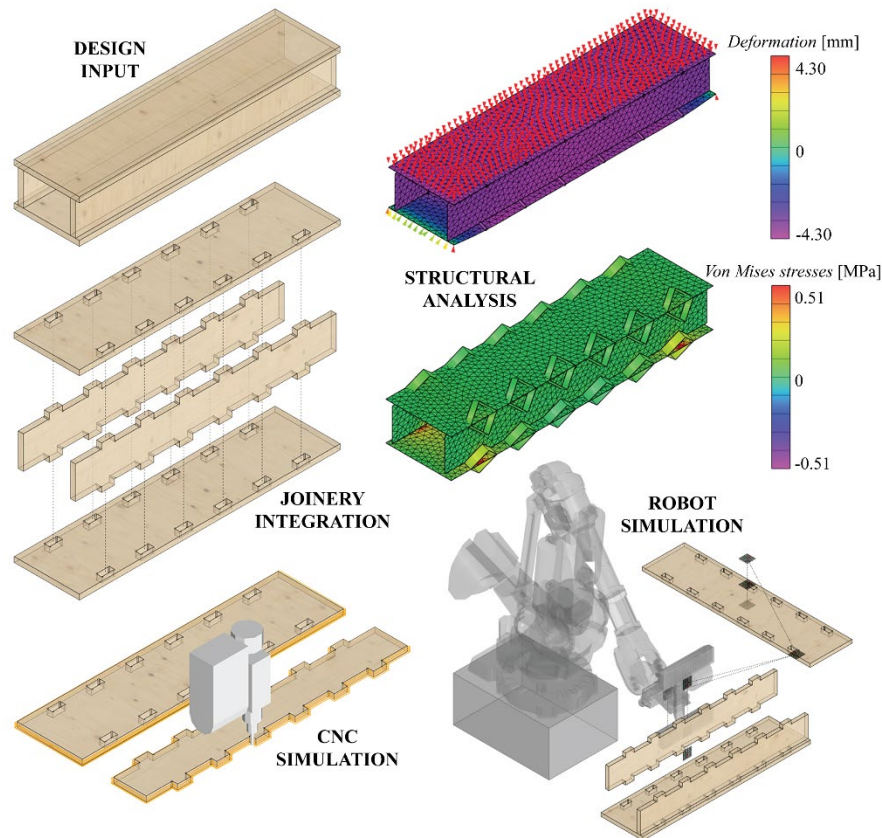

Figure 6. The developed plugin enables the integration of fabrication, assembly and structural constraints into the design process of an orthogonal slab made of 4 timber panels.

3.2. SECOND CASE STUDY: DOUBLY-CURVED TIMBER VAULT

A piece of the doubly-curved timber structure of Annen head office in Manternach (Rezaei Rad et al., 2020) has been chosen as the second case study. The prototype is a modular structure composed of 9 boxes with 4 panels each (Figure 7). Sunrise dovetails and through tenon joints connect the pieces to each other. The choice of the joint is automatically determined according to the relative position of the plates (Rogeau et al., 2021). As for the previous case study, the algorithm allows us to test different joinery configurations while visualising their influence on structural performance. A uniform load is applied on the top layer of the vault and subsequent deformations and stresses are automatically retrieved. The Finite Element Analysis of all 36 plates is performed with a computational time of approximately 1 minute which maintains the possibility of evaluating several design iterations. The full design workflow has also been recorded and is available on Vimeo (IBOIS EPFL, 2021).
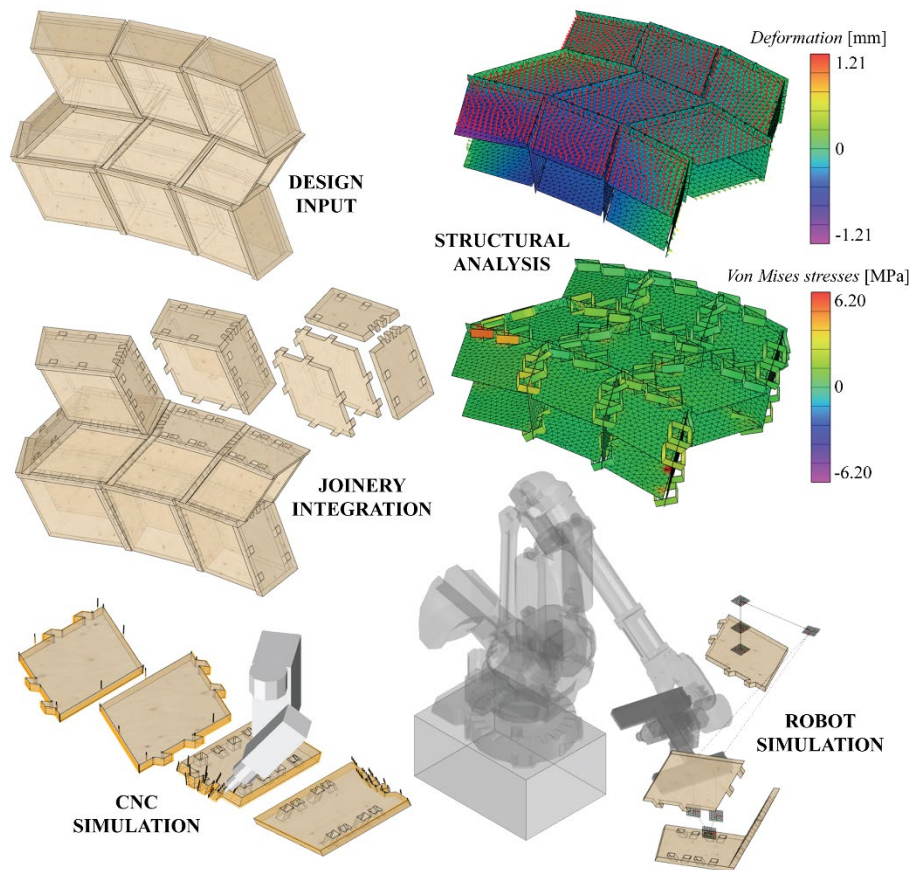

Figure 7. The tool design space ranges from standard to bespoke timber plate structures as demonstrated with this doubly-curved timber vault made of 9 boxes of 4 plates each.

To assess all steps of the design-to-fabrication pipeline, one box of the doubly-curved vault prototype was fabricated (Figure 8). The four panels of the box were cut with a 5-axis CNC after simulating the toolpath in the design interface. Next, robot trajectories, computed by the algorithm, made it possible to perform the assembly by seamlessly transferring the data to a 6-axis robotic arm (ABB 6400). The position of the first plate of the box was manually referenced. Then, the three remaining plates were lifted form a square base with a vacuum gripper attached on the robot end effector. To ease the insertion with the robot, the joints were manually sanded beforehand. This proved to be particularly necessary when inserting the last two plates of the module as 4 tenons had to be assembled simultaneously in two adjacent plates (Figure 8.7). This made it possible to compensate for the slight differences between the virtual model and the prototype.
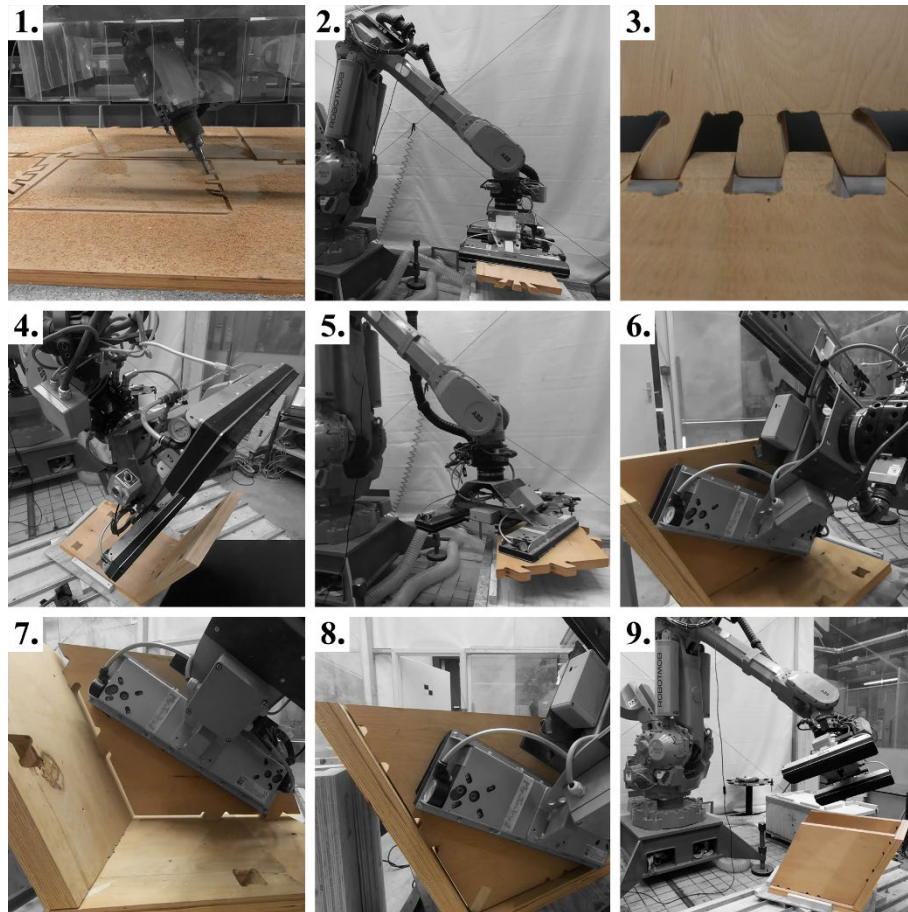

Figure 8. CNC cutting and robotic assembly of one module of the doubly-curved vault prototype.

4. Conclusion

An open-source collaborative design workflow for Integrally-Attached Timber Plate Structures (IATPS) has been developed and tested through two case studies. Using COMPAS and COMPAS_FEA frameworks allows to remain independent of the structural analysis backend. A major achievement consisted in unifying architectural design, structural analysis, digital fabrication, and robotic assembly in one single interface. Consequently, barriers among construction stakeholders are removed and the integration of physical constraints in the project can happen at a very early stage of the design process. Furthermore, both standard and bespoke geometries have been handled by the algorithm, demonstrating that a wide range of architectural applications can be explored.

While the present research facilitated the design of IATPS by enabling a collaborative design workflow, future research should focus on the construction phase and its automation. Indeed, to foster the use of timber in standard and bespoke architecture, streamlined prefabrication processes need to be developed and implemented. More specifically, upcoming investigations on IATPS should tackle challenges linked to the insertion of the joints with a robotic arm. Parameters such as the tolerance and the shape of the connections have a significant impact on the success of the robotic assembly as well as on the rigidity of the connections. Further experimental studies are therefore required to better understand the influence of those design parameters. From a broader perspective, the development of future robotic set-ups should aim for more flexibility by allowing the assembly of different types of joints in various configurations.

As far as structural engineering and associated simulation are concerned, the computational cost could be reduced by employing reduced-order Finite Element models for timber plates, i.e., macroscopic elements. The interdisciplinary aspect of this collaborative design workflow could also be expanded further by integrating other design considerations such as economic factors and environmental impact measures. Quantitative data about material savings and avoided CO_2 emissions would typically be a great addition to better inform the design team. Assembling the knowledge of different fields of expertise in a single platform will contribute to making better design decisions and lead to a more sustainable building environment. In this regard, the particular focus should be to develop design tools that accommodate for a holistic approach of specific building systems instead of generic tools dedicated to one professional discipline.

Acknowledgements

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