

Master Innovation & Development Plan

Technical Appendix

**TITLE: Mass Timber in High-Rise Buildings:
Modular Design and Construction**

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ABSTRACT

This report investigates relevant issues for analyzing the feasibility and constructability of using mass timber in high-rise structures. This research was conducted with support from a Sidewalk Labs small research grant.

Most relevant sections: Vol 2 (Buildings and Housing)



Mass Timber in High-Rise Buildings: Modular Design and Construction

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HIGHLIGHTS AND KEY POINTS

- The costs of mass timber may be higher, but the added premium on their prices make them economically feasible.
- Beyond the economics, mass timber structures present a unique opportunity to develop and test the resiliency of the owner organization and its capacity to innovate.
- A collective effort to strengthen the supply chain in Ontario (especially the manufacturing stage) is one of the key tools to reduce costs.
- Having a dedicated fire consulting firm and the early engagement of regulatory bodies and consecrators are some of the key means to control risks in this domain.
- Earlier projects relied on covering/insulating mass timber sections to achieve the required fire requirements. Increasingly, charring is becoming an acceptable means for fire protection.
- Using Integrated Project Delivery system (IPD) and Building information modeling (BIM) can provide the contractual and technical platforms to boost coordination and promote collaborative design and construction.



Church in Kizhi, Russia (constructed entirely out of wood--log building technique)

EXECUTIVE SUMMARY

This report investigates relevant issues for analyzing the feasibility and constructability of using mass timber in high-rise structures. New to the Ontario market, uncertainties and risks associated with such structures are under-studied. The motivation for adopting mass timber as the main structural element in high-rise buildings spans three dimensions. First, on the technical side, the key motivation for using mass timber structures is their positive contribution to energy management and resource conservation. Timber has a low embodied energy compared to concrete and steel. However, such advantage can diminish in situations where timber has to be transported for long distances. Second, from a business perspective, exposed mass timber is a bold architectural feature that can be appealing to customers. In addition to the physical appeal, customers are becoming increasingly interested in supporting sustainable and locally-sourced material. A less obvious third dimension (or benefit) is to test and advance the resiliency and innovation capacity of the developer/contractor. The industry is poised for major changes due to factors that range from increased demands for sustainability, to the advent of smart building and artificial intelligence to, possibly the most important factor, the growing role of customers in decision making and co-creation of knowledge. Innovation and effective change of management abilities are keys to the competitiveness of developers and contractors in this emerging market. Taking on mass timber structures as means to test and enhance organizational capacity for managing change and innovation can by itself be a good enough justification for such decision.

Evaluation of related work and cases in the domain and the study of the main challenges for mass timber structures clearly indicate that detailed and collaborative analysis of the design and construction plans are essential to coordinating the innovative exploration and the successful execution of such new systems. Nevertheless, two issues of major significance need to be addressed. First, permitting and code compliance, particularly in regards to fire safety. Second, the newness of the system, which may be perceived as increase risk by contractor. This is why, for the time being, mass timber structures in Ontario cost more. The increasing number of projects in Toronto should bring these costs to within range of regular structures. To this end, one of the key means for reducing the costs of mass timber is a collective effort by developers to streamline and strengthen the supply chain in Ontario—especially in relation to the manufacturing stage.

Investment in effective, open and interactive partnership with code agencies and research and testing institutes is one of the most important steps to be taken given the novelty and “unchartered” nature of such structures in Ontario. Code agencies will need sufficient testing/evidence and analysis before approving such structures. A dedicated program and/or group should be established to plan and

continually update a collective effort to 1) synthesize and benchmark already existing knowledge and facts about the structural and fire performance of mass timber; 2) proactively commission testing, simulations and analyses to address any gaps or Ontario-specific needs; 3) consistently reflect the lessons learned in future projects; and 4) use smart, possibly IoT-based, monitoring systems to measure actual building performance, study and model behavior, and validate initial assumptions/simulations.

To address construction risks, developer and consulting teams should be actively engaged with the contractor. They should collaborate in modeling and sharing risks, training labour and supervisors, and monitoring productivity. In fact, owners should consider using the integrated project delivery system (IPD). This new practice creates a partnership between the owner and the contractor to share knowledge and work together to innovate, reduce risks, manage the project effectively, and, consequently, share the benefits and rewards. The use of BIM (Building Information Modeling) and virtual reality systems can be of great value to mass timber structure. First, virtual flythrough of the facility in 3D can be a key selling point to customers. Second, BIM can be used to visualize and create scenarios for the spread of fires and to study fire management plans and evacuation procedures. Finally, BIM can provide an effective platform for studying the project and co-managing its features (such as schedule and cost).



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INTRODUCTION

Mass timber use in high-rise structures is a relatively new domain—particularly in Canada. Building a business case for these structures and planning for their design, construction and operations should span three dimensions. First, the technical aspects, such as structural capacity and fire performance. Second, construction and maintenance practices and challenges. Finally, relation to organizational resilience and innovation capacity. The later dimension refers to the fact that adopting such new systems can be a tool to build and validate organizational capacity, to manage change, and to take risks. Selling, building and operating such structures challenge organizational capacity for innovation: how to develop new practices for leading and implementing new products and services. The land development and construction industries are changing very fast due to increased urbanization, the advent of smart and interactive buildings, and the increased demands for sustainable practice. While a formal economic feasibility study may not favor mass timber structures, successfully taking on such new and challenging systems can have great value in terms of building the innovation capacity of the organization.

This report was commissioned and funded by Sidewalk Labs Toronto, which is in the process of planning and building a smart development on Lake Ontario shoreline: Quayside project. In addition to evaluating the benefits of mass timber structures, this study examined the main challenges for their construction. This report is divided into two main sections. The first section covers the important role and impact of modularization in design and construction on the feasibility of such systems. Whereas, the second section focuses on mapping the technical challenges of mass timber structures--particularly in relation to fire safety and the perceived increase in construction risks. The report provides a review of related work, including identification of challenges and opportunities, decision criteria, and best practices. A set of case studies and interviews with relevant stakeholders and experts in the domain were conducted to further enrich the analysis. The following section provides details about the methodology of the research project, its scope, and limitations.

METHODS, SCOPE AND LIMITATIONS OF THIS STUDY

The main objective of this research project is to develop a case-based analysis framework for modular construction--especially as it relates to the use of mass timber in high-rise buildings. The aim is to study the technical as well as the management aspects of modular construction. For example, who makes decisions and based on which criteria. Figure 1 outlines the scope of work in this project. The scope covers three main topics: modularity, fire safety and construction knowledge and practices. However, the main target of the analysis is to focus on the use of mass timber as load-bearing elements. The research included limited analysis of two other elements: non-load bearing timber systems, and modular wet boxes. They are related to the modularity topic and were discussed to put the analysis of mass timber elements in context. Modularity analysis mainly targeted modular construction with brief discussion of design modularity.

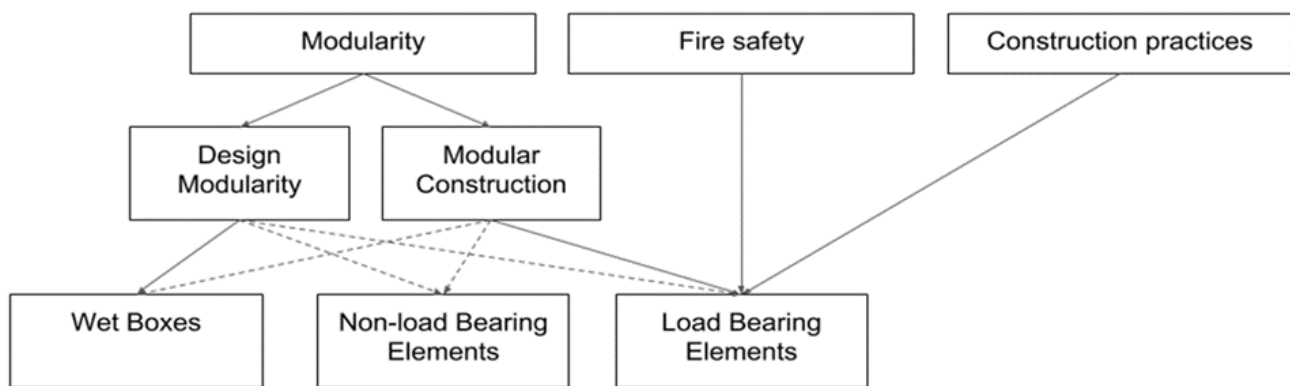


Figure 1: Scope of Work in Project

The methodology of this research included the following steps (see Figure 2):

Initial Scope: A baseline scope was developed based on the call for proposals and general knowledge about the domain. The main thrust was focused on generic analysis of modular construction through case studies.

Revised scope: A more focused scope was developed based on an initial review of literature and meetings with Sidewalk staff. Instead of following a generic analysis of construction modularity, the revised scope directed the analysis towards the relationship between mass timber structure and modular construction. This included the role of design modularity and the use of non-load bearing timber elements. More consideration was given to fire safety and local construction knowledge as they relate to mass timber--there is a clear need for integration between these two domains.

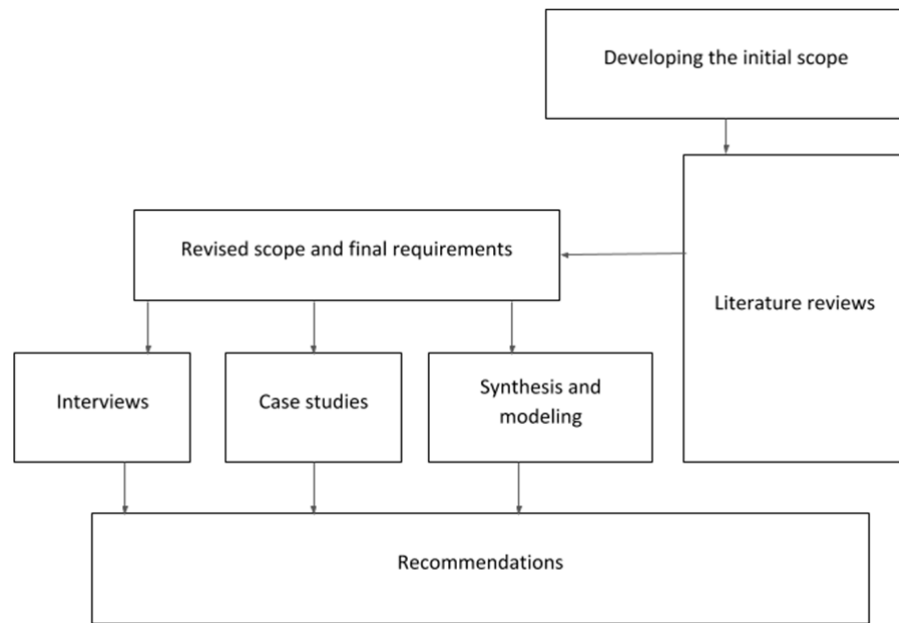


Figure 2: Methodology of Research

Literature reviews: We reviewed modularity-related research work as well as relevant cases in the use of mass timber. This covered the drivers, the practice, the benefits and the challenges of using mass timber. A special emphasis was placed on two important issues which are: 1) the role of modularity in reducing construction costs; and 2) the importance of modularity in supporting adaptive buildings and use reconfiguration during the operations stage. In addition to reviewing technologies and types of timber sections, performance of timber under fire was examined.

Interviews: We met with experts in design, construction and maintenance. The aim of these interviews was to complement the literature reviews; help select project cases; evaluate our analysis of the cases; and enhance the quality and relevance of the recommendations.

Case studies: We reviewed published cases and conducted two case studies which included the newly constructed building at the University of British Columbia and the proposed new building at the University of Toronto.

Modeling and synthesis: We conducted iterative analysis of the challenges and opportunities, risks, and best practices. We also placed added emphasis on issues of permitting and code compliance—the process of submitting alternative solutions under Ontario’s Building Code (OBC). Further, we examined the contracting issues in high-rise timber buildings in light of the available experience of stakeholders and the shortcomings of the traditional project delivery methods.

Recommendations: We, finally, summarized a set of findings from the literature and the cases, and recommended additional work in the future.

SECTION I: MODULAR DESIGN AND CONSTRUCTION



Background

Modular design is an approach that uses similar or repeated patterns in the layout and features of a facility. Modular buildings can be constructed through traditional approaches or through modular construction methods. Modular construction uses the same patterns of modular design to fabricate and then assemble building components. These can be as simple as standardized panels and walls or as complex as large 3D volumetric units (Jellen & Memari 2013). 3D elements (block containers) can be designed to include necessary internal plumbing and electric fixtures, interior and exterior finishing, and built-in furniture and equipment. Modular construction components can be built on or off site. Off-site construction produces and/or assembles modules in factories. Such practice provides for a safer construction environment (within a controlled and protected manufacturing facility); reduction in assembly time and, typically, costs; and enhancement of quality. However, having such facilities relies on the existence of sustained demand—something that is not there yet for mass timber structures in Ontario.

Modular construction practices can be very valuable in increasing the feasibility of mass timber structures. Cost and schedule savings associated with modular construction can offset the impacts of increased/perceived construction risk and some of the costs associated with added analyses and tasks in design and permitting. It should be noted that implementing modular construction does not necessitate strict modular designs: cookie-cutting and standardized layouts. The repetitive units can differ in size and complexity, and can be limited to the structural elements of the high-rise building (beams, columns, floorings, wall panels, etc.). However, even with the most standardized 3D units, innovative designs can be achieved.

Below, we discuss two major aspects of modular construction. First, we present a brief discussion about the types and technical issues of modular construction. We frame the discussion across three main categories of building elements: load-bearing elements, non-load bearing elements, and 3D modules. However, more emphasis is put on the first category. For the last category, we only consider wet boxes. While the first category is the most relevant to this study, the other two are needed to put the analysis in context. The second part discusses the management and economic rationalization for modular construction.

Part 1: Technical Aspects of Modular Construction

This section explores the main technologies and systems used in modular construction for load bearing elements as well as non-structural elements. It also gives a brief overview of the use of prefabricated units as wet boxes and discusses their incorporation in modular buildings.

Technologies and Systems for Modularization

Off-site production technologies can be categorized into four levels (Gibb and Pendlebury, 2006):

- Component and subassembly (factory-made and not considered for on-site production, e.g., lintels).
- Non-volumetric preassembly (pre-assembled units that do not enclose space, e.g., precast wall panels).
- Volumetric preassembly (pre-assembled units that enclose usable space, e.g., bathroom pods).
- Modular building (pre-assembled modules that form the whole building, e.g., hotel modules).

For tall buildings, the majority of applications of modular construction was related to cellular-type buildings such as hotels, student residences, and military and social housing. Limited research was conducted on other types of buildings. The analysis of modular construction in tall timber building is non-existent because of their novelty. Research work on tall steel structures presents the best benchmark in regards to mass/tall timber structures. Lawson et al. (2011) studied the use of modular construction in high-rise steel structures and recommended the following four key factors to be taken into account:

- The influence of installation eccentricities and manufacturing tolerances on the additional forces and moments in the walls of the modules (Lawson and Richards 2010).
- Second-order effects due to sway stability of the group of modules, especially in the design of the corner columns of the modules.
- Mechanism of force transfer of horizontal loads to the stabilizing system, which is generally a concrete core.
- Robustness to accidental actions (also known as structural integrity) for modular systems.

Load-bearing Elements

Structural load-bearing systems for high-rise modular buildings can be broadly classified as follows (see Figure 3) (Ramaji & Memari 2013):

2D Systems: Prefabricated panels for floors and walls that can be assembled to form the whole building (see Figure 3a). Connections used between the 2D panels transfer the loads (gravity and lateral loads) between them.

3D Systems: Stacking of 3D modules vertically and attaching them horizontally to create the building (see Figure 3b). Units are designed to be either wall-load bearing or (column) corner-supported systems (Lawson et al., 2010).

Open Building Systems: Combining different framing and module systems for transferring structural loads while enhancing the flexibility of space planning (see Figure 3c).

Hybrid Cored-Modular Systems: Using conventional stiff cores between modules such as concrete shear walls and frames, braced steel frame, or steel moment frames to reduce the lateral deformations of the whole structure while keeping modules light (see Figure 3d).

Hybrid Podium Systems: Building a podium of structural steel or concrete frames with long spans in the bottom stories of the building. This podium acts as support for installing modules on top of them and transferring their loads to the beams of the podium (see Figure 3e).

Framed Unit systems: Using a conventional frame to form the structure of the building. Prefabricated modules are placed and fitted between the beams and columns of the structural frame (see Figure 3f). This allows more flexibility for the modules since the frame bears all the loads while the modules carry their own loads only.



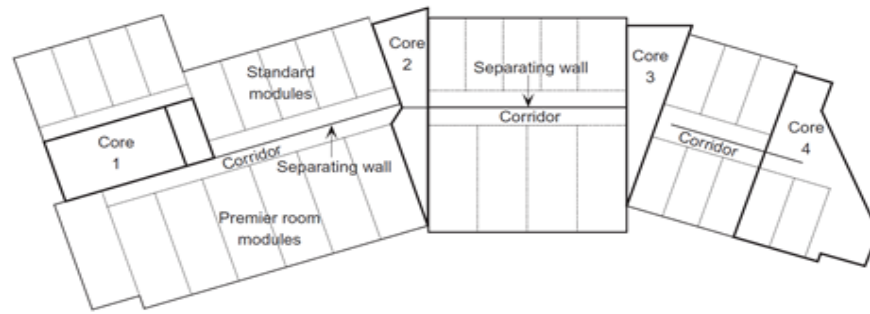
a. 2D Prefabricated Panel

(Adopted from: <http://builtoffline.com.au/issue-02/dimensions-design-2d-3d-hybrid-components>)



b. 3D Prefabricated Module

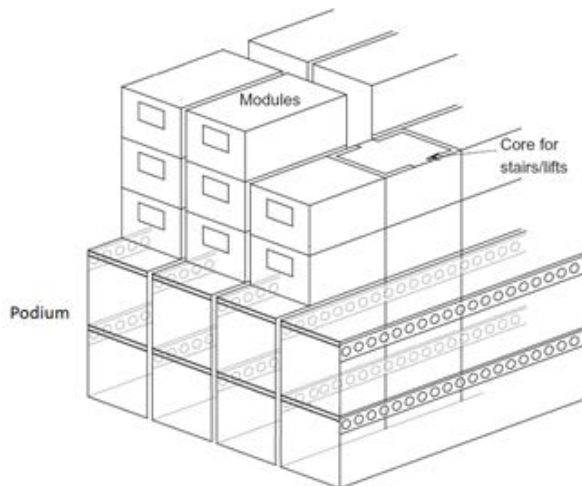
(Adopted from: https://www.steelconstruction.info/Modular_construction)



c. Hybrid Cored-Modular Systems (Ramaji & Memari 2013)



d. Open Building Systems (Ramaji & Memari 2013)



e. Hybrid Podium Systems
(Ramaji & Memari 2013)



f. Framed Building Systems

(Adopted from:

<https://www.yesterland.com/contemporary.html>)

Figure 3: Examples of Modular Systems

Non-Structural Elements

Non-structural elements in the building are the elements that do not contribute to carrying and transferring building loads. In general, non-structural elements vary based on the building structural system and include interior partitions. In the case of buildings that do not use load bearing walls, non-

structural elements can include walls, slabs, stairs, etc. These elements can be made of timber and can be widely used in timber structures or in structures where concrete or steel are used for the structural elements including columns and beams. Using timber members allows for energy savings during construction and also enables reducing the buildings' embodied energy. Moreover, these elements are commonly used in Ontario especially in single family houses. This means that substantial expertise in this area already exists in Ontario which would facilitate their incorporation in high-rise timber buildings.

Prefabricated Units (Wet Boxes)

Prefabricated components can be designed and equipped with plumbing, HVAC, and electrical fixtures prior to their installation (see Figure 4). One of the most used prefabricated 3D units is for wet areas in buildings such as bathrooms and kitchens and are typically called wet boxes. The interior of a module can be configured with a tile floor and walls, plumbing and electrical fixtures, cabinetry, and different accessories and features (Barry et al., 2014). Building these areas on-site is labor-intensive and requires high level of coordination since they involve different work areas including waterproofing, finishes, accessories, plumbing systems, electrical fixtures, and other concealed services. Accordingly, the prefabrication of these units offers good opportunities for improvement regarding productivity and quality of work.

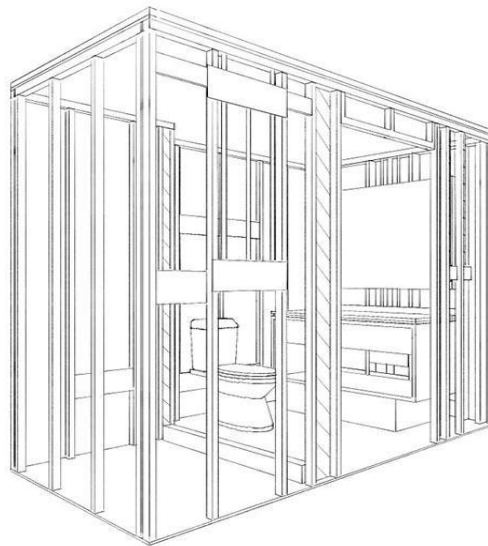


Figure 4: Modular Bathroom Pods

(Adopted from: <http://bandtmfg.com/modular-bathroom-pods/>)

According to the reference guide on standard prefabricated building components, there are various systems of prefabrication that can be used for wet areas including completed units (cubic Wet Boxes). Alternatively, wall panels and floor trays are assembled in their specified locations or pre-assembled

on-site or in a factory (Knock-down System) offering more flexibility of changing wall panels easily. Wall panels are usually made of fiber reinforced polyester, special cement board, sheet moulding compound, galvanized metal sheet, and sandwich paneling system. Whereas, floor trays are usually made of reinforced concrete, fiber reinforced polyester, or sheet moulding compound. As for the Installation procedures, they vary from one system to another but they have common considerations that need to be addressed:

- The weight of the wet units/boxes needs to be considered during the structural design process.
- The size and layout of the wet boxes need to be standardized in incremental dimensions to easily fit them within the building especially in case of the use of other modular units.
- The location of the units in the building needs to be carefully analyzed in relation to the building layout and site constraints.
- The designer must consider the availability of space to lift, maneuver and install the units.
- The units must be designed with a self-supporting framing in order to be lifted and moved around.
- After placing the units, sanitary discharge pipes are to be connected to the main discharge stack in the service duct, while electrical fixtures are to be connected to the main switch of the building. This emphasizes the need for standardization, accuracy and effective use of flexible joints/connections.
- To handle any potential gaps between the bottom of the units and the structural slab, the units should be designed such that a filling or non-shrink grout would be easy to install.
- The locations of connecting services from electric and mechanical fixtures need to be predetermined and coordinated to high levels of detail during design before the fabrication of units.

Although prefabricated wet units may be expensive, they provide benefits in other aspects such as:

- Higher quality of finishes; better quality control of waterproofing works in the factory-controlled environment.
- Easier installation.
- Lower waste of materials.
- Improved productivity of labor on site.
- Reduced construction times.
- Fewer defects and reduced wet work on site.
- More flexibility for alteration.

Prefabricated wet areas, especially the knock-down system, can be custom-designed (including having different finishing materials and fittings). In this case, economies of scale through mass production don't necessarily mean cookie-cutting manufacturing. Aside from using prefabrication for fixtures, these units can also be equipped to benefit from the potentials of the internet of things (IoT) since the prefabrication of units facilitates embedding sensors and controllers enables controlling the lighting, temperature, water-use, etc.¹.

Part 2: Management and Economic Aspects of Modular Construction

This section gives an overview of the management and economic aspects of modular construction. It discusses the rationale behind using modularization in construction and the opportunities of expanding the scope of modularity beyond construction to realize its full benefits. It also summarizes the main challenges and barriers that limit the application of modular construction, and reviews various decision support systems for its successful execution.

Rationale for Modularization in Construction

Modular construction has significant economic savings because of its factory-like manufacturing process which produces less waste and reduces time and machinery needed on-site. According to a survey by McGraw-Hill, 72% of contractors believe modularization shortens project schedules and reduce project budget. More than 83% of the contractors surveyed believe that modularization reduces onsite waste; and 66% also believe that modularization reduces the amount of materials used on a project (Bernstein et al., 2011). In general, the advantages of modular construction include: “design only once and reuse multiple times; design and procure in advance/respond to schedule needs; accelerated, parallel engineering for site adaptation; learning curve in commissioning/ start-up (planning and execution); learning curve in fabrication; learning curve in module installation/site construction; learning curve in operations and maintenance; volume discounts in procurement; operations and maintenance material management cost savings; and construction material management cost savings” (O'Connor et al., 2015)¹. Modularization does not only save money but also significantly enhances safety conditions—first due to the reduction of work hours on-site and also because workers will have more chance to work in a space that will not leave them exposed to the elements. It also subject residents to less site disturbance, noise and dust problems. Since almost all workers on the site work inside the building once the modules had been erected, construction workers enjoy a work environment that does not leave them exposed to temperature extremes, rain, wind or any combination of natural conditions.

¹See: <http://www.buildingtalk.com/blog-entry/how-the-internet-of-things-is-changing-bathroom-design/>

Equally important, modular construction is a key to any lean and green construction practices. This is significant in the realm of sustainable and smart homes, because the greatest barrier to the widespread application of green/smart designs is the higher initial costs due to lower productivity (learning curve) of workers as they deal with new technologies, and the added cost resulting from ill-defined construction processes (Nahmens & Ikuma, 2011). Further, despite the negative impact of transporting modular components to sites, modular construction has direct positive effects on sustainability (Phillipson, 2001) including: operational energy use, embodied energy, waste, and water.

Studies have shown that semi-prefabrication reduces GHG emissions with 336kg/m^2 in contrast to 368kg/m^2 for regular construction. Four elements positively contribute to this: savings in quantities of building materials, more efficient transportation of building materials, reduced resource consumption of equipment and labour, and more control and better transportation of waste and soil, accounting for 86.5%, 18.3%, 10.3%, and 0.2%, respectively. Transportation of prefabricated components increases GHG emission by 15.3% of the total emissions reduction (Mao et al., 2013)

One of the key problems of implementing modular construction is the limited work that has been done in integrating its analysis in BIM (Building Information Modeling). BIM technology has been developed and promoted as a means to integrate all information of building designs. However, it is overly focused on the traditional design of facilities. i.e. not modular-oriented. Further, with a global supply chain (not only of hardware but also of design expertise), communication between parties and logistical efficiency (in procurement, installation and operation) are suffering. This contrasts the premise of sustainable development, which targets holistic approaches of analysis. It also significantly reduces the potential for BIM as it requires smooth flow of information between design, construction and delivery processes (Arayici etc. 2011; Eastman etc 2008).

O'Connor (2015b) studied different economic advantages which can be achieved using modular construction augmented with prefabrication and standardized designs. This combination brings together the benefits from these different areas offering wide opportunities which were summed up as follows:

- It enables to “design-once” and reuse multiple times which enables saving costs during design and ensures more reliable cost estimation from the early stages.
- It requires early procurement which is ideal for schedule-critical projects since it guarantees less schedule risk.
- Engineering/construction of standard design is less iterative and more parallel thus accelerated with fewer errors.
- Receiving procurement discounts from volume or early commitment which may help in curbing cost escalation.

- Proper construction material management which saves costs through reducing material inventory and required storage as well as causing less material wastage.
- Learning curve benefits in fabrication regarding quality and safety, productivity, and containment of risks and uncertainties.
- Learning curve benefits in planning and module installation improves quality and safety, productivity, field schedule due to optimizing activity sequencing and the containment of risks.
- Learning curve benefits in operations and maintenance.
- Higher costs savings from the improved material management which allows reducing operations/maintenance material inventory, required storage, and spare-part outages.

Learning curve and mass timber construction

Timber construction is a familiar domain to labour force in Ontario in low to mid-rise structures. Mass timber in high-rise will include larger section sizes and new types of connections. The novelty of this should not be a significant issue given the large similarities in construction practices, the use and availability of easy-to-use connections in mass timber construction practices, and the fact that almost all mass timber sections are pre-manufactured, which provide higher accuracy in cuts and dimensions. Finally, experts have reported that the carpenter trade training centers have indicated that providing the required training should not be a significant burden. Modular construction, especially pre-manufacturing, in mass timber structures becomes a major boost to a faster learning curve.

Expanding the Scope of Modularity

In the context of innovative planning for smart and sustainable development, the analysis of modular systems should not be limited to saving cost and time during the construction phase. Additional considerations should be included to account for the full benefits of modularization—these include the following.

Buildings and infrastructure: In general, industry practices and research work have focused on investigating and using modular panels to make construction of buildings easier and cheaper. More focus was placed on buildings, such as high-rise apartments and housing units. However, modularity is also applicable to infrastructure. Pavement, curb, sidewalk, and sound barrier panels and other modular components has been used successfully in highway construction. Similar modules are used in bridges and manholes. Even in electric power infrastructure, several modular units are also used. The expected rapid change in street furniture, instruments that is associated with driverless car makes modularity in street design more valuable.

Consistency in geometry and material: the typical view limits modularity to units of consistent geometry that can be repeatedly and easily manufactured and shipped to site. But given the increasing interest in re-use, there must be a smart selection of consistent material of these units that enable combining them in the future in different configuration. Large disparity in the materials of modules may hinder reconfiguring them in the future. For example, can a wet box be fitted/fixed on different floor panel systems or be easily connected to different plumbing configurations. Can connections be mixed and matched?

Geometry vs dimensions: using open spaces and higher ceilings are needed to support adaptability (changing the layout and configurations of facilities based on users' needs). It is important that the dimensions of components be made such that different combinations of them can fit in the open/high ceiling spaces. In other words, and in a Lego-style, how can the dimensions across several modular components be consistent to allow several "assembly configurations". For example, can we create dimension-harmony between, say, modules of water/wastewater units and flooring systems that would allow quick assembly of different configurations of bathrooms that fits in different spaces irrespective of space use/functions?

Construction, adaptive use, and re-cycling: modularity is also needed to help use the same component in different settings. This is needed to enable the adaptive space mentality of the ongoing plans (the Stoa concept). In addition, as some of these panels get recycled, they should be designed in a manner that, when de-assembled, parts of them can be put to other use. Further, not all material will deteriorate equally—some can be reused as part of another assembly when the whole unit is decommissioned or re-cycled. To illustrate, increasing the use of plain concrete (instead of reinforced concrete) in building panels allows the re-use of these panels in pavement systems more efficiently.

Components vs tools: given the need for adaptability, these components will be re-assembled or configured by facility users. This means that we should study the modularity of tools: like the Ikeas Allen key, can we standardize the assembly tools to help users master the process faster?

Modularity of processes and rules: the next obvious step is to modularize the process of assembling or re-assembling modular components. Further, can we use IoT and smart hardware to help in studying possible reconfigurations and reflect that on module design? For example, can modular comports choose each other? In other words, can we embed "modularity and assembly rules" into components making it easy for users (including facility users) to discover opportunities for innovative configurations? Can the modular components be smart enough to help discover new layouts and/or usages?

In summary, the successful implementation of modular construction should consider the whole life cycle of the building from initiation to, (repeated) interim modifications, to demolition and disposal.

Such extended horizon of modular construction will require better tracking of the building components to assess their status and to study where they can be reused. This can be achieved through creating a “material/ components catalogue” for the building. Several technologies and practices can contribute to this such as:

Internet of Things (IoT): embedding sensors in the materials and components used in the building allows updating and keeping track of their locations and conditions. This enables asset managers to study their conditions, usage levels and needs for maintenance.

BIM: the ability to view and collaboratively re-design buildings through BIM can make it easier to re-use modules in different locations and/or develop new layouts for the facility without a module that has reached its end of life state.

Challenges and Barriers to Modular Construction

Despite the benefits that off-site production and modular construction offer, there are notable disadvantages to using these techniques. However, earlier engagement of stakeholders can enhance the chances of success of off-site and modular construction approaches. Blismas et al. (2005) identified a set of factors as follows:

Process Constraints: freezing the design and project specification early on is important for modular construction to allow the manufacturing process to start early and run in parallel with other construction activities. However, this is not typically easy given the procedural nature of traditional project delivery systems and the typical scope changes. Consequently, careful consideration of project delivery system and proactive communications with suppliers are important in achieving better efficiency in modular construction. Such constraint is magnified in the construction of mass timber structures given the expected higher rates of changes in their scope: a larger number of iteration and revision is to be expected due to the novelty of such buildings (at least in Ontario).

Knowledge Constraints: On average, contractors and also consultants are not as experienced with modular construction. The lack of practice and knowledge about the process may reduce the overall efficiency of modular construction. Collaboration and co-learning can be an effective step to address this issue together with establishing long-term partnerships with contractors, consultants and suppliers to help promote the generation and re-use of best practices.

Value Assessment: The practice of lowest-bidder can hinder the use of modular systems if they are more expensive in terms of direct costs. This is because it is hard to appreciate/quantify the other benefits of modular construction such as quality, safety and schedule performance.

Supply Chain Constraints: The relatively small number of suppliers/specialists from which clients can select may limit their options and increase prices. While longer lead times may help offset some of the

constraints, they can make changing suppliers very complex. They will also require an early freeze of designs.

Technical Constraints: O'Connor specified some key technical difficulties associated with the use of modularization, including dealing with changes in the shipping and work envelopes (expected to be larger with modular construction), selecting and configuring construction equipment (for example: cranes, their capacity and space requirements), and site layout and storage facilities--which will have to be (in many cases) larger and have to be managed with higher standards of care (damage to a developed module will cost more than wasting raw material).

Ontario supply chain for mass timber

Overall, experts have reported that the supply chain of mass timber in Canada is evolving but not as mature as that of Europe and parts of the United States. Ontario supply chain still needs some time to reach adequate levels for realizing the most optimal economics. A key component (a bottleneck) is the manufacturing step. It is sophisticated and requires expensive investments and, more importantly, is reliant on the existence of a demand for manufactured mass timber--which is still at its infancy. In fact, calculations by some industry experts show that it is cheaper to source mass timber from Europe.

This opens the discussion about the nature of costs that are being assessed. One of the key motivations for adopting such systems is their lower embodied energy. European timber, while less costing in cash, is certainly more expensive in its "energy costs".

Decision Support Systems

O'Connor et al. (2014) developed a framework for organizational success factors for executing modular construction including: alignment between owner, consultants, and critical stakeholders to establish the value and foundations for a modular approach. They pointed out the importance of timely design freeze where owner and contractor effectively implement timely staged design freezes so that modularization can proceed as planned. Rewards should be established for early completion that result from modularization and those resulting from minimal site presence and reduction of risk of schedule overrun. Similarly, all cost savings that can accrue from the modular approach should be recognized and allocated to the appropriate party. But in general, the success of modularization will rely on contractor experience and the capabilities of the fabricator. They also emphasized factors that have special influence on success including consideration of operations and maintenance of modules during their design; exchange of data between all stakeholders in a timely manner; and a well-structured risk avoidance plan.

In another study, O'Connor et al. (2015a) analyzed 107 ways that modular projects differ from stick-built projects in planning and execution. The majority of these were found to be related to the basic design phase. 37% of the planning differences pertain to four topics: planning and cost estimating;

modularization scoping, layout process, and plot plan; basic design standards, models, and deliverables; and detailed design deliverables. In addition, differences in execution plans should be addressed as one of the solution elements to successfully achieving higher modular project performance.

There are constraints and possible risks for adopting modular systems that if not addressed carefully, can increase cost significantly. Longer lead times are needed, especially for pre-planning and design. This is typically challenged if the prevailing design process is based on the traditional (sequential) mode. It is important to point out that the advantages are realized only if the building is designed for modular construction—not the other way around. However, this means that any post design changes will be very costly. Further, any production problems at the off-site location can cause extensive and unavoidable delays (O'Connor et al. 2015a). Additional issues that should be recognized are the high set-up (initial) costs as well as possible increase in the costs of crane usage. One of the most prevalent challenges for modularization is the limited expertise and training for project managers as well as design consultants (see Blismas et al. 2006; Neelamkavil 2009).

O'Connor (2015a) presented a set of key lessons learned from case studies performed on modularization. These key lessons encompass the following aspects:

- Front-end planning:
 - Develop modular execution strategy in front-end phase.
 - Identify the team consisting of all required disciplines early on.
 - Base plan on back to front (construction-driven module fabrication and module fabrication-driven engineering and procurement).
 - Consider numerous configurations.
 - Clearly set boundary conditions (transportation limits and scope limits).
 - Promote final design within the organization to avoid rejections during execution (Early design freeze).
- Design and engineering:
 - Include module engineering work packages specific to module envelopes.
 - Clarify definition of boundary conditions.
 - Promote repeatability.
 - Promote selection of common materials.
 - Promote detailed engineering to ensure technical compliance.
 - Minimize variations in product design.
- Contracts and procurement:

- Integrate vendors early on in the design of the modules (they are the ones who have to fabricate the modules and know what is or is not feasible).
- Incorporate smart bulk-buying process.
- Module fabrication:
 - Include quality assurance and alignment with the site.
 - Repeat the design of equipment.
 - Promote layout and design that support modularization.
- Module transportation:
 - Conduct transportation studies early on.
 - Use module index with weights and dimensions.
 - Clearly define transportation limits.
- Site installation:
 - Involve the contractor early on.
 - Verify the availability of lifting equipment.
 - Design module frames to be set on steel piles.
 - Procure clear installation manuals from the vendor.
- Staffing:
 - Include operation and maintenance, construction, purchasing, transportation, and vendor as part of the team.
 - Include vendor data coordinator.
 - Align all involved parties, from engineering to installation to contractor, with the concept of modularization (purpose, boundary conditions, targets, etc.).

SECTION II: THE USE OF TIMBER FOR HIGH-RISE BUILDINGS



Background

Steel and concrete are two of the largest sources for emissions in the building sector. Replacing them with timber/wood can certainly reduce the building sector contribution to GHG emission. Timber, as a building material, has lower climate change impact in the order of 34% to 84% compared to steel and concrete (Skullestad et al., 2016). Since taller buildings have higher embodied energy and GHG emissions per m² floor area compared to low-rise buildings. Consequently, the advantage of using timber in tall buildings is more obvious and achievable not only for structural elements but also in the case of non-structural elements. Although replacing steel and concrete elements with mass timber can contribute to reducing GHG emissions too, a tradeoff must be considered given the potential increased costs and the added risk due to the lack of construction knowledge in this situation. When and how should mass timber be used for load-bearing elements? Should steel and concrete be used to complement mass timber in certain areas? What are the advantages and business case for tall buildings that use mass timber for all structural elements?

Tall mass timber buildings are buildings constructed of mass timber elements that exceed current height limits for wood buildings set by building codes. Mass timber includes any product currently permitted for use in heavy timber framing construction, Type IV construction, such as large panelized solid wood construction including cross laminated timber and glued-laminated timber, or large heavy section sawn timber or lumber (Busta, 2017; Grieve, 2018). According to Ontario's tall wood building reference (2017), tall mass timber buildings in North America are commonly classified as buildings that are greater than 6-storeys and built using mass timber.

The growing role of mass timber

The debate about mass timber versus concrete and steel structures should not be an existential one. Natural timber has less embodied energy in major parts of Canada and has a higher rate of renewal. Constructed timber can be economical and an energy-efficient alternative in almost all jurisdictions. Concrete and steel are increasingly becoming more sustainable given the advancement in recycling, the use of recycled additives, and the increased efficiency of the manufacturing processes. The debate should focus on how to complement one with the other to face the expected increased demand for both, the increasing prices for energy and the growing need to promote sustainable development.

Rationale for Using Timber

There are wide benefits that can be gained from using wood in construction of high-rise buildings. These benefits are related to building design and performance, economic benefits, quality of the internal environment as explained below:

Energy and environmental benefits: The lower embodied energy of buildings in turn reduces their GHG emissions and mitigates the effects of climate change (wood is the only option that can offer net zero or net negative greenhouse gas emissions). However, this can change significantly if wood is transported for long distances.

Technical and construction benefits:

- The relatively lighter weight of wood can make construction easier and faster as less equipment capacity will be needed. This means that the assembly of timber segments could be easier than steel structures.
- The easier fabrication process can promote off-site manufacturing with all its advantages including cost and schedule savings, enhanced safety, possible reduction in total energy usage, and reduction in site noise.
- The levels of accuracy in producing timber can be similar to those of concrete and steel. However, it has a significant advantage in case of misalignment or inaccurate manufacturing--these situations can be handled much easier in case of timber. Similarly, re-work or rehabilitation (after fire, for example) are much easier in timber than in the case of steel or concrete.
- The re-usability of timber through finding new usage for timber sections is important in case of design changes or in cases of re-configuring existing buildings.
- The constructability of mass timber due to the ability to easily attach mechanical and electrical fittings/systems with it (only simple/common tools are needed).
- The reduction of the weight of the superstructure reduces the size of foundations, which saves cost and allows building on slightly poorer soils.

Business Benefits: Increase occupant satisfaction with the unique aesthetics of natural wood making will increase the price they are willing to pay for it.

The Business Case

With the recent increase in mass timber use in new developments (particularly in Toronto), it is clear that customers are willing to pay more for such facilities. Such higher price points make mass timber structures feasible despite any additional costs. Such costs are slated to decrease, which will only enhance the business case. However, while users of commercial and institutional facilities may be open to mass timber structures, a segment of residential users may hesitate to occupy them due to perceived risk of fire. Educating the users and engaging them in design work and analysis is, therefore important to the business case.

Challenges in Using Timber

Despite the wide benefits offered by mass timber compared to traditional materials, there are challenges and barriers that limit their adoption (Ontario's Tall Wood Reference, 2017; Holt, 2017):

- Costs to early adopters may be higher as with any new technology. Government and subsidies/ industrial incentives can be one solution in this regard. A more sustainable solution is a sort of partnership between producers, manufactures and developers that can create a stable horizon for off-site manufacturing, which is the cornerstone to reducing mass timber costs.
- Required worker training. The majority of trades are familiar with wood construction in Division B Part 9 but not mass timber construction. With proper training and the use of virtual reality and smart segments (segments with RFID, for example), it is possible that the skill levels in traditional wood can be upgraded to that which is required for mass timber work.
- Scarcity of heavy timber off-site manufacturers in Ontario compared to steel and concrete and the high capital investments needed for starting new ones.
- Lack of testing data and explicit support in building codes for mass timber high-rise structures. In the short term, this can be the most significant challenge to using mass timber in high-rise structures.
- Concerns about differential shrinkage, progressive collapse, acoustic performance, earthquake performance and fire performance.
- Physiological factors regarding how some building users may feel unsafe in buildings with mass timber structures.

However, most of these challenges will be reduced eventually as more suppliers, building owners, designers and builders become familiar with the technology (Ontario's Tall Wood Reference, 2017).

The softer costs

The novelty of mass timber structures in Ontario can add additional costs on the short term. First, consulting engineers may charge more due to additional time required to study and manage code compliance. A dedicated fire engineer is a must for any successful development of mass timber structure. Additional fees must be paid to permitting agencies to process mass timber structures as code and regulations for such structure are not well developed--the onus is on the proponent (and the fire engineer) to prove to permitting agencies the safety of the structure. While it is expected that local labour can be as productive with mass timber (given the ease of its construction), some contractors may add a risk premium given the novelty of the system in Ontario. Finally, insurance premiums for construction sites and for the building are much higher (currently about 1000% of those of regular buildings). It is, however, expected that such premiums will come down with the spread of mass timber use.

Types of Timber Sections

The two most popular forms of timber framing are the light timber framing and heavy timber framing based on their section size. The section size of the timber members impacts the fire performance and the method of fire protection used for them (Ontario's Tall Wood Reference, 2017):

Light Timber Framing: Light frame construction is not intended for use in buildings over 6-storeys and it does not use mass timber *per se*. In this category, the section size is typically 2" × 4" [50 mm × 100 mm] or 2" × 6" [50 mm × 150 mm]. At this size, unprotected or exposed members provide little fire resistance. Therefore, for fire protection, these members are typically encapsulated for fire protection using non-combustible gypsum plasterboard (in addition to sound insulation and final surface finishes).

Heavy Timber Framing: These can be made of solid sawn timber or engineered derivative timber products. Such manufactured products can have higher strength and stiffness as knots and cracks can be eliminated during their manufacturing. They are used for beams and columns, with a minimum size of 6" × 6" [150 mm × 150 mm]. As for fire resistance, these members can rely on the formation of a charring layer that can stop the progress of fire to the core of the section.

Engineered mass timber products are formed of very dense solid panels of wood through laminations of different layers. These layers can be fixed together using adhesives and glue or non-glued approaches (Daniell, 2015). The most common mass timber products used are the glued laminations, which are described below and illustrated in Figure 5:

- Cross Laminated Timber (CLT): This is made from layers of solid wood set at 90 degree orientations with adhesives or fasteners.
- Glue Laminated Wood (Glulam): This is composed of wood laminations that are bonded together using durable, moisture-resistant adhesives.
- Laminated Veneer Lumber (LVL): This is made from thin laminations of wood similar to plywood but much larger in scale.
- Laminated Strand Lumber (LSL): This is made from a matrix of thin chips.
- Parallel Strand Lumber (PSL): This is made of thin strands of wood glued together under pressure.



Figure 5: Examples of Glued Mass Timber Laminated Products

(Adopted from: <https://www.cbi.eu/market-information/timber-products/cross-laminated-timber/europe/>)

Fire Safety for Timber High-Rise Buildings

Timber elements in high-rise wood buildings are assumed to increase the fire load, affect the fire growth rate, and potentially compromise fire protection systems in buildings, all of which could result in more severe conditions for occupants and fire fighters and increase the threat of damage to the property and adjacent properties (Su et al., 2018).

Fire Safety for High-Rise Buildings

In general, the risks of fire increase in high-rise buildings due to various factors including the higher potential for crowding and slow movement of occupants in exit stairs, the increased time taken by occupants to descend a stairway as the height of the building increases, the difficulty for the fire department to reach fires at elevated levels which results in delays in reaching stranded occupants and handling fire, etc. (Richardson, 2002). This indicates that special attention should be given in general to the fire performance of high-rise buildings regardless of combustibility of the structural and non-structural materials used.

Fire Safety of Timber High-Rise Buildings

Performance of Timber under Fire

The performance of timber under fire is different from that of concrete and steel. When timber is exposed to fire at temperature of approximately 572 °F [300 °C], its outer layer burns and turns into char. This charring layer acts as insulation and delays the heating of the layer below as shown in Figure 6. Continuing the exposure to fire leads to deepening the char layer, which in turn creates more

insulation, slows down the burning rate, and reduces the unheated cross section of the member. This behavior continues until the end of heating, or the section has completely combusted (White, 2004).

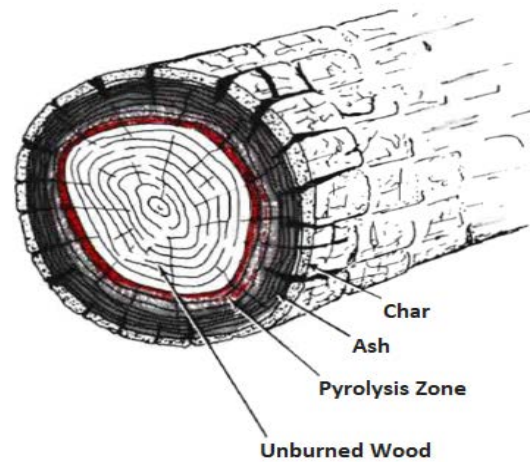


Figure 6: Zones of Burning Wood

(Adopted from: https://commons.wikimedia.org/wiki/File:Log_for_Heat_Conduction_and_Wildland_Fires_2010-08-17.png)

Charring rate refers to the rate at which the char layer propagates through timber. Through the charring rate and section size, the fire resistance time for a timber element can be calculated (Richardson, 2002). Accordingly, standardized charring rates are widely used in design to estimate the size of the remaining cross section that can still be structurally effective after a specified duration of exposure to standard fires (Yeh et al., 2012). Most standards assume constant charring rates on the order of 0.64mm/min for ISO fire exposure based on an average value obtained from tests on several timber species in a variety of conditions (Hall, 1968). However, charring rates of timber exposed to nonstandard heating are highly variable which means that charring rates used for design based on standard heating conditions may not be directly applicable to some non-standard fire scenarios (White, 2004; Bartlett et al., 2016). Of course, this fire resistance calculation is more applicable to heavy timber frame members (not light timber frame members) since charring is more a meaningful protector in larger section sizes.

Fire protection

Increasingly, and as the awareness and familiarity of mass timber grows, there is an acceptance of the use of charring as the main mechanism for fire insulation. Earlier buildings used gypsum boards to cover/insulate mass timber sections. In many cases, this defied a key rationale for mass timber structures: the architectural appeal (and higher price points). Post-fire repairs for charred timber has not been practiced, as there were no known incidents of major fires in built mass timber structures. Large scale tests resulted in very satisfactory outcomes. However, one major “fire-advantage” of mass timber, it seems that the rehabilitation of such structures, including replacing damaged sections, should not be more difficult or expensive than the case of fires in steel structures.

Procedures for Fire Safety of Timber High-Rise Buildings

The current building code requirements of the National or Provincial building codes do not directly address mass timber systems. Therefore, the combustibility of timber gives it a perception of being an increased fire hazard and the ambiguity of the code limits its use as a building material. However, following procedures to contain the spread of a fire would enable protecting the building structure and giving occupants enough time to exit the building, while allowing firefighters to prevent further property loss without the risk of building collapse (Ontario's Tall Wood Reference, 2017).

Most of the building height and area regulations in building codes are linked to the maximum height that a fireman and ladder could reach or the ability of the fire department's equipment to cover the building relative to water hose stream pressures. But with the use of automatic sprinkler protection, these building height considerations are no longer as important relative to fire fighting and fire safety within the building. Nevertheless, combined with modern fire suppression systems (automatic sprinkler systems, fire alarm and detection systems), there are two valid means of achieving reliable and safe structural performance for mass timber structures in fire: charring and encapsulation (Ontario's Tall Wood Reference, 2017; Hasburgh, 2016)

Charring Method: The ability of wood to form a char layer during combustion provides it with protection and fire resistance. In this case, the fire-resistance rating of large-sized members calculated based on minimum structural thicknesses and an additional thickness available for charring. Figure 7 shows the different zones of wood after being exposed to fire including a charring layer, a heated zone, and a cold zone which is not affected by the fire.

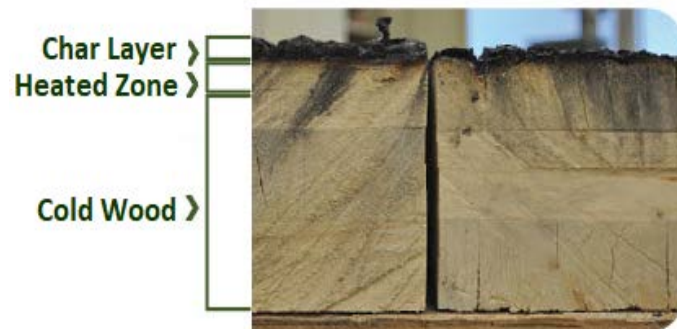


Figure 7: Charring Layer in Mass Timber

(Adopted from: <https://www.thinkwood.com/performance/fire-safety-and-protection>)

Encapsulation Method: This approach is based on providing full or partial protection of timber elements through using layers of fire-rated materials to the underside of floors, walls, columns, etc. This is the standard construction technique used to construct fire-rated floor, roof and wall assemblies in low-rise buildings as illustrated in Figure 8. Products used for encapsulation include type X gypsum board, mineral wool insulation, concrete, intumescent coating, rock fiber insulation, and spray applied

fire-resistant materials (SFRM) or other materials that can stay in place and prevent charring of the mass timber elements for specific duration when exposed to the standard fire resistance test exposure in CAN/ULC-S101 (Hasburgh et al., 2016).

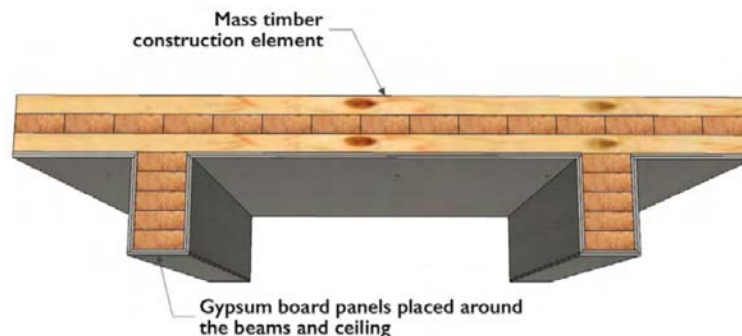


Figure 8: Complete encapsulation fastened directly to the wood elements

(Adopted from: <http://collections.banq.qc.ca/ark:/52327/bs2553717>)

Considerations of fire safety play a major role in the suitability of using mass timber in different building elements, as follows.

Exposed Timber: The use of exposed timber for ceilings and walls may be desired for aesthetical purposes and typically account for 50% to 75% of all surface finishes. However, the extensive use of exposed timber may have an impact that goes beyond the intrinsic attributes of timber—mainly increased burning rates and greater temperatures caused by having larger or connected exposed surfaces (Barber, 2015). For instance, although charring has been shown to offer significant resistance to fire, char fall-off has an effect on fire dynamics and may contribute to spreading the fire or increasing fire temperature. There is a gap in research regarding fire dynamics in mass timber structure beyond the standalone performance of the material (Barber & Gerard, 2015). Research done for Brock Commons project (a high-rise building in UBC) indicated that exposed wood structure would cost twice the cost of an encapsulated one. Exposed timber means exposed service lines, which may have an impact on the design and the overall feel of the building. In addition, exposed mass timber will require higher accuracies in manufacturing and more care in site handling (Acton, 2017).

Timber Panelized Structures: The performance of timber panelized structures in fire is similar to that of CLT panels. This is because panelized structures are effectively made up of a number of individual CLT panels that are quickly and easily assembled on site to form internal and external partitions. Despite the inherent fire resistance of heavy timber CLT panels, CLT elements are often required to be encapsulated by non-combustible gypsum board. This is intended to protect exposed CLT panels from heating and combustion and increase the fire resistance rating of the structural assembly.

Connections: There are different types of connections used in timber structures. Connections are mainly made of timber or steel and their protection against fire is a critical issue that needs close attention. Connections withstanding gravity loads on the structure are required to have a fire resistance rating not less than that required for the supported elements. Such connections should be concealed within the reduced cross-section of CLT elements or protected against exposure to fire (Su, 2018). The fire protection of connections differ based on their materials but in both cases sufficient protection is required to exposed, or unprotected, connector elements to maintain stability. The connection protection can be achieved using gypsum board encapsulation, embedding steel connectors in timber elements, applying fire-protecting or intumescent paint.

Treatment for Timber Members: The fire retardant treatment (FRT) is widely applied to decorative wood used in interior walls, hallways, or stairways. The FRT delays ignition, reduces the heat release rate and flammability, and slows the spread of flames when wood is exposed to fire. The FRT is generally believed to result in reducing the mechanical properties of wood and exposing metal fasteners to corrosion. Therefore, it is rarely used in structural members made of heavy timber (Mohammadi and Ling, 2017).

Wood Use Matrix:

WoodWorks, a program of the Canadian Wood Council, presents a user-friendly online matrix that summarizes the current best practices in the use of wood building materials for various building elements. This matrix demonstrates where engineered solutions may be necessary for approval. It shows where an engineered solution may be necessary, or where performance-based solution could be used². As illustrated in Figure 9, the Matrix uses a scale from 1 to 4 (consistent with the BC Building Code), which indicates where a wood section/type would be accepted under different conditions:

1. An acceptable solution with wood is permitted.
2. An alternate solution with wood is relatively easy to implement.
3. An alternate solution with wood will require advanced analysis.
4. An alternate solution with wood will require extensive research.

² Retrieved from: http://www.woodusematrix.com/resources/wood_matrix_database.php

BUILDING TYPE		Local Government Buildings									
* Click on these cells to view sample projects.		More Storeys	All	Small	Large	< 1,000 m ²	1,000+ m ²	Up to 6 Storeys	7 or More Storeys	Up To 4 Storeys	5 Storeys
Building Elements		Libraries	Transit Stations	Arenas/Pools	Fire Houses/First Response Centres	Community Housing (excl. Assisted Living)	Office and Buildings, City Police Station Lock-Up				
Primary Structural System	Columns, Beams & Braces	1 *	1 *	2 *	1 *	2	1 *	3	1 *		
	Floor Structure	1	2	2 *	1 *	2	1 *	3	1 *		
	Exterior Walls	1	1 *	2 *	1 *	2	1 *	3	1 *		
	Foundation (iv)	3	2	4	1	4	3	4	1		
	Shear Walls	1	1	2 *	1 *	2	1 *	3	1 *		
	Bearing Walls	1	1 *	2 *	1 *	2	1 *	3	1 *		
	Fire Walls	3	3	3	3	3	3	3	3		
	Roof Structure (inc. columns and braces)	1 *	1 *	1 *	1 *	1	1 *	3	1 *		
	Stairway & Elevator Shafts	1	1	2	1	2	1	3	1		
Secondary Structure	Convenience Stairs	2	1	2 *	1 *	2	1 *	2	1 *		
	Entrances & Canopies	2	1 *	2 *	1	2	1 *	2	1 *		
	Fire Separations	2	1	2	1	2	1	2	1		
	Enclosures for Mechanical										

Figure 9: Screenshot of the Wood Use Matrix

(Adopted from: http://www.woodusematrix.com/resources/wood_matrix_database.php)

Solid timber versus mixed material

In commercial and institutional buildings, the large beam spans will mean that mass timber beams will have to be much deeper. This may be avoided if steel is used. It is important that the developer and design team address the acceptability of mixed material versus pure timber structures. It is expected that such a problem may be limited in the case of residential buildings given the smaller spans and the growing tendency to increase floor heights.

Fire Safety-Related Testing and Costs

Managing fire safety for timber structures requires various understanding its performance through extensive testing which in turn incurs additional costs on buildings.

Testing Timber Components in Fire:

Testing of timber components is different for light and heavy assemblies. For light timber frame assemblies, the focus is on gypsum board protection for floor and wall assemblies. As for heavy timber assemblies, the focus is on engineered timber products, post-tensioned timber framing and CLT assemblies.

Carleton University in Ontario has been engaged in a significant body of research in both light timber and heavy timber buildings with two other research agencies: FPInnovations and the National Research Council (NRC) (CU, Fire Safety Engineering, 2013). Recent research is focused on fire

performance of CLT sections, as part of an initiative to promote tall timber construction (Karacabeyli & Lum, 2014). Common tests done on the fire performance and charring rates of mass timber products indicated the following:

- Fire performance and charring rates of glulam, LVL and SCL are similar to that of large, solid wood sections.
- For unloaded CLT, tests performed by FPInnovations in Canada using exposed CLT and CLT protected by gypsum board panels confirmed the existing charring rate values for CLT panels, and demonstrated that gypsum board protection delays the onset of charring and combustion for the protected CLT panels.
- For loaded CLT assemblies under protected and unprotected scenarios, results indicated that the greater the depth of the section, the greater the fire resistance.

According to the 2012 International Building Code (by the International Code Council--ICC), buildings over 11 stories (without automatic sprinkler systems) need to have a 3-h fire-resistance rating (ICC 2011). This requirement is increased to 4 h in NFPA 5000 (NFPA 2011a). These ratings were for non-combustible materials. The fire-resistance requirement for timber members for small or medium cross-sections is limited to 2 h (in the design method of the NDS). New adjustment factors for the allowable design stress for section reduction (because of fire) will need to be developed to meet the 3-h and 4-h fire rating required by the ICC and NFPA, respectively. The ratings may increase given that timber is combustible.

For timber members to provide 3- or 4-h fire resistance, they will need to be built with a relatively large cross section. This may cause an overcapacity issue in design and reduce usable areas, increase the total weight of the building, and add to transportation energy consumption and cost. For the purpose of reducing member size when it is designed for fire, investigations need to be done for innovative approaches—for example, investigating if a polymer or a high-performance (transparent) membrane could be used as insulation.

As part of Phase 2 of the Fire Protection Research Foundation (FPRF) project, six large CLT compartment fire tests were conducted to quantify the contribution of CLT building elements to the compartment fires. The fire tests were conducted without sprinklers and without firefighting intervention until the end of the tests. From the tests performed, the following points were concluded (Su et al., 2018):

- For CLT compartments fully protecting with gypsum board: the physical barrier was an effective means to delay and/or prevent the ignition and involvement of the timber structural elements in the fires, limiting and/or eliminating their contribution to the fires.

- For three-layer gypsum board system, complete prevention of the ignition and involvement of the CLT structural elements in the fire was achieved and the system performed as non-combustible structural systems.
- For two-layer gypsum board system, the CLT structure was successfully protected with limited impact of the fire on the CLT structure causing only surface char but no contribution to the compartment fire.
- For partially exposed CLT structure, it contributed to compartment fires to an extent depending on the area and orientation of exposed CLT surface and ventilation conditions.

Moreover, the CLT compartment fire tests produced a large amount of technical data, including the heat release rate, interior and exterior heat fluxes, gas and flow conditions, temperatures inside and outside the compartment, temperatures between gypsum board layers and inside the CLT structural panels, char depth, etc., under various exposure conditions. The tests also indicated that ventilation conditions have a large impact on the CLT contribution to the fires (Su et al., 2018). Therefore, the area of exposed CLT surfaces should be determined while considering potential ventilation conditions to limit the contribution to a fire (Su, 2018).

Fire Costs (Relative to Conventional Construction)

The costs associated with fire in tall timber structures are not well studied. There are, for sure, potential added fire-related costs for combustible tall structures compared to non-combustible ones. These costs can stem from developing fire protection strategies or the rehabilitation costs in case of fire occurrences as explained below (Gerard et al., 2013).

A. Fire Protection Costs:

Building and fire codes require tall buildings to have fire proofing, automatic fire suppression systems, and automatic fire alarm systems. This makes the estimation of fire protection costs for tall timber buildings challenging given the limited number of examples and the uncertainty associated with the fire protection design. Fire protection strategies could range from full encapsulation of timber elements, to exposed timber elements with significant fire resistance.

B. Post-Fire Rehabilitation:

Post-fire rehabilitation efforts for strengthening or reinforcing members in an existing building can be very costly. In timber structures, post-fire rehabilitation costs often include both structural and non-structural elements as follows:

- Structural elements exposed to high temperatures may require inspection, and replacement or strengthening before occupation is allowed

- Non-structural elements may suffer smoke and fire damage, at significant cost to repair or replace.

Moreover, the time and extent of repair may impact the business continuity. The more extensive the rehabilitation, the greater the likely impact on business operations and continuity. However, post-fire rehabilitation may be one of the main advantages of timber structure. It is much cheaper and faster to rehabilitate these structures compared to steel or concrete structures.

Ontario Code and Regulations

The regulation of building construction in Ontario is a provincial responsibility. Enforcement of the provincial codes is typically undertaken by municipalities and the respective Chief Building Official (CBO). The model National Building Code of Canada (NBCC) is developed under the direction of the Canadian Commission on Building and Fire Codes as one of five national model codes. In Ontario, a majority of the model NBCC is adopted along with other Ontario-specific changes and is published as Ontario's Building Code (OBC). Similar to the NBCC, Ontario's Building Code is comprised of three divisions: Division A, "Compliance, Objectives and Functional Statements;" Division B, "Acceptable Solutions;" and Division C, "Administrative Provisions."

Compliance with OBC can be demonstrated in one of two ways:

- Complying with the acceptable (specified) solutions outlined in Division B.
- Using an alternative solution that achieves at least the same level of performance as required by the acceptable solutions outlined in Division B of OBC.

Acceptable and Alternative Solutions under Ontario's Building Code (OBC)

Provincial building codes in Ontario still do not present specific acceptable solutions for tall wood buildings. This makes the submission of alternative solutions a requirement for permitting tall wood buildings in Ontario. Alternative solutions typically include additional engineering analysis by a fire safety engineer to demonstrate fire safety performance and testing (or results from relevant testing). The analysis and testing are then proposed to building officials and the Authority Having Jurisdiction (AHJ) for approval on a project-by-project basis.

The level of performance required for alternative solutions is based on the acceptable solutions in Division B of OBC. Any building greater than 6-storeys in height is required by OBC to have sprinkler system in accordance with NFPA 13, "Standard for the Installation of Sprinkler Systems" (NFPA, 2013). In buildings of 7 stories or more, Division B of OBC (Acceptable Solutions) requires floors to have fire separations with a fire-resistance rating of not less than 2 hours. Load-bearing walls, columns, and beams that support the floor assemblies must also have a fire-resistance rating of 2 hours. Therefore, an alternative solution for tall wood buildings will likely require the mass timber structure

to have at least a 2-hour fire resistance rating (Ontario's Tall Wood Reference, 2017). However, because timber is combustible, the requirements will always be longer than 2 hours.

FPInnovations has published a technical guide for the design of tall wood buildings. It gives recent examples of heavy timber construction in Canada, with useful sections on the fire resistance and a summary of fire risk assessment methods. The guide promotes “complete encapsulation” of wood to provide fire safety equivalent to non-combustible steel or concrete construction (Östman et al., 2017). However, increasingly, charring of exposed timber is being used as the main insulation mechanism.

Also, Ontario Tall Wood Building Reference is a technical resource for assisting architects, engineers, builders, and developers in developing alternative solutions for tall wood projects with mass timber under Ontario's Building Code and to help facilitate the approval by a Chief Building Official (CBO) under Ontario's Building Code (OBC) (O. Reg. 332/12, Div. A Section 1.2.). The primary focus in this technical resource is on structural and fire safety requirements “site-specific regulations”.

Several of the case projects analyzed in this report used a two stage reporting process of Fire Engineering Brief (FEB) and a Fire Engineering Report (FER). This process involves relevant stakeholders as the design team, client and building certifier, and may include the fire brigade, local council, insurer and other interested parties. The *Fire Engineering Brief* communicates to the relevant stakeholders and approval authorities the objectives and basic strategy by which the fire safety engineering analysis will be conducted and outlines the proposed alternative solutions. The *Fire Engineering Report* details the formulation and analysis of the fire safety design solutions against the fire safety objectives developed in the Fire Engineering Brief process. It contains all required calculations, analysis of test evidence and fire modeling to support the recommendations for the formulated fire safety design solution for the building.

Permitting agencies

The cities of Vancouver and Toronto have taken very progressive steps to support expediting the permit process for mass timber structures. In Toronto, a special committee has been overseeing the approvals--especially in relation to fire insulation. Such committee can play a major role in documenting and sharing innovative solutions and best practices as well as setting a supportive research and educational/training agenda.

Contracting Challenges

The relative newness of the use of mass timber for high-rise buildings and the limited experience in designing, constructing and operating such structures impose challenges and complexities that hinder their wide adoption. The issues do not only come from the construction process itself, but also from the

complexity of the pre-construction stages with its high level of uncertainty whether in the design, bidding, planning, procurement, permits, etc. Moreover, there are some systematic problems with traditional project delivery approaches that do not suit the required flexibility of mass timber high-rise buildings. Traditional delivery approaches limit cooperation and innovation since agreements tend to specify in details what the stakeholders were to provide and how to provide them.

Dealing with these issues requires close management and detailed strategies specially through using well-fitted contractual agreements. It is proposed that the key to solving some of the problems accompanying mass timber structures is to change the mindset of project participants to allow for more innovation while reducing risks as possible. This cannot be achieved through the traditional contractual agreements, instead other partnering approaches such as the Integrated Project Delivery (IPD) approach can be used.

Integrated Project Delivery (IPD)

IPD is a collaborative process where all project teams are integrated from early stages of the design throughout the whole project life cycle. This ensures that overall design decisions meet the needs of the owner, achieve project goals, and are achievable by the project team. IPD has unique characteristics that differentiate it from the traditional delivery method such as multi-party contract, early involvement of key participants, collaborative decision making and control, shared risks and rewards, liability waivers among key participants, and jointly developed project goals.

IPD approach is adaptable to the continuously changing conditions. It focuses on choosing the right people, implementing the right processes, and using an efficient and reliable organizational structure in order to influence the project success (Ashcraft, 2014). Since the most important feature in IPD projects is collaboration, IPD contract is created through simultaneous contract negotiation workshops that are held between the project parties (Fischer et al., 2017). Negotiations begin with an open discussion in which the parties discuss and document their goals, concerns, interests, success metrics, etc. The selection of the parties involved in the contract negotiations differs from one project to another. But in all cases the parties that will sign the agreement, upon which the negotiations are made, should participate (Fischer et al., 2017). There are different standard form agreements that are currently available, all forms of agreement explain the following (Dal Gallo et al., 2009):

- Decision making process
- Setting of project target cost
- Setting the structure for project compensation and incentives
- Addressing changes in the work and contingencies
- Allocating risks, including insurance, indemnity, and limitation of liability

- Having access to project documents and records
- Resolving disputes

Dal Gallo et al. (2009) specified the common responsibilities of the parties under IPD agreements which include:

- The Owner, A/E and the contractor must collaborate throughout the project life cycle. They should work together for setting project goals from early project stage.
- The A/E and the contractor together create a single design approach/model to be used for the whole project.
- All project participants are required to share knowledge and information, make decision in collective manner, communicate with each other to proactively and jointly manage risks.

Supply Chain Challenges

One of the most important partner in mass timber structures at this stage is manufacturing facilities. With the limited number of facilities existing and the absence of sustained demand, this part of the supply chain will remain the most important and the largest contributor to costs. Developers of mass timber structures (especially large ones such as Sidewalk Labs) must establish a healthy and business-based partnership with manufacturers. This is needed to not only create economics for such industry, but also to set the standards for this (evolving) industry, particularly the sustainability standards: how to promote mass timber as a means for wood re-use, how to plan and measure the impact of this sector on sustainability of forests, how to integrate environmental and social costs in the financial models, and how to share best practices across the sector.

The use of BIM can be very helpful to modularization as it helps streamline planning, design, shop drawings development, manufacturing and construction process. Physical conflicts between the structure, mechanical, electrical and plumbing systems can be easily identified early in the design process (Lu & Korman 2010). In one project, it helped detect 590 conflicts saving an estimated \$200,000 of budget and avoiding months of potential delays (Azhar et al. (2008). El-Asmar (2013) showed that the level of project waste (in material) is negatively related to increased use of BIM. Further, Ruiz et al. (2009) found that the majority of professionals surveyed agree that BIM can improve productivity (75.2%), schedule (83.2%), cost (84.2%), and quality (88.1%). Around 41% of the respondents realized an increase in overall project profitability and 58% found that overall project duration was reduced (Becerik-Gerber and Rice 2010). In two case studies, Giel and Issa (2009) found that ROI on the use of BIM was over 16.2%, with much higher rates claimed by researchers (Azhar 2011). However, limited work has been done for integrating analysis of modularity in BIM (Becerik-Gerber and Rice 2010).

Through enabling rule-based modelling, BIM allow for using the “computer as an agent” for analyzing and coordinating the processes of design modularization (Singh et al. 2015). Areas where BIM can be instrumental in supporting modular construction (especially in pre-cast concrete systems) include the following (Ramaji et al. 2014):

- Clash detection among different disciplines.
- Precast fabrication, where the boundaries of the precast parts and the hollow cores can be analyzed.
- Production and delivery sequencing through 4D modeling systems.

New Horizons in Building Technology and Modularity

Mass timber structures offer new means for flexibility and innovation. The nexus between them and smart buildings opens the doors for new horizons in the design and operations of buildings. Some of these are listed below.

Adaptability: increasingly, developers are interested in enabling users to change the layout of their facilities (the concept of Stoa). This means that the building components must be “modular” to different contexts. It also means that the users/builders of modular components are not only contractors, but also operators and even facility users. For example, it is expected that new (unplanned) usage cases will evolve—for example, what will happen when automated vehicles are deployed? How can we embed in the modular components the means to upgrade them, or use parts of them into new components? In other words, can we design several metamorphoses for modular components?

Finally, still, a main challenge is that the building should be designed to fit people’s needs and activities. How can we design modular components, yet generate customizable layouts?

Scalability and economies of scale: how do different policies for modularization scale? This is not just in relation to the ability to mass produce these units. We should also look into the waste associated with modularization. For sake of standardization to generic use, overdoing modularity can result in time and material wasting. In some cases, to make a component modular, designers lump several functional items into it—this can lead to situations where the components of a module are over-designed or are unneeded.

Advances in technology: how does modularity fit into the new opportunities in construction and operation planning? For example, how can we design components that can be ready for 3D printing?

Conclusions (Summary of Risks and Actions)

There are various risks associated with the use of mass timber for high-rise buildings. These risks can be attributed to the relative newness of these materials, the limited experience of contractors with this type of buildings, and lack of clear regulations. These risks can be classified into three main categories: technical, project management, and business management risks. Each of these risks and the actions required to deal with them are illustrated below and summarized in Table 1.

Technical Risks

The use of mass timber is not well-studied or covered in the research, but there are signs of its wide benefits despite the various risks involved. The main technical risks arising from the use of mass timber in high-rise buildings are due to the combustibility and code compliance.

Fire Protection: The extent to which mass timber is used for structural parts and non-structural parts of the high-rise buildings affects the fire rating of these buildings. Based on the members used, different fire protection procedures are used as explained in Subsection 2.6.2. However, this makes obtaining permits a lengthy process (see Subsection 2.7.2).

Fire Tests: Using well-designed and long-term pre and post construction testing scheme is crucial for reaching the required level of fire safety especially for the structural members in the building. For non-structural parts, they still must be analyzed to study their impact on fire dynamics and propagation. To address this risk, it is important to engage a fire engineer, the fire departments as well as permitting authorities. On the long run, establishing a relationship with researchers and manufacturing can help in discovering new means to enhance fire resiliency.

Fire Recovery: The post-fire rehabilitation process of mass timber high-rise buildings requires extensive assessment of the structural condition of the buildings to determine the members that would require repair or replacement, if any.

Collaborative management

Sustained and effective communication and collaboration between all parties is the most crucial aspect for the success of mass timber structures. The contribution of the fire engineer in advising and guiding the architectural and engineering designs cannot be over emphasized. The role of fire engineer in establishing an evidence-based early engagement process with permitting agencies is equally important. Engagement of users, insurance providers and contractors are also essential.

Project Management Risks

The project management-related risks arise from the lack of design, construction and operation knowledge for this type of structure. This will have significant impacts on costs and the nature of contract/relationship between stakeholders.

Construction Experience: The risks associated with the limited construction experience can be addressed though performing adequate pre-project planning. The analysis should include commissioning a formalized constructability analysis by experienced contractors, learning from cases and engaging all stakeholders early on. A formalized assessment of design and construction scope should be conducted using relevant tools, such as the project definition rating index (PDRI).

BIM and VR: The use of Building Information Modeling (BIM) and Virtual Reality (VR) from the early stages of the design enhances the flow of information and promotes sharing knowledge. Collaboration between stakeholders is important for identifying risks and analyzing the constructability of the building. In addition, they allow planning the various construction stages to a high level of detail early on, which reduces the uncertainty associated with the new techniques.

Contracting Issues: The risks associated with these buildings need to be incorporated in the contractual agreement between the different stakeholders. With the too many unknowns and risks, the traditional project delivery systems may not be suitable. Partnering and/or IPD approaches should be considered as explained in Section 3.

Price of Reliability: On average, timber structure will require a simpler construction technology with less power and, hence, lower chances of major risks. It is also typically easier to handle errors and re-work in the case of mass timber. The post-fire recovery and repair work is also easier and less costly with timber structures. These considerations can make timber construction (once widely practices) more reliable.

LEED Points: The LEED points gained from using timber allows for relaxing the specifications and requirement of other systems in relation to energy/environmental which reduces the overall costs of other systems.

Business resiliency and innovation

From a business perspective, the use of timber offers the opportunity to venture into new and innovative areas. Accordingly, the use of timber fits with the new mindsets of organizations with their changing decision criteria to cover different aspects and not only economical aspects. This enables organizations to think and build out of the box. Organizations willing to participate in the innovative approaches accompanying mass timber need to go beyond the technology. Mass timber construction is about change management and organizational abilities than the engineering aspects. Taking on

building with mass timber in high-rise, is a chance to study and reengineer organizational decision making and drive lessons learned.

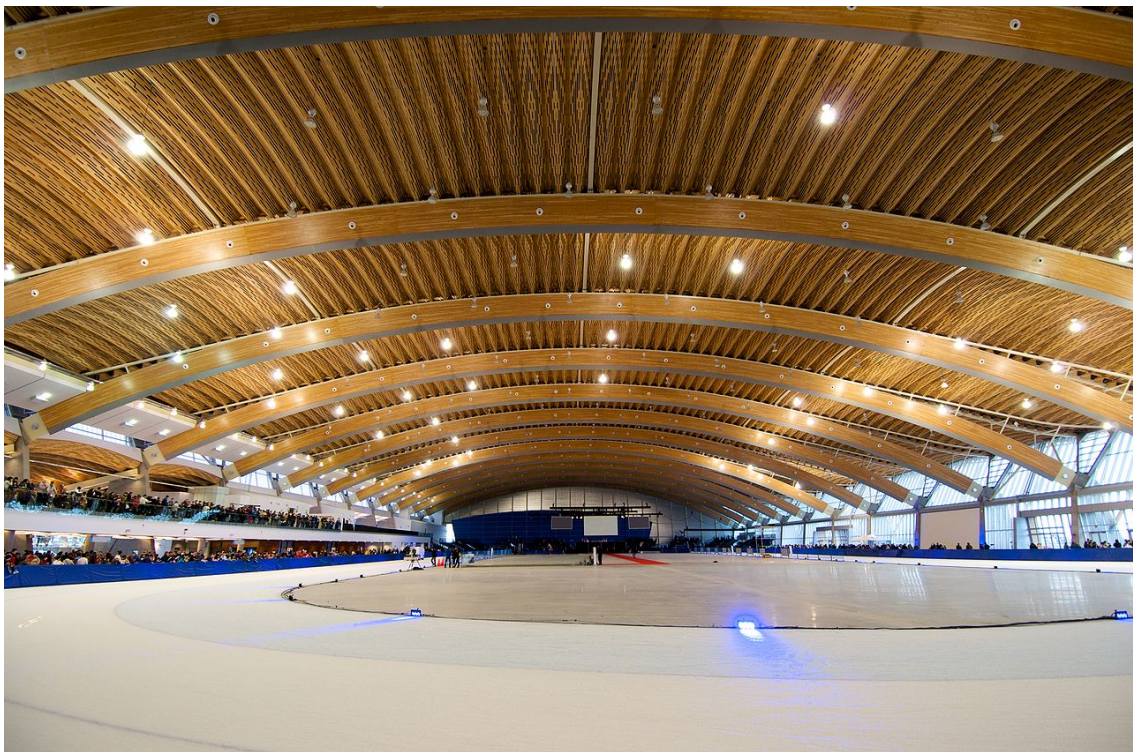
Moreover, as the role of customers views on sustainability progress, the visual appeal of mass timber will not be the only selling point or condition. It is very plausible that the environmental requirements, urban complexity and shortage of skilled labor, will make prefabrication and manufacturing of buildings (all buildings) the main stream approach. In this regard, it is very possible that timber systems will be superior: 1) they are easier to pre-manufacture, 2) they need less equipment capacity on and off site—especially in comparison to pre-cast concrete. So, the decision to experiment with timber construction can/should be part of any strategic look for construction practices. You cannot just evaluate it based on today's conditions. Knowing the imminent changes, leading companies must venture into innovating the future of mass timber.

Global and long term impacts. It is never too early to consider the long term possible impacts of widespread use of mass timber. Currently, it is cheaper to buy mass timber from Europe. If demand increases, then a China entry to this market must be proactively managed in a sustainable manner. Increased attention should be considered to certifying mass timber sections--especially those exported by developing countries. One of the most effective steps in this regard is to invest in manufacturing technology to make “constructed sections” cheaper than natural ones. Formalizing the energy costs and increasing awareness of such concept can also be very helpful.

Table 1: Summary of Risks and Actions

	Issues	Risks	Actions
Project Management Aspects	Relative newness and limited experience of designers contractors, labour.	The main opportunities that mass timber offers regarding the time and cost savings might not be achieved.	These risks can be addressed though performing extensive analysis that includes commissioning a formalized constructability analysis by experienced contractors, learning from cases and engaging all stakeholders early on. BIM and VR. They can be used from early design stages to identify the issues, analyze the constructability of the buildings, and to allow planning the various construction stages to a high level of detail reducing the uncertainty associated with the new techniques.
	Contracting issues due to the increased risks associated with these buildings	The use of traditional contracting approaches for these buildings limit the degree of innovation of participants given the increased risks. In addition, the occurrence of conflicts or disputes among the project participants might be very common under the uncertainties available	Partnering and/or IPD approaches should be considered instead of the traditional agreements. IPD enables participants to collaborate from the early stages of the project and provides an environment of planned negotiations and amicable settlements that offer high degree of flexibility.
Technical Aspects	Combustibility of timber and the absence of available regulations in building codes for timber high-rise buildings	The fire resistance rating of the building may not satisfy the acceptable levels of the code set for concrete or steel structures. This prevents buildings from getting the needed permits and approvals.	Fire Protection. The use of proper fire protection procedures either through using large cross-sections of timber members which provide safety through charring effect, or through encapsulation using different types of gypsum board depending on the members used Fire Test.: Using well-designed and long-term pre and post construction testing scheme for reaching the required level of fire safety especially for the mass structural parts in the building. This can be achieved by engaging permitting agencies and fire departments as well as researchers. For non-structural parts, while used on mass scale in Canada, they must be analyzed in the context of their impact on fire as part of a high-rise.
		The damage of the timber members in case of fire.	Fire Recover. Post-fire rehabilitation of the mass timber elements can be performed through extensive assessment of the structural condition of the elements and members that would require repair or replacement can be easily fixed.
	Exposing timber members to contribute to the indoor aesthetics.	Since timber is a combustible material, exposed timber members may contribute to the fire in case it occurs. This reduces the buildings' fire resistance rating.	Timber members will have to be encapsulated to provide the needed fire safety. However, search for alternative encapsulating materials (eg. Fiber glass) can be done to replace the commonly used gypsum board layers with other transparent materials that provide the needed fire safety.
Business resiliency and innovation aspects	The resilience of the organization and its innovation capacity	Current organizations and practitioners might fail to participate in the innovative approaches accompanying mass timber	Organizations need to go beyond the technology, change their management strategies and management capacity, and start to think and build out of the box. Organizations can then test their ability to deal with new ideas and develop new markets. Study organizational decision making and communication patterns and drive lessons learned.

SECTION III: INTERVIEWS AND CASE STUDIES



This section summarizes relevant case studies in the use of timber in high-rise buildings. The case studies include information about projects found online. For few of these, additional information and analysis are provided. In addition, two Canadian case studies were developed and are summarized in this section.

Online Project Cases

Through online search, examples of high-rise timber buildings were explored to study the range of possible features. Table 2 summarizes details of these projects including their location, year of completion, height and number of stories, structural system, and fire safety procedures.

Table 2: Summary of Details for the Online Project Cases

Building	Type	Location	Height, # stories	Structural System
Wood Innovation Ctr		British Columbia, 2014	96 ft 8	CLT as the elevator/stair core and floor diaphragm of the building. The gravity system consists of Glulam beams and columns
Albina Yard	Office	North Portland, Oregon, 2016	4	Glulam frame and CLT panels CLT as a structural diaphragm incorporated into a glulam frame.
Carbon 12	Commercial	Portland Oregon	85 ft, 8	Steel brace frame core, surrounded by a timber and CLT structure.
The Hines T3 Project	Office	Minneapolis MN, 2016	80 ft, 7	Nail laminated timber panels for floors with concrete overlay for acoustics. One concrete story, 6 wood stories; concrete elevator core.
Candlewood Suites Hotel	Hotel	Huntsville AL, 2015	4	CLT for exterior walls, parapet walls, interior walls, elevated floor slabs and roof deck. Glulam columns and beams for structure.
Origine Building*	Multi-Residential	Quebec City, Quebec, 2017	40.9 m, 13	
Brock Commons	Student Housing	Vancouver BC, 2017	174 ft/53 m; 18	Wood-concrete hybrid. For gravity loads, CLT floor panels as two-way slabs supported on a glulam column grid. Columns transfer axial loads via steel bearing connection. Concrete core for lateral loads.
Integrated Design Ctr		University of Massachusetts		CLT with glulam zipper trusses.
The Radiator	Office / Commercial	Portland, Oregon, 2015	5	Loads handled through a system of glulam beams and columns. Structural floor diaphragm, mass timber deck with wood structural panels. Dimension lumber walls sheathed with wood structural panels provide shear capacity. Exposed beams, columns, and the underside of the floor decking.
T3	Office	Minneapolis, MN, 2016	7	Glulam columns and beams, NLT floors, and a concrete core.
Chicago Horizon	Public Pavilion	Chicago		CLT roof supported on glulam columns. Exposed CLT
Common Ground High School	Education	New Haven, Connecticut, 2016		CLT panels provide the tension surface. Vertical CLT panels form bearing and shear walls throughout the building while glulam rafters and heavy timber trusses span a large ground floor multi-purpose space. A treated glulam bridge deck on laminated timber piers provides access from the upper campus.
Forte*	Residential	Australia, 2012	10	

*These projects are further detailed in the report.

Origine, Quebec City

Origine is a multi-residential building in Quebec city, comprised of 13 stories (12 wood + 1 concrete, including underground parking) with a height of 40 m. The project designers opted for a hybrid solution for fire resistance. They sized the wood elements for one hour of fire resistance and protected them with Type X gypsum board to increase the time it takes for CLT to catch fire and consequently limits CLT's contribution to the growth and intensity of a fire over this period. Gypsum increases the fire resistance of the assembly by one hour; the wood and gypsum combined provide the two hours of resistance required. Fire resistance is achieved through fire separation walls that work to prevent flames and smoke from spreading. In general, these walls must also provide insulation to limit temperature increases on both sides of the separation. Depending on where they are in the building, the Code requires fire separation walls to be fire resistant for one to two hours.

Engineers carried out tests at Intertek's laboratories to verify the calculations. The test results proved their solutions met the Code's fire safety objectives. Further tests were performed on a wall and a floor in accordance with Standard CAN/ULC-S101. Both tests were conclusive. The wall resisted for 3 hours 39 minutes and the floor resisted for 2 hours 8 minutes. The wall consisted of a 5-layer (175 mm, 67/8 in) CLT panel protected by two 16 mm (5/8 in) Type X gypsum boards on either side. The floor was made up of a 5-layer CLT panel covered in glass wool and a 16 mm (5/8 in) Type X gypsum board on the side exposed to the fire.

Forte Living Building, Melbourne Australia

Forte Living building is an apartment building in Melbourne, Australia. It is comprised of 10 stories with a height of 32.2 m built up of CLT panels. The use of CLT does not comply with the non-combustible Deemed-to-satisfy (DtS) provisions of the National Construction Code (NCC) which requires that external walls are to be constructed from non-combustible materials, and load bearing internal walls are designed to achieve a fire rating or to be constructed from concrete or masonry.

Fire resistance was achieved through direct fixing of fire grade plasterboard combined with the charring of the timber ensuring that the structural component is protected through the provision of sacrificial layers. Each CLT panel is typically, 5 layer 128 mm thick used for the walls and 5 layer 148mm thick CLT panels for the floors. Structurally, only 3 layers are required providing 2 layers of additional protection from the sacrificial layers of timber.

As for the connections of the wall panels to floor panels maintain the appropriate fire ratings through being incorporated within the center layer of the panel or through being covered by screed / fire grade plasterboard. The fire isolated stair shaft and lift shaft protection have been achieved through the design of a double shaft system in which each shaft achieves the required fire rating however do not rely on the other for structural connection.

Case Study #1: The University of British Columbia Brock Commons Project

Background

Brock Commons Tallwood House is a student residence recently completed at the University of British Columbia (UBC) in Vancouver (see Figure 10). The 18 story building was opened in July 2017 and was built at a height of 174 ft (53m). It is considered as one of the tallest buildings with timber structure in the world.



Figure 10: Brock Commons Building after Completion

(Adopted from: <http://vancouver.housing.ubc.ca/residences/brock-commons/>)

The project team was formed of:

- Developer: University of British Columbia
- Owner's Representative: University's Infrastructure Development department
- Project Manager: UBC Properties Trust
- Architect: Acton Ostry Architects Inc.
- Structural Design: Fast + Epp
- Engineering: Urban One Builders, Seagate Structures and Structurlam Products Ltd.
- Tall Wood Advisor: Architekten Hermann Kaufmann ZT GmbH

Rationale for Using Prefabrication

The owner and the project team wanted to use prefabrication as much as possible due to its numerous advantages, such as increased accuracy and productivity in a controlled factory environment, reduced on-site construction time, and fast enclosure of the mass-timber structure.

Building Structural Design

Facts:

- Height: 53 m (18 storeys)
- Site area: 2,315 m²
- Gross areas: 15,120 m²
- Footprint: about 15×56 m (total: 840 m²)
- Typical floor-to-floor height: 2.81 m for the mass-timber structure on the upper floors, and 5 m on the ground floor

The structure is a mass-timber and concrete hybrid as follows:

Concrete Components: The foundation, ground floor, second-floor slab, and stair/elevator cores were designed as reinforced cast-in-place concrete elements. This helped streamline the structural design and reduce costs, while simplifying the complicated permitting and approval processes. The second-floor slab was designed to act as a transfer slab, which transfers the gravity load from the upper-level mass-timber structure to the lower-level concrete structure. While the cast-in-place reinforced concrete cores provide the building with the necessary rigidity to resist wind and seismic lateral forces.

Mass Timber Components: The superstructure was designed to be composed of prefabricated cross-laminated timber (CLT) panel floor assemblies supported on glue-laminated timber (GLT) and parallel strand lumber (PSL) columns with steel connections. Each mass timber component was to be assigned a unique identifier for quality-assurance and quality-control tracking and on-site measurement of the structural system assembly heights.

Building Envelope, Interiors and Building Systems: The building envelope was made of prefabricated, steel-stud frame panels with a wood-fiber laminate cladding, and a traditional SBS (styrene-butadiene-styrene) roof assembly on metal decking. As for the interior partitions, they were made of conventional steel stud and gypsum board.

Figure 11 illustrates the structural design for the Brock Commons building with its main structural components of the concrete and mass timber.

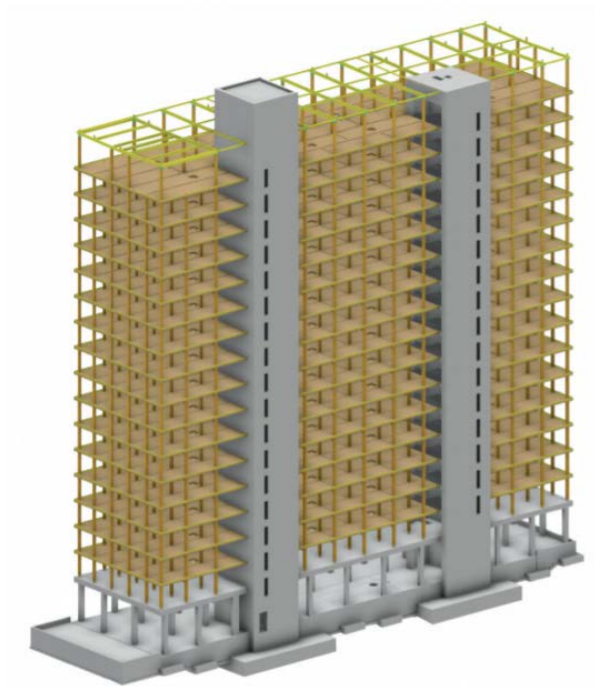


Figure 11: Main Structural System for Building (CIRS, 2016)

Fire Management Plan

Given the noncompliance with the BCBC (British Columbia Building Code) regarding building height, non-combustible materials and the fire resistance rating required for structural assemblies, the project had to provide a performance based approach and prove that the proposed solution achieves regulatory requirements of Division B, Part 3 of the 2012 BCBC.

Fire protection was provided by full encapsulation of the mass timber using three and four layers of gypsum wall board (GWB) rather than relying on charring of the timbers. Fire testing was conducted in laboratories for different assemblies. The concrete shafts posed no concern for the building officials. The alternative design was approved in British Columbia using a site specific regulation.

The fire-management plan during construction relied heavily on Type X gypsum board, which was installed below the CLT panels for fire protection. However, the encapsulation speed held back the installation of mass timber. This led to the revision of the management plan with the permission of the authorities to allow up to six floors of wood structure without immediate gypsum board encapsulation. Thus, mass-timber columns were encapsulated concurrently with the ceiling encapsulation of each floor while additional layers of gypsum board were added during the interior work.

Building Construction

The schedule for this project was tight with design and approvals taking 8 months, and construction taking 18 months. On-site construction was broadly divided into three phases: concrete, mass-timber structure and building envelope, and interiors and building systems.

Concrete Work: Concrete work was scheduled during the winter months and was completed entirely before the rest of the building (The concrete foundation, levels 1 and 2, and the two concrete cores were completed in 7 months). The mass-timber structure work took place during the spring and summer. This approach simplified the scheduling and use of the project's single crane, and minimized congestion of crews and materials on the narrow site. Figure 12 shows the concrete components after being cast-in-site.



Figure 12: On-site Concrete Components

(Adopted from: https://seagatestructures.com/wp-content/uploads/2017/04/brock_commons_-_construction_overview.pdf)

Mass Timber Structure: The mass-timber structural components and the envelope panels were prefabricated concurrently with the completion of the concrete work by separate manufacturers over a 3-month period. Erection of the mass-timber CLT panels and GLT/PSL columns and installation of the building envelope panels took about 3 months. Figure 13 illustrates the mass timber columns and floors as after being in placed in site.

The average speed of the mass-timber erection and envelope installation was two floors per week. This included the erection of the columns and CLT panels, encapsulation of the wood components with a single layer of gypsum board, the pouring of a concrete topping, and installation of all but one of the

envelope panels which was left to provide an easy entry point for the delivery of interior materials and components till the end of construction.

Construction productivity analysis showed a consistent increase in the net crew productivity, which confirmed the learning curve effect--as follows:

- The net crew productivity related to the CLT panels increased from 8.9 m² per labor-hour at floor 3 to 29.2 m² per labor-hour at floor 14.
- The net crew productivity related to the envelope panels increased from 6.84 m² per labor-hour at floor 3 to 15.59 m² per labor-hour at floor 15.

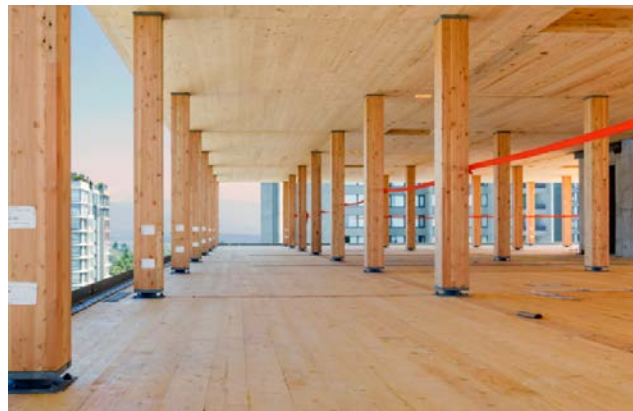


Figure 13: On-site Mass Timber Elements

(Adopted from: https://seagatesttructures.com/wp-content/uploads/2017/04/brock_commons_-_construction_overview.pdf)

Figure 14 shows the progress in the execution of the mass timber components as well as the building envelope through 6 weeks of the project's execution. The figure illustrates how the use of prefabricated elements enabled fast erection and progress on site.



Figure 14: Progress across Six Weeks for Mass Wood and Envelope

(Adopted from: <https://www.designboom.com/architecture/wooden-skyscrapers-timber-tower-construction-roundup-07-31-2016/>)

Building Envelope, Interiors and Building Systems: Work on the interiors, finishes, and building systems took about 10 months, at an average of about 65 working days (13 weeks) per floor, with crews working concurrently on multiple floors. The VDC model was used to create a detailed bill of materials that included the exact dimensions and sizes for systems and interior components allowing for more of the MEP work to be completed off site. Figure 15 shows the prefabricated panel of the envelope as it is being placed on site.



Figure 15: On-site Prefabricated Envelope Erection

(Adopted from: <https://www.archdaily.com/879625/inside-vancouvers-brock-commons-the-worlds-tallest-timber-structured-building>)

The envelope is a combination of a curtain wall system (ground level) and prefabricated panel system (levels 2 through 18), with a conventional built-up roof system of metal decking supported by steel beams. A prefabricated envelope system was used to allow each level to be rapidly enclosed as the wood structure is erected, thus providing protection from rain as well as reducing risk of damages.

Different envelope options were explored which are: 1) Curtain wall system with large insulated spandrel pieces and glazing; 2) Pre-cast carbon fiber reinforced concrete insulated sandwich panel with pre-installed windows; 3) Wood frame stud systems with pre-installed windows; and 4) Structural steel stud system with preinstalled windows (the selected option). The decision was based on cost, weight, ease of installation and overall performance including noncombustible construction.

Mock-Up

As part of the preconstruction phase a full-scale mock-up of a section of the building was built to test and validate a variety of the design solutions, to determine constructability and appropriate sequencing, and to inform the manufacturing and installation schedules and trade coordination. The mock-up allowed the project team to identify challenges and improvement opportunities in advance of the actual construction (see Figure 16a). In addition to the structural mock-up, the envelope manufacturer

conducted laboratory tests on a full-scale, 2-storey, corner-panel mock-up (see Figure 16b). These tests, which included structural (wind and design loads), thermal cycling, thermal performance, condensation, and air and water tightness, were required to get the envelope consultant's approval, prior to the final fabrication.



a. Mass Wood Structural Mockup

(Adopted from: <https://www.canadianarchitect.com/architecture/worlds-tallest-timber-tower/1003734324/>)



b. Envelope Mockup

(Adopted from: https://seagatestructures.com/wp-content/uploads/2017/04/brock_commons_-_construction_overview.pdf)

Figure 16: Mockups for Building Components

Virtual Design and Construction (VDC)

The project team used an integrated design process enhanced by the use of VDC modeling. The VDC modelers acted as facilitators among the team members and collected information throughout the design and construction phases from all the consultants, the construction manager, and the trades in order to develop a comprehensive and highly detailed 3D virtual model of the building.

During design and preconstruction, the 3D virtual model was used to assess the constructability and cost of different options and identify conflicts, to communicate with trades during the bidding process, and to develop shop drawings for the proof-of-concept and lab mock-ups. The modelers created animated sequences of the installation and assembly of all the components on the project. The VDC model was also used in the prefabrication of mass-timber elements and to coordinate these with the mechanical, electrical, and plumbing (MEP) systems to ensure all the system pathways and structural penetrations were designed prior to on-site construction which reduces the number of design changes while identifying and addressing areas of potential conflict or improvements ahead of time.

Contracting

The University of British Columbia utilized a construction management project delivery method which helped ensure the completion of the project with the required quality, on budget and on time. Under this contract arrangement, the project manager supervised the design, construction, and commissioning processes on behalf of the University. The project manager contracted directly with the consultants as well as a construction manager, who was involved from the design phase onward. As for stakeholders within the University, they were engaged throughout the design and construction process.

In addition, many of the key construction team members were involved or consulted in the design and preconstruction phases including the mass-timber fabricator, the timber erector, and the concrete forming and placement contractor. Their input regarding the feasibility, constructability, and cost estimating of design decisions was crucial in facilitating and accelerating the construction phase.

Lessons Learned

The most significant lessons learned in this project include:

- Integrative planning and communication were crucial for the project success:
 - The use of comprehensive VDC visualization helped identify constructability issues and cost implications, which in turn reduced the number of changes during construction.
 - Continuous and consistent communications amongst the project team ensured the construction plan was realistic, efficient, and safe.
- Implementation of novel construction solutions can contribute to the project success while meeting aggressive timelines.
 - Tested and validated alternative designs and construction methods through iterative planning enabled optimizing the actual construction process.
 - Trades experienced a learning curve while adjusting to the aggressive schedule, the high level of coordination, and the new techniques.
 - The integrative design and construction strategy encouraged the entire project team to take ownership of and actively contribute to the success of this innovative project.
- The prefabrication opportunities of mass timber increased the construction accuracy and productivity, reduced on-site construction time and waste, and allowed for concurrent off-site work to occur in controlled conditions.
- The use of VDC model to develop a full design of the MEP systems helped in determining the exact locations for shafts and penetrations to be cut into the CLT panels during prefabrication. And also enabled the accurate off-site cutting of ducts, pipes, and other systems, and partial off-site assembly of the mechanical room.

Case Study #2: University of Toronto New Academic Wood Tower

Background

University of Toronto is planning to build a 14-storey wood tower above the Goldring Centre for High Performance Sport (see Figure 17). This building will house a number of academic units. It is still in the design phase, awaiting zoning changes to increase the height allowance for tall wood buildings. Construction could begin at the end of 2019.



Figure 17: UofT New Academic Wood Tower

(Adopted from: <https://www.utoronto.ca/news/u-t-build-academic-wood-tower-downtown-toronto-campus>)

The project team is formed of:

- Developer: University of Toronto
- Architect: *Patkau Architects of Vancouver in partnership with MacLennan Jaunkalns Miller Architects (MJMA) of Toronto*
- Structural Engineering: *Blackwell*

Structural Design

Facts:

- Category: Academic
- Status: Design
- Height: 80 m
- Storeys: 14

The Goldring Centre was planned to support the new tower, thus no additional structure would be required for the tower. And the tower is designed to be built with cross-laminated timber (CLT). The main issues explored so far through attending project meetings.

The structure of tall-wood buildings is formed of both engineered wood products and heavy timber members. Heavy timber or solid members of large cross-sections in their natural or semi-fabricated form, and building codes cover their use under Type IV of construction. Whereas, mass timber or fabricated wood members and engineered products, and they are not included in the current building codes. They are diverse with high performance and offer wide range of opportunities through their high strength to weight ratio and fire safety capabilities.

From the interviews conducted with stakeholders in this project, it was concluded the tradeoff between timber versus concrete or steel should consider the benefits and challenges of using timber as described below. The benefits of using timber include:

- Exposed timber offers aesthetic appeal
- Timber products can be supplied from all over Canada (ease of supply) (sustainable supply chain)
- Timber offers less embodied energy and Less carbon emissions
- Quicker erection which saves costs
- Lighter which make it suitable for weak soils and reduces the needed foundation
- Mass timber provides tight envelopes for buildings which improves thermal performance for tall buildings.

As for the challenges of using timber, they include:

- The unfamiliarity with timber for high-rise buildings imposes a lot of risks. This makes stakeholders raise their risk margins.
- Currently, it can be of higher costs because of the limited number of suppliers and the lack of experience
- The design of connections is more challenging and costly because timber is softer than steel which makes the design of connections more complicated (Steel is equally strong in tension and compression).
- Fire safety is an issue for timber structures (Concrete and large cross-sections of wood have inherent fire safety, whereas typical sizes of wood don't and they require additional protection)
- The design of timber structures for earthquakes is challenging compared to concrete and steel since wood is not as ductile. This is satisfied with proper design of connections. (Steel is very ductile and wood is not. Concrete is ductile if it has the right proportion of steel it in. For members that need ductility, like failure under lateral forces, ductility is necessary. This makes it hard to use mass timber as a lateral system).

There are other important points that need to be considered when comparing the use of timber against concrete or steel. Examples of these points are explained below.

Timber exposure for aesthetic appeal: the use of timber may not be cheaper to build than steel or concrete, however, timber buildings could get a premium for the [wood] aesthetic when they are leased out. The main drawback in this case would be the exposure of timber to fire. Being exposed to the same fire, wood would damage faster “aesthetically” compared to concrete and steel. And concrete would take much longer to damage structurally. More exposure of wood makes the project “high-profile”. The current option to allow for exposing timber in buildings is to have a minimum char layer available for the timber members through using large cross-sections of timber. Other than that timber members will need to be encapsulated to provide the needed fire safety. Mass timber can be encapsulated in fiber glass for weather resistance and strength improvement but in case of fire protection it would be very expensive (It is important to consider the capital cost against the functionality).

Fire recovery: post-fire rehabilitation works for timber are much simpler than concrete since the timber members can be easily replaced whereas concrete elements will require a lengthier process of assessing the status of the reinforcement bars.

100% timber or hybrid systems: choosing whether to go with 100% timber or hybrid systems (such as using concrete core) depends mainly on the geometry of the building and required spans. However, reducing the percentage of timber use in the building will in turn reduce its potential benefits. Thus, the aim is to maximize the use of timber as possible. But timber projects can be much simpler than concrete and steel when they are well planned since less equipment and workmanship would be needed.

Transportation costs: for the transportation costs of timber, timber can be obtained from Vancouver or Quebec which means that the transportation costs would represent only a small percentage relative to the overall costs. This shows that transportation of timber isn’t an issue for these buildings in Canada.

Modular construction: the use of timber for building modules for modular construction is better than concrete. The light weight of timber makes lifting of timber modules easier and requires less equipment.

Permits: compliance with building codes is the main factor challenging the broader adoption of mass timber. Various buildings were developed using mass-timber by implementing wood structural systems at a smaller scale, within the scope of current building codes. However, obtaining permits for high-rise timber buildings is challenging regarding the buildings’ fire safety. This challenge is contributed to the fact the current building codes don’t cover mass timber aspects, and alternative solutions will have to be submitted.

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APPENDIX A: SUGGESTED TECHNICAL SPECIFICATIONS

Appendix A contains summarized tables showing technical specifications of mass timber and its encapsulating materials. Table A-1 shows the minimum dimensions of structural timber elements in case of encapsulation. The indicated elements include walls, floors, beams, and columns. Table A-2 shows the fire-resistance rating for ceiling membranes for different encapsulating materials. As for Table A-3, it illustrates the additional fire-resistance that can be achieved with different layers of gypsum board protection. Table A-4 elaborates the fire safety requirements for different categories of building heights showing the needed performance and scenarios for occupants in each category. Table A-5 gives minimum dimensions that can be used for structural wood elements in case they are left exposed. Finally, Table A-6 provides a comparison of OBC-2012 requirements for wood buildings of different number of storeys.

Table A-1: Minimum Dimensions of Structural Timber Elements in Encapsulated Mass Timber Construction

Structural Timber Elements	Type of Dimension	Minimum Dimensions (mm)
Wall, floor, and roof assemblies	Thickness/Depth	96
Beams, columns, and arches with 2-sided or 3-sided fire exposure	Cross-section	192 x 192
Beams, columns, and arches with 4-sided fire exposure	Cross-section	224 x 224

(Adopted from: <http://wood-works.ca/wp-content/uploads/2018-06-ABWW-MassTimberInTheCodeAltSolns-v2-1.pdf>)

Table A-2: Fire-Resistance Rating for Ceiling Membranes

Description of Membrane	Fire-Resistance Rating, minutes
15.9mm Type X gypsum wallboard with at least 75mm mineral wool batt insulation above wallboard	30
19mm gypsum-sand plaster on metal lath	30
Double 14.0mm Douglas Fir plywood phenolic bonded	30
Double 12.7mm Type X gypsum wallboard	45
25mm gypsum-sand plaster on metal lath	45
Double 15.9mm Type X gypsum wallboard	60
32mm gypsum-sand plaster on metal lath	60

(Adopted from: <http://cwc.ca/wp-content/uploads/publications-FireSafetyDesign-s.pdf>)

Table A-3: Additional Fire-Resistance Achieved with Gypsum Board Protection

Gypsum Board Protection	Additional Fire Resistance (min)
One layer of 12.7mm Type X gypsum board	15
One layer of 15.9mm Type X gypsum board	30
Two layers of 12.7mm Type X gypsum board (applies to CLT only)	60
Two layers of 15.9mm Type X gypsum board	60

(Adopted from: <https://www.omfpoa.com/wp-content/uploads/2017/11/Ontarios-Tall-Wood-Building-Reference-2017.pdf>)

Table A-4: Performance Requirements Related to Building Height

	Possible level of specified performance	Possible design strategy for timber elements
Low-rise buildings	Escape of occupants with no assistance. No property protection.	No encapsulation
Mid-rise buildings	Escape of occupants with no assistance. Some property protection.	No encapsulation
Taller buildings	Escape with firefighter assistance. Burnout with some firefighting intervention.	Limited encapsulation
Very tall buildings	Protect occupants in place. Complete burnout with no intervention.	Complete encapsulation

(Adopted from: <http://www.solaripedia.com/files/1260.pdf>)

Table A-5: Minimum Dimensions of Structural Wood Exposed Elements

Structural Wood Elements	Type of Dimension	Minimum Dimensions (mm)
Wall, floor, and roof assemblies with 1-sided fire exposure	Thickness/Depth	136
Beams, columns, and arches with 2-sided or 3-sided fire exposure	Cross-section	248 x 248
Beams, columns, and arches with 4-sided fire exposure	Cross-section	336 x 336

(Adopted from: <https://www.omfpoa.com/wp-content/uploads/2017/11/Ontarios-Tall-Wood-Building-Reference-2017.pdf>)

Table A-6: Comparison of OBC-2012 Requirements for Wood Buildings

Wood Buildings								
Category	≤ 3 Storeys	≤ 3 Storeys*	≤ 3 Storeys	≤ 3 Storeys	≤ 4 Storeys	≤ 6 Storeys	7-12 Storeys	> 12 Storeys
OBC Designation	Acceptable Solution (Part 9 residential, some Part 4)	Acceptable Solution (Parts 3 & 4)	Acceptable Solution (Parts 3 & 4)	Acceptable Solution (Parts 3 & 4)	Acceptable Solution (Parts 3 & 4)	Acceptable Solution (Parts 3 & 4)	Alternative Solution	Alternative Solution
Maximum Building Area (Area per floor)	1, 2, or 3 storeys: 600 m ²	1 storey: 2700 m ² 2 storey: 1350 m ² 3 storey: 900 m ²	1 storey: 3600 m ² 2 storey: 1800 m ² 3 storey: 1200 m ²	1 storey: 5400 m ² 2 storey: 2700 m ² 3 storey: 1800 m ²	1 storey: 7200 m ² 2 storey: 3600 m ² 3 storey: 2500 m ² 4 storey: 1800 m ²	1 storey: 9000 m ² 2 storey: 4500 m ² 3 storey: 3000 m ² 4 storey: 2250 m ² 5 storey: 1800 m ² 6 storey: 1500 m ²		
Maximum Physical Height	-	-	-	-	-	18 m from ground floor to top floor		
Sprinklers	None	None	None	NFPA 13R	NFPA 13R	NFPA 13R for 1-4 storeys; NFPA 13 for 4 and 6 storeys		
Floor Assembly Construction	-	45-Minute Fire Rating	1-Hour Fire Rating	45-Minute Fire Rating	1-Hour Fire Rating	1-Hour Fire Rating		
Stairwell Construction	-	45-Minute Fire Rating	1-Hour Fire Rating	45-Minute Fire Rating	1-Hour Fire Rating	1.5-Hour Fire Rating for all exit enclosures (noncombustible construction)		
Elevator Shaft Construction	-	45-Minute Fire Rating	1-Hour Fire Rating	45-Minute Fire Rating	1-Hour Fire Rating	1-Hour Fire Rating		
Building Category	Low-Rise	Low-Rise	Low-Rise	Low-Rise	Low-Rise	Low-Rise & Mid-Rise	Mid-Rise	High-Rise

*Maximum building area applicable if building is facing three streets; smaller areas permitted for facing one and two streets

(Adopted from: <https://www.omfpoa.com/wp-content/uploads/2017/11/Ontarios-Tall-Wood-Building-Reference-2017.pdf>)

APPENDIX B: SAMPLE TALL WOOD BUILDINGS

Appendix B shows a sample of tall wood building around the world of heights 7 stories or more. Details of some of these buildings were already provided in Section III of this report.

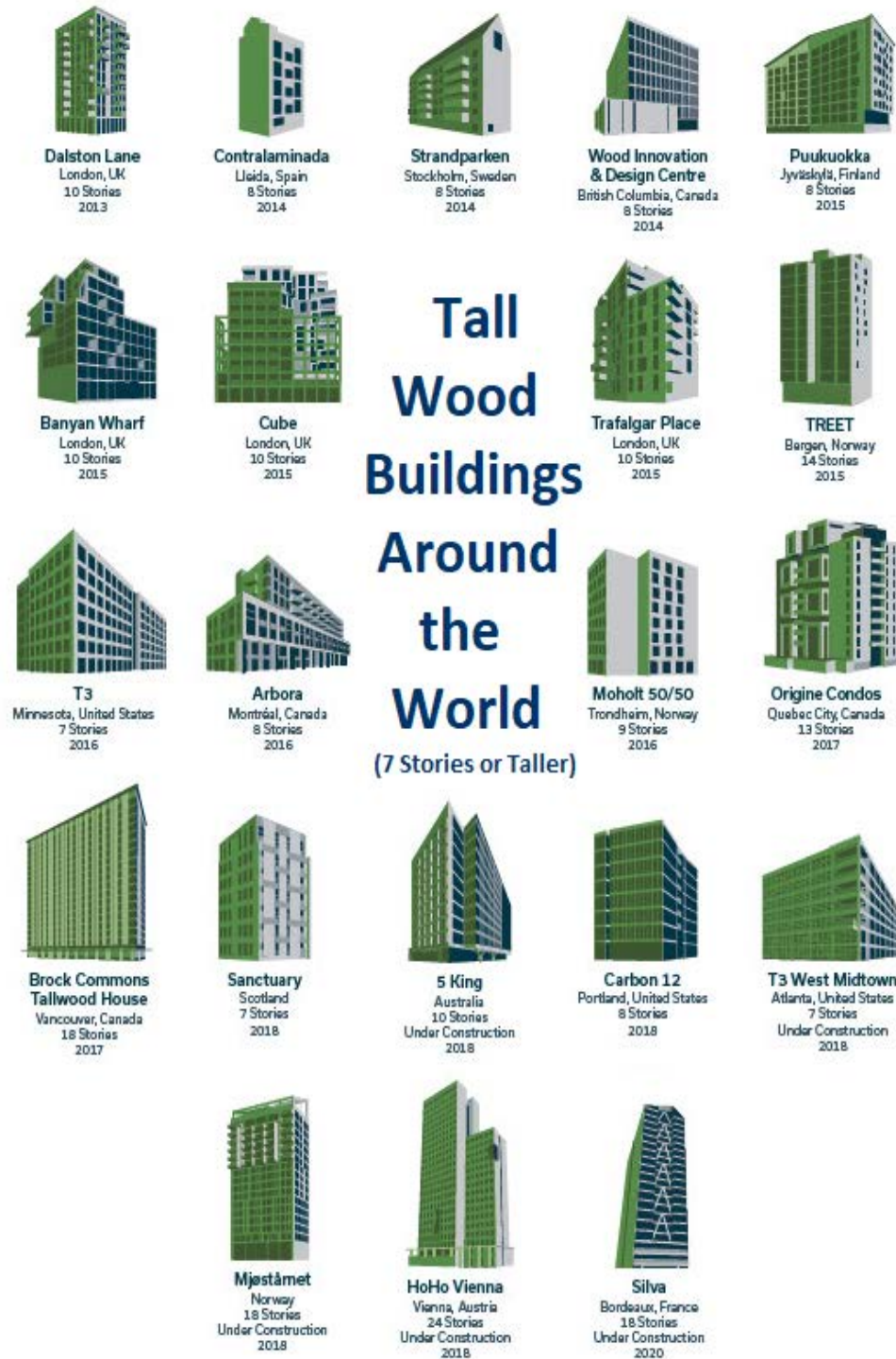


Figure A-1: Examples of Tall Wood Buildings

(Adopted from: <https://www.thinkwood.com/building-better/taller-buildings>)

APPENDIX C: FIRE TESTING FOR TIMBER STRUCTURAL COMPONENTS

Appendix C focuses on the fire testing of timber structural components. In general, there are two categories of fire tests which are standardized testing and experimental testing as explained below.

Standardized testing: refers to fire tests performed using internationally recognized standard fire time-temperature curves. This includes ASTM E 119 in the United States, CAN/ULC S101 in Canada, and ISO 834 in the UK and Australia, and others.

Experimental testing: refers to fire tests performed using non-standardized fire time-temperature curves. This includes natural fire tests, full-scale fire tests, furnace tests, or any other tests that use a non-standardized fire time-temperature curve. These tests are often performed for research purposes to better understand the fire performance of timber structural components.

Standardized Testing on Heavy Timber Assemblies

These tests have been performed on engineered timber products, post-tensioned timber framing and CLT assemblies.

Laminated Veneer Lumber (LVL) Products: A series of fire tests to determine the charring rate for different sections of LVL (Tsai, 2010). Results indicated charring rates for LVL compared favorably to rates for solid wood. See also Harris (2004) and Lane (2001). Testing was also performed for structural composite lumber (SCL), which consists of laminated veneer lumber (LVL), parallel strand lumber (PSL) and laminated strand lumber (LSL) (White 2006).

Glulam Sections: Tests to establish the charring rates for glulam sections were also performed (Buchanan & Moss 1999). Results for charring rates in glulam compared favorably to solid wood sections. Primary findings demonstrate that fire performance and charring rates of glulam, LVL and SCL are similar to that of large, solid wood sections. However, Barber and Buchanan (1994) performed tension testing with steel rods epoxied into glulam sections indicated strength loss with increasing temperature.

The fire resistance time for wood elements can be increased by providing gypsum board protection at exposed surfaces. Fire testing with LVL beams has shown that 30 minutes fire resistance can be added for a single layer of 16mm gypsum board. Application of a double layer of gypsum board achieved at least a 60 minute increase in fire resistance time (White 2009).

CLT Panel Assemblies: There has been considerable research in fire testing of CLT panel assemblies. A review of fire testing and numerical analysis results was conducted by Frangi et al. Results indicate that the fire performance of CLT panels depends on the behavior of single layers, accounting for

delamination or fall-off. Fire testing of unprotected and protected CLT panels was performed to establish the fire performance of panels subjected to out-of-plane loading. Results were compared to finite-element models used for sequential thermal and structural analysis to evaluate the model accuracy. Results indicate failure times of 99 minutes and 110 minutes for unprotected and protected CLT panels, respectively, and good agreement with the finite-element models (Fragiacomo et al., 2012). Fire testing on 5-layer CLT floor panels is summarized by Fragiaco et al. Testing results indicated that numerical predictions for CLT panel performance proved to be accurate for predicting fire resistance. Testing on unloaded CLT members was performed by FPInnovations in Canada using exposed CLT and CLT protected by gypsum board panels (Craft et al., 2011). Results confirmed existing charring rate values for CLT panels, and demonstrated that gypsum board protection delays the onset of charring and combustion for the protected CLT panels below.

Testing on CLT walls and panels was performed to demonstrate the performance of loaded CLT assemblies (Osborne et al., 2012). Testing considered the effect of gypsum board protection for CLT panels, as scenarios included protected and unprotected CLT. Results indicate that the greater the depth of the section (3, 5 or 7 layers), the greater the fire resistance. Additionally, gypsum board protection was shown to also increase the fire resistance time. Discussion on performance of gypsum board protection and charring rates is also provided (NRCC, 2013).

As the understanding of fire performance of engineered timber products increases, more innovative solutions will be set to combine timber with conventional materials to optimize structural design (O'Neill, 2010).

Experimental Testing on Heavy Timber Assemblies

Valuable information has been obtained from experimental fire testing of heavy timber assemblies. Testing generally focused on demonstrating the effects of different fire protection systems in heavy timber assemblies, such as sprinklers and gypsum board protection. Results can be used to investigate the potential for exposed heavy timber elements.

Glulam Structures: In October 2000, a large gymnasium fire in a glulam structure prompted a series of tests by Waseda University in Tokyo, Japan. Tests involved exposing glulam partition walls to a constant heat exposure from a propane burner to better understand the fire performance of glulam partition walls (Nam et al., 2002). A first exposure test resulted in charring of the wall, with no significant combustion occurring on the member. The second exposure, approximately 2.5 times more severe, resulted in full panel burnout, consistent with expected conditions within the gymnasium. Charring rates were recorded for both tests and were shown to be consistent with literature values and estimates for the case study fire.

CLT Structures: A full-scale fire test of a 3-story CLT building was performed in 2008 to evaluate the fire performance of a CLT building with gypsum board protection and no sprinklers (Frangi et al., 2008). The test simulated a standard residential fuel load and evaluated temperatures in adjacent fire compartments, both to the side and above the fire room.

The fire room consisted of 3.4" [85mm] CLT wall panels protected by two layers of 0.5" [12mm] gypsum board. The floor and roof included 5.6" [142mm] CLT panels with one layer of 0.5" [12mm] gypsum board. The fire was allowed to burn a full 60 minutes, at which point it was manually exterminated. Intense burning consistent with flashover occurred about 6-7 minutes into the fire growth (Frangi & Fontana, 2005). Findings indicate that flame spread and elevated temperatures were restricted to the room of fire origin. The study also suggested that protecting the timber structure with non-combustible gypsum board resulted in minimal damage to the CLT structure.

Reference:

Gerard, R., Barber, D., & Wolski, A. (2013). Fire safety challenges of tall wood buildings. National Fire Protection Research Foundation.