WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA
Advancing Timber for the Future Built Environment

TOWARDS RECIPROCAL FEEDBACK BETWEEN TIMBER ARCHITECTURE, ENGINEERING AND ADDITIVE MANUFACTURING BY STRATOCONCEPTION®

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ABSTRACT : Additive manufacturing (AM), recently adopted by the construction industry to enhance productivity and efficiency, is not yet fully recognized as a production method that challenges conventional approaches to designing architectural components. The Stratoconception® additive manufacturing process presents an opportunity to merge AM's inherent potentials with the existing technical and material capabilities of the timber construction industry. This study examines how timber parametric design practices and the Stratoconception® process influence and enhance each other to address the limitations of timber construction. Using a research-by-design methodology, it compares two different CAD-CAM workflows to deepen the understanding of the reciprocal feedback between design and production processes. The first workflow highlights the extensive feedback required to reconcile freeform, mass-customized architectural components with industrial production constraints. To streamline this process, we propose a new digital file-free continuum using Rhino.Inside TopSolid, integrated within Grasshopper parametric models to interact directly with TopSolid'Strato add-in. This approach aims to establish a more efficient framework for developing innovative architectural components that meet contemporary challenges.

KEYWORDS: Timber Architecture, Computational Design, Design for Additive Manufacturing, Stratoconception®, RhinoInside TopSolid

1 – INTRODUCTION

1.1 GENERAL BACKGROUND

The continouos evolution and spread of digital technologies in the architecture, engineering and construction (AEC) field has introduced new paradigms, leading to a closer interaction between the design and the fabrication phases, ensuring the transition from abstract geometries to a constructive reality by integrating data representative of this reality[1-2]. This digital continuum [3], applied to the timber construction industry, has thus enabled the development and the production of parametric, mass-customized, freeform, functional components and structures[4-5-6]. Additionally, the emerging application of the additive manufacturing (AM) processes in the construction industry introduced the pledge of overcoming the functional and shape's limitations of the existing fabrication processes [7-8]. However, the main motivations

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https://doi.org/10.52202/080513-0531

for the AM adoption, mostly related to the digitalization of the concrete construction field, focus on the productivity and efficiency gains whereas an architectural paradigm shift is required to explore the AM inherent potentials then to improve the current design approaches [7].

In this context, the Stratoconception® AM process [9] has been highlighted as an innovative technology impacting directly the design process and has shown a promising capacity of implementation in the timber construction field, using its basic technical and material industrial means such as three-axis CNC machining and timber panel materials [8]. Three categories of multi-scale structural components has been identified as relevant to be produced by Stratoconception® : small scale components, such as connections, middle scale components, such as beams, and large scale components, such as non-standard, multi-functional architectural envelopes [10]. The research presented in this paper focuses on the implementation of a digital design-to-fabrication workflow for timber connections made by Stratoconception®, applied to spatial structures.

1.2 TIMBER CONNECTIONS

The spatial structures, composed of short, prefabricated elements assembled on-site, leverage the absorption of project geometric complexity by the connection design, to use simpler elements, called *members* by McNail[11], in the rest of the scheme. These structures feature a two-fold advantage by their ability to develop a rich architectural language and by their response to contemporary environmental issues through the relative low consumption of materials needed to bridge long spans. A significant proportion of the environmental impact, and financial cost, of the spatial structures results from the predominant use of steel in the connection design[12]. Some examples of timber-based connections, incorporating steel rods, can be listed but remain limited like, for example, the space frame connector in Philip J. Currie Dinosaur Museum situated in Alberta, Canada[13] and the oak plywood nodes proposed by *Dennis Franz Albert Röver in the* Workshop project of the Timber Construction Campus of Diemerstein, Germany[14].

The Stratoconception® process enables the design and the production of free-form, multi-functional timber connections, without steel, within a formalized production process [8]. The inherent design opportunities of this AM process enhance the architect's mastery of structural language, enabling a deeper geometric exploration of its connections. The functionalization can integrate lighting, fire safety or enveloping system support. The development of connections prototypes, for rigid grid shells and three-dimensional truss, composed of plywood strata glued together, has highlighted the need to optimize the geometries, the size and the weight of the parts to improve the fabrication and the on-site assembly processes and costs[10].

1.3 DIGITAL WORKFLOW

To go beyond the production of art parts, which can be produced individually with a high shape complexity, the Stratoconception® fabrication constraints need to be integrated right from the early stages of the design process, leading the designer towards a rationalized industrially viable result. The integration of the fabrication constraints, used in Design for Manufacturing (DfM) methods, encompasses the production of data used as feedback and the presence of design guidelines, specific to the fabrication process[15]. Previous experimental work on the complete digital design-to-fabrication by Stratoconception® chain has underlined a range of data to be integrated into the design stages. The relationship between the stages of the design-to-fabrication process and their evaluations, as part of an iterative approach, has been formalized in a proposal for a theoretical method called TADAM(s)[10]. However, the data still needs to be clarified, particularly in the scope of the production of timber connections. Moreover, the method has not yet been implemented on a real project.

Recent research has highlighted the persistent discontinuities in the digital timber value chain, caused by the presence of disparate software programs associated with each production stage, which prevent the establishment of the digital informational continuum and the full benefit from its potential[2-16]. Existing research approaches aim to develop integrated design within a unique software environment, through the development of solutions customized to the machines used by laboratories[17]. Nevertheless, direct digital feedback between production capabilities and the design system is still underdeveloped, and these approaches remain largely disconnected from the challenges of professional practice. The inter-organizational collaboration of the construction industry implies a continuous and facilitated integration into the technical and material means of the contractors selected for each operation, without the need for custom programming. It also requires the establishment of a workflow, consistent with the range of practices and tools used by architects, engineers and manufacturers. Another limitation is the omnipresence of human intervention and expertise in timber construction, from sourcing to logistics, to material processing and application, which is complex to abstract and integrate as input data for the project design. Svilan[2] emphasizes the need for research that reconciles professional constraints to the promise of the digital information continuum, by interfacing design and fabrication through more fluid and open information models.

1.4 RESEARCH OBJECTIVES

This paper aims to achieve two main goals. First, an update of the data used and exchanged in the design-to-fabrication process of timber connections for three-dimensional trusses is carried out, by documenting and analyzing the study case

https://doi.org/10.52202/080513-0531

of a demonstrator pavilion, built under inter-organizational collaboration conditions, between players with complementary and heterogeneous skills and tools. In this context, the TADAM(s) method is discussed and specified. Second, a continuous digital chain, based on the use of specialized professional software and the Rhino.Inside TopSolid'Strato (RITSS) interoperability solution, is proposed to support the implementation of the TADAM(s) method and improve the existing digital chain experienced in the study case project. The interaction of these two objectives is aimed at strengthening the design for Stratoconception® manufacturing approaches, making it viable to produce mass-customized components with high added value for the timber architectural field.

2 – RESEARCH METHOD

The following experiment of the full design-to-fabrication workflow (A) in a full-scale demonstrator look at the data transfer and the CAD/CAM interactions between the project players, their skills and their specific software during the development of the design geometries of the timber connections through to their production. The fabrication data guiding the rationalization of the design is updated, the discontinuities in the value chain are highlighted and the efficiency of the workflow is analyzed by measuring the time consumption of the manual data modification process.

This first experiment, with the update of the theoretical model TADAM(s), led to the proposition of an alternative workflow (B), using the developed Rhino.Inside TopSolid'Strato (RITSS) add-in, which enables the direct, file-less, reciprocal communication between the Grasshopper parametric CAD environment and the TopSolid'Strato CAM environment. Improving the technological dimension of interoperability in the design-to-fabrication process for timber connections enables direct feedback of the fabrication constraints into the design environment, which will be tested and discussed by comparing the effectiveness of the developed file-to-factory workflow (B) with that initially tested (A).

3 – CASE STUDY : RAM'EAUX PAVILION

3.1 DESIGN CONCEPT

A design-build experiment was conducted on a spatial structure, named "Les Ram'eaux" as part of the French Culture Ministry project Archi-Folies aimed at designing and building pavilions to host the sports federations for the Paris 2024 Olympic Games (Figure 1). The design concept was developed on the basis of the functional requirements in terms of walkability and scenography, and by incorporating the imaginary world of rowing. The concept is a 120 m² pavilion distinguished by its three-dimensional truss, supported by fir reclaimed columns embedded in five glued-laminated timber beams, produced by Stratoconception®, representing an imaginary upside-down race between five skiffs (Figure 1).

The Stratoconception® process is used to produce the 55 unique timber connections of the truss, increasing the architectural expressivity of the project and bringing together all the complexity of the structure in its design (Figure 2). The connection design process benefits a parametric generator algorithm implemented into the Grasshopper visual programming environment, based on pre-defined design rules identified on the production of preceding prototypes. The fact that nodes are connecting points of the network of bars requires a precise 3D model with little to no geometric tolerances thus the choice of parametric modeling tool. Furthermore, this former allowed structural analysis to validate architectural choices in early stages of design without needing to change software and exchange data.

Figure 1. Frontal view of the "Les Ram'eaux" pavilion. CGI view (right), photo (left). © URM MAP

A minimal surface is generated, providing tangential continuous surfaces between all branches and adopting the right extrusions, branch angles and sections. As a first measure of design optimization, the massive connections were decomposed into two parts: the core and the sleeves. This configuration allowed serialization of an important part of the nodes while the remaining part represents single-instance geometry, mass-customized.

Figure 2. Photography of one out of 55 timber connection of the spatial structure, designed bu URM MAP and manufactured by Stratoconception® additive manufacturing process. Photography by authors in Paris, La Vilette park, May 2024.

3.2 COLLABORATION ENVIRONMENT

The pavilion was developed, produced and assembled thanks to a multidisciplinary team. Three R&D laboratories and two timber construction companies collaborated merging different resources and assets for the project. The URM MAP and LERMAB laboratories held the design, the structural analysis and the mechanical testing of the connections while the CIRTES manufactured them and provided Stratoconception® fabrication data and tools. Charpente Houot and Weisrock companies produced the linear elements of the spatial structure. Each project player nourished the project with its heterogenous skills, infrastructure and tools (Figure 3).

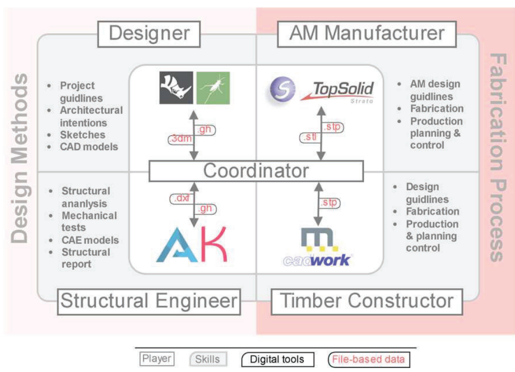


Figure 3. Players' skills and tools mobilized during the development of the pavilion Les Ram'eaux spatial structure. URM MAP

The key player in the interaction and CAD-CAM updates is a coordinator team who translates architectural intentions to industrials and vice versa. The human interface remained indispensable among the tools to address project constraints. However, the risk of error was high, especially with dozens of iterations accumulating data dependencies throughout all the project phases. In the final phases of

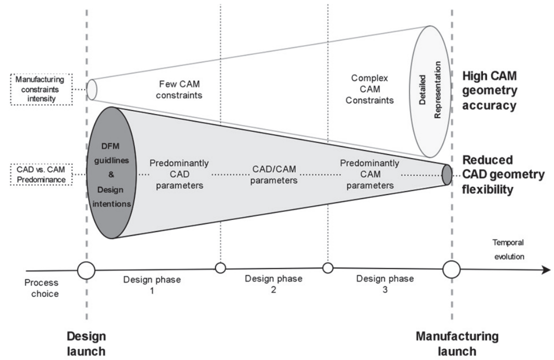


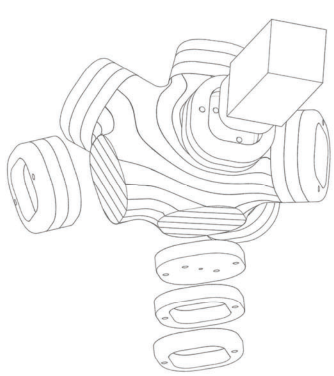
Figure 4. The convergence of manufacturing parameters and geometry through the project phases. URM MAP

development, the data flow became denser and increasingly difficult for the mediators alone to manage, as they juggled files between CAD and CAM programs and manually verified the geometry parameters.

3.3 FABRICATION CONSTRAINTS INTEGRATION

The industrial production at restricted costs and with short deadlines has led to the optimization of the connection's geometries design for additive manufacturing by Stratoconception®. In this part, we analyze the decision triggering criteria, based on fabrication constraints, impacting the defined connection topology (figure 5). The parameters of the algorithm were subject to continuous modifications leading to certain defined numerical and geometric variables which kept speculating at different rates and interactions during the development phases until the end of the project (Figure 4).

As mentioned before, the nodes are decomposed in a way that allows industrialization of the sleeves. Such an approach reduces *flipots* (see Glossary) and allows precise



Component		Parameter	Parameter type	Modification trigger					Itérations	Total
				SA	CAM	MA	N	Arch		
	Connection cores x55	Connection decomposition	GEO	●	●			●	3	17
		Sleeve base extrusion	NUM		●			●	2	
		sleeve section	NUM	●		●			4	
		sleeve size	NUM	●		●			4	
		Integrated functions path	GEO	●	●	●	●	●	2	
		Integrated functions section	NUM	●	●	●	●	●	2	
	Sleeves x260	Sleeve section	NUM	●		●			5	25
		Sleeve shape	GEO	●		●			6	
		Pocket section	NUM	●	●	●			4	
		Pocket shape	GEO	●	●	●			4	
		Offset thikness	NUM	●				●	4	
		Assembly tolerences	NUM	●	●		●		2	
	Members x186	Section size	NUM	●		●		●	4	25
		Section shape	GEO	●	●	●		●	6	
		Half-lap joint	GEO	●	●				3	
		Bolt choice	NUM	●	●	●			2	
		Countering traction forces	GEO	●	●				5	
		Assembly tolerences	NUM	●	●		●		2	
		Aesthetics	GEO		●			●	3	
			Iterations :	17	13	11	4	8		67

SA : Stuctural Analaysis **CAM :** Manufacturing Constraints **MA :** Material Availability **N :** Norms **Arch:** Finition Aesthetics
GEO : Geometric Modification **NUM :** Numeric value

Figure 5. Workflow (A) iterations of the development of timber connections in "Les Ram'eaux pavilion, URM MAP

https://doi.org/10.52202/080513-0531

manufacturing of the pockets that are going to receive the bars. The direction of stratification of the sleeves is always parallel to the bars. As for the bars, they are decomposed by bolted half-lap joints. This configuration puts us in front of three major levels of geometric interactions (Figure 6) impacting the connection design:

- Overall three-dimensional truss with connection (Macro);
- Connection core and sleeves (Meso);
- Sleeves and timber truss bars (Micro);

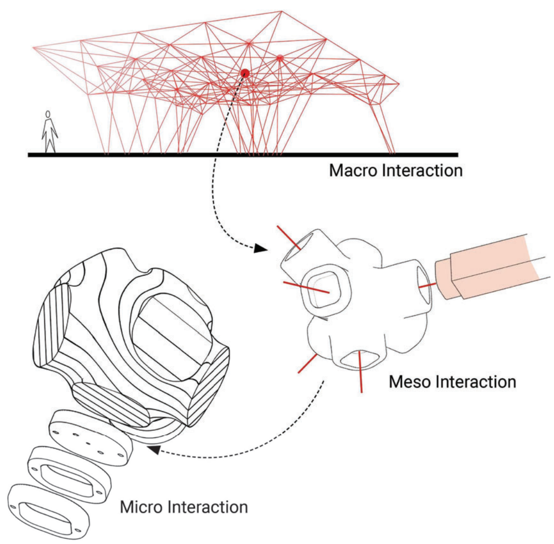


Figure 6. Levels of interaction in the development of spatial structures and their connections, URM MAP

Each interaction level shares parameters with at least one other level. For example, the section of the bars influences the form of the sleeve and behind it the algorithm generating minimal surface nodes.

Multiple CAM factors trigger the need to make iterations in the CAD models to encompass constraints such as:

- The machining duration;
- The presence of inaccessible undercuts;
- The presence of *flipots*, which are thin parts of strata creating assembly and clamping problems;
- The strata size limitations ;
- The surface finishing tolerance;

The surface finishing in 2.5 axis milling impact directly the machining timeframe as well as effecting visible aesthetics. The tool size, the machining feed rate and spindle speed play fundamental roles in adjusting the fabrication duration. The inaccessible zones, due to the axis limitations and tool form, require particular attention and actions to the way a connection is designed, decomposed and stratified for its fabrication. Strata are nested and milled while being fixed on the CNC table either by double sided tape or vacuum. Thus, a minimum contact strata surface is required to ensure clamping, avoid detachments and failures in the middle of the machining process leading to unwanted material energy and time consumption.

Further factors, depending on the choice and supply of materials, have also a direct impact on the design. With the Stratoconception® process, the panel thickness modifies the required quantity of nested panels, undercuts and manual gluing of strata. Thinner panels mean more panels leading to changing more panels on the machine to obtain the same product. However, thinner strata are faster to machine and often overcome undercuts.

Nevertheless, design rules pay set out specific requirements. The time constraints have limited the development of optimal solutions and have led to the choice of glueing the bars in the sleeves using a two-component epoxy adhesive to justify the structural capacity of the project. This decision requires a clearance of less than one millimeter for the epoxy to adhere properly, which has an impact on the pocket cross-section of the sleeves. Architectural guidelines and dimensions of the pavilion are also always subject to verification and could impact design parameters as well as other modification stimulus.

3.4 DIGITAL WORKFLOW

The digital design-to-fabrication workflow begins with an initial geometrical design proposition. The geometry data is transferred to the manufacturer in two forms: the first form is visual and textual description while the second in the form of CAD files STEP or STL files. The evaluation of the fabrication viability and efficiency combines both the informal discussion during the meetings, integrating design guidelines, and the results of the CAM simulations, executed in the StratoPro CAM software by the manufacturer. The optimization decisions are then manually integrated and verified in the parametric design environment. Iteratives feedback from CAM simulations and interdisciplinary meetings fulfill the development of the final design of the connections.

The design-to-fabrication workflow represented more than sixty interrelated iterations to converge on satisfying results involving metrology, manufacturing duration, assembly tolerances, aesthetics considerations, structural integrity and part weight and size. Mapping the interaction levels and verifying the exactitude of parameters between files and keeping them updated to the latest conclusions was an essential yet unpredictable, time-consuming and inefficient action in the process. From another perspective, due dates generated moments of no return in the decision making. Some iterations became irreversible due to material delivery constraints or simply a lack of time for development. As time progressed, parameters became increasingly non-adjustable. However, meeting a deadline does not necessarily mean that an optimized design has been achieved. The slow speed of feedback deprived the team to explore alternative solutions to further fulfill overall criteria.

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Despite the power of parametric software used in the development of the pavilion's connections, the lack of direct CAD-CAM communication and associativity in the whole process phases is time & energy consuming as well as representing a high level of error risk. The workflow centered on working meetings proposing the integration of guidelines and the lack of interoperability between software reduced significantly the process inefficiecy and increased the design and the fabrication preparation time-frame.

4 – INTEGRATIVE DESIGN PROCESS

4.1 RHINO.INSIDE TOPSOLID STRATO

The previous experiment results highlighted the need to develop more flexible workflow and to implement a digital informational continuity between the design and the fabrication ensuring parametric design by preserving the data association between two distinct ecosystems rather than relying on two closed ecosystems that communicate through file exchange. To adress this issue, the authors propose the Rhino.Inside TopSolid'Strato (RITSS) as an interoperability tool that allows the direct, file-less and in real time, data transfer and feedback between the Grasshopper CAD software and the TopSolid CAM software[18], with its add-in TopSolid'Strato, use to design the fabrication process using Stratoconception®. The direct link allows to harvest the potential of both digital environments, such as parametric modelling in CAD environment and fabrication design rules then manufacturer technical and material means in CAM environment. Unlike the previously portrayed workflow, RITSS transfers solid modeling geometry directly, without converting it to a mesh. Solid modeling is based on exact mathematical representation, using NURBS geometry and Boundary Representation (BRep) instead of mesh approximations. It's Boolean algorithms, determines whether each point in space is inside or outside a solid, allowing for precise calculations of physical properties. This method is widely used in design and manufacturing thanks to its accuracy and reliability[18].

4.2 PROPOSED DIGITAL WORKFLOW

The parametric 3D model of the spatial structure facilitates multiscale modifications starting from the overall 3D wireframe and ending with details' adjustments. The structure's components interact geometrically in various ways, adjusting dynamically based on the degrees of freedom defined by the designer. This results in a residual maneuverability, which can be further constrained by direct CAM feedback that adds value to the system without impacting the overall architecture.

The design-to-fabrication workflow of the timber connections consists of sending native exact geometry as BRep and the slice axis at the output of the Grasshopper algorithm to the TopSolid CAM software through the RITSS plug-in. At this stage, the Breps and their corresponding axes are baked into TopSolid, addressing the first step of preparing a Stratoconception® piece which is specifying the stratification direction then associated from the CAD model. Next, the panel dimensions are entered, and the user should precise details concerning the placement dowel type and dimensions and the method of machining (single or double sides machining). In the

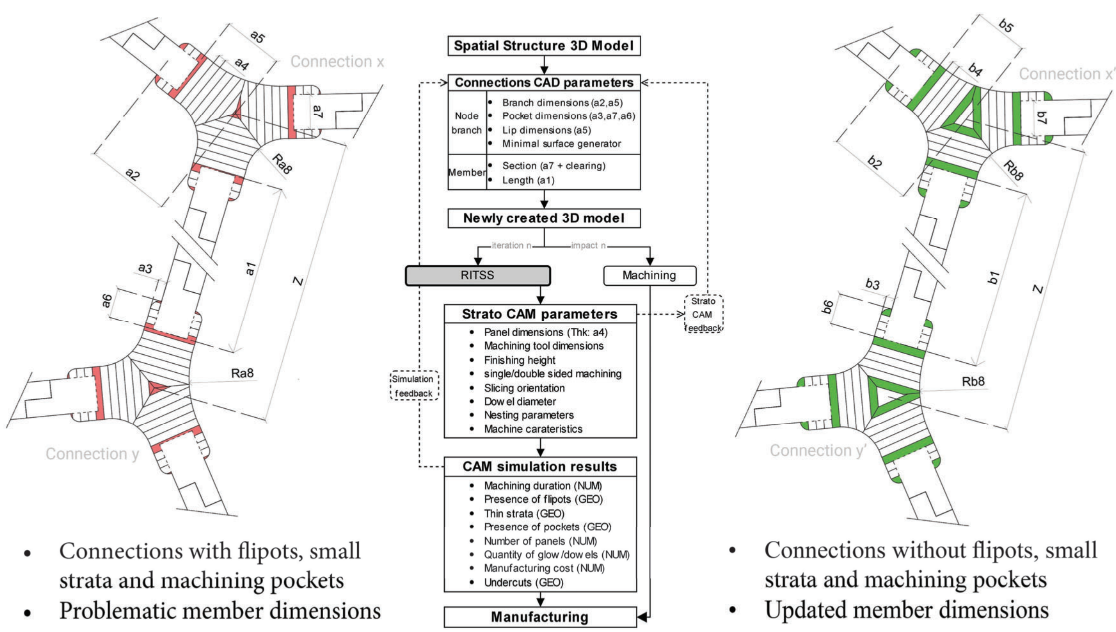

Figure 7. Workflow RITSS (B) between Rhinoceros/Grasshopper and TopSolid Strato through RhinoInside TopSolid add-in (developed by Ahmed Wael Ismael), URM MAP

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following step, the geometry is sliced into strata which in turn are nested onto the panels to prepare the machining toolpath. Once all these steps are accomplished, the user can simulate the machining duration, machining possible collisions, inaccessible zones, number of necessary panels and multiple other parameters. According to the designer's requirements, the CAM data generated is returned to the Grasshopper CAD software through the RITSS plug-in.

Unlike the first workflow, the RITSS tool then allow clearer visibility of the designer's choices impacts on the fabrication process such as:

- the machining timeframe
- the presence of *flipots*
- the presence of small strata
- the number of nesting panels

Given the hypothesis of applying the RITSS workflow to the "Les Ram'eaux" project, the roles of the actors will remain largely unchanged, except for the mediator, which in this case integrated in the design team. This requires the development of a basic understanding of the Stratoconception® process and its fabrication constraints, constituting design guidelines, in order to use the proposed tool and workflow effectively through out all geometric interactions (Figure 6).

4.3 EXPERIMENTATION AND RESULTS

To experiment with the proposed design-to-fabrication workflow, the authors propose to work on a more advanced approach of decomposing and slicing the timber connection allowed by the direct RITSS CAD-CAM

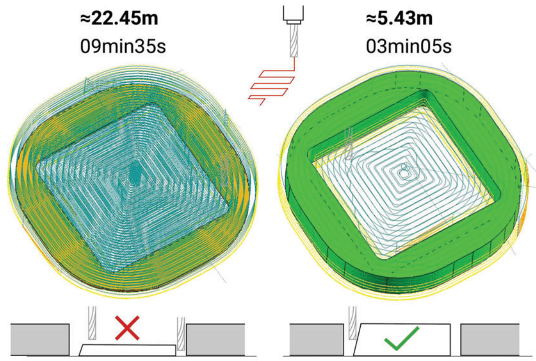

Figure 8. Tool path length difference between thin strata (left) and strata matching panel's thickness (right). TopSolidStrato machining simulation with a feed rate of 4500mm/min

feedback. The connections are decomposed concentrically, creating branches which will be stratified with planes perpendicular to each branch axis (Figure 7). This way of stratification manages better the resulting *flipots* and small strata and limit undercuts.

The development of the design of this connection typology is informed by integrating two fabrication constraints, which are the number of nesting panels to use and the presence of small strata. The milling timeframe is directly impacted by the overall length of the toolpath, which increases significantly with the presence of pockets (Figure 8) and strata thinner than panel thickness, due to the time-consuming surfacing operations. The display of the number

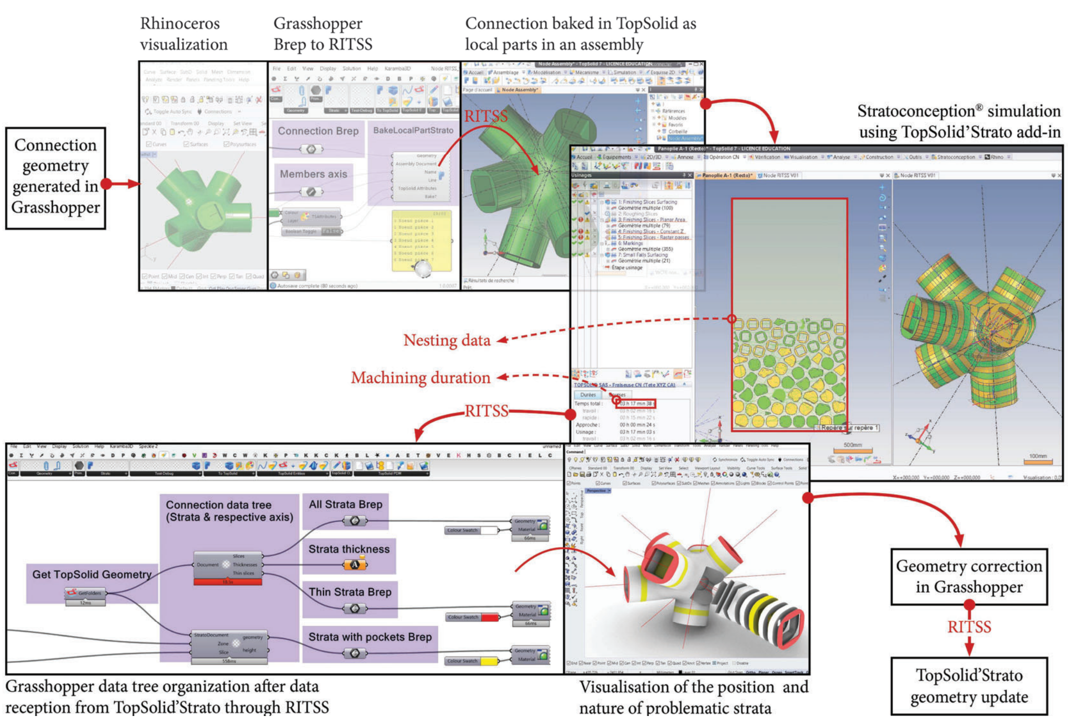

Figure 9. Digital workflow from CAD to CAM and the feedback through RITSS, URM MAP

of panels influences the designer choices with the aim of reducing the material consumption. To ensure more fluid and controlled machining operations, the small strata are avoided because of their difficulty machining and assembly. The reduction of small strata is achieved by adjusting the start and the end points of stratification as well as adjusting the design geometry itself, preparing for a new fabrication evaluation iteration.

The CAD-CAM data transfer then the CAM-CAD feedback is achieved in this study case. The TopSolid'Strato shape and entity data of the connection are organized into a data tree to ensure the display and the processing during the feedback in CAD environment. Thus, the list of strata is sent back to Grasshopper for refinement.

The RITSS CAM-CAD feedback sends back the strata native geometry in data trees from TopSolid'Strato to be visualized in Rhinoceros (Figure 9). The strata's thickness is compared to the imported panel thickness and the results are illustrated by the means of boolean operations. The users can extract data and show graphically the position and quantity of thin strata on the node. Once invalid strata are identified, the connections design geometry can be parametrically adjusted to ensure that the nodes branches have a correct extrusion height and position thus eliminating the residual slices. The new geometry of the node impacts the bars' pockets thus the bar length *(Z)* between two nodes (Figure 7) which is updated correspondingly after each iteration as dictated by the CAD parametric algorithm (Figure 10). This workflow helps cut down manual modifications on the entire bar data tree.

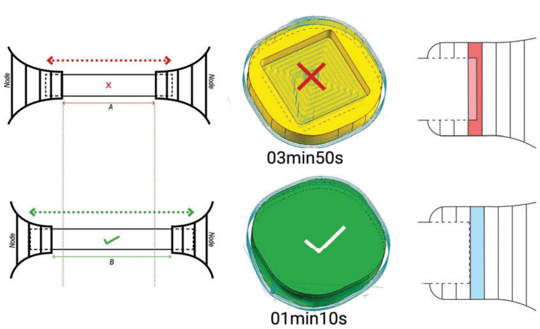

Figure 10. Machining duration optimization due eliminating unnecessary pockets, ***TopSolidStrato*** *machining simulation with a feederate of 4500mm/min, URM MAP*

Stratoconception® consists of slicing an object and nesting its slices on the desired panel. Sometimes, the number of strata requires more than one panel to obtain the whole object. The designer can, with the help of RITSS, have direct visibility of the number of panels necessary to produce their design. Machining time frame increases as well as material consumption and waste. In certain cases, a whole panel is added to the manufacturing process to fabricate one or two resting strata and slight intervention in the object geometry could spare this excess.

Once the modifications on the geometry are applied in Rhinoceros, the data is baked again in TopSolid and the attributes update automatically the TopSolid'Strato data tree avoiding the need to *restratify* and enter again machining details.

The RITTS tool helped to evolve three major topics in the development of highly complex spatial structures and their timber connections:

- the reduction of time-consuming iterations.
- improving convergence toward more optimal solutions.
- the direct adaptability of connected bars.

The workflow 'A' used in the development of the 'Les Ram'eaux' pavilion involved over 60 iterations focused solely on node geometry, each requiring manual, individual modifications and taking an average of two weeks per iteration. In contrast, with RITSS, multiple modifications could be implemented within a single iteration, benefiting from rapid feedback and reducing the time to under an hour per iteration thus gaining time and effort for more advanced design enhancements. Moreover, direct CAM visualization and real-time feedback accelerate convergence toward optimal solutions more efficiently than a manual file-exchange workflow. This enables early design decisions to swiftly eliminate unsuitable options while selecting the most viable variations, allowing for broader coverage and faster evaluation of design parameters. Parametric tools enable mass customization by dynamically updating various components of the spatial structure from the CAD to CAM environments through data association.

5 – DISCUSSION

The production of the timber connections in three-dimensional trusses by Stratoconception® has reaffirmed the critical role of the integration of the fabrication constraints into the design process to achieve with the aim to gain environmental and cost efficiency. Even minor design flaws can significantly increase machining time and costs. Often, small CAD adjustments can greatly enhance a design's industrial viability. Achieving such added value requires multidisciplinary expertise, close collaboration, and efficient digital tools.

In this context, the reciprocal feedback loops between the architectural, engineering and manufacturing software supported by the RITSS tool, address the identified need to reconcile professional constraints with design challenges through a more fluid and open workflow[2]. Updating the data used and exchanged in the design-to-fabrication process in a real project has enabled the TADAM(s) method to be refined for the specific case of timber connections, leading to the implementation of a relevant and complete workflow.

https://doi.org/10.52202/080513-0531

However, while the RITSS tool has resolved the technological dimension of interoperability between design and fabrication environments, organizational and procedural dimensions remain to be tested and validated in real-life projects. The tool does not eliminate the need for human expertise. Despite enabling direct CAD-CAM feedback, users must have a clear understanding of machining parameters and CAM software. Furthermore, effective implementation requires in-depth knowledge of project details and fabrication data.

This expertise can be integrated into the project in various ways, either through a designer with proficiency in design guidelines and the ability to interpret feedback data or by collaborating closely with a specialized manufacturer. Additionally, the current RITSS tool is primarily limited to single-user feedback between specific software packages. Expanding its application to inter-organizational collaboration between designers and manufacturers will require further technological advancements in collaboration models and reciprocal feedback mechanisms.

New open-source interoperability frameworks, such as those based on client-server connectors could extend the developed workflow in a broader project collaboration context and involve a broader range of software tools, thus facilitating smoother and more efficient integration across multiple stakeholders.

6 – CONCLUSION

The use of the Stratoconception® process in a study case highlights the importance of CAD-CAM reciprocal feedback in the fabrication of the timber connections of the spatial structures. Even minor design flaws can significantly increase machining time and costs, whereas small CAD adjustments can greatly enhance a design's industrial feasibility. Unlocking this added value requires multidisciplinary expertise, collaboration, and efficient digital tools. In this context, the reciprocal feedback loop between architectural, engineering, and manufacturing software continues to evolve, fostering refinement and innovation.

This paper compares two design-for-manufacturing digital workflows for timber spatial structure connections. Through this comparison, we provided real-world insights into the challenges of developing complex timber structures, exposing the difficulties and missed opportunities inherent in a fragmented design-to-manufacturing approach using Stratoconception®.

To address these limitations, we explored the RhinoInside TopSolid (RITSS) add-in, which enables seamless, real-time CAD-CAM communication. Unlike the conventional file-based exchange used in the first implementation of the TADAM method, RITSS allows direct feedback between TopSolid'Strato (CAM) and Grasshopper (parametric CAD) with the exclusive use of native data without intermediate formats. This real-time interaction enhances material utilization, maximizes machining efficiency, and minimizes production time and costs, without compromising architectural or structural integrity.

However, while the implementation of RITSS improves workflow efficiency, its adoption still requires overcoming several challenges. The reliance on user expertise, the need for training in CAM parameters, and the persistent role of human intervention in design adjustments must be addressed for broader industry adoption. Furthermore, ensuring compatibility with existing industrial practices and facilitating smooth collaboration between stakeholders will be crucial for maximizing its impact.

Ongoing developments aim to automate geometric adaptation in Rhino based on TopSolid'Strato feedback, establishing a real-time, dynamic workflow that continuously refines designs in alignment with predefined objectives. Additionally, expanding RITSS beyond connection node fabrication to other architectural elements and larger scales will further validate its effectiveness and broaden its application in timber structure fabrication.

ACKNOWLEDGEMENTS

This project benefited from a continuous support and collaboration with CIRTES. Moreover, Charpente Houot, and Weisrock provided invaluable support and collaboration as industrial partners in the fabrication and construction of "Les Ram'eaux" pavilion.

We sincerely thank them for their generous contribution.

GLOSSARY

Flipots : (French) thin strata or parts of strata created by material removal after machining causing assembly and clamping problems as well as releasing the material inherent constraints.

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CODE AVAILABILITY: The source code of the described development, RITSS, is open-source and published on GitHub (accessible on : https://github.com/ENAC-CNPA/Rhino.InsideTopSolid). For more information, please email the authors.

 https://doi.org/10.52202/080513-0531