Adaptive Automation Strategies for Robotic Prefabrication of Parametrized Mass Timber Building Components

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Abstract –

This paper presents applied research into automated and adaptive robotic prefabrication strategies for a generative platform design enabling mass customized, mass timber modular construction. The development is part of an ongoing effort by the company to bring a holistic approach of design-driven modular mass timber housing and advanced prefabrication techniques into the market of urban densification. The presented work is currently developed for the delivery of two mass timber housing projects with four and 12 storeys, the latter acting as a case study in this paper. In the first part, the paper explains the possibilities and challenges of large-scale robotic fabrication in timber construction as well as strategies for embedding robotics within a digital design workflow. The focus will be on the required change in the industry's design thinking for automation strategies to be effective. In the second part the development of an adaptable construction system suitable for robotic automation will be presented. We argue that while automation of conventional assembly steps might be suitable in some cases, the construction system, and ultimately the individual building parts, must be developed in reciprocity with the capabilities, or the design space, of the machine. The authors share their experience of the application of such an integrated process and its requirements towards the collaboration between, and the automation of, design, construction, engineering, and manufacturing. In its conclusion, the authors argue that a long overdue paradigm change in the architecture and building industry can only be achieved through the complete convergence of all disciplines.

Keywords –

Robotics; Prefabrication; Timber construction; Mass timber; Automation; Modular building; Computational design; Digital fabrication; Affordability; Platforms for life;

1 Introduction

Throughout human history wood has almost always played a dominant role as a building material. Its wide-spread availability in most climate zones, combined with the relative ease of shaping and processing the material allowed humans to develop and refine resourceful, resilient and adaptive construction techniques over thousands of years. In fact, many hundred-year old buildings in China, Japan and Europe are still standing today and prime examples of the creative and intricate constructions made from mostly linear elements.

The required labour and material knowledge for harvesting and processing trees led to a wide-spread but locally differentiated culture of timber fabrication. The interdependency of available materials, tools and culture is evident in the differences between structural systems and buildings throughout the world [1].

However, as the Industrial Revolution took hold of the building industry in the 19th century, it led to a shift from local knowledge and local fabrication to industrialized and globalized mass production, which also brought a shift from value-added products to value-engineered and standardized components [2]. The replacement of manual but customized processes with automated but standardized manufacturing also resulted in standardized construction systems still applied in various forms today. Although standardization brought the advantages of higher quality control and the economies of scale, standardized construction systems lacked geometric flexibility and therefore the ability to adapt to different internal and external conditions. With a dramatic increase in available energy, the focus shifted away from wood and towards the mass production of steel and concrete, which became the primary building material of an industrialized world.

Given the environmental challenges we are facing today, and the struggle for sustainable living and urban densification, it is clear that the future of building construction needs to be energy-efficient, adaptable, lightweight, multifunctional and prefabricated in factory environments. Although wood is one of the oldest building materials, new engineered wood products such as Cross Laminated Timber (CLT) are answering to all of these criteria. Although wood in its natural occurrence exhibits a great range of variation in material characteristics [3], engineered timber has a high and controllable structural strength, a positive carbon footprint [4], and a very low embodied energy compared to other building materials [5, 6]. Moreover, its mostly localized availability makes the material particularly suitable for the development of sustainable construction methods with short transportation routes [7]. Lastly, its accessibility as a renewable resource makes wood a prime candidate for new design and manufacturing developments, and it comes to no surprise that the general interest in mid-rise and high-rise timber construction has grown significantly over the last decade. On the example of robotically prefabricated mass timber building components, the paper presents an approach to a new paradigm of a sustainable and digitally designed architecture.

2 Context

2.1 Systemic Innovation and Digital Design

The Industrialization initiated a paradigm change in the building industry that, although advantageous at first, proved to be a barrier in our post-industrialized world [8]. During the 19th and 20th century, design, engineering, manufacturing and construction became fragmented and compartmentalized into highly specialized and disconnected disciplines [9]. The result was a highly hierarchical model with specialized organizations that soon developed individual interests opposing each other, ultimately limiting the free movement of knowledge and slowing down innovation. This is particularly detrimental as innovation in architecture is highly dependent on many different disciplines. Research on innovation explains this interdependency with the term "systemic innovation", where multiple and interdependent industries need to change all their processes in order for innovation to take place [10]. Systemic innovation diffuses slowly in project-based industries such as the construction sector. When multiple organizations must act together in order to implement change, innovation is dependent on an interorganizational network [11].

The industry's ongoing resistance to innovation becomes evident in its spending on research and development. In Canada, construction accounted for 8.8% of the nation's 2014 Gross Domestic Product (GDP) while its R&D spending was at 0.06% of the GDP. By contrast, the manufacturing sector comprised 13% of the GDP while its R&D spending was at 3.91% of the GDP [12]. Productivity has lagged accordingly: in the U.S., construction labour productivity has barely gained 10% over the past 70 years, versus a 760% productivity increase in overall economic productivity during the same period. Even worse, for the past 50 years construction productivity has actually declined [8].

A good example for this slow change is the adaption of digital planning processes such as Building Information Modelling (BIM), which requires a multitude of organizations distributed across all hierarchies of the construction industry to employ the technology. And although BIM is slowly being implemented by companies and municipalities today, the rise of digital planning processes has been almost independent from developments of digital fabrication. While both industries have slowly been digitalized in the past decades, they are still within the same hierarchical and fragmented model with limited information exchange and flexibility [9].

While digitalized planning processes may allow for more complex shapes and potentially more adapted and performative buildings, they are still characterized by a traditional top-down design method, leaving questions of producibility and materiality for a later stage [13]. Designers and architects are usually uninformed about manufacturing capabilities, leading them to either overestimate or underestimate the possibilities [14]. This lack of information exchange not only causes higher planning costs through late changes in the design, but it also requires more time and effort for manufacturers [15]. Ultimately, design decisions can not be based on transparency and idea generation but are instead driven by assumed cost efficiencies and risk mitigation.

We argue that in order to truly advance architecture and the building industry, systemic innovation throughout the fields of design, material science, manufacturing and construction is necessary, ultimately leading to a reconceptualization of how architecture is designed, made and delivered, while avoiding the friction inherent in the conventional building industry of today. This is the basis of production immanent planning [16] where reciprocities between fabrication possibilities, materiality and the design process are enabled through interactive digital tools [17]. Only through the convergence of design and manufacturing, and a constant feedback between the disciplines, the true potentials of technological innovation, namely affordability, precision, quality and sustainability will be unlocked.

2.2 Robotics in Timber Construction

The renewed interest in timber construction goes hand in hand with digital fabrication tools such as CNC machines having become well established in the industry. But although most wood processing machines are speeding up typical processing steps, they are task-specific and reinforce the use of already known fabrication methods and construction systems.

Meanwhile, the automobile industry witnessed the introduction of industrial robots in the 1980s, which came together with new manufacturing paradigms such as mass customization [18]. During the 1990s, early exploration of large-scale robotics for automated on-site construction were carried out in Japan [19]. Although technical challenges of building-sized machines on construction sites, and the decline of the building economy proofed to be too big of a hurdle, robotics has again been explored in architectural research more recently [20]. To some extend, this renewed interest is due to the concept of the industrial robot constituting a very different approach. The main difference when compared to process-specific CNC machines is that industrial robots were designed as mass-produced, affordable, high quality and flexible machines. They serve as a generic platform on which different tools and functions can be attached. Their controls are easy to access and can be directly implemented with an adaptive, digital design and manufacturing process.

The potential of industrial robots in timber construction ultimately derives from their extended kinematic range and their adaptability to new fabrication processes, allowing for the development of more complex and differentiated building components [21]. This introduces a shift from machines being made for specific processes towards the building or component being viewed as a product. Following the pattern of innovation consequences during the Industrialization in the 19th and 20th century, technical innovation such as the implementation of industrial robots can have a large impact on the development of architectural design.

Ultimately, innovation in manufacturing techniques for architecture has to go hand in hand with a rethinking of how building systems are conceived. In order to take full advantage of the industrial robot's flexibility, the main focus has to lie in the development of a comprehensive, digital design-to-fabrication workflow with a direct transfer of machine data.

2.3 Potentials of Applied Research

Research in advanced robotic fabrication in timber construction has shown promising results in the reciprocal development of manufacturing processes, construction systems and architectural potentials. The fundamental difference to typical innovation in the construction industry lies in the bottom-up research methodology.

The roof of the Arch_Tec_Lab at ETH Zurich is an example for automation of complex assembly processes that would not be feasible with manual labour (fig. 1). The precise spatial positioning of wooden components requires a new kind of manufacturing process with high precision and without any additional formwork [22]. The roof was designed and developed by the Gramazio Kohler Research group in collaboration with a larger planning team. The roof is made from large wooden trusses that consist of small timber slats stacked together in an alternating manner [23]. Instead of continuous top and bottom cords the trusses are entirely made from short slats nailed together at different angles. The type of nailed connection, the position and order of assembly were all developed in conjunction with a new robotic manufacturing technology that is able to cut, position, attach and photograph in one sequence. The design space derived from this process was explored through the undulation of the roof, which ultimately changed the angle and nailing position of each of the over 94,000 connections.

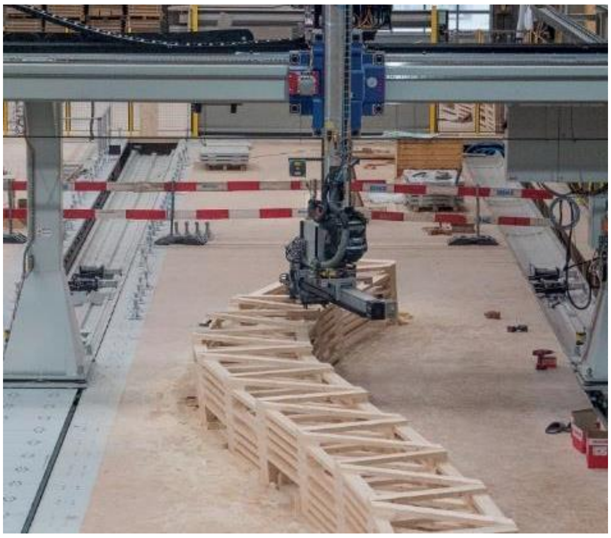

Figure 1. Robotic assembly of large timber trusses for the ETH Zürich Arch_Tec_Lab. Source: ETH Zürich, Apolinarska 2016 [21]

The Institute for Computational Design and Construction at the University of Stuttgart is leading research for robotic fabrication methods for segmented timber shells. Here, the manufacturing technology is developed in conjunction with a computational design method to generate and control the geometry of each segment of a larger shell structure and output the required manufacturing data [24]. For the development of a construction system made from double-layered, hollow cassettes, the researchers employed industrial robots to precisely assemble and then format each component in a multi-step manufacturing process (fig. 2). The complexity of the manufacturing process and the customized shapes of each building element necessitates a digital design-to-fabrication method and is ultimately only possible because of the adaptability of the developed manufacturing system. This approach allowed the researchers to design extremely lightweight and efficient shell structures [24].

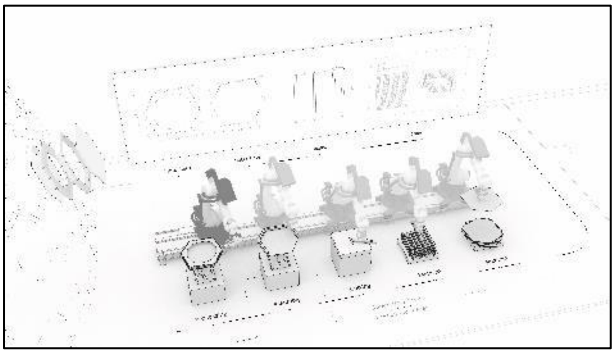

Figure 2. Robotic manufacturing process for hollow sandwich cassette panels. Source: ICD University of Stuttgart [22]

2.4 Project Aim and Application

Although industrial robots have size and weight restrictions that originally related to car manufacturing, the above examples show their potential application for the prefabrication of medium-scale building components for large-scale structures. They also show how adaptability can play an important role when developing a completely digital workflow in relation to the available machines and tools.

While traditional processing steps and construction systems have been developed in relation to human strength and size [1], so are newly available machines related to the size and weight of building elements, as well as to the dexterity required for assembly or processing. It can therefore be argued that the machine setup defines the design space of the manufacturing process as much as the material.

The authors have applied the approach of production-immanent planning in the development of a mass timber building system. The aim of this development is the careful application of innovative manufacturing techniques, and therefore bridging the gap between academia and practice. In this process, industrial robots are applied for additive processes in order to allow for the assembly of heavy, medium-sized elements into larger panels. The task of formatting those elements stays within the realm of standard CNC machines but is implemented within the digital design-to-fabrication workflow in order to allow for a direct output of machine data. This holistic approach to design and manufacturing not only streamlines the entire process but, more importantly, allows for an inherent flexibility and adaptability without additional complexities. In its application, the developed processes can combine the consistency and quality control of mass production with the variability and individuality of cultural and societal responses to the built environment. Only then can quality, performance, scalability and differentiation replace repetition and manual construction.

3 Methods

The development presented in this paper is situated within the context of the architecture and building industry's need for affordable, sustainable, customizable and qualitative urban living. Through an integration of design, architecture, manufacturing and off-site prefabrication, the authors are introducing a new paradigm in the construction industry: empowering people to live better and more sustainably with the help of highly digitalized design and fabrication processes.

While the manufacturing development is based on robotically assisted, complex assembly processes, it is also connected to a larger development effort of parametric design methods that allow for a product-design approach in architecture, incorporating the entire value chain from design to delivery of innovative buildings. The main motivation is not to build shapes that were otherwise not possible, but to develop the ability for a variable response on a consistent platform.

3.1 Platform-Based Design

In the context of manufacturing automation, the concept of platform-based design is one of the key factors for allowing architecture to embrace a product-oriented design approach incorporating fabrication, material, engineering and functionality. Platform-based design is an integration-oriented design approach for the systematic use of an underlying logic, system, or platform, for the development of complex products that share compatible hardware or software [25]. This allows to establish a general knowledge base on which variant forms of the same solution can be realised. It also directs the development of the design process towards a class of products that can have a variety of design solutions for customized requirements within a common framework [26]. While platform-based design has been an established and decade-old concept in many other industries such as car manufacturing, its application in the highly individualized construction industry has not yet been explored to a level that would satisfy the need for customization in relation to a building's context, owner and tenants. By developing a platform within a computational design framework, the focus lies on a high degree of variability in the design process.

The platform is based on the modularised or panelised prefabrication of mass timber building components that can be shipped and assembled on site. The main structural components are defined by their relationship to the modular framework, and their geometry is derived from a parametrically defined logic further explained in chapter 2.3. For the explanation of the building system and its robotic assembly the authors will focus on the floor panels, which can also be assembled into volumetric modules at a later stage in the process.

The platform can be described as a four-sided but not necessarily rectangular, panel made from two layers of smaller Cross Laminated Timber (CLT) panels that are interconnected with smaller Laminated Veneer Lumber (LVL) beams. This panel is later connected to a varying number of columns on site, which are placed on the axis of the panels' borders and intersect with the panels in a way that allows steel connectors to connect and ensure a continuous force-flow. The panels are further connected between each other with thin strips along their edges to form a structurally continuous slab and allow for lateral force transer. Connections to concrete cores or CLT shear walls are special cases for which specific details have been developed. While smaller CLT panels are chosen as the main structural element due to their global availability, the width of a panel is not necessarily constrained by shipping container dimensions as they can be transported vertically on trucks.

The exact arrangement of CLT panels within one floor panel, their width and length, and the number of columns to be connected to a specific panel is parametrically defined and derived from a 3D model that incorporates design intent and structural requirements (fig. 3). The panels and their shapes are generated in an algorithm taking into account all connection details that will lead to certain penetrations or cuts within the panels. Following the geometry of a boundary condition from a preceding digital design process, the design space is ultimately defined by transportation constraints, but generally between 25 ft and 53ft in length, and between 10 ft and 40 ft in width (fig. 4). This allows to accommodate studios as well as up to 3BR and double-storey apartments.

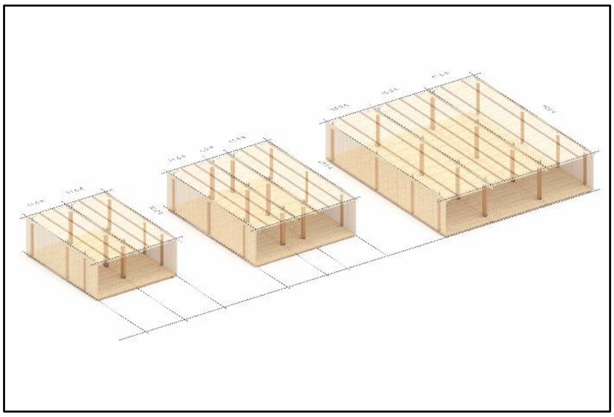

Figure 3. Visualisation of the parametric model adapting to the design space. The individual building elements populate the available space and obtain certain connection details through locators

3.2 Integrated Robotic Assembly

Timber is a great fit for modular construction due to its machinability and relatively low weight, meaning it can be more easily transported and assembled on site when compared to steel or concrete. Mass timber specifically, however, regardless of its structural and fire safety advantages compared to lightweight timber frame, is leaving the realm of human-scale building elements due to its weight and size, and therefore emphasizing the need for advanced manufacturing techniques. While many building materials and construction systems have been developed for the human scale and manual assembly, focusing on robotic processes allows for a reconceptualization of building element dimensions and weights. Most medium-sized mass timber elements are within the size and weight range of common industrial robots and therefore ideal for the introduction of automated and adaptive manufacturing. As a result, intersection points between human labour and robotic processes need to be carefully integrated.

The presented digital design process is developed in conjunction with appropriate manufacturing techniques and their possibilities: The arrangement of CLT panels and their connections were developed to be executed by similar but adapted robotic processing steps with offline programming. Contrary to traditional CAD/CAM processes where the geometry of the building element is imported into special software for machine code generation, the digital design-to-fabrication workflow developed by the authors generates machine code directly with the geometry. This seemingly complex digital connection between manufacturing and design is in fact easier as the geometry and meta-data of every building element is already parametrically generated, and all information can be further processed to generate the required machine code within one program.

The main development goal was to automate the process from CNC formatting to the assembly of the main structural components visualised in the previous chapter. Not only would this allow for an expedited assembly process but also reduce the complexity of manually measuring and laying out heavy timber elements. Instead, previously CNC-formatted timber elements are being handled by industrial robots, put into a measurably correct position and joined together. Robots are positioned on tracks parallel to either side of the panels in order to pick and place material as well as to connect elements with screws and nails (fig. 4). The size of the elements and the dimensions of the robotic manufacturing cell was developed in relation to the required design space. The manufacturing process is currently being implemented at the company's factory. First prototypes will be produced in the first half of 2019 and full manufacturing capacity will be expected by the end of the year.

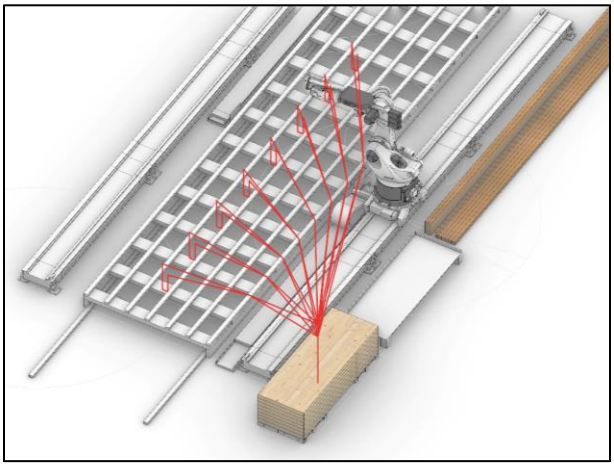

Figure 4: Diagrammatic overview of the robotic assembly process with the highlighted tool path of a robot for handling a stack of CLT panels during assembly

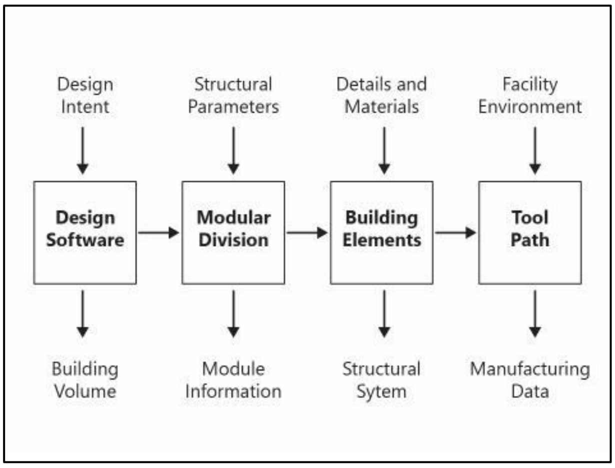

Figure 5. Flow chart of the design process towards the fabrication model. The early design model gets transferred to a modular division, its building elements and finally machine data

3.3 Parametric Design Process

The automatic generation of building components and manufacturing data is preceded by a digital design process that allows the exploration of different building designs within the design space of the construction system. In a digital design process, larger building volumes with up to 18 storeys are subdivided based on the requirements of the modular or panelised construction. After the subdivision, several structural parameters can be inserted in order to control the position of columns and concrete cores if necessary. The modular subdivision will adjust pass on the geometric information together with structural information in the form of locators. Each building group essentially acts as a data container, continuing to collect information as the digital process continues (fig. 5). When populated with all structural elements described in chapter 2.1, each element is already connected to information regarding its robotic assembly. In the case of the CLT panels, the assembly process can be stored depending on the overall size of a floor panel and the position of the CLT panel within it. Hence, each CLT panel has a certain number of geometric locations in its data model, along which the industrial robot will pick and place it in relation to the facility environment. These locations are previously defined and will result in tool path instructions for the robot. In the algorithm, all building elements of one building group will be processed simultaneously in order to export one file for the manufacturing process. A similar process is also created for the generation of CNC machining data before the assembly. The geometry of each building element is directly transferred into the necessary machining steps in order to cut the boundaries and penetrations of each CLT panel.

4 Result: High-Rise Modular Buildings

The platform-based design and manufacturing process has been developed to serve a multitude of urban infill developments ranging from 4 to 18 storeys, with sites ranging from 33 to 400 ft in width. To date, the platform has been tested on a dozen project proposals, six of which are currently in the design process. Among one of the first to showcase the platform in a real-life, large-scale application is a project called Corvette Landing (fig. 6)

Corvette Landing is a 12-storey mixed-use development designed to transition the still low-density single- and multi-family Township of Esquimalt BC, adjacent to Victoria. Planned and developed as an industry-first panelized and prefabricated mass-timber hybrid building, it seeks to combine the low carbon footprint with a high level of livability and expedited construction. The building is an affordable housing project to be Passive Haus certified in order to act as an example for adaptable, repeatable, scalable and sustainable condominium buildings.

Mass timber construction based on the building system described in this paper is applied from the second floor up. Around 150 panels will be prefabricated in the company's manufacturing facility specifically developed for this kind of application. On site, the panels and columns will connect to so-called concrete micro-cores necessary for lateral stability in this high seismic zone. As the elevators and stair cases are in an external, open courtyard, the concrete cores are only as big as a bedroom in this project.

The project received rezoning and development permit approval from the Township of Esquimalt due to its innovative character, green building strategy, and the broken-up and terraced building volume. It passed the Review Board for Site Specific Regulation by the BC Housing Ministry's Building Safety Standard Branch in 2018 and will be one of the first mass timber high-rise housing projects in Canada. Start of construction is scheduled for 2019.

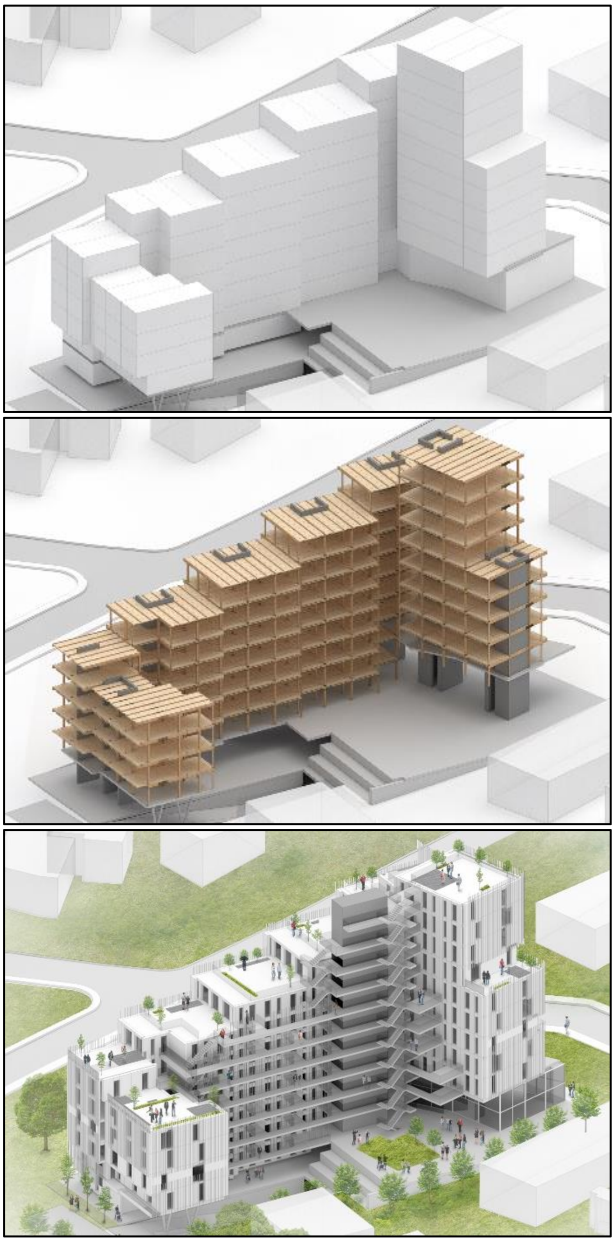

Figure 6. Visualisation of the modular layout (top) and the resulting construction system (bottom) for Corvette Landing. Each panel has a different geometry due to the setbacks, column positions and concrete cores

5 Conclusion

The development presented in this paper is a manifestation of a new paradigm in architecture and construction, converging design, material, structure and manufacturing. It enables the urgently needed transformative change of the urban housing sector towards a resilient urban densification and sustainable and livable future.

Mass timber construction most notably provides the opportunity to develop more adaptive and geometrically differentiated construction systems while still being realized with a certain economic efficiency. However, in order to adapt a construction system and its building parts to specific structural or architectural situations, a parametric design process and a direct and automated fabrication data generation is required.

We argue that in order for a paradigm shift to take place in the architecture and construction industry, already existing knowledge needs to be combined, calibrated and exchanged. A wholesale shift towards prefabricated buildings with mass timber components is challenging but possible. Collaboration across the spectrum of industry players will be necessary. The barriers to innovation run deep and cannot be solved by one actor alone.

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