

Development of a Design-Driven Parametric Mass Timber Construction System for Modular High-Rise Urban Housing

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ABSTRACT

This paper presents the outcome of an ongoing research and development process at Lang Wilson Practice and Architecture Culture and Intelligent City on a parametric mass timber construction system for modular mid- to high-rise urban housing that started in 2006. The system was developed to systematically address the urban housing crisis in North America, and it is currently applied in two Canadian housing projects in seismic zones with 4 and 12 storeys in an evolution from previous modular housing projects by the companies. The first part of this paper explains the holistic, design-driven and parametric approach to urban housing, and how platform-based design is critical for an adaptable, sustainable and qualitative urbanization. Criteria of livability, affordability and sustainability inform the development of a customizable and modular mass timber building system, which can adapt to grid spacing and module sizes as well as to structural requirements for up to 18 floors in seismic zones. The building system is developed to meet Passive House certification and to be fully prefabricated. Constructional innovations within the system reduce the typical redundancy of doubled-up material layers of modular construction. In the second part, the authors explain how the building system is also the result of the development of a fully parametric design tool that allows not only for the optimization of building typology, home layouts or even energy consumption, but also automatically adapts the geometry of all mass timber building elements. This high level of parametrized building information density in an early stage of the design process allows for an unprecedented collaboration of designers, architects and engineers while ensuring constructability. In the last part the authors present a case study, explaining the advantages and challenges of such a collaborative effort and explain how they successfully obtained approvals to build a 12-storey mass timber housing project.

KEYWORDS

Mass timber; Parametrics; Modular construction; Prefabrication; Urban housing; Passive house

INTRODUCTION

The architecture, engineering and construction industry is facing unprecedented challenges brought upon by a continuing increase of the density in major metropolitan areas and intensified by global warming. Although technology holds the potential to solve these issues, the industry has failed to respond, being one of the slowest to adapt to innovation, and has in fact only increased its labour productivity by a mere 0.1% over the last 70 years in the U.S. Globally, the industry's growth averaged 1 percent a year over the past two decades compared with 2.8 percent for the total world economy and 3.6 percent for manufacturing (Barbosa et al. 2017). The slow-paced adaptation of the building sector coupled with pressing ecological, economical and livability challenges need to be addressed in innovative ways. Recent technological developments in digital design, manufacturing and data processing promise to offer solutions for a variety of issues. The companies argue, however, that only in the convergence of technologies and only through a holistic approach to architecture, design, engineering and construction will the industry be able to meet the ambitious goals of the 21st century. The motivation behind the authors' development of a parametric, modular mass timber construction system for high-rise urban housing can be traced back to several pressing issues especially prevalent in the North American market.

Both the pace and demand for urbanization and urban densification have led to a highly formulaic and unsustainable status quo of development models focused on investment return and profit without a desire for quality in built form. The lack of available housing solutions and choice is made worse by the affordability crisis we can see in so many North American cities. In a recent study, 32 out of 50 locations analyzed in North America were either "seriously unaffordable" or "severely unaffordable", with an affordability median multiple of more than 4.1, and Vancouver at first place with a multiple of 17.3 (Mindru 2017). Meanwhile, the population of the world's urban areas is increasing by 200,000 people per day (Renz et al. 2016). In addition, changing needs and desires of urban dwellers caused by social and cultural transformations in the last decades are outpacing the adaptability of static urban housing models, making them even less attractive. This lack of housing diversity serving a modern life style has prompted a re-examination of urban livability, building typologies and the design and delivery process in architecture and planning. The companies's holistic approach, called Platforms for Life (P4L), is based on these criteria and is currently being applied to a 12-storey mass timber building in British Columbia (fig. 1).



Figure 1. Mass timber construction system (left) and the finished building (right) of the 12-storey 'Corvette Landing' mid-rise urban housing project beginning construction in early 2019.

Global warming and local pollution within cities due to construction are another major concern the industry needs to address quickly. Although they only account for 6% of the global GDP, constructed objects cause 25 to 40% of the world's total carbon emissions (Renz et al. 2016). This evident gap of sustainability inequality can be reduced by governmental or municipal enforcement of a holistic sustainability agenda for the use of sustainable and scalable systems, making urbanization affordable. Global growth in green and sustainable building construction is estimated to have averaged 22.8 percent between 2012 and 2017 (HM Government 2013). The biggest impact in environmental improvement can be achieved through the use of more sustainable building materials, more efficient construction techniques, Green Building or Passive House standards, combined with expedited construction times. Mass timber and offsite prefabricated building elements promise these advantages and were the basis of the developments in the following chapters.

Currently, however, low-rise stick frame and high-rise concrete buildings dominate North American cities, and lack intelligent, community-oriented mid-rise forms of developments - the missing middle building form of buildings between 4 and 18 storeys. We argue that this more sensible solution to urban densification is ideal for permanent, modular mass-timber construction at a livable scale. In order to take advantage of mass timber modular construction techniques and customized buildings with a high level of livability and quality, digital design techniques and a fully controlled digital chain need to be fully implemented from the design phase until fabrication. Therefore, the companies have been developing a design-driven, parametrized construction system, which implements criteria of livability, affordability and sustainability in the design process while ensuring producibility and a high degree of data feedback for a continual optimization of our operations. The parametric design process described in chapter 2 can be adapted to a variety of site and program conditions and design intents while providing constant feedback to the designers and consultants.

Quality and affordability are not mutually exclusive if the industry embraces technological innovation. A previous project by LWPAC+IC was assembled from prefabricated modular construction in 2012 and proved that design quality and livability can be much more affordable if design and construction processes are rethought in the context of technological innovation (fig. 2).



Figure 2. ‘Monad’ by LWPAC+IC. Construction of a modular housing project with stick-frame modules (left) and the resulting interior space (right) in 2012.

1. LIVABILITY, SUSTAINABILITY, AFFORDABILITY

There is currently a fundamental lack of qualitatively desirable, high-density urban housing. A study of 11,000 people by the Downtown Vancouver Business Improvement Association has shown that people primarily want four things: (1) High livability; (2) A strong connection to the outdoors, nature and a green city; (3) A true sense of community and public facilities; and (4) Life in close proximity to the cultural, entertainment, work and infrastructure (DVBIA 2015). Downtown’s current “sense of community” received the worst rating, and “open spaces” was rated as one of the top spending priorities for future developments.

The authors developed a family of criteria to define a degree of livability and sustainability. Criteria are grouped into the following categories: Light, exposure, openness, indoor and outdoor access, acoustics, health, comfort, flexibility and community (fig. 3). Furthermore, they are evaluated with four different levels: The quality of the envelope design, interior space design, exterior space design, and context. At this stage in the development process, most of the criteria are quantified by simple geometric calculations. For example, natural lighting is calculated with the orientation of the façade and the amount of window openings. Views and connectivity are calculated by a standardized position from the interior of every housing unit looking out through the windows. These simplified calculations ensure that many iterations can be computed within a very short amount of time. More computationally expensive calculations such as energy input and consumption are calculated at a later stage in the design process.

Visualizing these criteria can inform all stakeholders in the earliest stages of the design process. But most importantly, they can be implemented in a parametric design model that can generate and evaluate different options automatically, to help with multi-variable decision making. While similar methods have been applied for design processes in the past (Beesley et al. 2006, Camporeale and Czajkowski 2015) the presented process is different in two ways: First, it’s a tailored evaluation for the generation of building typologies but still adaptable enough to generate many different solutions in many different urban scenarios. And second, although being a preliminary process in an early design stage, the next chapter shows how these calculations are directly linked to a parametric building information model that generates all architectural and constructional elements.



Figure 3. Evaluation of livability criteria for three different apartment types: a 1BR one-sided apartment (left), a 1BR two-sided apartment (middle), and a 2BR two-sided apartment (right). Due to the double-sided exposure of the latter two, many criteria are evaluated higher.

2. PARAMETRIC BUILDING INFORMATION MODEL

Parametric design can be seen as the missing keystone for connecting the complexity of urban or architectural design and the manufacturing process, which are normally fields of expertise, which do not interact in an integrated and mutually beneficial way. The methods presented in this paper, however, follow a product-oriented approach, meaning that manufacturing informs the development process of a common platform linked to the design intent. Therefore, fabrication or even materialization can not be an afterthought. Instead, a fully parametric building information model based on the criteria of the previous chapter allows to use all available information during all stages of the design process, and gain feedback from all stakeholders.

This paper presents the development of a parametric platform that allows the design of buildings that share only fundamental aspects of a building such as their use and the topology of modules while keeping their size and shape as well as the building volume highly flexible. This is based on the computational design principle of a morphospace (Menges 2012), also called a design space, which defines the range of design possibilities for a constrained process. In this case, the design space is defined by the possible sizes of each module, setbacks of module stacks, the overall building height and other structural parameters and their permutations. The parametric design process is divided into four main steps and multiple sub-steps, starting at the urban scale.

Urban Parametrics: Based on the context and site-specific constraints such as setbacks and height restrictions, the parametric model fills the available volume with modular containers that represent the boundaries of each module as well as the grid spacing. The envelope is added at a later stage in the process. Depending on the available space and preferred settings for ceiling heights and module width this spacing is automatically generated but can be adjusted manually. In a second stage, modules can get an individual setback or get grouped so that “clusters” with several modules of the same size get generated (fig. 4). At this point several key performance indicators can already be extracted, such as the envelope area, foot print and floor space ratio. Because of the interconnectivity of the process, even the amount of material such as wood and steel can be roughly calculated before proceeding to the next step.

Home Typology Population: The resulting arrangement, or topology of modules allows for the population of a variety of home types. These home types have been developed in parallel and can be automatically applied based on the module sizes. For example, a 2BR apartment will populate two modules, while a studio apartment only requires one. Based on the requirements this process can also be manually controlled through a table-like input protocol. With the home population, early design stage plan drawings are created at the same time and can be exported to BIM software.

Construction Details: Based on the information above, construction elements, which were previously defined parametrically, are related to each module. For example, the main structural elements populate the modules and adjust to their length, width, as well as to skewed angles (fig. 6). The data generated in this stage can also be exported to BIM software when necessary, for example for virtual preconstruction.

Fabrication Data: Information for the manufacturing of individual parts is another layer of data that can be exported from the parametric building information model. The authors have so far focused on CNC data for each timber element such as the definition of edges and penetration of timber panels. Additionally, shop drawings are generated from the fully detailed 3D model.

Optimization processes can be included in all stages of the design. The parametric design of the urban volume can generate different variations within set boundaries and output the results or choose an optimized design for aspects such as the surface-to-volume ratio, orientation, views, or simply number of modules. Livability criteria from chapter 1 are applied at the second stage of the design process when home types are defined, and façade openings are placed.

Although some of these functions are still under development, the necessary paradigm change for this process already becomes evident when looking at the development of the construction system. Instead of defining the system by drawings and 3d models, every building element is parametrically defined. A building module consists of many elements that are only defined by their geometric relation to the module bounding box and neighbouring elements. For example, columns are defined by their cross section based on the height of the building, and their position in relation to the overall grid, which in turn is defined by the overall building shape and how modules are placed in relation to each other. If a column changes position or dimension, other building elements such as steel connectors or CLT panels adapt accordingly.



Figure 4. Steps of the parametric design process: First, an urban volume gets generated adjusted to the site constraints (left), then the volume gets populated by different home typologies (right).

3. MODULAR MASS TIMBER

The building industry is one of the last analog holdovers that still follows the artisan and industrial paradigms, where other industries have long moved on into the digital information age using advanced design-to-fabrication solutions as well as platform-based design and systems thinking. Modular mass timber construction can fulfill the requirements for this paradigm change. Timber is a renewable and structurally efficient material. In the form of Cross Laminated Timber, the material is machinable, strong and dimensionally stable. It is ideally used in a factory environment where a much higher level of quality control can be achieved. However, a sudden transition into this paradigm is challenging for the Architecture, Engineering, and Construction (AEC) industry as the successful incorporation of offsite fabrication and modularization requires careful upfront planning and early decision making. It may also increase the level of details required in the design and the requirement for procurement logistics (Huang et al. 2009). What might seem contrary to traditional building industry processes is fundamental for a modern, product-oriented approach. Statistics show that although only 3.2% of the value of new buildings in 2016 was prefabricated modular construction in the U.S. (MBI 2017), the number is slowly rising as modern design and fabrication technologies allow for customization and economies of scale at the same time.

The construction system developed by the authors is based on standardized building elements but allows for a high level of design flexibility in the combination and articulation (fig. 5). The system can either be deployed as modular or panelized construction. Mass timber elements are mainly used for the floor panels as well as for shear walls when necessary. Glulam columns are placed on the module and support two neighbouring panels. Steel connectors between the columns and the CLT panels allow for enough stability during transportation and can easily be accessed on site. For the case study project ‘Corvette Landing’, a thin layer of concrete topping will act as a composite slab that helps transfer lateral forces and covers the steel details at the same time. In order to allow for a fast assembly of a lock-up shell, façade panels are also prefabricated from CLT panels and Glulam beams as the main structure.

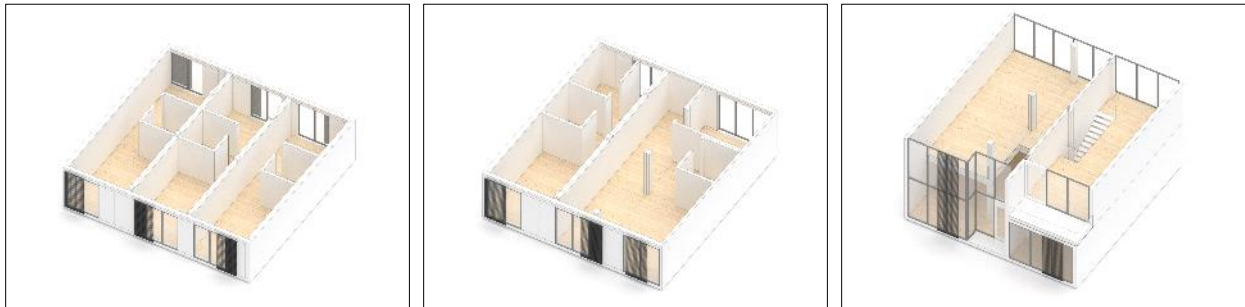


Figure 5. Different permutations of the same platform allowing for studios (left), 2BR (middle) and 3BR (right) apartments.

RESULT: CORVETTE LANDING

The platform-based design has been developed to serve a multitude of urban infill developments ranging from four to 18 stories, with urban infill and development sites ranging from 33 to 400 ft. To date, the platform has been tested on over ten project proposals, seven of which are currently in the design process. Among one of the first to showcase the platform is Corvette Landing.

Corvette Landing (see fig. 1) is a 12-storey mixed-use development designed to transition the still low-density single family and multi family Township of Esquimalt BC, adjacent to Victoria. Planned and developed as a panelized and prefabricated mass-timber hybrid building, it seeks to combine a low carbon footprint approach with a high level of livability and expedited construction. The building is an affordable market housing project to be Passive Haus certified. Mass timber construction based on the building system described in this paper is applied from the second floor up. The mass timber panels and columns connect to concrete “micro-cores” necessary for lateral stability in this high seismic zone on a site with poor soil class. The project received rezoning and development permit approval from the Township of Esquimalt due to its excellence in design, green building strategy, and terraced articulated building volume. It also passed the Review Board for Site Specific Regulation for its innovative approach 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 early 2019.

CONCLUSION

The fully parametrized design-to-fabrication workflow described in this paper is elemental for a paradigm change in the architecture, engineering and construction industry. It allows for

interdisciplinary collaboration from an early design stage and can ultimately lead to a leap in sustainability, efficiency and affordable quality the industry has missed for so long. However, this leap necessitates systemic innovation, where all involved parties need to change their workflows and embrace the use of new technologies. We argue that this paradigm change as shown with the P4L approach requires a product-oriented approach that achieves an integration of design, functionality and manufacturing. These developments will ultimately change how architecture is conceived, built and delivered.

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