World Conference on
Timber Engineering
Oslo 2023

STRATOCONCEPTION®, AN ADDITIVE MANUFACTURING PROCESS FOR TIMBER ARCHITECTURE: CHALLENGES AND OPPORTUNITIES

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ABSTRACT: The additive manufacturing has been recently adopted by the construction industry to overcome the existing design limitations and to build large-scale structures. The timber architecture and construction have not yet adopted the additive manufacturing technologies. This paper focuses on the understanding of the use of the Stratoconception® additive manufacturing process for timber architecture and construction by identifying the opportunities it offers and the challenges it presents. First, we outline the Stratoconception® process. Furthermore, we highlight and assess by experiment the opportunities and the challenges of the implementation of this process. We target the complex shape design and the multi-functionalization of the components as important opportunities that can lead the design of new high-value building components for timber architecture. Next, we introduce the potential use cases for the process and emphasize the capacity of the technology to be implemented in the common timber construction practices. The lack for Stratoconception® use in the context and in the dimensions of architecture brings the challenges of scaling-up the process and integrating it into the multicriteria architectural design process which exceed the existing methods and tools. We describe the overriding issue of managing the waste of material caused by the micro-milling phase of the process. The building of a knowledge base of relation between Stratoconception® and timber architecture reveals the need for an adapted and efficient design framework for the process use for timber architecture projects. Thus, we propose and describe a theoretical design framework achieving the integration of the AEC issues into a design process and fostering the development of new efficient building components by guiding the designer towards rational decision making.

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

1 INTRODUCTION

1.1 CONTEXT

The adoption of computational design and digital fabrication in architecture, based on Computer Numerical Control (CNC) machining and robotics, fosters a development of an innovative, efficient, and expressive contemporary timber architecture [1]. The formal and structural advances from the digital tools adoption encompass an emergence of new architectural tectonics [2-4], which in the current environmental context are fostering the use of timber [5].

The Additive Manufacturing (AM), comprising a range of processes [6,7], shares the common origin with CNC machining but differs in the ability to produce directly the high level of complexity parts that cannot be achieved by subtractive or formative methodologies. In recent years, we have observed a substantial increase in research topics studying the use of AM methods and their first implementations in the construction industry [8-11] for the large-scale building components and structures by applying the processes based on cementitious materials [12-15], alongside with earth-based [16,17], sand-based [18], polymeric [19], or metal materials [20].

The motivations for the adoption of AM by the construction industry mainly focus on the productivity gains, the reduction of materials waste, the worker availability and safety, or the reduction of the production cost of the complex parts. Also, these motivations correspond to the core challenges of the automation in construction and of digital fabrication adoption. The AM use today is often limited to these core challenges but does not *"reshape the way we think about architectural components"*[21]. According to Labonnote et al. [8], an architectural paradigm shift exploring the inherent potentials of AM is required to improve current construction design approaches. To foster this paradigm shift, the AM constraints must be considered on the early stage of the design, to allow rational decision-making.

Furthermore, the environmental issues require for the use of more sustainable, renewable, and non-petroleum-based materials. Wood could be used in several AM processes [22-24], however the research and technology advances are still needed to meet the requirements of large-scale construction.

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https://doi.org/10.52202/069179-0482

This paper reviews the use of Stratoconception® for timber architecture and its integration into the design-to-manufacturing process. First, we define the Stratoconception® process (Section 1.2) and research scope (Section 1.3). Second, we define the experiment context (Section 2). Third, the paper discusses the opportunities of the implementation of this AM process in Architecture, Engineering and Construction (AEC) (Section 3) and summarizes the challenges of its implementation (Section 4) identified during our experiments. The last section outlines the proposal of a framework of architectural design for additive manufacturing (DfAM) by Stratoconception® (Section 5).

1.2 STRATOCONCEPTION®

Stratoconception® belongs to the sheet lamination family of AM processes [6], [25]. It consists in slicing the 3D model of the part by computing into a set of layers called *strata* (Figure 1). Each *stratum* is laid out on a sheet material and is machined on both sides with 2.5 axis rapid micro-milling. Next, the strata are assembled with the relevant techniques. In the production of parts whose dimensions are larger than those of the machines or those of the raw material, the strata decomposition step is added to the process. This process refers to the initial patents [26-27] based on cutting and joining the multiple sheets of material to form the part. The use of multi-axis CNC machining to mill in 2.5 axis the edges of each stratum offers the elimination of the stair-step effect issue due to the sheet lamination process and thus allows to better match the 3D model's shape [28].

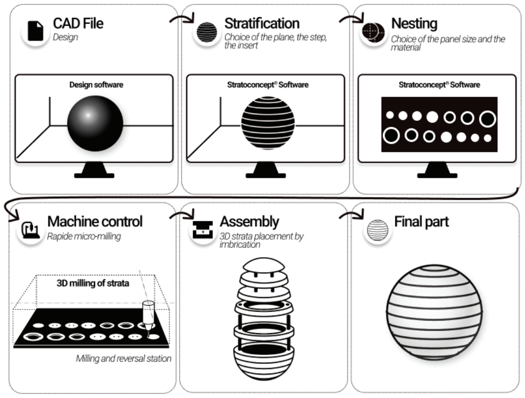

Figure 1: *Scheme of the Stratoconception® process.*

1.3 RESEARCH SCOPE AND ADDED VALUE

The Stratoconception® process application to architecture are currently limited to the scale models and the prototypes, to the formworks for concrete construction, and it is not yet applied to building components. However, the basic technical and material means such as three-axis CNC machining and timber panel materials are commonly used today in timber architecture and construction, thus they create potential opportunities for Stratoconception® process implementation. Despite the lack of the implementation in AEC, we hypothesize that the Stratoconception® process could be beneficial for the construction of complex and expressive large-scale structures or for the production of high-value-adding multifunctional building components.

An identification of the opportunities, of the limitations and the challenges of its implementation in timber architecture and construction is necessary to establish the knowledge base and the design-to-manufacturing framework. This will guide the architects, the engineers and the builders in their work in ways to benefit from the Stratoconception® process. Moreover, this will guide their digital collaboration and the workflow of the design and production of novel timber architecture products and projects.

2 EXPERIMENT DESCRIPTION

Our research is a practice-led research project identifying, emphasizing and analyzing the mechanisms of the use of Stratoconception® design-to-manufacturing process for AEC projects. Thus, our research aims to conduct experiments of Stratoconception® design and manufacturing and to build a knowledge base for the future proposal of a framework of design to additive manufacturing by Stratoconception®.

The experiment had three phases (Figure 2) studying the project *design*, the scale model *prototyping* and the project components *manufacturing*. The phase 1 studies the influence of Stratoconception® use at the early design stage on the final design of the project, by identifying the technical and architectural impact of the design choices, and by collecting the used and exchanged project data. In the phase 1.1, we ran a design experiment with the master program students at the National School of Architecture of Nancy (France). First, the main features of the AM process were introduced. Next, the students worked in teams on freeform architectural projects corresponding to a given program. Stratoconception® was imposed as a constructive system, influencing their design choices. In the phase 1.2, we study the issues of the strata use and influence on the architecture and design with renderings and scale models.

In the phase 2, scale models are used as prototypes to assess the existing digital workflow from design to manufacturing. This highlights the interoperability issues between the architectural CAD software and the Stratoconception® software.

In the phase 3, we design and manufacture the *functional prototypes* to identify the process scale up issues and to analyze the specifics of a building component design (phase 3.1) as well as an entire architecture (phase 3.2). In phase 2 and 3, we updated the inventory of the data exchanged between design and manufacturing.

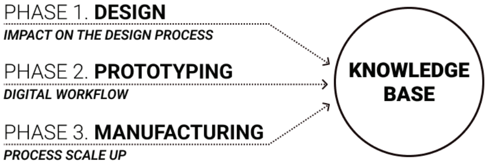

Figure 2: *Scheme of the aim of the experiment phases.*

The results of this experiment are summarized and discussed in Section 3 (opportunities) and Section 4 (challenges).

3 STRATUM AS AN OPPORTUNITY

The architecture development follows an iterative cycle, where the new technologies are developed in response to overcome the existing limits establishing new design paradigms with their own limits [29]. In this context and with its ability to design any shape mathematically [30], AM is a promising new technology to overcome the current limits of timber architecture with the new applications of freeform shapes or multifunctional building components which are today expensive or impossible to produce using the standard fabrication methods. This section overviews the new timber architectural opportunities of the Stratoconception® use.

3.1 NEW DESIGN OPPORTUNITIES

3.1.1 Timber construction existing limitations

The history demonstrates the ability of timber architecture to reinvent itself to develop the optimized building systems allowing to design the freeform shapes. Yet, the limitations still exist in the production of double-curved parts, the management of the envelope-structure relationship in complex shapes, the access to internal geometries or the challenge of achieving three-dimensional timber joints. These limitations are due to the high costs of production of the complex parts, requiring specific and unique approaches; or due to the technical inability to manufacture the three-dimensional parts with exterior and interior geometries on an industrial scale with the current means of timber construction.

3.1.2 Complex shapes: expression and optimization

As AM can mathematically produce any shape [30], it is a relevant solution to fabricate the double-curved geometries of parts. By overcoming the limitations of the standard manufacturing methods, architects can design new shapes for timber architecture and can *"encourage the appearance of new constructive and architectural vocabularies"* [4]. This exploration of new designs encompasses both the purely formal expression and the topology optimization to satisfy technical criteria. Thus, Labonnote et al. describes AM as *"an opportunity for making the link between well-developed, computational-based, optimization and the previously missing physical processes required to reproduce optimized structures"* [8,31]. The optimization usually aims to reduce the material consumption, and it is performed within the functional limits of the part, the material properties, and the constraints of the manufacturing processes. This optimization can also be applied to the thermal, acoustic, or other fluids properties. The recent research on the use of topology optimization in architecture illustrates how AM can enable the production of new complex shapes for the architecture within the limits of its processes [32].

3.1.3 Lightweight and multi-functional parts

The ability to easily access the inside of a part by the designers is, perhaps, AM's most disruptive and relevant contribution to timber construction. Thus, the hollowing out of the parts becomes possible, and it optimizes the amount of material used in the final part. Unlike the other AM processes, Stratoconception® can reduce the weight of the part by designing voids, but it does not allow to optimize the amount of consumed material by the hollowing out material, because the creation of voids during the micro-milling phase generates of as much material waste (see 4.1.2).

Today, timber buildings are composed of the materials layers with different functions such as structural, thermal, acoustic, waterproofing or building systems. The design of the voids allow to integrate a range of such various functions into a single part [7,13]. This can reduce the use of different materials, including the materials with a high environmental impact as well as the amount of assembly operations and it can provide new technical solutions for timber architecture. This may also improve the management and the properties of the envelope-structure relationship for complex structures and produce high-value-adding multifunctional building components.

The section 3.2 emphasizes how these opportunities of AM can be applied to timber construction, using Stratoconception®, by strengthening the envelope-structure relationship of the complex walls or by designing new technical parts.

3.2 APPLICATION EXAMPLES

The phase 1 design experiment proposes a non-exhaustive outline of the fields of structural and non-structural Stratoconception® uses for timber architecture. We present a shell wall project and a three-dimensional mesh joint as two use-cases of Stratoconception® application opportunities.

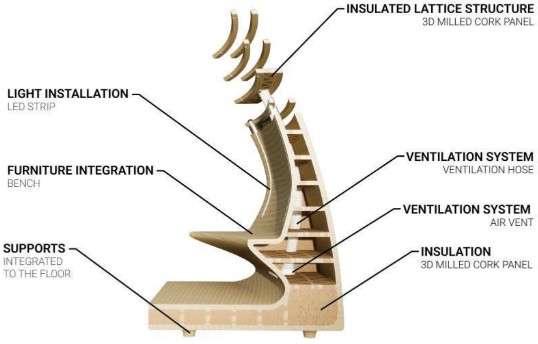

Figure 3: *Proof of concept of a complex multifunctional wall.*

Figure 3 presents a *stratoconceived* shell wall integrating various functions such as structural, thermal, and acoustic insulation, ventilation, electrical systems, and even as the element of furniture (a bench). In the conventional designs of three-dimensional structures these functions are held by different components, systems and materials, which are often assembled with the complex junctions. However, with Stratoconception® these functions may be united in a single component. In such complex double-curved shell wall, the envelope-structure relationship is enhanced. Thus, with the strata, we minimize the amount of the high environmental impact materials and of the joining operations between the building wall layers. However, we hypothesize that the use of the Stratoconception® process for large-scale structures could have a high impact on the consumption and the wastes of material (see 4.1.2) and thus on the efficiency of the constructive system facing environmental and economic issues. The assessment of the performance of large-scale *stratoconceived* structures is required to validate, or not, the relevance of this particular use of Stratoconception® in AEC projects.

A three-dimensional timber mesh structure type is an elegant and efficient building system. However, it is often built with the metal joints, altering the environmental impact of such type of structure. The Figure 4 presents a timber joint of a three-dimensional timber mesh as an alternative to the metal joints. With Stratoconception®, the timber joint is lightened by hollowing out and it functions as structural element and as lights installation slot. Its use reduces the environmental impact of the project by avoiding the use of metal.

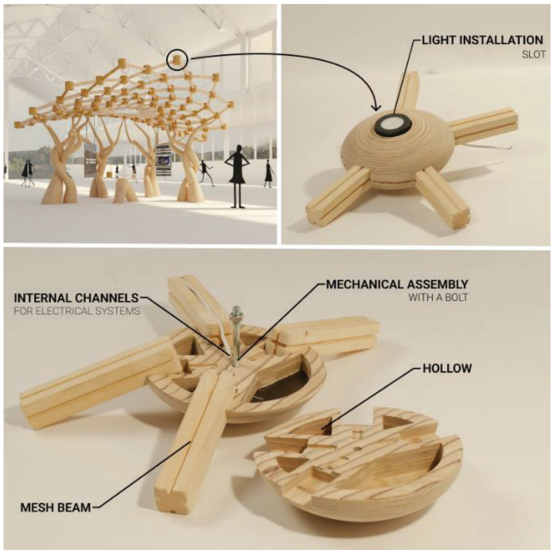

Figure 4: *Prototype of a multifunctional timber mesh node.*

The experiment results indicate other Stratoconception® relevant applications like the technical building parts production and maintenance, the windows and stairs manufacturing, the architectural heritage restoration, the furniture design, the bending mold or even the ornamentation. The further works will portray these identified relevant applications.

3.3 CAPACITY OF IMPLEMENTATION

The attempts of implementation of the automation principles of the manufacturing industry into the construction industry have not yet succeeded, nor have been transferred as a common practice to make a more sustainable impact. According to Wagner et al., *"there is a 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"* [33] depending on machinery and digital workflows. They identify two relevant success factors of such implementation, which are the economic viability and the architectural discourse which emphasize the opportunities to "*enrich the spatial and cultural qualities of the built environment*" [Ibidem]. We highlighted in the previous sections how the Stratoconception® process provides new opportunities for the timber architecture design.

Stratoconception® uses the basic technical and material means of the timber construction industry such as three-axis CNC machining and timber panel materials. The implementation of the adaptive slicing strategies for the fabrication in the computational design with Stratoconception® allow to machine the strata with the three-axis micro-milling following a digitally generated customizable toolpath.

This means that complex and *stratoconceived* parts can be machined in the same way as the standard parts, thus achieving a high degree of flexibility without additional fabrication costs.

Furthermore, the use of the similar machines in the timber construction companies facilitates the transfer of this new technology to the local construction context and to be used for specific contextualized projects.

However, in order to provide a full flexibility to the Stratoconception® process, the use of the standard technical means must be supported by a relevant digital and physical workflow linking computational design, the CNC milling and the manual construction operations.

3.4 ARCHITECTURAL VALUE

Most architectural projects use the timber panel as the topographic stratum, like in the case of the office and cafe building in Osaka where Kengo Kuma stacks the timber layers (Figure 5). In addition to directing the space and the circulation, the designed shape makes it possible to create a space with the floor, ceiling or walls function also as furniture. This example of the open flight strata emphasizes the layering and confers the apparent lightness of the space. It contrasts with the dense, monolithic strata as if the space was carved out of in a single piece of timber like the National Museum of Qatar Gift Shops where the architect Koichi Takada was inspired by the Dahl Al Misfir, also known as the "Cave of Light" (Figure 5).

Figure 5: *Open layered panels by Kengo Kuma (left) and carved cave by Koichi Takada (right).*

In most cases, timber strata are not used as structure but only as cladding or decoration. In architecture, a "stratum" may offer a design order or a superposition of various layers comprising structural (walls, floors, roofs, floor joists, beams, columns) and finishes (wooden cladding, siding, decorative elements) parts of a building. The stratum is important in the design and construction of a building because it helps to define the overall aesthetic and structural integrity of the building. In timber architecture, multiple strata can create a light and shadow play effect, generate natural textures and patterns, and provide a sense of warmth to the building.

The layering technique, in the case where the stratum remains visible, may prove aesthetic benefits to the design. For example, the lines created by the strata orient and structure the architectural space: high vertical strata generate a perception of monumentality while long horizontal strata give an impression of stability.

Actually, the architecture of strata overcomes the necessity to be thought through such separate elements as walls, floor or roof as is rather a continuous structure that encompasses the space because it creates a seamless integration of the different layers of the building [4]. Each stratum may have different functions and features. From the technical point of view, each stratum can carry different functions, such as structural support, insulation, weather resistance, or aesthetic appeal. The strata are also connected and integrated together in a cohesive system. From the architectural space point of view, the concept of the encompassing space is often used to create an impression of privacy, security, intimacy of the space, and can serve distinct functions for comfort, aesthetic and sustainability of a building.

4 RELEVANT CHALLENGES

In this section, we present the observed from the experiment challenges of the implementation of this process in AEC such as the design and the manufacturing of large-scale structures *stratoconceived*, the material waste management and the lack of the relevant and efficient design framework and methods.

4.1 PROCESS CHALLENGES

4.1.1 The scale-up is not a homothety

The manufacturing of large-scale structures challenges the ability of Stratoconception® process to scale up. The machines and the materials are limited by their dimensions, and the builders are limited by the human physical abilities. These limitations do not allow the scaling-up by a simple homothety applied to the slicing strategies, the fabrication, the assembly and the finishing operations. The phase 3 of the project components manufacturing experiment highlighted that the small building components and the large-scale structures differ significantly in their design-to-manufacturing process because of their size and of their functions.

The production of large-scale structures requires the use of strata decomposition strategies to overcome the limitations of the machines and material size by decomposing each stratum in smaller parts, consequently increasing the number of required assembly operations. The operations of clamping, flipping the panels for machining, assembling the strata and finishing are altered by the large-scale of the project and cannot perform as the small parts manufacturing. Thus, the Stratoconception® use for large-scale projects requires for the specific methods. There is a lack of knowledge about the effects of the project scale on the fabrication and the construction phases of Stratoconception® in AEC industry context, thus further research is required to confirm and precise our observations about these limitations.

4.1.2 Material waste management

Although Stratoconception® is an AM process, it includes a micro-milling phase of removing material to manufacture the designed strata. Therefore, the material waste needs to be analyzed and managed at the design phase to use this process and to satisfy both the economic and environmental performance criteria. For the analysis and the management of the material waste, we outlined the use of the raw material against its products, the strata and the reusable panel offcuts, and its wastes, the wood sawdust and the non-reusable panel offcuts (Figure 5). The material waste is caused by the nesting strategies, to the 3D milling of the strata edges, and to the light-weighting of the part (see 3.1.3).

The scale model prototyping and the project components manufacturing experiment allowed us to measure the material waste (Table 1) from the fabrication of the prototypes and to identify the relevant factors impacting the amount of these wastes in this specific use-case.

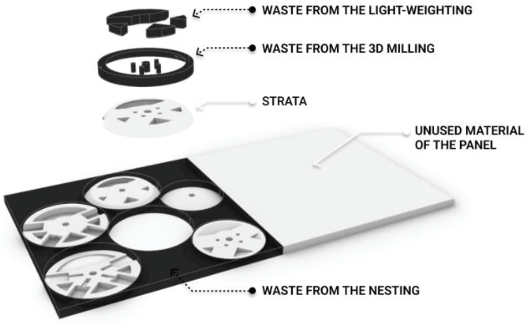

Figure 6: *Material use in the Stratoconception® process. Example of the multifunctional timber mesh joint fabrication (see 3.2).*

Table 1: *Material yield of the multifunctional timber mesh joint fabrication. The results are obtained by the geometric analysis of the nesting presented in figure 5.*

Waste type	Proportion of the material used (%)
Strata	26.13
Total material waste	73.87
Waste from the 3D milling	*31.32*
Waste from the nesting	*34.22*
Waste from the light-weighting	*8.33*

The results highlight that the waste from the 3D milling of the strata is significant when the thickness of the strata is thin in comparison to the thickness of the panel, requiring for the large facing operations. The thin strata are the result of the implementation of the slicing planes required to guarantee the feasibility of the part and of the use of panels whose thickness does not perfectly fit the size of the part (Figure 6A). In addition, the higher tilt of the strata profile results in higher material waste. Yet, in the fabrication of the large-scale strata, the thickness of the timber panels is limited to their relatively small dimensions in comparison to the final structures. Thus, the profile of the part is highly discretized in strata and reduces the material waste in proportional comparison to the small part composed of strata which share the same order of magnitude with the final part (Figure 6B).

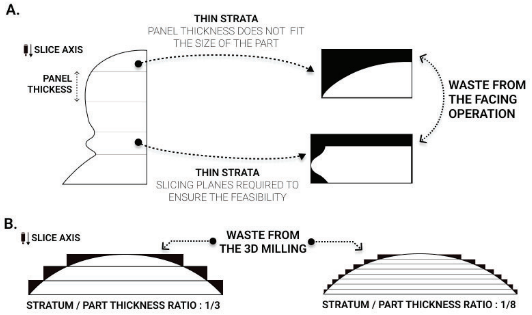

***Figure 7:** Factors influencing the wastes from the 3D milling: the facing operations caused by the thin strata (A) and the ratio between the strata thickness and the size of the part (B).*

The waste caused by the nesting of the strata on the panel depends on the nesting algorithm implemented, as well as on the ability of the strata to nest in each other through their geometry (Figure 6). Thus, the minimization of nesting wastes requires for development of specific decomposition and slicing strategies considering the size and the shape of the strata, to enable optimized nesting.

At the present time, there is the lack of analysis tools to measure the material use balance, of evaluation tools to optimize the design choices and, of design strategies and methods based on the material waste management since such management is crucial to provide the economic and ecological efficiency of the use of the Stratoconception® in timber architecture and construction. We identified that a novel design approach is required for the use of Stratoconception® for AEC to manage the material waste. Further work will quantify the material waste balance depending on the size of the parts, for the small building components and the large-scale structures prototypes. The influence of the size of the part on the preponderance of a material waste type will be analyzed in further works.

4.1.3 Timber for Stratoconception® use

The Stratoconception® process uses all available material types in the panel format. The process use for timber construction requires for the structural engineered timber products in panel format such as Cross-Laminated Timber (CLT), Laminated Veneer Lumber (LVL) or Plywood. These are preferred due to the standardized format, the improved dimensional stability and to more homogeneous mechanical and machining properties which facilitate their processing by the CNC machines. However, we must consider that the use of these families of engineered timber products limits the thickness of the strata because of the available timber panel thicknesses, which are small in comparison to the large-scale structures. Thus, the timber panel thickness is a relevant parameter in the manufacturing process for large-scale structures project. This requires for decomposition strategies, the fabrication and the assembly of the large number of elements due to the size limitations. For the small parts, reducing the thickness could minimize the wastes from the 3D milling (see 4.1.2), but also it could complicate the machining and the assembly because of the possible need for thin strata. The use of panels also encompasses the waste materials issues caused by the nesting of the strata on the panels, a lack of diversification of the species used and an environmental impact due to the wood transformation process and the transport, as the transformation plants are rarely local to the projects and the construction firms.

However, timber is not only available as the panel products, thus our research must consider all the products as alternatives that can bring added value to the process. Thus, we hypothesize that the use of Glue Laminated Timber (GLT) can provide an alternative for the fabrication of large-scale strata by avoiding the nesting operation, each stratum corresponding to a single glulam element, and overcoming the dimension limitations of the panels thickness since the GLT products can be thicker. We also hypothesize that the use of the plank timber as an economic and ecological alternative for the manufacturing of small parts although it increases the complexity of the mechanical simulation and of the 3D milling surface quality control for example. Further research is required to explore the use of these alternatives in *stratoconceived* AEC projects.

4.2 DESIGN CHALLENGES

4.2.1 The need of new design approach

The Stratoconception® process follows the design of the part phase, and it begins with a manufacturing preparation phase in which the designer's choices are evaluated from the one prospect of the feasibility. The first experiment phase emphasizes that an AEC project design should be guided by the potentials and by the limitations of the manufacturing process from its early stages. We observe that there is an interdependence between the design and the manufacturing, the design is driven by the manufacturing process and the success of manufacturing depends on the design choices.

Furthermore, the design choices of an AEC project using Stratoconception® also must be assessed and optimized for the architectural, the engineering and the construction requirements for the project success. The slicing design strategies are typical of this phenomenon. They influence the design of all aspects of the project and highlight that the multi-criteria decision-making is required for the design based on the feasibility and performance evaluation. The slicing and the decomposition of the large-scale strata choices influence and are influenced by the visual aspect of the project, the material size and properties, the structural performance, the material yield,

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the complexity of the construction and are limited by the fabrication feasibility (Figure 7).

These design criteria are interdependent and may have contradictory purposes. For example, the most efficient slicing direction choices may be contradictory to the intended aesthetic of the project. Similarly, maximizing the structural properties of the part in one direction involves orienting all the strata on the panel in the same direction to respect the wood's grain direction, hence altering the management of the wastes caused by the nesting.

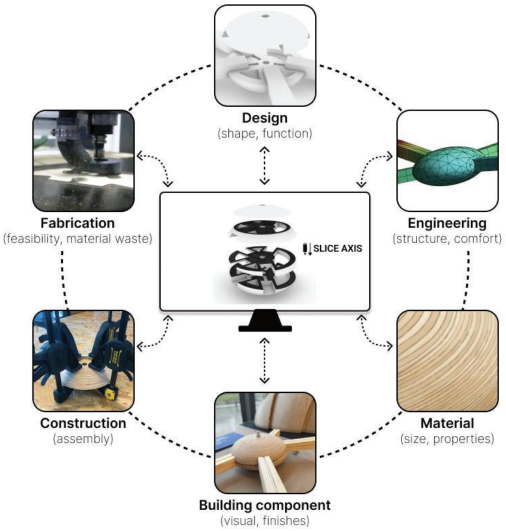

Figure 8: *Scheme of the interdependence of the slice strategies and the AEC project multi-criteria.*

The design experiment with the students has illustrated that the AEC multi-criteria approach of the project, the shape complexity and the functional complexity make the design process unintuitive, and they do not lead to efficient and rational decision-making; nor it is efficient without the implementation of an adapted design environment at the early design stages. The design to manufacturing process becomes a non-linear, dynamic and iterative process with the use of the Stratoconception® process. The level of integration of the AEC issues and the interdependence of design and manufacturing goes beyond the existing construction and Stratoconception® frameworks and design tools then requires for a new customized approach. The increase of a more detailed knowledge of the use of Stratoconception® in AEC projects and the interdependence of the design criteria will help the architects to seize this new manufacturing process and to explore new ways to design and build.

4.2.2 The lack of relevant digital workflow

The customized design to manufacturing approach with Stratoconception® requires for collaboration of the architects, the engineers and the builders. Such collaboration is based on data exchange efficiency which is correlated with the ability to connect different software of each project stakeholder. We have emphasized the lack of relevant design tools for architects and engineers (see 4.2.1). The second experiment phase identifies the lack of interoperability between the design software and the Stratoconception® CAM software.

Two CAM Stratoconception® software tools exist. The first one is StratoPro® CAM software which lacks the tools for evaluation of design choices and has limited exchange from CAD software to the 3D model through an import of the part as the STL file which structures the design-to-manufacturing process as linear with no feedback of the manufacturing preparation to the design (Figure 8). The second software is TopSolid'Strato, an add-in, with the same functionality as StratoPro®, integrated to TopSolid which is a CAD-CAM software used for mechanical engineering. With the development of the add-in of TopSolid the digital information continuum from design to manufacturing with Stratoconception® is supported by the same and only one software. However, this software is not a tool adapted to architectural design. The use of design software adapted to architecture breaks the digital information continuum of the TopSolid'Strato software by the import of the 3D model of the part which, again, prevents the feedback of the manufacturing issues at the design phase whereas we highlight the interdependence between the design and the manufacturing (see 4.2.1). This lack of feedback is not inevitable and the development of the interoperability between TopSolid' and the AEC design software provides an alternative to the existing workflow [34].

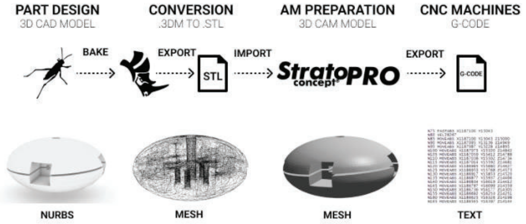

Figure 9: *Linear and non-retroactive digital workflow of the multifunctional timber mesh joint design to manufacturing experiment.*

The experiment confirms that the existing workflow is not continuous (digital data continuity is hindered), inefficient (need for various software tools without clear interoperability) and uninstructive (does not illustrate all the project information and design possibilities, thus hindering the design choices). Despite the interdependence between the design and the manufacturing choices of the Stratoconception® process, the software solutions do not offer an efficient collaboration due to their linear workflow structure, with no feedback on the design, and the lack of multi-criteria evaluation and optimization tools. A new digital workflow must be implemented with the relevant tools for the design and the manufacturing process and with interoperability between all the software for efficient collaboration.

5 PROPOSED DESIGN FRAMEWORK

In section 4, we emphasized the lack of methods and tools integrating the AEC issues, for example the structure or the visual aspect, in the design to manufacturing process by Stratoconception®. We present in Figure 9 the proposed design framework for the integration of AEC issues into the multicriteria design process. The design framework comprises three phases consistent with the three categories of the Design for Additive Manufacturing research identified by Wiberg et al. [35], thus the "*system*, *part* and *process design"*. It is intended to be flexible to the scale of the designed building component and to the muti-objectives of the project. Three further phases follow the design and include the fabrication of the strata, the construction by assembling the strata and the delivery of the building components. The framework has not yet been fully implemented. It is developed to be independent from a specific software, with a parametric environment which is better adapted to optimize the design choices.

5.1 SYSTEM DESIGN

The *system design* phase aims to identify which project components may be designed and manufactured with Stratoconception® and to define the geometrical and functional boundaries of the design. This phase is led by the opportunities of the Stratoconception® use in timber architecture and construction (see Section 3). The designer relies on the knowledge base of these opportunities to assess whether the use of the AM process adds value to the design or the manufacturing of the component. Next, we establish the specifications of the component which include the geometrical boundaries of the component, its interconnection with the other components of the system and the functionalities that the component must integrate. The multi-functionalization and the shape complexity opportunities provided by the AM use could improve creativity and foster novel designs.

5.2 PART DESIGN

Following the *system design phase*, the *part design phase* leads the designer towards the best design of the previously selected component. The result of this phase is the precise definition of the strata geometry approved for manufacturing.

The phase has three steps: the initial design, the slicing and decomposition of the 3D model, and the assembly of the strata. The initial design is achieved with one of two approaches, either the architect creates the geometry of the component or the architect creates the process generating this geometry in the definition domain stated in the system design using, for example, topological optimization algorithms.

Then, we integrate the slicing and the decomposition of the 3D model at the part design phase before the preparation for manufacturing where it occurs in the existing process. Yet, we have identified that the strata impact the visual aspect of the architecture, if they are visible, and can therefore influence the slicing direction choices. Moreover, the optimal slicing strategies are not always the most intuitive and they depend on the goals defined by designer. Finally, the assembly step creates the final geometry of the strata.

The main contribution of the proposed framework is the coupling of each step of the part design to simulation engines. It satisfies the identified need for assessment of the design choices to lead to efficient and rational decision-making in a flexible and dynamic process. The assessments can be launched at every step of the part design and they adapt to the increase of the level of detail of these steps and to the expectations of the designer. We use four main simulation engines: the fabrication, the construction (the assembly of the strata), the structure and

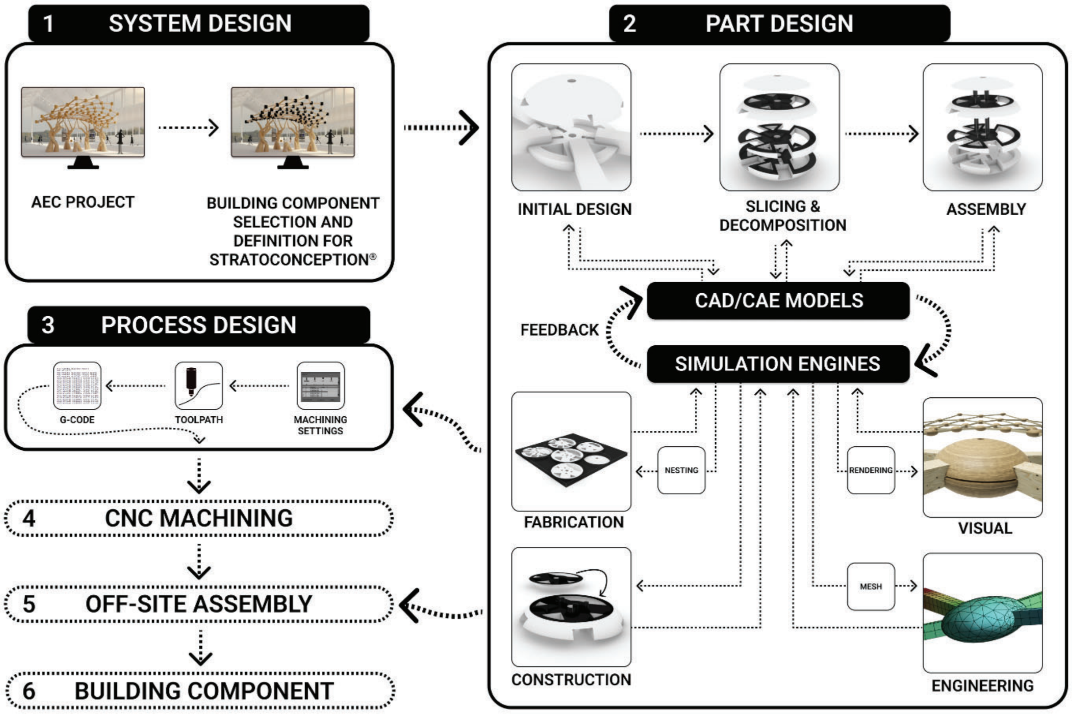

Figure 10: *Proposed design framework comprising the three phases of the system, part and process design.*

https://doi.org/10.52202/069179-0482

the visual aspect of the project if the strata are visible. The fabrication assessment addresses the feasibility and the material yield of the part design. Therefore, the nesting of the strata is integrated into the core design process. Thus, it is a support for optimizing the design choices and it is not confined to a step in the manufacturing preparation process as it is now. Other simulation engines can be developed such as life cycle analysis or time and cost assessment. The simulation engine supports the optimization of the design choices. The optimization objectives may be the minimization of weight of the component, the material waste, the cost, the environmental impact, the structural or the thermal performance. The optimization objective may be one or various.

The integration of the simulation engines into the part design process fosters an integrative approach, involving the strengthening of the relationship of the architect, the engineer and the builder, and goes beyond a design focused solely on architectural concerns or construction feasibility.

5.3 PROCESS DESIGN

Next, the *process design phase* prepares the fabrication of the component and results in the generation of the G-Code that will control the CNC machine. The phase is based on the nesting of the strata approved at the *part design phase*. The steps of this phase are those of the existing process such as the definition of the machining settings and the generation of the toolpath. A contribution to the existing methods and tools of this phase would be to consider the wood anatomy, the species and the wood grain orientation in the definition of the machining settings to improve the surface quality by using adaptative milling.

The design process is followed by the fabrication of the strata, the construction by assembling the strata in the workshop and the delivery of the building components. The assembly of the strata is guided by the assembly documents from the construction simulation engine.

5.4 FURTHER WORK

The implementation of the proposed design framework requires for further work on:

- The summary of the knowledge base of the opportunities and the limitations of the Stratoconception® use in timber AEC, with a detailed study of use-cases, so that architects, engineers and builders can adopt this new technology and identify the building components they can thus design.
- The automation of the non-creative activities of the process and the development of new strategies adapted to the building components, for example, decomposition strategies of the strata minimizing the material wastes.
- The interoperability between different software of the fragmented AEC industry in order to minimize the data waste and the errors caused by the file exchange and to gain efficiency and design integration.
- The development of reliable mechanical, thermal or Life Cycle Assessment (LCA) simulation engines for each step of the part design and go beyond the limits of the conventional tools that lack flexibility for use on non-standard building components.
- The introduction of new materials, such as glue laminated timber, and the adaptation of the operations and practices thus induced in the process to offer an alternative to the use of the timber panel.

Further steps of the research and developments should be conducted to improve step by step the proposed framework.

6 CONCLUSION

As additive manufacturing becomes increasingly implemented in the construction industry, it is important to understand how these new technologies affect the way we design and build timber architecture. By assessing the use of the Stratoconception® process with several experiments, this study established that additive manufacturing could overcome the existing limits of timber architecture to produce new high-value-adding building components. We have addressed a number of key issues and identified the relevant challenges of scaling-up the process and managing the material wastes. We also outlined that *there is a lack of design framework adapted to the multi-criteria decision making required using Stratoconception® in timber architecture and construction*. This paper contributes to the proposal of a framework of timber architectural design for additive manufacturing using the Stratoconception® process in a design-to-manufacturing process. Further research will focus on the implementation and the assessment of the proposed framework.

ACKNOWLEDGEMENT

This research was financially supported by the partnership chair *“Timber architecture and construction: from heritage to digital”* and by the French Ministry of Culture. The authors also acknowledge the students at the National School of Architecture of Nancy for their participation in the pedagogical exercises related to this work.

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