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STANDARDS RESEARCH

High-Rise Modular Construction

A Review of the Regulatory Landscape and Considerations for Growth

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Executive Summary

With rapid urbanization and population growth, more people live and work in cities. This has led to an increased need for taller buildings in urban environments and a lack of affordable housing in cities. The construction industry continues to grapple with rising labour costs because of shortages in skilled labour and persistently stagnant construction productivity. These market dynamics present an opportunity for innovation.

Modular and off-site construction can help to address these challenges. Modular construction has origins dating back to the 17th century beginning predominantly with single-family homes. Today, modular construction is used in many applications, including residential, commercial, health care, and others. Most existing modular buildings are low or mid-rise, however there have been several high-rise volumetric modular buildings constructed in the last decade and demand appears to be increasing.

This research report explores the current state, drivers, benefits, and barriers to the growth of high-rise volumetric modular construction. This report includes findings from a workshop and interviews with modular manufacturers, designers, regulators, and industry trade groups as well as existing research in modular construction.

North American model codes and standards organizations, including the Canadian Standards Association (CSA) and the International Code Council (ICC), have recognized the need for codes and standards to be developed or tailored to respond to the specific challenges of modular construction. A review and gap analysis of codes and standards related to modular construction has yielded several recommendations for the Canadian market.

The following are the four highest priority items that were identified through this research project with respect to codes and standards development for modular construction (see Section 7 for more information):

1. Develop a new standard for off-site/modular construction.
2. Increase and expand adoption of CSA Standard A277 by the provinces.
3. Review and update CSA Standard A277.
4. Develop guidance for AHJs for off-site/modular buildings.

There are many factors that contribute to the uptake of modular construction. The above recommendations will support growth in modular construction by providing a more comprehensive and consistent regulatory environment for the design, construction, and approval of modular buildings.

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"The benefits of volumetric modular construction can be maximized when as much work as possible is completed off-site."

1. Introduction

This research report explores the current state, benefits, drivers, and barriers of growth of high-rise volumetric modular construction as well as provides a review and gap analysis of the regulatory landscape pertaining to modular construction in Canada.

1.1 Methodology

A literature review was completed to evaluate available published information regarding high-rise volumetric modular construction. Resources included research reports from academia, industry trade groups, and subject matter experts. Additionally, interviews were conducted with industry stakeholders that were identified as having extensive knowledge in the modular construction industry, including designers, manufacturers, regulators, researchers, trade groups, and general contractors. Finally, a workshop was conducted with industry experts to explore and validate findings that had been identified through the literature review and interviews. The research included sources, interviews, and experiences from within and outside of Canada. Although generally having a North American focus, most of the content could have applicability internationally as well.

Due to the limited number of completed high-rise volumetric modular projects, the report also incorporates research and expertise from low-rise applications. Therefore, the information presented has relevance to low-rise applications as well. This report does not directly consider modular construction for single-family dwellings.

1.2 Terminology

Conventional construction refers to approaches where components, systems, and assemblies are constructed at the final installed location of the building.

Off-site construction refers to manufacturing and assembly of building elements at a location other than the final installed location of the building. Panelized construction and modular construction are both methods of off-site construction.

Panelized construction refers to the manufacturing and assembly of wall panels and floor panels off-site that are shipped to a site and require additional assembly to form three-dimensional spaces and a completed building. It is off-site construction but not modular construction.

Modular construction refers to the manufacturing and assembly of modules off-site such as a fully finished bathroom pod, or a subassembly for mechanical, electrical, and plumbing (MEP) systems. The modules are shipped to site and assembled to form a completed building.

Volumetric modular construction refers to the manufacturing and assembly of modules that will include complete spaces such as an apartment, bathroom, and corridor (or portion thereof) in a single module. These can be fully finished off-site. Volumetric modules usually arrive on-site complete with all elements intact, including finishes, and only require placement and connections to be made [1]. The distinction from panelized and modular is that volumetric modules can be erected or stacked on-site to form the completed building. Structural and building service connections need to be made on-site to the foundation and to the utilities, and between modules.

This report will use the term ***high-rise volumetric modular construction*** given the focus on high-rise applications. Other terms are used in the industry for three-dimensional modular construction such as prefabricated prefinished volumetric construction (PPVC), permanent modular construction (PMC), and prefabricated prefinished modular construction, off-site construction.

1.3 Modular Typologies

The benefits of volumetric modular construction can be maximized when as much work as possible is completed off-site. While the foundations will be constructed using conventional construction methods for all projects, the remaining portions of the building could be fully modular up to a certain number of storeys. For taller buildings, a conventionally built lateral system may be required. However, modular construction does not have to be an all or nothing strategy. Where subassemblies (e.g., bathroom pods) are built modularly, these can be combined with either volumetric modular construction or conventional construction methods.

Modular projects can be constructed from structural materials, including steel, concrete, or wood, or a combination of these. It is estimated that in the United States and Canada, wood frame, steel, and concrete make up respectively 70%, 25%, and 5% of materials used in modular construction. This distribution relates directly to the material choices for low-rise construction, which has historically been the largest portion of the modular market. In Singapore and Hong Kong, concrete modules are more common than in North America.

For high-rise volumetric modular buildings, a steel structural system has been the predominant type in North America. Prefabricated concrete floors have been used in volumetric applications in North America and internationally. In the United States and Canada, recent and upcoming code changes allow for the use of mass timber (e.g., cross-laminated timber) in high-rise applications, providing another option for structural materials. Mass timber in high-rise applications has typically been panelized, though there are volumetric systems emerging as well.

1.4 History of Modular Construction

The first applications of modular construction can be traced back to as early as 1670 when prefabricated buildings were shipped from England to the United States [2]. During the gold rush of the 1800s and the post–Second World War era of the 1940s, modular construction was used to provide fast, low-cost housing for workers and returning servicemen [2].

Prior to the 1940s modular construction was primarily used for single-family homes. It was at this time that modular construction methods were applied to commercial projects and later used in hospitality and multi-family residential buildings [2]. The common thread with these historical booms in modular construction was a rising demand for housing.

The tragic collapse of the Ronan Point 22-storey apartment building in London, England, in 1968 resulted in public distrust in prefabricated construction. A gas explosion caused the prefabricated concrete floors and slabs to fail in one corner of the building, causing four fatalities and 17 injuries [3].

Modular construction has been used for many different types of building occupancies, including single-family dwellings, multi-family residential units, student housing, hospitality, health care, office, commercial, and educational.

While most of the existing modular construction is low-rise, there are several high-rise volumetric modular buildings that have been completed globally (see Table 1). As of July 2019, the Clement Canopy building located in Singapore is known as the tallest volumetric modular building in the world. This project includes two 40-storey towers with 505 residential apartments. The towers are made up of 1,899 modules and took 30 months to complete.

Table 1: *Select completed high-rise volumetric modular buildings [4]*

Building	Height	Year Completed
Victoria Hall, Wolverhampton, UK	24 storeys, 251 ft	2009
Felda House, Wembley, UK	19 storeys	2015
461 Dean Street, Brooklyn, NY, USA	32 storeys, 359 ft	2016
CitizenM Shoredich, London, UK	10 storeys	2016
Chapter Lewisham, London, UK	12 storeys	2016
Grand Felda House, Wembley, UK	17 storeys	2016
Apex House, Wembley, UK	29 storeys	2017
11 Mapleton Crescent, Wandsworth, UK	27 storeys	2018
Alt Hotel Calgary, Alberta, Canada	9 storeys	2019
101 George Street, Croydon, UK	44 storeys	2019
Clement Canopy, Singapore	40 storeys	2019
AC Hotel NoMad, New York, NY	26 storeys	Under construction

As designers and manufacturers look to build taller, many are focusing their interest on volumetric modular construction because of the amount of work that can be completed off-site, in addition to the numerous benefits it provides to project stakeholders and the community.

2. Current State of Modular Construction

This section describes the current state of modular construction, including the prevalence and market penetration as well as the perception of modular construction in the marketplace.

2.1 Prevalence and Market Penetration

Permanent modular construction represented nearly 4% of the overall construction market in Canada in 2018 [2], and the market penetration is similar in the United States. Prevalence and market penetration is attributable to various factors that include the quality perception of modular construction, which was identified by McKinsey as one of seven determining factors [5]. The other six factors are access to materials, supply chain and logistics, labour dynamics, local site constraints, and consolidated and continuous demand volumes [5]. Based on these factors, certain geographical markets may be better suited to promote the growth of the modular construction industry than others. Currently, the use of modular construction is present in most markets; however, some markets have been quicker to recognize its benefits and adopt modularization.

A given market's access to materials, supply chain, and logistics can have a major impact on the financials of a project. In many cases, these factors become interrelated. As modular construction increases in popularity, countries may not have the manufacturing capacity to keep up with demand, which may result in the outsourcing of manufacturing to foreign markets. This provides a solution to the issue of supply chain quantity; however, difficulties may arise when addressing differing material ratings and testing requirements between jurisdictions. Additional project costs may accrue if there is a need to perform component/assembly testing or instead source previously tested and approved materials that comply with the requirements of the final build site. Utilizing a global supply chain can therefore help ensure volume demand is met but requires additional considerations that are not necessary when utilizing a domestic supply chain.

Modular construction can help address skilled labour shortages by broadening the labour pool. For modular projects, most work is performed off-site in factories where workers at stations tend to have a narrower scope of work and therefore may not need the same breadth of skills that tradesmen on a traditional site would require. Factory and module certification programs may have requirements for qualifications and licensing of construction workers and design professionals that need to be considered. Similarly, labour laws, prevailing wages, and union/non-union labour agreements should be taken into consideration but given the complexity and geographic differences will not be examined further in this report.

Site constraints can impact the ability of modular construction to penetrate a market. For cold weather climates, such as in Northern Canada, modular construction can be a positive alternative to conventional construction methods because progress can continue irrespective of weather conditions.

These factors have and continue to shape the market penetration of modular construction globally. Singapore's desire for quick construction has led its Housing Development Board to build roughly 20,000 to 30,000 units a year using off-site construction [5]. In Japan modular construction is viewed in higher regard than conventional construction methods, helping the country achieve a broader adoption of modular construction principles. The United States has relatively fragmented and small-scale construction ecosystems due to low-capacity manufacturers and a multitude of differing jurisdictions [5]. While the world's tallest modularly constructed building resides in Singapore, it is generally regarded that Europe, specifically the United Kingdom, is the most developed geographical area in the modular construction industry. Industry professionals believe that North American countries are behind, but the combination of housing demand, skilled labour cost and availability, as well as several other factors have these markets poised for significant growth in the coming years.

2.2 Preconceived Notions and Views

Generally, perceptions of modular construction are accompanied by criticism and skepticism regarding the benefits that can be derived from its implementation. While there are some markets that recognize modular construction as a step up in quality from conventional construction methods, many populations and geographical locations have yet to adopt this view. Modular construction can evoke images of prefabricated structures such as trailers located behind schools (i.e., pods or portables), trailer homes, or temporary structures that are being used well beyond their intended life cycle. It has been associated with a stigma of being old, cheap, ugly, of poor-quality, and lacking in innovation [5]–[7]. One company believes so strongly that the word "modular" carries a stigma that it instead uses the term "off-site construction" [7], which is becoming more prevalent.

Despite current perceptions, industry professionals believe that modular is going to play a major role in the future of construction. In recent years, people have begun to see modular construction in a more positive light, which is leading to higher demand and increased industry growth.

Increased advocacy and success stories are pivotal in transforming the negative views and stigmas surrounding modular construction [8]. News articles accompanying stories about Clement Canopy, for example, contain information about the Government of Singapore's push to improve construction productivity along with a brief outline of some of the construction timelines, labour utilization, and sustainability benefits that modular construction can provide [9]. Publicity about successful projects that include information about the structure as well as the benefits that modular may offer to the community or environment may help to combat negative views. Project experiences that highlight modularly constructed buildings as indistinguishable from traditional ones are also important in combatting negative views [7].

3. Drivers and Benefits of Modular Construction Growth

Current industry challenges as well as an increased recognition of the benefits of modular construction have recently helped it gain traction in the marketplace. Skilled labour shortages are currently at an all-time high and they are reflected by the increasing cost of on-site labour. Build Force Canada predicts a net labour loss of more than 33,000 workers over the next decade [10]. Other challenges such as housing shortages and the desire for shortened project schedules are also driving the growth of the modular construction industry. Conventional construction is "laden with issues such as inefficiency, resource waste, a large carbon footprint, and health related issues for workers and nearby residents" [8]. Comparatively, modular construction's means and methods have the potential to mitigate issues surrounding sustainability and worker/community safety and to benefit many other aspects of the procurement and construction process, including the predictability of construction costs and project schedules.

3.1 Cities and Urbanization

Mass urbanization of cities contributes to an ever-growing affordable and available housing crisis that is prevalent across the globe. The United Nations estimates that 68% of the world's population will live in urban areas by 2050 – a 13% increase from 2018 [11]. The World Bank estimates that 300 million new housing units will be required by 2030 to accommodate the approximate 3 billion people who will need new housing and basic infrastructure. [12].

Countries such as Singapore, the United Kingdom, and the United States have begun exploring modular construction in order to keep up with the projected demand for new housing that will be needed. In New York City, the Department of Housing and Preservation Development piloted a construction program, Modular NYC, to examine how modular construction could "deliver affordable housing opportunities faster and more effectively" [13]. The program included solicitations for expressions of interest from owners/developers to participate. The city has a goal of building 300,000 affordable homes by 2026 and is interested in leveraging the innovative, sustainable, and speed benefits of modular construction to do so [13], [14].

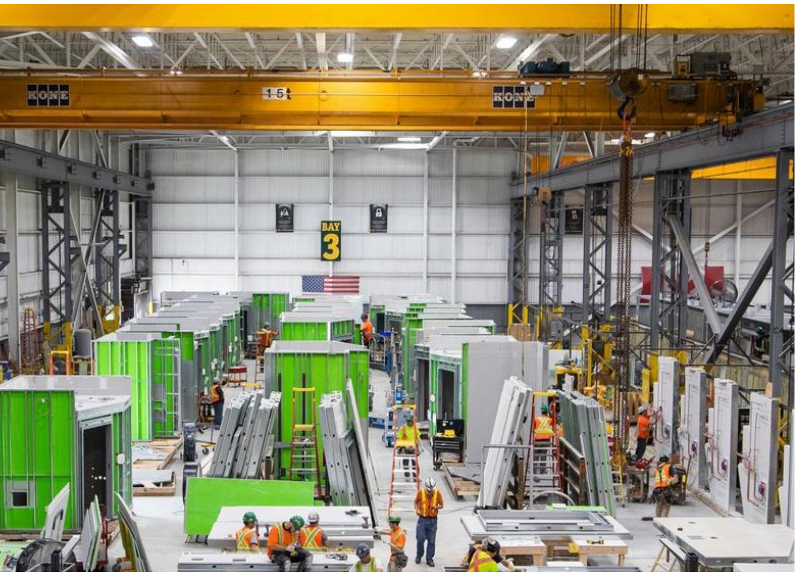
Modular construction is particularly well suited to address the affordable and available housing crisis. The repeatable floor plates of residential structures favour modular construction (see Section 4.1.1) and can amplify the construction schedule's predictability and cost certainty generally associated with a modular approach (see Section 3.4).

3.2 Sustainability

The sustainable concepts of modular construction practices are an opportunity to satisfy shifting attitudes towards attaining greener practices, combatting climate change, and reducing carbon emissions.

Waste reduction is a significant benefit of modular construction. One case study of a high-rise volumetric modular construction building in England saw waste production equivalent to about 5% of the overall construction weight compared to an industry average of about 10 to 13% [15]. Compared to conventional construction methods where almost no waste is recycled, approximately 43% of waste created during the modular manufacturing process is recycled [15].

Material efficiencies begin in the factory where studies have shown that the manufacturing process is more sustainable than conventional construction even before getting into specific building systems and material selections [7]. This is because modular construction provides greater control over materials as they are purchased and sized for a specific project, and the controlled environment of the factory allows unused materials to be recycled back into the system to be used in future projects [16], [6].



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"Workers on modular projects experience less hazardous conditions when constructing modules in a factory, including less exposure to extreme weather conditions, decreased noise, and improved air quality."

The use of off-site/modular construction results in less work being completed on-site, which benefits the local environment and community. It reduces the impact on local habitats, reduces site disturbance [7], and lessens noise pollution as it requires fewer workers and resources on-site, such as scaffolding, cranes, and building materials [6]. Modular construction has also resulted in up to a 70% reduction in the number of visits to the site by delivery vehicles [15]. The amount of air and water pollution due to dust and other construction byproducts is also decreased. Overall, the community surrounding the project site also benefits because most of the work is completed off-site and the work on-site is done on a reduced project schedule.

Environmentally conscious individuals are demanding greater accountability regarding wasted resources, such as construction debris that ends up in landfills. This population is actively seeking avenues to incorporate sustainable practices into their everyday lives, and modular construction is a proven solution to reducing construction waste [2].

3.3 Workplace Safety

Completing a project modularly can result in improved safety for on-site workers as well as a reduction in time lost due to resulting injury [5], [6]. It is estimated that in most modular construction projects, up to 80% of the labour activity can be moved off-site [5] to controlled environments thereby substantially increasing workplace safety.

Workers on modular projects experience less hazardous conditions when constructing modules in a factory, including less exposure to extreme weather conditions, decreased noise, and improved air quality [16], [6], [1]. The increased level of automation and the use of robotics in some factories may pose new safety considerations but they can also reduce risk as fewer workers are near construction materials. Additionally, because much of construction occurs off-site there is a reduction in worksite debris that may otherwise present a trip hazard or a fire hazard [17].

Workers may also experience less hazardous operations in modular construction as work that was traditionally conducted at high elevations (within or exterior to structures or overhead) is shifted to a low elevation within a controlled factory environment. Reported fall rates on modular construction sites are substantially lower compared to those on conventional construction sites [16] that result in a significant reduction in the hours of leading-edge work. Fall risks are also reduced because less work is completed from scaffolding. As those entering the workforce look for employment opportunities, placement in a hands-on position with comparatively better safety is a substantial benefit to workers and has the potential to drive significant growth for the modular construction industry.

It should be noted that there may be a potential additional safety risk in modular construction associated with the added step of transporting modules from a factory to the site, which may include transport of modules across provinces or countries via multiple modes of transport. Once modules are at the site, crane and hoist activity to place modules can also present an additional risk to workers. This risk can be mitigated by using experienced professionals, and reducing the use of heavy equipment, swing stages, scaffolding, and leading-edge work can help further decrease the overall safety risk to workers.

Overall a modular approach may offer a safer work environment than conventional construction by reducing some of the risk factors associated with the highest number of labourer fatalities in the construction industry [18].

3.4 Project Schedule and Cost

Modular construction can be a faster and more cost-effective building strategy when compared to conventional construction methods. Many projects can realize significant cost savings by completing work using modular methods, with some planned projects forecasting cost savings of as much as 20% [5]. However, there are documented cases where project costs increased using modular methods compared to completion using conventional construction. The ability of modular construction to reduce project costs is dependent on many factors; therefore, every project may not be able to achieve the potential financial benefits of modular. These varying factors must be considered holistically to determine if modular construction will be financially beneficial.

One of the greatest influencing factors for cost savings in a modular construction project is the predictability and acceleration of the project schedule [8], with some recent projects achieving a time savings of between 20 and 50% [5]. When completing a project modularly, a large majority of the decision-making and communication must occur at the beginning of the process. This heightened level of early coordination can help a project avoid costly change orders or delays. In one review of 17 conventional construction cases, two of the projects' construction timelines more than doubled due to change orders [19]. Modules can be built in a factory at the same time that foundation and other prep work is being completed at the final build site [20], potentially decreasing the overall construction time by as much as 45% [19].

Off-site construction can also reduce schedule risk associated with factors such as weather, as off-site construction work is typically completed inside factories and can usually continue regardless of weather conditions [21]. For harsh climate regions, such as Canada, this may help balance the decline in productivity and overall construction activity that is typical in the winter [22].

There are additional factors that need to be considered for modular construction, such as the lead time for production of modules and the time for transport of modules, especially if there is a large distance between the factory and the build site. Additionally, the accelerated project schedules associated with modular projects contribute directly to project cost savings by reducing the hours needed for skilled labour, on-site equipment rentals (e.g., cranes), and construction insurance. Accelerated schedules also allow for a quicker return on investment for owners and developers as a building can be occupied more quickly.

4. Considerations for Modular Construction Growth

Modular construction differs in many ways from conventional construction in terms of the planning, design, and approval of projects. This report has identified several considerations that influence the success of modular projects.

4.1 Planning

4.1.1 Project Suitability

Volumetric modular construction is better suited to certain building types than others. Volumetric modules are rectangular with maximum spans limited to the length of a module which in turn is limited by transport regulations [7] (see Section 4.2.8). Buildings with highly repeatable floor layouts, systems, and finishes like housing, hotel, health care, and educational facilities tend to be some of the best candidates for modular construction [5], [6]. Corporations such as Marriott International, McDonald's, and Greystar have adopted modular construction to accelerate construction, reduce design and construction costs, and to maintain consistent quality across their brands.

Some architects and designers believe that modular construction limits design creativity [16]. For example, given the above geometric constraints, modular construction is not well suited to open floor plans or vaulted ceilings. Manufacturers will typically optimize their plant to specific systems and materials, which may further limit the customization options available to designers.

Another geometric consideration is that the floor-to-floor heights for modular construction may need to be taller than for conventional construction to accommodate the top and bottom structure of the modules. For example, city zoning requirements may limit height of development for a site. This may affect how many storeys can be built, especially in high-rise applications where the floor-to-floor differences compound over the height of the building. Additionally, construction types (i.e., required fire ratings) in the building code place limits on the permissible height of a building. Increased floor-to-floor heights might require more stringent fire ratings to permit the increased building height.

4.1.2 Procurement Methods

Owners and developers of modular projects should carefully consider which procurement method is appropriate for their modular project. While modular projects have been constructed using many of the common procurement methods, including Design-Bid-Build, Design-Build, Integrated Project Delivery, and Construction Manager at Risk, there are several important factors to consider.

The extent of off-site construction being proposed is an important factor. For example, if only the HVAC racks are modular, these could be subcontracted by the general contractor in a Design-Bid-Build framework, whereas a fully volumetric building requires that additional factors be considered, as follows.

Each modular manufacturer may have different modular dimensions, systems, and finishes. As such, the design of the building is intrinsically tied to the modular system to be used and requires that the design team coordinate closely with the modular manufacturer. For these reasons, modular manufacturers should be engaged in the planning and design process early on. Early involvement allows manufacturers to share feedback and can lead to greater quality and accuracy in construction [10]. It can also provide greater cost certainty in the beginning stages of a project.

The need for early engagement with a manufacturer needs to be balanced against the desire for a competitive bidding process, as is typical for construction projects. Each manufacturer will have a different value proposition, including price, quality, capabilities, and production capacity – each of which may factor into the selection criteria for an owner or developer. For this reason, selection based on low cost, as is common for public/government institutions, may not make sense for modular projects. Instead, value-based bidding should be implemented with consideration based on best value and past performance rather than on cost alone [8].

To complicate matters further, the in-house capabilities of manufacturers varies greatly. Several manufacturers have in-house architectural and engineering teams. General contractors like PCL, EllisDon, and Laing O'Rourke (UK) now have dedicated modular divisions that can provide general contractor and manufacturing as an integrated service. Some manufacturers, such as Katerra in the United States and Daiwa House and Sekisui House in Japan, are fully vertically integrated with in-house planning, design, general contractor, and manufacturer capabilities.

The consensus among industry professionals is that there is not currently a single best strategy for the procurement of modular projects. However, most industry professionals seem to agree on the importance of early communication and well-defined responsibilities between parties.

4.1.3 Roles and Responsibilities

For each modular project, it is critical that the roles and responsibilities of each party throughout the project's life cycle be defined and agreed on. The owner, designers, general contractor, and manufacturer must be clear on who is responsible for the design and construction of the off-site and site-built elements. This also extends to responsibilities for factory certification, inspections, and approvals (refer to Section 4.3).

The level of development of construction documents and Building Information Modelling (BIM), where used, should also be defined. Modular projects require a much greater level of detail earlier in the design process across all disciplines. BIM has been used to help address the high level of detailed design coordination required for modular construction.

4.1.4 Project Financing

Project financing can be a challenge for developers of modular projects. Manufacturers require that the developer pay a significant amount upfront to commence production so that they can purchase raw materials and construct the modules. This is a challenge for lenders who typically disburse funds based on construction progress at the final building site, which can be used by the lender as secured real estate. Some lenders have overcome this by having greater oversight of production, including the use of digital tracking such as radio-frequency identification (RFID), live video monitoring systems, and inspections. The lender may also take a collateral or security interest in the raw materials and completed modules [23].

Additionally, since modular construction is a relatively small portion of the overall construction market, it is often not well understood by lenders. This can lead to increased financing costs for developers. Some institutional lenders are increasing their focus on off-site construction such as Citi with a division focused on new technology. Citi recently partnered with manufacturer Factory_OS on affordable housing projects in California [24]. Private lenders such as AVIVA Capital have financed several modular hotels and have cited the experience of the manufacturer and project stakeholders such as Marriott International as helping to mitigate the risks [25].

In the United States, the Federal National Mortgage Association (Fannie Mae), which provides financing for mortgage lenders, has guidance for lenders of factory-built housing. This includes modular, prefabricated, and panelized construction but is limited to single-family homes. Fannie Mae is currently working with the National Institute of Building Sciences' Off-Site Construction Council – a research, education, and outreach centre – on a lender's guide for modular buildings.

4.1.5 Project Insurance

Insurance carriers find that addressing modular through existing methods can present unique challenges, such as determining who maintains the liability during various stages of a module's transport. Most of the work in modular is completed off-site, making traditional policies such as an owner-controlled insurance program (OCIP) and contractor-controlled insurance program (CCIP) difficult to utilize [16]. As such, clear distinctions are needed in contracts regarding who holds what liability and at which stages of the process. Implementing clear delineations in contracts and liability policies can help to mitigate the risk of disputes between parties in the event of a claim.

4.1.6 Production Capacity

The production capacity of modular manufacturers is a key enabler to expanding the market share of high-rise volumetric modular construction. To fully realize the schedule benefits of modular construction, production capacity must be able to keep pace with the on-site placement of modules. To illustrate this point, one design professional estimated that the cranes on-site could erect approximately 16 modules per day while the production capacity of the typical modular factory was two to three modules per week. Ideally, the manufacturer will have enough finished modules that are ready for placement before the foundation works are completed on-site. Currently, some industry stakeholders believe it may be difficult for manufacturers to produce at the capacity and speed needed to facilitate high-rise volumetric modular construction.

Many of the modular manufacturers that do have a steady production capacity typically complete wood-frame projects and are not currently focused on high-

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"All materials and assemblies need to meet applicable codes and standards irrespective of the source – whether they are from the country where the project is located or from another country."

rise buildings, as light-frame wood is not permitted by building codes for high-rises. Production capacity is a lesser issue for low-rise projects as the number of modules that need to be stored before they are placed is relatively small. In this case, the production of modules can typically start at the same time as on-site work and be completed at the same time as the foundation.

To facilitate the growth of the volumetric modular high-rise, there needs to be a balance between production demand and production capacity. Some parties believe that if there were larger factories with a higher production capacity, the industry would shift towards building taller structures modularly. On the contrary, others believe that if there were a large enough project that required a higher production capacity, manufacturers would naturally rise to meet that demand. Yet others expressed the need for capacity and demand to play off each other and slowly help the other grow, without a "first one, then the other" approach. These challenges might also lend themselves to more complex supply chains that rely on different suppliers or manufacturers for components, systems, or subassemblies, as in other industries.

4.1.7 Supply Chain

The supply chain for modular construction has several important considerations. While many modular manufacturers perform all production of the modules in a single facility, others have more complex supply chains. For example, steel structural frames may be fabricated in one facility and then sent to another facility to be fit out with systems, walls, and finishes. There are also international manufacturers with factories located overseas that are serving projects located in North America. These more complex supply chains may be driven by the need to leverage the best capabilities available for a given project. It is also likely that these supply chains allow a project to take advantage of reduced labour and real estate costs in order to meet production capacity needs.

These advantages need to be weighed against the challenges of using this approach. Factory certification and inspections will need to be conducted at each facility. Transport and logistics between factories and the build-site need to be factored. All materials and assemblies need to meet applicable codes and standards irrespective of the source – whether they are from the country where the project is located or from another country. This can be particularly challenging for manufacturers located in other continents and supplying modules for the North American market. This is because their typical supply chain will not include North American components. As such, they must test and certify components and assemblies to meet applicable codes and standards for multiple-performance aspects such as flame spread, mould, sound transmission, and many others. Alternatively, international manufacturers may modify their supply chains to use North American components with the required testing and certification, which can increase transportation costs. For overseas manufacturers, the finished modules will need to be processed through customs on arrival at the country of installation.

Supply chains have the potential to introduce unanticipated costs and project delays. Every stage of the supply chain from material procurement to shipping of fit-out modules to the final build site needs to be considered. Discussion needs to be had early in a project with all the parties that will be involved – including, but not limited to, manufacturers, transporters, and regulators – to predict as accurately as possible the costs, impact to project schedule, and logistics associated with the supply chain. Projects should have a tracking system for managing raw materials, subassemblies, and finished modules. A lack of communication and transparency between those managing a project's supply chain can compromise the success of a project [8].

4.2 Design and Construction

4.2.1 Design for Lateral Loads

Designing a building's lateral system for wind and especially for seismic loads can be challenging for volumetric modular structures. Building codes do set out requirements for seismic design; however, there is limited, if any, guidance with respect to volumetric modular construction. Whereas low-rise buildings can utilize integrated lateral systems where the modules themselves function as the lateral system, high-rise buildings may require independent lateral systems in high-wind or high-seismic areas. In high-seismic areas, independent steel frame systems (e.g., brace frames or moment frames), concrete shear walls, or cores have been used for taller buildings. Where independent lateral systems or separated cores are required, this may reduce the cost and schedule benefits of modular construction.

Managing the performance specifications of individual modules and design elements (e.g., facade and bolted connections) can be difficult. Modules and individual elements need to be stiff and stable enough to withstand forces associated with manufacturing, transportation, storage, and final placement but provide enough flexibility to deflect in the case of a seismic event. Seismic activity can cause large shear forces in a structure as well as deformation. These forces must be considered for the overall structure as well as for each component within the modules.

Structural engineers have suggested the following areas for further research:

- Classifying the ductility factor for modular-specific tubular steel moment-frame and braced-frame solutions integral to the modular framing,
- Confirming that integrated lateral systems meet various code requirements in high-seismic areas via additional full-scale testing,
- Exploring the relationship between the seismic energy dissipation of a module, stiffened by a core wall under a seismic event, and
- Exploring the ductility of modules under seismic events with and without lateral separation.

Such research could help structural engineers develop better modular structural systems as well as encourage other engineers to participate in modular construction.

4.2.2 Connections – Structural

Once the modules are placed in their final position on-site they must be secured to the surrounding modules, and to the lateral system where applicable, via structural connections. These connections facilitate the functioning of individual module frames as a single structure. For modules constructed with structural steel, the two primary connection methods are welded or bolted connections.

In general, it is preferred to minimize the extent of welding on-site as hot work can pose a fire hazard and is a closely controlled process. Hot work permits are typically issued by a local authority for a specific time frame and to a specific person performing the work and could limit the speed of progress in connecting modules. Welding may not be desirable in high-seismic areas due to the more stringent qualifications for performing work and post-work inspections. For these reasons, bolted connections have become more common in volumetric modular design.

Access to connection locations during placement must be provided and should be incorporated into module design early in the process. The project team must also consider where and at what point in the setting process will access be available. There must be a plan in place that outlines how many connections will be incorporated and at which mate lines. Generally, accessing connection points from inside the modules is not desired due to the potential damage to the fit-out materials and interior finishes. Access to connection from the exterior of modules must consider impacts to temporary waterproofing systems.

Due to the prevalence of bolted connections in volumetric modular construction and the lack of standardization in this area, several manufacturers are developing proprietary methods of connecting modules. In some cases, manufacturers are patenting their connection systems and licensing them for use by other manufacturers.

4.2.3 Connections – Building Systems

Building systems will have connections between modules vertically and horizontally that must be considered. These include heating, ventilation, and air conditioning (HVAC), electrical, plumbing, fire protection, information technology and communications, among others. As with conventional buildings, system infrastructure will typically be distributed vertically by risers/shafts and then horizontally across the floors. Where building systems are installed into the modules off-site, connections will need to be made between shaft modules and module-to-module on-site.

The key challenges for on-site connections are access, ease of connection, and tolerances. These challenges must be thoroughly considered during the design phase. Access via riser/shafts, access panels, or the exterior of modules are typical. Access to connections for inspections, testing, and maintenance must also be considered. Additionally, access should be provided to allow for future needs.

Ease of connections should be considered in the design and selection of connection methods (e.g., pressure fittings, where permitted). Modular tolerances must be maintained as well as flexibility in tolerances for building-system connections to ensure that connections can be made.

The incoming service locations for building systems are typically placed based on site-specific conditions, including existing utility locations in the street and differences in local requirements. This may restrict manufacturers from fully standardizing the layout of affected modules at the base of the building (i.e., a bespoke layout for each project may be needed).

4.2.4 Fire-Rated Assemblies and Structural Fire Protection

In one study, fire ratings were identified as one of the biggest challenges for modular construction [7]. Modular projects must meet the same code requirements as conventional buildings, such as hourly fire ratings for structural members and fire-rated floors, walls, and roofs. Codes also specify if structural members need to be individually protected or membrane protected and provide horizontal and vertical continuity requirements for fire-rated walls, floor, and columns.

These code requirements can be particularly challenging for modular projects for several reasons. Some codes such as the International Building Code (US) require certain structural members such as columns to be individually encased. Understanding which structural elements may require this and developing viable solutions for those instances are key design challenges.

Maintaining continuity of fire-rated assemblies can also be challenging, where required. Volumetric modules are stacked vertically and horizontally creating joints vertically and horizontally at floor/ceiling and walls that need to meet code. While most of the fire-rated assemblies can be installed off-site, these joints may need to be finished on-site. For on-site finishing, access for installation needs to be considered. Additionally, certain fire resistance materials may require special inspections, so a procedure for access to perform these inspections needs to be developed.

The concealed spaces/voids created between modules may require fireblocking, draft stopping, or continuation of fire-rated walls through floor/ceiling assembly, depending on the applicable codes, construction type, and if the building will be sprinklered. Access for installation and inspection is a key issue.

Another challenge is a lack of existing testing/listed fire-rated assemblies (e.g., ULC) for modular construction. This tends to result in manufacturers needing to perform fire tests on each of the fire-rated assemblies in their modular system to demonstrate that hourly fire ratings can be met. Modular projects often have variations to the manufacturers' standard fire-rated assemblies to account for site conditions or local regulations. These variations must be addressed via additional fire testing or the local jurisdiction may accept engineering judgments or equivalencies where differences to tested/listed systems are minimal. Most modular fire-rated assemblies are proprietary.

Local authorities need to be engaged by the project team during the planning stage to review and align on relevant code requirements and agree on any testing needed prior to performing the tests. This is critical as fire testing takes a substantial amount of time to perform and the results must be submitted to the authority in order to receive a construction permit.

4.2.5 Acoustics

The same considerations for acoustics that apply to conventional construction also apply to modular construction, namely room acoustics, external sound isolation, internal sound isolation, and control of a building system's noise and vibration. Of these four areas, the modular construction's impact on acoustics is primarily seen as being in the control of internal sound isolation.

The control of sound between two adjacent spaces is dictated by the build-up of wall or floor partitions, how structurally connected the spaces are, and if there are any building elements (e.g., ducts, pipes) that allow sound to effectively "short-circuit" the demising partition.

Partitions that occur at module mate lines can result in less structural connections than in non-modular construction, reducing the ability for structure-borne sound to transmit between the spaces and increasing the sound isolation. Partitions that do not occur at mate lines but within modules can have higher levels of structural flanking at the floor and ceiling, which can result in reduced sound isolation. Locating the modular mate line between corridors and acoustically sensitive adjacent spaces, such as guestrooms or offices, can be an effective strategy to help limit the potential for disturbance.

Modular construction can utilize lighter weight non-concrete floor constructions, which can increase the risk of low-frequency footfall sound and other low-frequency sound transmission such as door slams between vertically stacked spaces. Using resilient floor materials within the floor build-up, or using a carpeted floor finish, combined with increasing the mass of the floor-ceiling build-up and limiting the structural connection between vertically stacked modules, can help improve the vertical sound isolation.

4.2.6 Construction Tolerances

Construction tolerances refer to the allowable deviations between the designed position and dimensions of a module and what is achievable on-site. Modular buildings can have tolerance requirements for module interfaces as well as individual modules. Tolerance requirements for both fabrication and construction placement should be included by the design team in specifications and design drawings for a project. Failing to properly account for tolerances in the design or failing to maintain the required tolerances in fabrication, transport, and on-site assembly can lead to significant problems in a construction project. At their simplest level, premade modules may not fit into predefined areas if the dimensions of the modules are outside of the allowable tolerances. Deviations could prevent the current level of modules and levels of modules above from fitting if deviations are compounded across levels. This is especially important for high-rise projects that have many storeys.

Issues with tolerances build upon each other and accumulate through the life cycle of a module, from

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"Communication between trades is also paramount to ensure that proper connections are made, as issues concerning tolerances between trades have been cited as a reason for modules not fitting together."

its fabrication to its final placement. For interface tolerances, it is important to consider possible site variances and systems that may be more complicated, such as independent lateral systems that require interfaces on the base and sides. Also, various construction materials have different achievable construction tolerances. Concrete is generally expected to require larger placement tolerances. Over the height of the building, the core can be "wavy," and the design must accommodate space for the tolerances between the core and modules. Care should also be taken where modules are connected within areas that have minimum dimensions to meet egress or accessibility requirements such as exit stairs or corridors, or that have maximum dimensions such as at joints that require firestopping.

For individual module tolerances, the chain of custody for modules needs to be clear. It must define who is responsible for the module at every stage and therefore responsible for meeting tolerances of the module to ensure that the module is in tolerance prior to handover.

Communication between trades is also paramount to ensure that proper connections are made, as issues concerning tolerances between trades have been cited as a reason for modules not fitting together [26]. One design professional shared an example in which volumetric modules met the tolerances requirements when they left the steel fabricator and were sent to a factory to be fitted out. However, the factory stored the modules in a yard on uneven ground and did not true them up before beginning the work. The modules were only found to be out of tolerance after the fit-out was underway. There were disagreements about which party was responsible for the deviations and how to correct the modules to be within tolerance at the time of fit-out. A good practice is to ensure that maintaining geometry within tolerance is the responsibility of whichever party is in custody of the modules at the time. Delineating requirements for tolerance checks throughout the module's life cycle and communicating clear responsibility for tolerances are required to limit risk.

Another method suggested for addressing tolerances is to indicate them explicitly on the design drawings. While this is a practical way of outlining the requirements, it is counter to the traditional architectural approach to drawings, which typically use absolute dimensions. However challenging it may be, documenting tolerances to account for items such as glue thickness and screw heads needs to be thought about, and a higher level of detail and increased coordination is needed during the design process [7]. Workers completing traditional projects on-site usually have the knowledge and expertise to make small adjustments and account for and interpret nuances that arise from unaccounted tolerances [7]. However, this is not necessarily the case on modular projects since workers in the factory may be focused on a discrete portion of the module rather than the overall tolerances, assembly of the larger structure, or concept of the final building design [7].

One general contractor had skilled labourers participate in construction both in the factory and on-site. This helped the workers achieve a better understanding of the challenges between on-site and off-site work and how work in each location affects the other. This approach resulted in a higher level of quality control in the factory and provided the added benefit of increased levels of accountability. Overall, modular construction can provide a higher level of quality control as compared to traditional on-site construction. Due to the use of standardized manufacturing processes, tolerances can be met better in a factory and it is easier to make sure things are made properly [7].

While modular practitioners have learned best practices through experience, there are no standards or guidance. For the reasons discussed, tolerances ought to be addressed as part of new modular standards development, as is the case in the UK (see Section 5.3) or in Canada for steel modules (see Section 5.1.3). A standard could address defining, documenting, managing, and maintaining tolerances through a module's construction, transport, and placement on-site.

4.2.7 Building Envelope and Waterproofing

It is paramount that modules are properly waterproofed for transport, storage, staging, and on-site assembly. Poor waterproofing can allow moisture to infiltrate and damage systems, materials, and furnishings in the modules. Given modules are often finished/closed prior to transport, even minor amounts of water could potentially cause mould, which can lead to costly problems. Waterproofing design must consider all locations where connections are made between modules, exterior walls, and the roof. There are currently no standardized practices for waterproofing and related module dryness.

For high-rise volumetric modular buildings, the facade will typically be installed off-site to avoid the need for scaffolding or swing stages on-site. Facades can add significant weight to modules and impact the design of volumetric frames, which must be designed to support the load of the facade without deflecting out of construction tolerances.

4.2.8 Transport, Staging, and Storage

Transportation of modules from the factory where they are assembled to the site where they will be placed is a consideration that is unique to modular construction. One of the most significant barriers to transportation is the distance from factory to site [19]. Transport routes must be planned and account for transport regulations, which can be challenging and will vary by project location [7]. Transport regulations may limit the height, width, length, or weight of modules that can be transported on a truck. There may be federal, state/provincial, or local regulations, depending on the factory and project locations. These regulations may require a police escort or a follow car if the module is over a certain size and may restrict the time or day when the module transport can occur [7].

It is good practice to complete "road surveys" during project planning. Road surveys involve inspecting the route that trucks will follow to deliver modules from the factory to the site. Key considerations are the road width, vertical clearance, and weight capacity that could influence the size and weight of modules [1]. Before modules are delivered, routes should be inspected again to identify any changes that have been made or components that could potentially damage the modules and that need to be mitigated [7].

Transport needs to be considered in the design as well. Volumetric modules experience different forces during transportation versus when then they are placed in a building and therefore need to be designed with both objectives in mind. Modules need to be rigid enough to withstand the transportation process, yet flexible enough to withstand different lateral loads once they are placed and connected. Some projects have used stiffening members that are added for transportation and removed before final assembly to address this. CSA Standard A277 (see Section 5.1.2) requires that modules be designed to withstand or accommodate imposed loads and stresses during transport and placement. Waterproofing, temperature, and humidity control for modules are critical aspects that must be considered from the factory to the final assembly location.

Modules may need to be stored or staged at or near the project site to ensure a ready supply of finished modules for on-site placement. For larger modular projects like high-rise buildings there usually needs to be a surplus of modules before on-site work begins. Just-in-time delivery, where modules are delivered to a site and placed almost immediately, can be an effective way of mitigating the need for large storage areas on-site [1] but can add schedule and cost risks to a project should the actual production not keep pace with planned production. During storage or staging, modules need to be protected from potential harms such as extreme weather or fire. To achieve this, modules are often shrink-wrapped before they are transported to ensure protection. Tarping or other solutions might be necessary for extended transportation times or storage needs.

If any damage occurs to the modules during transportation, storage, or staging, there needs to be "return and repair" procedures in place if the work cannot be done on-site [26]. Some regulators have raised concern that the transporting of modules may damage fire-rated assemblies that have already been inspected and certified. One approach to address this concern might include visual inspections on-site to the extent that fire-rated assemblies can be easily accessed. This is an area that may require further research.

Aside from requirements on vehicle/load dimensions and road safety, transport regulations do not specifically address transport and storage of modules intended for the built environment. The current practice for modular transport and storage is experience-based and there is no widely used guidance that addresses all the factors that need to be considered or that describes best practices.

4.2.9 Lifting, Placement, Installation, and Finishing

Modules are ready to be lifted, placed, and installed once they are delivered to a site. Lifting is typically done using cranes with spreader beams and vertical lines to support points on modules in order to ensure even weight distribution and to avoid excessive distortion of the finished module. The loads being lifted during a modular project are often significantly heavier and bulkier than the materials being moved in conventional construction.

Care is needed to ensure the protection of modules from water (see also Section 4.2.7). Coordination and communication regarding waterproofing between the set crews, the general contractor, and manufacturers must take place before on-site assembly begins and should cover as many potential water-based scenarios as possible. Some important concerns might include:

- Procedures and materials to use if it begins to rain suddenly,
- Measures that need to be taken if rain is accompanied by heavy wind, and
- How to get water off the roof and make sure it does not enter through other pathways, like an open facade.

These concerns have been addressed by installing coordinated tarping systems or temporary gutters to protect modules and divert water. Another approach used is to have a roofer who follows behind an ironworker, and after the ironworker makes each connection, the roofer immediately makes any patch required to ensure the module is watertight. In many respects, these and other methods of protecting modules from water infiltration can be likened more to renovation rather than new construction. Establishing standard means and methods for waterproofing of modules during transport, storage, and placement may help maintain the finished quality of modules.

Lifting, placement, installation, and finishing methods have generally been developed by manufacturers and project teams in absence of any regulatory guidance. This would minimally include instructions and procedures for the site construction team and coordination between the manufacturer, general contractor, and design team.

4.2.10 Fire Safety During Construction

Fire safety during construction is an important consideration for any construction project. It is typically the responsibility of the contractor to develop a plan. Standards such as the National Fire Protection Agency (NFPA) 241 outline the aspects that should be considered, along with the International Building Code

(IBC) Chapter 33 and the National Building Code (NBC) Part 8. However, there does not appear to be guidance or provisions for modular construction to address its specific risks. Off-site construction typically results in a reduction in on-site hot work, heat-generating equipment, and combustible waste, which reduces the risk of fire ignition. Conversely, where a project has fully finished volumetric modules these have potentially higher quantities of combustible content such as furniture and finishes, increasing the potential fire load. For instance, some modular hospitality projects are delivering modules for placement that are fitted out with items such as bed frames and built-in dressers. It's possible that these risk reducers and enhancers offset one another, but the larger point is that fire safety plans should consider these factors. It is unclear if these differences are being factored by insurers as well. Modular-specific guidance or revisions to applicable construction safety standards are two methods to address this. This could be informed by a fire risk assessment.

4.2.11 Chain of Custody

Clear and concise documentation must be maintained and provided by the party responsible for the module and its condition throughout every stage of the module's life. Some have expressed a desire for a more robust way to track equipment and materials [8] and help monitor quality. RFID or other technologies could be used to label modules and to track modules throughout the construction, transport, and assembly processes. These labels can provide information about the modules for easy tracking (e.g., where it was manufactured, who it was inspected by, and what approvals it has met).

4.3 Approvals

This section will cover the various elements of the approvals process for an off-site project.

4.3.1 Authorities Having Jurisdiction (AHJs)

Establishing who the Authorities Having Jurisdiction (AHJs) are for a project is a critical initial step for any construction project. The AHJs will vary, depending on the type of project and its location. AHJs are typically responsible for reviewing construction permit application drawings, issuing construction permits, doing inspections during construction, and issuing occupancy certificates. AHJs are also responsible for approving alternative solutions to code.

For modular/off-site projects, there are several key differences that affect the AHJ. Modular manufacturers often advocate that volumetric modules are products that are certified through factory certification and quality control programs. However, unlike appliances, furniture, and the like, modules still need to be reviewed and approved by AHJs as a building or a portion of a building for compliance to applicable construction codes and standards.

The AHJ for the project site may differ from the AHJ for the factory certification program. For example, a municipal building department may be responsible for administering the construction process, while a province may be responsible for administering the factory certification program. In these cases, there must be collaboration between the two agencies.

AHJs, including plan reviewers and inspectors, need to understand which portions of the building will be built off-site versus site-built. This requires that permit application drawings clearly delineate between off-site and site-built elements and that the inspection responsibilities are clearly defined. This is not addressed in construction codes currently.

AHJs must have knowledge in the design and construction differences of modular buildings, as discussed in Section 4.2. For example, AHJs have found it particularly challenging to review and inspect fire-rated assemblies and structural connections between modules. Given modular construction is still a fraction of the construction market, AHJs have limited exposure, if any, to modular construction. As a result, AHJs may need more time to review modular projects until they gain more experience. This is particularly true for high-rise volumetric modular construction.

To date, one solution that has been adopted on some modular projects is to invite AHJs into the process early on. Earlier engagement allows more time to clearly

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"Most buildings must be inspected during and after the installation or construction of various components or assemblies in a construction project."

define roles and responsibilities, to review the project, and to identify and address any concerns that the AHJs might have.

To mitigate some of these challenges in a more enduring way, there needs to be greater clarity and consistency of the process, including the interrelationships between municipal AHJs and factory certification program administrators. This should also clarify roles and responsibilities for in-factory inspection, on-site inspection, and special inspections. AHJs also need more education and project experience in key roles in modular construction projects, including plan reviewers, inspectors, and department managers. These actions will benefit AHJs and the modular industry.

4.3.2 Factory and Product Certification Programs

Most buildings must be inspected during and after the installation or construction of various components or assemblies in a construction project. For off-site/modular projects, many of these elements can only be inspected during assembly in the manufacturing facility.

A certification program can assist AHJs to confirm compliance with requirements and can benefit manufacturers and project stakeholders by allowing for a repeatable process from project to project [27].

Certification programs typically address the in-factory certification procedure, which includes certification and auditing of the factory quality program (i.e., quality assurance procedures for the facility). The program also includes certification and in-factory inspection of the off-site/prefabricated products or modules (i.e., quality control for the product). Certification programs do not typically address site-built portions of the building, on-site inspections, and testing. These programs may also not address transport, lifting, placement, or installation at the site – though they may require that the manufacturer provide instructions on some of these aspects, as in Canada.

For a factory to become certified, the AHJ may require that the AHJ conduct the certification and auditing of the program. Alternatively, the AHJ may allow for a third-party accredited certification body recognized by the AHJ to carry out these responsibilities as well as in-factory inspections.

Factory certifications are only applicable for jurisdictions in which the certification is recognized. For instance, consider a module that has been completed in a certified factory that is ready for installation on a build site in a jurisdiction that does not recognize the certification. In this case, inspections would need to be conducted as they would be for conventional construction. As such, factories serving projects in North America need to typically get certified in each state or province (and in some cases city) in order to supply modules for a project in those locations.

Information on existing certification programs, codes, and standards can be found in Section 5 of this report.

4.3.3 Third-Party Accredited Certification Bodies

Most factory certification programs allow for third-party accredited certification bodies to conduct the certification and auditing of the program. The third party must be qualified to perform that work and must be recognized by the AHJ. Once accredited, the third party can evaluate, certify, and audit a manufacturer's quality system and quality program, conduct in-factory inspections, and certify the finished modules.

There are a few third-party bodies in North America with specialist knowledge and experience in off-site/modular construction. However, it is critical that standards set out the qualifications and capabilities required of third-party bodies and to consider their periodic review and oversight to ensure the health and safety of the public.

While third parties act as a supplement to the AHJ, they are usually hired by the manufacturer. As such, codes or standards should make clear that third parties must be objective, competent, and independent of the manufacturer performing the work.

4.3.4 Inspections

For certified factories, in-factory inspections can often be performed by an accredited third-party body instead of the AHJ. This benefits the AHJ by reducing their inspection workload while also relieving the manufacturer from reliance on the AHJ inspectors' availability and schedule. Additionally, elements that are inspected in the factory may not need to be inspected again on-site, which is an advantage for modular construction.

On-site inspections may include inspections by the AHJ and third parties that may or may not be the same as the in-factory inspections. To this end, stakeholders must be clear on which items must be inspected by the AHJ or by a third party.

4.4 Education

Many of the considerations discussed previously touch on the need for providing further guidance and education to different stakeholders, including owner and developers, lenders and insurers, designers, manufacturers, and contractors. It is likely that industry professionals have been slow to adopt modular construction because it is unfamiliar, and they don't feel that they have sufficient experience to perform this type of work. One poll found that 46% of contracting, engineering, and architectural firms believed that improved education and awareness would help the industry better understand the benefits of modularization and be a driver for future adoption [28]. In recent years there have been several guidance documents published, including Design for Modular Construction: An Introduction for Architects [29] and the Handbook for the Design of Modular Structures [33], which are intended to assist designers.

Similarly, providing education and training resources for AHJs will help to raise the level of awareness and understanding of off-site/modular construction. This, in turn, will benefit AHJs and the communities they serve.

Lastly, providing guidance, standards, and frameworks for procurement, financing, and insurance would go a long way in supporting lenders, insurers, owners, developers, and manufacturers address the commercial aspects of modular construction projects.

4.5 Additional Considerations

Through the course of this research, a list of additional topics were identified for further consideration.

- Labour laws, prevailing wage requirements, and union/non-union labour agreements in the fabrication plant location(s) and in the final building location.
- Impact of off-site/modular construction on insurance and workers' compensation policies.
- Building Information Modeling (BIM) and Design for Manufacture and Assembly (DFMA).
- Performance testing to better understand the structural limits of different module designs.
- Evaluation of modular buildings compared to conventionally constructed buildings with respect to structural performance, fire performance, and material usage.

- Building materials research and development for use in off-site/modular buildings.
- Collaboration among AHJs, certification program administrators, and standards organizations to increase education and promote harmonization of the approvals process.
- Recognition of off-site/modular construction in voluntary sustainability programs such as the US Green Building Council's LEED.
- Post-occupancy audits of modular buildings to ensure maintenance and longevity.

5. Codes and Standards Review

In general, off-site/prefabricated buildings must comply with the same codes and standards as conventionally constructed buildings. The existing construction codes in many countries do not have a subset of a provisions tailored to off-site/prefabricated buildings. Instead some countries may recognize factory-built elements and refer to other standards which have specific off-site requirements, or defer to states and provinces which may have programs in place. Off-site construction has unique considerations such as transport and the lifting and placement of modules that are not addressed by existing codes and standards. These gaps and the patchwork approach to regulation is suboptimal for the industry.

Codes and standards development must continue to keep pace with the increasing prevalence and scale of modular, panelized off-site construction and emerging trends and technologies, such as shipping containers repurposed as buildings, 3D printed buildings, and tiny homes. The challenge for codes and standards organizations is to develop or adapt regulations in response to these industry trends to ensure public safety while allowing for continued innovation.

The following provides a high-level targeted review of applicable codes and standards related to modular construction in Canada and several other countries and regions.

5.1 Canada

5.1.1 National Building Code

The National Building Code (NBC) is the model building code in Canada. The NBC is adopted by individual provinces and territories, allowing each to review and consider if any jurisdiction-specific variances are required prior to implementation. The NBC, as with other construction codes, references a range of different standards that become enforceable as an extension of the code. In relation to modular construction, the 2015 edition of the NBC mentions a few existing standards, as described in the following sections.

5.1.2 Standard on Certification of Prefabricated Construction

CAN/CSA Standard A277-16 *Procedure for Certification of Prefabricated Buildings, Modules, and Panels* (CSA A277) is referenced in the NBC. CSA A277 specifies procedures for certification of prefabricated products, factory quality programs (certification and auditing), and in-factory inspections of prefabricated products [30]. The scope of this standard covers prefabricated buildings as well as volumetric and panelized modules for any building occupancy.

Certification of quality systems and programs are addressed and include the requirements of those responsible for the quality program and the documentation required of the program in order to maintain factory certification. Certification of assemblies, such as modules and panels, must include proper markings, specification sheets, and instructions for connections of structural components and services. CSA A277 also includes requirements for factory surveillance by the certification body to confirm proper implementation and operations of the quality program and proper construction of pre-fabricated buildings and components. The appendix of this standard covers the welding reference standards for aluminum (CSA W47.2) and steel (CSA W47.1), as well as pre-cast concrete (CSA A23.4).

CSA A277 requires that modules be designed to withstand or accommodate imposed loads and stresses during transport and placement, but the scope excludes other activities outside the factory such as transport, lifting, placement, installation, and site-built elements.

CSA A277 can be used for high-rise volumetric modular projects. It should be noted that it is not a reference document in all provinces and for all building types. For instance, in some provinces it may be referenced in Part 9 (housing and small buildings) but not in Part 3 (other buildings, typically larger and include high-rise buildings), and so on. Additionally, the edition of CSA A277 that is referenced varies by province (the 2015 NBC references the 2008 edition, for example). These variations provide for an uneven regulatory landscape for modular stakeholders working across the country.

5.1.3 Standard on Certification of Manufacturers of Steel Building Systems

Notes in the NBC refer to CSA Standard A660-10 (R2019) *Certification of Manufacturers of Steel Building Systems* (CSA A660). CSA A660 provides the requirements for a certificate of design and manufacturing for steel building systems supplied by a manufacturer [31]. This standard covers the requirements for personnel involved in all stages of the design and construction process as well design requirements for steel components. Fabrication requirements such as specific welding standards that need to be met and tolerances of structural members are also included. Finally, information is provided about the need to demonstrate proper packaging and shipping methods as well as requirements for the needs of erection documents.

5.1.4 Standard on Manufactured Homes

CSA Standard Z240 MH Series-16 *Manufactured Homes* (CSA Z240 MH) is not referenced in the NBC, but is included in this review as it addresses manufactured homes and outlines general requirements for technical design, quality control, and markings required for these structures. The scope of CSA Z240 MH is limited to one-storey buildings and is not intended for high-rise volumetric modular construction.

5.2 United States

5.2.1 International Building Code

In the United States, the International Code Council (ICC) produces the International Building Code (IBC), one in its series of I-Codes, which is adopted by local and state jurisdictions with or without amendments. References to approved fabricators, fabricators' certificates of compliance, and factory-built components are made in administrative portions of the I-Codes; however, modular/off-site construction is not specifically addressed. Overall, there is currently very little in the I-Codes that is specific to modular construction.

5.2.2 State Certification Programs

The US National Bureau of Standards published a model document for evaluation, approval, and inspection of manufactured buildings in 1973 [29]. Today, there are at least 35 states and some local jurisdictions with regulatory programs for modular construction. The state programs typically cover factory certification and product certification along with quality program elements, such as inspection and auditing. The programs do not typically have design requirements and modular buildings must comply with the same codes and standards as conventional buildings.

For these state-led programs, project designers submit their drawings for modules to the state-wide program for review and approval rather than submitting them to the local municipality [29]. Individual state programs may have different requirements for which stages of the process require inspections, but generally if they are required, a state-licensed third-party agency is employed to complete inspections [29].

While the state programs cover similar areas, the regulatory requirements and text differ from state to state. This is burdensome for manufacturers. Harmonization of certification programs is needed to enable manufacturers to more easily operate nationally.

5.2.3 Standards in Development

In 2019 the ICC began the development of two new standards to support the off-site construction industry. The draft titles for the two standards are *ICC 1200, Standard for Off-Site Construction: Planning, Design, Fabrication and Assembly and ICC 1205, Standard for Off-Site Construction: Inspection and Regulatory Compliance* [30]. The intent of ICC 1205 will be to largely supersede the substantive elements of the state programs and allow the states to focus on enforcement rather than code development, and to simplify the regulatory environment for modular manufacturers and designers. To drive

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"The International Standards Organization (ISO) and British Standards (BS) had produced standards for modular coordination as early as the 1980s."

adoption, these standards will need to be recognized in the ICC model codes and then adopted by each state.

ICC G5-2019 Guideline for the Safe Use of ISO Intermodal Shipping Containers Repurposed as Buildings and Building Components was published in 2019 for conversions of shipping containers into buildings. This document is currently a guideline.

UL LLC Outline for 3D Printed Building Construction is currently under development by Underwriters' Laboratory (UL) to address 3D printed buildings, which is an emerging technology.

5.3 Europe/United Kingdom

The International Standards Organization (ISO) and British Standards (BS) had produced standards for modular coordination as early as the 1980s. One of these is *ISO 21723:2019 Building and civil engineering works- Modular coordination- Module* that establishes value and coordination information as well as preferred vertical modular and multi-modular dimensions [31]. Other ISO and BS standards have been produced to address joints, accuracy, and tolerances that have been identified as out of date or limited in scope [26]. The British Standards Institution (BSI) is currently working to review *BS 5606: Guide to Accuracy in Building* that covers accuracy and tolerances.

The Building Research Establishment (BRE) has produced BPS 7014: *BRE Standard for Modular Systems for Dwellings* that outlines system and component performance and verification requirements. European Standards (EN) has also written standards regarding precast concrete and prefabricated timber. Some issues with the standards regarding tolerances and coordination have been identified. Standards regarding design of steel structures and framing also exist that might be applicable to modular construction but that do not address it specifically. Overall, there are no standards that address major elements such as pods or panelized systems, and there are no standards that address modular construction holistically [26].

BSI completed a review of existing standards relating to off-site construction in 2019 and concluded that there is a need for new standards to address [26]:

- Agreed processes for design teams
- Supply chain relationships
- Quality control, testing, and maintenance
- Accuracy and tolerances

5.4 Australia

In Australia, Monash University published a guidance document in 2017 entitled the Handbook for the Design of Modular Structures [32]. While this document is not written with the intent to become an enforceable standard, it does cover many of the key considerations for modular construction, which could lay the groundwork for standards development.

6. Codes and Standards Gap Analysis

This report has described several considerations that should be addressed to facilitate growth of the high-rise volumetric modular construction industry. These considerations are the culmination of interviews with industry stakeholders, a workshop conducted with industry experts, literature reviews of published information, and a thorough analysis of existing codes and standards.

The information presented in Section 5 indicates that the scope of existing standards excludes activities conducted outside of the factory such as transport, lifting, placement, installation, and site-built elements, and that currently no codes or standards exist that address modular construction holistically. This coupled with the use of different regulations from province to province (or state to state), make it difficult for manufacturers to efficiently operate across the country.

The research conducted has helped identify that many of the existing industry challenges could be addressed through new standards, updates to existing codes, and, in many cases, non-mandatory guidance documents where an enforceable code or standard is not required or not an appropriate solution. This section outlines recommended actions to address these areas.

As the modular industry is still relatively new in Canada, guidance and education are needed across several aspects of this construction method. Depending on the specific subtopic, guidance may take the form of guidelines, which could be developed by standards development organizations or other groups and associations. The topics identified and discussed in this report are listed in Table 2, along with a breakdown of the stakeholder groups that would most benefit from comprehensive guidance. Looking beyond guidance development, the table also presents important recommended actions, including improvements to standards and codes that are related to each of the topics.

***Table 2:** Recommended actions to support the modular construction industry*

Consideration/Gap	Stakeholders Requiring Guidance	Recommended Actions
PLANNING		
Project Suitability (Section 4.1.1)	Developers and designers	
Procurement Methods (Section 4.1.2)	Developers, designers, manufacturers, and contractors	
Roles and Responsibilities (Section 4.1.3)	Developers, designers, manufacturers, and contractors	▪ Codes/standards should recommend that roles/ responsibilities be defined.
Project Financing (Section 4.1.4)	Lenders, developers, manufacturers, and contractors	
Project Insurance (Section 4.1.5)	Developers, designers, manufacturers, and contractors	
Production Capacity (Section 4.1.6)		▪ Dissemination of knowledge should be enhanced through sharing of high-rise volumetric modular case studies, including the module production rate and construction schedule.
Supply Chain (Section 4.1.7)	Developers, designers, manufacturers, and contractors	▪ Codes/standards should clarify that global supply chains must comply with applicable codes and standards at the project location. ▪ Standards for factory and product certification programs should include supply chain guidance.

Consideration/Gap	Stakeholders Requiring Guidance	Recommended Actions
DESIGN AND CONSTRUCTION		
Design for Lateral Loads (Section 4.2.1)	Designers and manufacturers	▪ Codes/standards should require consideration of transportation, storage, lifting, placement, and assembly in the structural design.
Connections – Structural (Section 4.2.2)	Designers, manufacturers, contractors, and AHJs should be developed	▪ Codes/standards should address required documentation for plan review; installation instructions for contractors and consideration for inspections and maintenance.
Connections – Building Systems (Section 4.2.3)	Designers, manufacturers, contractors, and AHJs	▪ Codes/standards should address required documentation for plan review; installation instructions for contractors and consideration for inspections and maintenance.
Fire-Rated Assemblies and Structural Fire Protection (Section 4.2.4)	Designers, manufacturers, contractors, and AHJs	▪ Codes/standards should require that AHJs submissions include documentation (e.g., drawings) for plan review.
Acoustics, Sound Transmission and Vibration (Section 4.2.5)	Designers, manufacturers, contractors, and AHJs	▪ Codes/standards should require that AHJs submissions include documentation of compliance for plan review.
Construction Tolerances (Section 4.2.6)	Designers, manufacturers, contractors, and AHJs	▪ Codes/standards should address defining, documenting, managing, and maintaining tolerances through a module's construction, transport, staging/storage, and placement on-site.
Building Envelope and Waterproofing (Section 4.2.7)	Designers, manufacturers, contractors, and AHJs	▪ Codes/standards should address waterproofing during transport, staging/storage, and placement on-site; as well as maintaining envelope integrity once assembled. ▪ Testing procedures should be developed.
Transport, Staging and Storage (Section 4.2.8)	Designers, manufacturers, contractors, and AHJs	▪ Codes/standards should address the need for designers/manufacturers to design modules to withstand transport loads/forces; transport/storage procedures for waterproofing, temperature, and humidity control; and considerations for handling modules that are damaged during transport.
On-Site Assembly and Finishing (Section 4.2.9)	Designers, manufacturers, contractors, and AHJs	▪ Codes/standards should address defining and documenting erection, placement, and assembly.
Safety During Construction (Section 4.2.10)	Manufacturers, contractors, and fire services	▪ Modular-specific non-mandatory guidance should be added to applicable construction safety standards (e.g., NFPA 241, NBC Part 8).
Chain of Custody (Section 4.2.11)		▪ Codes/standards should address defining, documenting, and managing the chain of custody while allowing for new technologies to enable this. Module labelling and tracking should be addressed in existing or new standards for factory and product certification programs.

Consideration/Gap	Stakeholders Requiring Guidance	Recommended Actions
APPROVALS		
Authorities Having Jurisdiction (AHJs) (Section 4.3.1)	Plan reviewers, inspectors, and management levels	▪ Guidance could be included in a standard as non-mandatory guidance in annex/appendix or in a standalone document.
Factory and product certification programs (Section 4.3.2)		▪ National standards for factory and product certification programs should be developed (US) or updated (Canada). ▪ Adoption by states/provinces across all occupancy types should be enhanced. ▪ State/provincial programs should be repealed where redundant with above standard(s) noting that administrative requirements would likely remain on a state/provincial level (e.g., application forms, fees).
Third-party accredited certification bodies (Section 4.3.3)		▪ National standards to address third-party requirements that include minimum qualifications, accreditation, and independence should be developed (US) or updated (Canada).
Inspections (Section 4.3.4)		▪ National standards for factory and product certification programs should address definition of roles/responsibilities for inspections by various parties (i.e., AHJs, third party).
EDUCATION		
Education (Section 4.4)	As noted in the sections above	▪ Guidance should be tailored to specific user groups. For example, focused guidance for lenders/insurers on procurement/financing/insurance and similarly for AHJs on plan review/inspections/certification.

7. Conclusion

Modular construction is well positioned to help respond to societal challenges such as urbanization, the availability of affordable housing, and skilled construction labour. This research report has explored the current state, drivers, benefits, and barriers to the growth of high-rise volumetric modular construction. Due to the complexity of this emerging construction and design method, more guidance and education will aid significantly in the uptake of modular construction. A long history of well-established practices and a wealth of available industry codes and standards have led to a great confidence in traditional construction. The modular construction industry stands to gain similar benefits from a more comprehensive codes and standards framework that is tailored to this construction method. The idiosyncrasies of high-rise volumetric modular construction are not holistically addressed by current codes and standards.

The review and gap analysis of codes and standards related to modular construction (Section 5) has yielded several recommendations to support the Canadian modular construction industry. The proposed actions presented in Section 6 were analyzed further to determine the most important items of consideration that will provide the largest impact and most benefit to the industry. The following are the four highest priorities for modular construction stakeholders, with respect to codes and standards development:

1. **Develop a new standard for off-site/modular construction.** The goal of the standard should be to address gaps in the existing codes and standards rather than to "double-regulate" off-site/modular buildings. More specifically, the standard should be a complement to CSA A277 (which addresses the factory and product certification) and to building codes. If portions of the building codes are found to be suboptimal for off-site/modular construction, those should be addressed separately through the code development cycle. As with the NBC, it is recommended that the standard be performance-based. It is also recommended that standard definitions be used for off-site/modular construction nomenclature. The new standard should minimally include the following areas:
   - Roles and responsibilities
   - Supply chain
   - Chain of custody
   - Design for lateral loads
   - Connections – Structural
   - Connections – Building systems
   - Fire-rated assemblies and structural fire protection
   - Acoustics, sound transmission, and vibration
   - Construction tolerances
   - Building envelope and waterproofing
   - Transport, staging, and storage
   - On-site assembly and finishing
   - Safety during construction
2. **Increase and expand adoption of CSA A277 by the provinces**. Provincial codes and rules should be updated to directly reference the latest version of the standard and to allow for its use for all occupancy groups and buildings of any height. Each province and the national codes have code development cycles and these actions should be prioritized according to those schedules.
3. **Review and update CSA A277.** The next periodic update of the standard should consider the following updates and review for other updates to address the considerations identified in this report:
   - Harmonization of any substantive provincial requirements (e.g., Alberta)
   - Labelling, identification, and chain of custody practices and procedures
   - International supply chain (expand on guidance in A4.1)
4. **Develop guidance for AHJs for off-site/modular buildings.** The guidance should cover the following areas:
   - Administration
   - Plan reviews
   - On-site inspections
   - Factory and product certification programs
   - Coordination between local and provincial AHJs, where applicable
   - Third-party accredited certification bodies

As discussed in Sections 3 and 4, there are many factors that contribute to the uptake of modular construction. The above recommendations will enable growth in modular construction by providing a more comprehensive and consistent regulatory environment for the design, construction, and approval of modular buildings.

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