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Theme: Industrialized Wood Construction - Part 1

Editorial

Industrialized wood construction is part of a larger movement to modernize the design and construction delivery process. Industrialization, offsite prefabrication, pre-manufacture are all words that describe the continuous improvement process of moving construction operations off the job site and into the factory where components, panels and modules are produced with quality and speed and then shipped and delivered to the site for installation. The intention of this Wood Design Focus 2-part series is to address research topics related to the growing demand for industrialized wood building systems. Part 1 of deals with light wood platform frame construction. Part 2 will include topics related to mass timber construction.

The first paper by Rupnik from Northeastern University provides an overview of global industrialized wood market by featuring the following three unique geographies: 1) Asia including India and China where industrialized wood construction has low adoption and low level of industrialization; North America including the US and Canada where there is a high adoption of wood construction, but industrialization is low; and 3) Europe and Japan where there is a relatively high adoption of wood construction compared with Asia and a significantly higher level of industrialization when compared with both Asia and North America. The article concludes with lessons learned and additional questions about the future of industrialized wood construction internationally.

The second paper authored by Memari, Lulo and Griffin from Pennsylvania State University addresses air barrier membranes that are essential for Passive House light wood frame prefabricated wall panels. The study evaluates the serviceability and performance of self-adhered and fluid-applied air barrier membranes and sealant tapes and their failure mechanisms considering lateral racking. The article concludes that air barrier performance and serviceability are a function of the material properties of the barrier, self-adhering or fluid applied, the mechanical properties of the substrate, and testing data. This study demonstrates that in high seismic regions, most self-adhered membranes and tapes do not preserve airtightness while fluid applied membranes have a higher elongation capacity and provide a better service life.

The final article in Part 1 by Barkokebas, Alwisy, Altaf and Al-Hussein from the University of Alberta addresses the knowledge gap between the potential benefits of industrialized wood construction and the realized impact. This article proposes a framework to evaluate the impact of industrialized light wood frame wall panels by comparing scenarios for lumber waste and usage. Applying the framework, the research demonstrates that reductions of more than 60% can be realized by prefabricating wall panels in the factory and reducing wastage and 18.39% usage can be reduced through advanced framing techniques.

We hope you find this issue of Wood Design Focus informative. As always, comments and questions are welcome.

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The Geographies of Industrialized Wood-based Construction for Mass Housing

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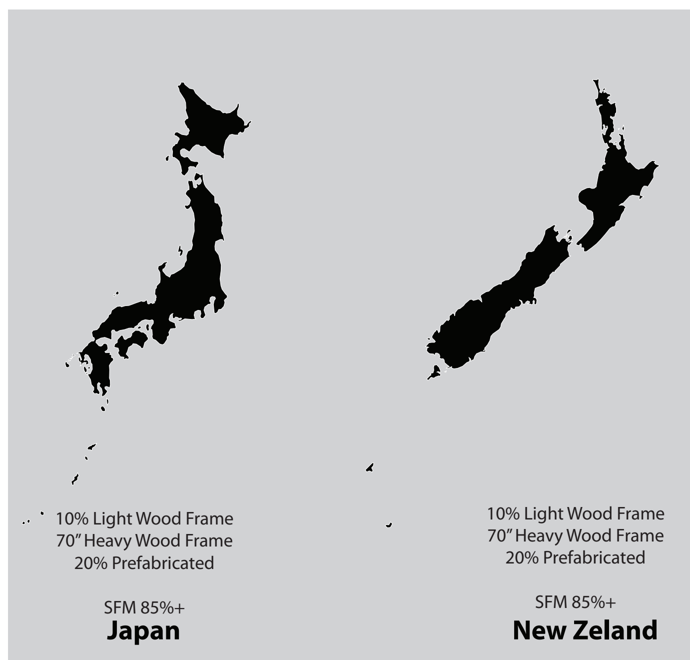
Innovative approaches to industrialized wood-based construction (IWBC) have impacted a variety of building typologies, including mass housing. Nevertheless, when viewed from a global perspective, IWBC still constitutes less than 2% of the construction market. (Mahapatra and Gustavsson, 2009) Even those regions where this approach is more common, market share has struggled to grow, particularly when it comes to mass housing, despite of the concerted effort of companies, trade associations and a supportive public sector. This article maps out the current market penetration of industrialized wood-based construction in mass housing by region, identifying the key factors that have helped the industry grow, as well as those that have limited further expansion. Short case studies from each region will supplement the general overview. In conclusion, the article will distil the current international trends in industrialized wood-based construction as applied to mass housing.

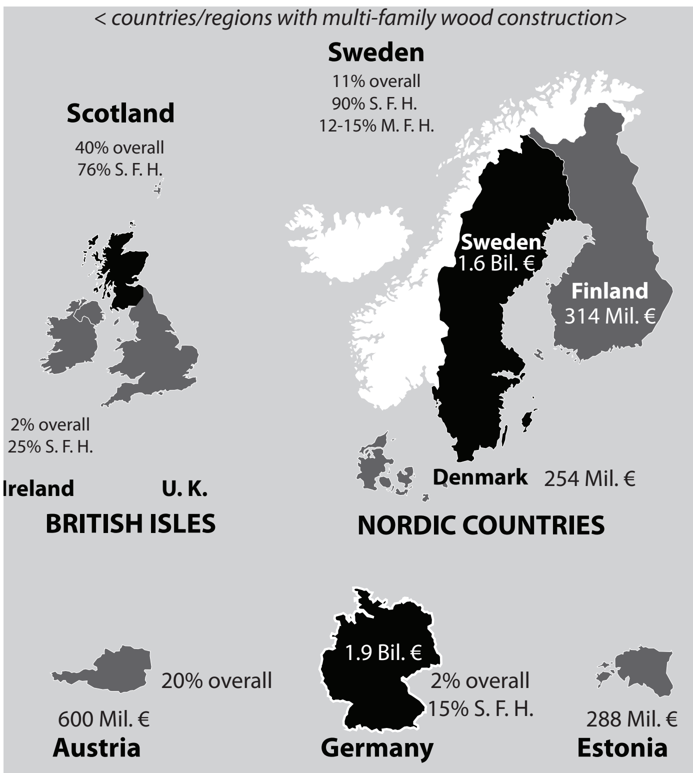
Three Geographies of IWBC

As is common with many other industries, industrialized-wood based construction methods have rapidly expanded from the contexts within which they were first developed across the globe. Cross laminated timber (CLT), initially developed in Austria, or light wood frame construction, concentrated in primarily in the United States for more than a century, are now found in parts of North America, Europe and Asia. Despite the globalization of these methods, particular geographies of acceptance and advancement related to IWBC in mass housing persist, but are all too often ignored when considering the future of this mode of project delivery. Precisely because of the globalization of certain methods of IWBC, it is possible to begin to map the geographies of the broader acceptance of this approach to mass housing.

The first and most prevalent of these geographies is marked by a low use of wood-based construction and a low degree of industrialization. This includes much of Asia, including India and China, where IWBC construction is less than 2% (Mahapatra and Gustavsson, 2009), Africa, Latin America, as well as much of southern and eastern Europe.



The second geography, and most geographically compact region, comprised of the United States and Canada, where wood-based construction dominates all sectors with market shares of over 90% (Mahapatra and Gustavsson, 2009), including single as well as multi-family construction. Wood construction has prevailed for much of the twentieth century, but where industrialization remains relatively low, despite significant private and public investment initiatives. New Zeeland, and to a lesser degree, Australia, could also be described as belonging to this geographic region.



The third geography, which includes Central and Northern Europe as well as Japan, combines a relatively high acceptance of wood-based construction as compared to the first geography with a significantly higher degree of industrialization, when compared to second geography. For much of this geography, with the exceptions of Japan and the United Kingdom, where light gauge steel is also a significant percentage of industrialized construction, industrialized building and wood building are often synonymous. With regard to mass housing, however, with the exception of Sweden, IWBC has been relegated to single family, despite of significant efforts by the local industries and, more recently, by the public sector, to enlarge the market share of multi-family.

In both the second and third geographies, a number of private and public initiatives suggest that the two may be converging, with new actors in the second seeking greater industrialization and existing actors in the third seeking higher acceptance of wood-based construction in multi-family mass housing.

IWBC's Second Geography – High Acceptance, Expanding Industrialization

Wood-based construction constitutes the wide majority at 90% market share. This is as high as 94% in single-family housing in North America (Mahapatra and Gustavsson, 2009), Even more exceptional, when viewed from a global perspective is that the most prevalent building system, light wood frame construction, has dominated since the mid 19th century (Peters, 1995). Highly standardized, requiring low skill and utilizing on-site improvements to gain efficiency, this system survived and thrived despite challenges from non-combustible building systems at the turn of the last century. These, same systems have now become predominant throughout the rest of the globe. In the years following World War II, light wood frame construction, particularly as applied to single family housing delivered in large developments, also achieved a high degree of onsite industrialization.

Following trends in other industrialized countries during the postwar period, the US, through the expanded Department for Housing and Urban Development, sought to transform mass housing from site built single family light wood frame construction to factory built multi-family concrete construction, through the Operation Breakthrough program (circa 1969 -1974). Ultimately deemed a failure in 1976 by Congress, the program did pave the way for the largest federally mandated industrialized wood-based system in US history, the Manufactured Housing Program. Manufactured homes, also known as HUD Code home, or more colloquially "trailers", existed prior to this program and regulatory framework, but by receiving its own code, this form of industrialized light wood frame construction grew immensely in market share. The manufactured housing industry hit its peak in 1998, with 330 plants delivering a total of 372,843 homes, which constituted 30% of new single-family homes sold that year (census.gov). The industry has experienced a steady decline over the last two decades, with about 120 plants holding 10% market share of single-family housing construction in 2018.

As early as the late seventies, a number of manufacturers of HUD Code homes began producing a different variant of industrialized light wood frame construction, now commonly referred to as volumetric construction. The Modular Building Institute, that industries trade association, formed in 1983, defines permanent volumetric modular construction as "a process in which a building is constructed off-site, under controlled plant conditions, using the same materials and designing to the same codes and standards as conventionally built facilities… in "modules" that are then put together on site". Whereas HUD Code homes have their own code, modular buildings have the advantage as well as the disadvantage of falling under conventional building code, either the IRC or IBC. While some modular manufacturers utilize a combination of structural and light gauge steel systems, approximately 70% of commercial permanent modular construction, a designation that does not include single-family housing, is light wood frame (Permanent Modular Construction, 2013 Annual Report).

For much of its recent history the modular building industry, now estimated to include as many as 200 manufacturers, has struggled to gain market share, hovering around an estimated 2%, although data is not as readily available as with manufactured housing. Since 2010, the industry has experienced growing market share, particularly in hospitality and multi-family housing (Modular Advantage). Manufacturers that previously focused on single-family are retooling and reorganizing for these new markets. In a first for the industry, demand is exceeding manufacture's capacity and capability, especially in hospitality, where Marriott International has taken a leadership position in advocating for the advantages of volumetric modular construction on the one hand while at the same time critiquing the industry for not expanding to meet these opportunities.

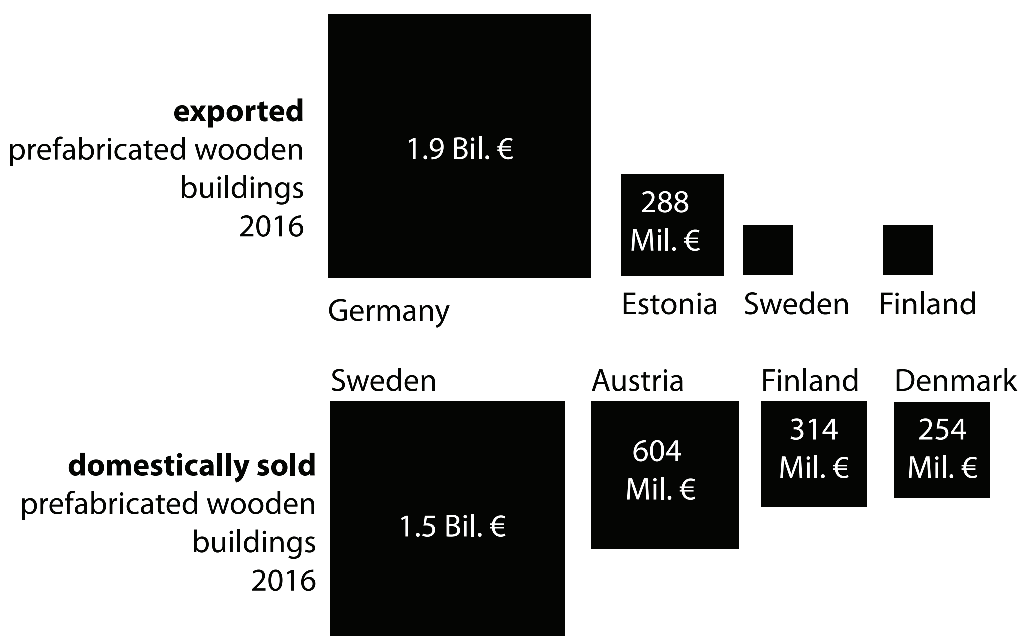
Some of the most significant investment in the area of industrialized wood-based mass housing construction has focused on panelized systems and not on the more established manufactured and modular construction industries. One established company, Bensonwood, based in New Hampshire and two new companies, Blueprint Robotics in Maryland, and Katerra, based in the Bay Area but with a growing presence throughout the country, have all invested in the kind of factory fit outs common in Europe and Japan but rare, even nonexistent in the US. Like their international peers, these companies are also developing much more vertically integrated delivery systems, especially

Katerra. While all three are currently producing light wood frame open panel systems, Katerra has also made a major investment in a new composite laminated timber (CLT) factory, located in Spokane, Washington, with plans to replace the floor components of their current multi-family light wood frame open panel system with mass timber panels.

IWBC Third Geography – High Industrialization, Expanding Acceptance

While different in many ways, within the context of IWBC, northern and central Europe and Japan share many characteristics in common. In comparison the rest of the globe, both regions have a high percentage of wood-based construction, in comparison to the US and to Canada, their construction industries are more industrialized, and have been for some time. However, in most cases industrialized wood-based construction has been focused on single-family housing, despite of significant efforts, particularly in parts of Europe, to expand into multi-family housing. Sweden, the European country with the most success in expanding market share of IWBC multi-family, and Japan, the most industrialized construction industry in the world, both adopted light wood frame construction, the latter in the nineties, the former in the seventies, offering examples of how this most American system could evolve over the next few decades in the country of its origin.

While there is significant research on the market penetration of IWBC in Europe, the most consistent data has been tracked by the European Union in the form of "prefabricated wooden buildings" as constituting the yearly "domestically sold construction products" and "most exported construction products" of a member state ('Country Profile Sweden, 2018). The largest prefabricated wooden buildings industry, by value, is located in Germany, where the 1.9 billion euro industry constitutes 6.4% of the overall value of that countries construction industry. This figure reflects exported products, with internal consumption of IWBC mass housing in Germany still relatively low, at 2% of overall construction and 15% of single-family construction (Country Profile Germany, 2018). Austria, the home of CLT, shows more significant domestic consumption, with prefabricated wooden buildings constituting 9.4% or about 600 million euros of that countries construction industry (Country Profile Austria, 2018). Overall market penetration of IWBC in that country is estimated at 20%, significantly more than European Union average of less than 5% but still less than that of the "Nordic" countries, where market penetration is estimated at 45%, and as much as 85% in single-family construction (Mahapatra and Gustavsson, 2009; Hurmekoski, 2016). While Estonia, like Germany has a significant export industry, Denmark and Finland have



significant domestic consumption, 254 million euros for the former, 314 million euros for the later, Sweden is the largest domestic consumer of prefabricated wooden buildings, with the highest market value share, of 29.3% (the number one sector in terms of value) and an overall value 1.5 billion euros (Country Profile Germany, 2018). While single family housing construction has been dominated by IWBC for some time, Sweden has managed to also significantly increase market penetration of multi-family, up to 15%. The two other European countries where IWBC has above average market share are Ireland, where it is 25% of single family but still a small segment of construction as whole, and the United Kingdom, where it is about 20% of single family, but where "prefabricated buildings of metal" still constitute a much larger portion of the overall construction industry (Country Profile UK, 2018). In the UK, Scotland has achieved IWBC market penetration on par with Scandinavian countries (Mahapatra and Gustavsson, 2009).

In the early nineties, Sweden's IWBC industry was similar to that of other Scandinavian countries, as well as other parts of northern and central Europe, with high market share concentrated in single family housing. The expansion of IWBC into multi-family can be traced back to a research project conducted at Upsala University, funded by one of the country's largest forest products companies. That project compared American light wood frame and European concrete frame construction, finding the former more economical. Over the next two decades, multiple research initiatives and demonstration projects led to changes to building code in that country, allowing for taller wood-based structures. This broader transformation parallels that of one Sweden's largest and most innovative volumetric modular companies, Lindbäcks.

Originally founded in 1924 as a forest products company, Lindbäcks began producing panelized light wood frame structures, almost exclusively for the single-family market in the 1960s. By the nineties, the company had achieved a degree of industrialized construction comparable to the new US players, such as Katerra, whose own equipment is being supplied by Randek, a Swedish manufacturer of automated equipment. In 1994, the company decided to shift gradually from panelization, with a focus on the single-family market, to volumetric modular, with a focus on multi-family construction. Since 2000, the company has entirely focused on this new approach and market segment, opening the largest volumetric modular factory in the European Union last year, in Luleå, Sweden. Following the success of Lindbäcks, another large forest products company currently working primarily with panelized lightwood frame systems for the single-family market, Derome, has recently developed a volumetric modular system for multi-family housing.

In Japan, industrialized wood-based construction constitutes approximately 45% of overall construction, similar to Scandinavian countries. Wood-based construction dominates single family construction at around 80% or more, which itself is broken down into three categories, the first being heavy timber frame, at 70% of market share and light-wood frame construction at 10% as well as a portion of the "prefabricated" sector, which itself is 20% of single-family housing but which is primarily light-gauge steel (Matsumura, 2004). In Japan, industrialized building during the postwar period was initially led by concrete and then light-gauge steel, with local and imported wood-based systems becoming more industrialized after the energy crisis of 1973. Japan was one of the first countries outside of North America to introduce light-wood frame construction in 1974, and has been importing dimensional lumber from Canada and Sweden since. (Rupnik and Smith, 2018)

Sekisui Heim, the world's largest and most technologically advanced volumetric modular manufacturer, has developed a light-wood frame volumetric modular system since that time. While still only 20% of their business, the remainder being light-gauge steel, Sekisui Heim's wood-based system still generates 2400 housing units a year. During the same period that light wood frame construction was adopted and adapted into a volumetric modular systems by Sekisui Heim, CADCAM technology started to applied to traditional heavy timber frame construction, the dominant constructive system in mass housing in that country. After thirty years of transformation, 74% of that wood-based constructive system can be said to be at least partially industrialized, a percentage that has continued to grow in the last decade (Matsumura 2006). In 2017, Japan's Ministry of Agriculture, Forestry and Fisheries has expressed interest in expanding the countries forestry products industry in general, including greater adoption of CLT products, following the model of Austria and other European countries. Whether Japan's sophisticated industrialized wood-based constructive systems will expand from single family to multi-family housing is not yet clear.

The Future of IWBC in Mass Housing

After a century of disuse/decline wood-based construction has experienced a renaissance, albeit one that has so far been limited to certain geographies and typologies. Will it continue to expand in those regions? Will it expand to other parts of the world where non-combustible materials and site construction dominate mass housing delivery? A century ago, the fledgling global concrete industry was boosted by the expansion of regulations and standards that virtually eliminated wood construction from much of the world, outside of the United States and Canada, even in low and mid-rise construction.

A comparable paradigm shift could come from the kind of regulations and standards coming to the European Union in 2020, where performance-based guidelines will expand the focus from the performance of static structures to the construction process more broadly, including its use of energy and renewable resources in the equation. This shift combined with the EU's broader carbon sequestration goals have the potential to finally expand wood-based construction into southern and eastern Europe and into low and mid-rise multi-family mass housing to market shares comparable to Sweden and Scotland. With nearly all wood-based construction in Europe already being significantly industrialized, a second paradigm shift driven by a shortage of labor in construction, skilled and unskilled, and the abysmally low productivity on conventional construction, could push the IWBC in the EU towards the kind of market share that currently exists in the US.

In the US, it is this second factor that has been driving the construction industry, already dominated by wood-based systems, toward higher industrialization. This has in turn also led to increased interest and effort from the Department of Energy to study the positive potentials of IWBC, since the process is already underway. Current research is focusing on the performance of offsite structures but the real advantage of IWBC would really require a complete cradle-to-cradle investigation. In Japan, where energy performance has been a lower priority there are also indicators that shortage of labor combined with a desire to preserve a job-base in rural areas will also lead to increased support for IWBC, following the EU model (Annual Report on Forest and Forestry in Japan Fiscal Year 2017).

While these larger trends may seem to suggest a homogenization of the construction industry, at least in the two geographies where IWBC already has a significant market share, a more global, interdisciplinary and comparative approach to this dynamic transformation could not only assist in taking full advantage of these transformations it while at the same time taking advantages of regional differences. Long viewed as somehow more generic than conventional construction, when viewed through the new circular economy lens, offsite construction, and particularly IWBC, demands a closer and more nuanced look at local conditions and at a myriad of complex factors. This *glocalism* has been influencing the development of the IWBC, as can be seen in translations of light wood frame construction and regulation from the US to Sweden and Japan in the seventies or that of German and Swedish offsite tools and techniques for light wood frame construction to the US over the last few years. To move the industry forward, we need a better understanding of these exceptional exchanges examined through a myriad of disciplinary lenses. What can the EU learn from the wide-spread acceptance of wood-based construction in the US and Canada? How have countries like Sweden and the UK been able to commercialize offsite construction methods still as costly in the US? What can these experiences in translation offer those parts of the world where IWBC is still novel or even non-existent as they consider more sustainable futures?

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Study of Vulnerability of Air Barrier Membranes and Sealant Joint Tapes Applied over Wood Sheathing Panel Joints Due to Racking Movement in Passive House Designed Residential Buildings

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Abstract

Effective air barrier membrane over the entire building envelope and sealant tapes applied over exterior panel joints (e.g., wood sheathing joints or wood sheathing to sill plate or concrete joints) in Passive House (PH) designed wall panels are an essential component of passive house design. Air tightness is one of the most important attributes of PH design and should not be compromised. Unaccounted air leakage in PH buildings not only lowers performance, it also increases the vapor transport through the wall, increasing chance of condensation that can lead to decay and mold growth. Due to the finish surfaces that cover wall construction, one cannot visually detect the paths where air leakage occurs. Therefore, in order to protect against the loss of airtightness, the PH building air barrier system and wall panel joint sealant tapes must be protected against tear and puncture. One concern that has arisen, in particular on the west coast, is the capacity of the air barrier membrane and sealant tapes spanning over panel joints to resist compromise when the wall assembly, including sheathing, is subjected to seismic induced racking displacements. The objective of this paper is to evaluate the serviceability and performance of self-adhered and fluid-applied air barrier membrane and sealant tapes based on available manufacturers test data, and to characterize the potential failure mechanisms considering available racking test results.

Introduction

Buildings in the US account for over 40% of energy consumption and carbon emissions. In order to radically reduce this environmental impact, buildings need to be designed and constructed to minimize energy used for heating or air conditioning. Building envelopes – including walls – are the primary source of heat loss in cold climates due in part to air leaking (infiltration). The Passive House (PH) Standard is a framework for achieving energy efficient buildings through five building science strategies, including air tightness, making the envelope as airtight as possible to reduce infiltration. Over 200 buildings – primarily residential – have been certified in the US as meeting the PH Standard.

While most serviceability related building failures can be attributed to moisture penetration through building enclosure, air leakage can cause energy loss and vapor that can condense on interstitial surfaces. It is crucial to maintain airtightness in PH designed buildings. The wall systems used for PH design can vary depending on the material for the structural framing system, insulation, air barrier and vapor barrier, and finish options. What is common in most designs, however, is the use of timber framing systems (e.g., use of 2x8 studs, Z-joist studs, vertical dimensional lumber or Larsen

trusses) sheathed with panels of OSB, plywood or a coated sheathing system (e.g. Zip®) to resist gravity and lateral loads, or wood-based panels (e.g., Structural Insulated Panel, SIP). Regardless of wall type, there is a common need to ensure airtightness through the panel joints in PH construction.
This underlines the importance of evaluating the performance of air barrier membranes and joint sealant tapes spanning the joints between panels. The common method of creating airtightness for homes is to apply air barrier membrane on the exterior of the enclosure using a variety of means such as mechanically fastening membrane sheets, self-adhering membrane sheets, or a liquid-applied membrane created by spraying or rolling the material over the sheathing. For PH designs, with more stringent airtightness requirements, sealing the joints and between panels, floor and roof edge/perimeter and fenestration components plays a significant role. While air barrier can be provided on different layers of the envelope system, the most effective approach for sealing panel joints is to apply specialty tapes, liquid sealers, or a continuous membrane, as shown in Figure 1. Whether for sealing joints between panels or providing whole building air barrier, the objective is to provide a continuous air seal for the building envelope system.

Figure 1. Example application of air barrier and joint tapes.

PH SIP Construction: Unsealed interior joints.

Exterior mechanical fastened air barrier.

Self-adhered sealant tape at panels and window.

Liquid applied air sealing applied at panel joints.

A lack of knowledge exists about the performance characteristics of air barrier membranes and sealant tapes or other joint sealing technologies under building deformations or drift resulting from lateral loads. The information available is limited to manufacturers product and marketing literature. With more intricate and complicated building envelope details for PH systems, the evaluation of the airtightness performance provided by air barriers and joint tapes under the structural response of the building envelope is essential, especially in seismic and extreme weather conditions. Once installed, air barrier membrane and panel joint sealants are not typically accessible for maintenance and repair, but are expected to remain serviceable for the life of the building wall assembly. If during a seismic event the joint sealant tears, the result is a breached PH building envelope that will most likely go unnoticed until potentially damage to interior finish related to vapor transport condensation is noted, and health issues related to airborne mold spores and other suspended particles, and energy loss have been realized. Therefore, If the PH Standard is to be widely adopted, walls must be designed and proven to resist wind and earthquake induced lateral loads without compromising performance.

Literature Review of Air Barrier Membranes and Joint Sealant Tape Properties

Conventional air barriers include liquid-applied, mechanically fastened, and self-adhering membranes applied over the exterior sheathing or rigid insulation panels. Under racking conditions wood sheathing panels over wood-frames or SIP type panels tend to rock to accommodate building drift between floors or between roof and top floor, and as a consequence, the joints tend to open up potentially compromising continuity of the air barrier. Since self-adhesive and liquid-applied membranes spanning such joints will be stretched in tension or shear, tear vulnerability needs to be evaluated. The same is true for sealant tapes spanning over the joints. Under such conditions, mechanically fastened membranes may experience tear at the fastener locations. This research focuses on self-adhered and liquid-applied membrane air or vapor barrier systems. It also considers sealant tapes that may be applied over panel joints to eliminate air leakage.

Self-Adhered Membranes

Self-adhered membranes are rolled sheets that are attached to the wood (e.g., OSB) substrate by means of an adhesive on the back of the membrane (peel-and-stick application). Self-adhered membranes are comprised of a rubberized asphalt compound that is integrally laminated to a cross laminated high density polyethylene film. Typical membrane and film thicknesses are .9 mm and .1 mm, respectively. The film is located on the exposed face of the membrane and is intended to provide dimensional stability, and strength against tearing, puncture, and impact.

Table 1: Self-Adhering Air and/or Vapor Barriers (Thiede and Memari 2013)

No.	Manufacturer Product	Tensile Strength (psi)	Elongation Strain	Peel Strength (lb/in width)	Puncture Resistance (lbs)	Lap Adhesion (lb/in width)
1	Carlisle CCW-705	500	300%	7.5	50 (min)	7
2	Grace Perm-A-Barrier	400 (membrane) 5000 (film)	200%	-	40	4
3	Henry BlueskinVP 160	41 lb			-	-
4	Poly Wall Self-Adhering Sheet Membrane	325 (membrane) 6500 (film)	600%	15	40	8
5	Tremco ExoAir 110/110LT	500 (membrane) 5000 (film)	250%	-	55	-
6	W.R. Meadows Air-Shield	4000 (film)	400% (film)	10	40	-

Table 1 shows material information and test data for self-adhering membrane products by several manufacturers. Tensile strength and elongation values are critical properties for determining the performance of the membrane under building drifts. The percent of elongation corresponds to the maximum tensile strength, which is the load required to tear the membrane. Therefore, if the elongation of the membrane is exceeded, tearing can be expected to occur. It should be noted that the lap adhesion value is slightly less than peel strength, so failure should occur at the seams before the product's adhesive failure.

Liquid Applied Membranes

Liquid applied membranes cure to form a continuous flexible elastomeric membrane without laps or seams, which can accommodate typical designed building movements. Table 2 shows material information and test data for liquid applied membrane products produced by some manufacturers. Similarly to self-adhered membranes, tensile strength and elongation are critical properties because they indicate when tearing of the membrane will occur.

Table 2: Liquid Applied Air and/or Vapor Barriers (Thiede and Memari 2013)

No.	Manufacturer Product	Material Composition	Tensile Strength (psi)	Elongation Strain	Peel Strength (lb/in)	Adhesion Strength (psi)
1	Carlisle Barritech VP	Single-component membrane	175	500%	exceeds facer strength	-
2	Dupont Tyvek Fluid Applied WB	Single-component elastomeric polyether-based polymer product	169	420%	13.3	>25
3	Grace Perm-A-Barrier Liquid	Two-component synthetic rubber, cold-vulcanized membrane	-	500%	-	18
4	Henry Air-Bloc 31MR	Single-component, water-based, rubber-like membrane	138	925%	-	-
5	Momentive SEC2500 SilShield	100% Silicon	175	350%	-	33
6	Poly Wall Airlok Flex VP	Single-component, water-based, polymeric membrane	-	500%	-	100
7	TK AirMax 2102 NP	Single-component rubberized polymer formulation	-	637%	11.9	81.6
8	Tremco ExoAir 120	Polymer-modified emulsion	-	1500%	6.5	-

Self-Adhered Joint Sealant Tapes

Table 3 shows material information and test data for self-adhering sealant tape products by several tape manufacturers.

Table 3: Self-Adhering Joint Sealant Tapes

No.	Manufacturer Product	Tensile Strength[1] (psi)	Elongation Strain	Peel Strength (lb/in width)	Puncture Resistance (lbs)	Lap Adhesion (lb/in width)
1	Zip System Tape[1]	938	400%-800%	-	-	-
2	Tescon Vana Pro Clima No. 1[2]	-	-	-	-	Adhesion to OSB: 3.34 lbs/linear inch/
3	3M All Weather Flashing Tape 8067[3]	-	-	3.8 lb/in on OSB	-	Adhesion to OSB: 66N/100 mm width
4	SIGA Wigluv 60 (2.25")[4]	Pass ASTM D5034 per AAMA 711-13	-	Pass ASTM D3330 per AAMA 711-13 on OSB Substrate	-	-
5	Dow Weathermate (2 7/8 in.)[5]	ASTM D882: 20 lb/in.	125%	15 Ounces/in on Housewrap; 75 Ounces/in on stainless steel	-	-
6	3M Venture Tape Polypropylene Sheathing Tape 1585CW[6]	20 lb/in (90.4 N/25 mm)	130%	45 Ounces/in	-	-
7	Polyken Shadolastic Seam and Seal Construction Tape (3" wide)[7]	32 lb/in	-	Adhesion to steel: 45 Ounces/in (4.92 N/cm)	-	-
8	Polyken Nashua 361-11 Waterproofing Repair tape (2 in.)[8]	20 lb/in	-	75 Ounces per in	-	-

[1]http://www.huberwood.com/assets/user/library/ZIP_SystemTape_-_Product_Data_Sheet-v3.pdf

[2]https://foursevenfive.com/content/product/air_sealing_system/tescon_vana/spec_sheet_tescon_vana.pdf

[3]https://multimedia.3m.com/mws/media/816485O/8067-all-weather-flashing-tape-technical-data-sheet.pdf

[4]https://www.ecosupplycenter.com/assets/docs/SIGA_Wigluv.pdf

[5]http://msdssearch.dow.com/PublishedLiteratureDOWCOM/dh_0991/0901b803809919e1.pdf?filepath=styrofoam/pdfs/noreg/179-07768.pdf&fromPage=GetDoc

[6]https://www.wind-lock.com/content/files/SDS/3M_Venture_Tape_Polypropylene_Sheathing_Tape_1585CW.pdf

[7]https://catalog.berryglobal.com/catalog-images/5041_TDSPolyken628_121117.pdf

[8]https://www.findtape.com/Nashua-361-11-Waterproofing-Repair-Tape/p723/

Evaluation of the Manufacturers' Material Test Data

Panel rotation correlates to the elongation of membrane or sealant tapes spanning the sheathing or panel joints. If it is assumed that the panel sheathing joint initially has a 1/16 in. gap at the time of construction and have a 7/16 in. gap after racking tests (e.g., Terentiuk and Memari 2012, 2014), then the membrane or tape would have to elongate 3/8 in. beyond the initial gap, which means an elongation strain of 600%. A 600% elongation is greater than most of the reported elongation capacities of self-adhered membranes and tapes, which mean that the tape will tear under tension unless adhesion fails first. On the other hand, most of the reported liquid applied membranes seem to have much higher elongation capacity compared to the self-adhered membranes and tapes, and several can survive such racking conditions without tear. This type of analysis can also be used to estimate the maximum drift that a given membrane or tape product can accommodate without tearing. However, based on the presented analysis and manufacturers' test data, it seems that liquid-applied membranes have the capacity for much higher drifts compared to self-adhered membranes for seismic regions.

Additional Laboratory Testing Required

While standard ASTM test results are available from manufacturers for some membrane and tape products as reported in this paper, for a more accurate evaluation of the performance of tapes for PH application, we need component testing for tension and peeling capacities when tapes or self-adhered and liquid-applied membrane are applied on substrates used at panel joints in PH construction. In particular, substrates such as OSB and plywood should be included, as the wood substrate is a critical component of the wall lateral load resisting systems. Furthermore, because the concern is failure of membranes or tapes during an earthquake event, there is a need to simulate such conditions in a laboratory using full-scale mockups under racking conditions, after testing small specimens.

Full-scale racking tests have been carried out for evaluation of the joint opening in SIPs when different spline systems have been used (e.g., Terentiuk and Memari 2012, 2014) and also in timber frame walls to evaluate performance of drywall joint tapes (Memari and Solnosky 2014). Failure mechanisms related to the current study include separation of the panels in both the vertical and horizontal plane, separation of the sheathing from the top plate, damage to the wood studs (particularly end studs), and damage to the hold-downs. Building on such experience, racking tests on mockups made up of at least two side-by-side panels appropriate for PH design with joint sealant tapes applied over joints and also self-adhered and fluid-applied air barriers applied over the entire sheathing is necessary to determine the extent of damage and its effect on air leakage potential. Accordingly, air leakage test on the mockup following ASTM E283 needs to be performed to determine the rate of air leakage though the wall joint before and after racking tests. The racking test would follow ASTM E564 to determine the static load (monotonic) application performance and ASTM E2126 to evaluate cyclic racking performance of the wall assembly. Failure mechanisms of interest are adhesion of tape to substrate and tearing of the tape spanning the vertical joints. The objective of this testing would be to evaluate the range of drifts associated with each type of failure and for each type of tape and substrate.

Conclusions

Membrane air barrier and air sealant tapes on panel joints are an essential components of wall construction systems for PH airtightness design. Any building movement and deformation that may affect the performance of the membrane air barrier and sealant tapes in providing airtightness should be evaluated and considered in design of the panel configuration, boundary conditions, and detailing. While a comprehensive testing program is needed to address such issues, based on available manufacturers' product data and past research, the following conclusions can be made from this study:

- Tensile strength and elongation resistance are the critical properties for estimating the membrane air barrier and sealant tape performance under building lateral deformation as induced in earthquake events.
- The mechanical properties of the membrane air barrier and sealant tapes depend on the manufacturer and the substrate over which the tape is applied, and as such, they vary significantly.
- Based on preliminary evaluation using manufacturers test data and available full-scale racking test information, in high seismic regions, most self-adhered membrane and tapes may not preserve airtightness due to potential tear as a result of seismic induced large joint opening (e.g., larger than 3/8 in.) between adjacent panels. On the other hand, most liquid-applied membranes seem to have much higher elongation capacity than the self-adhered membranes and tapes, and therefore are less vulnerable.
- Full-scale racking tests of different membrane systems and sealant tapes are necessary to determine the acceptable range of drift to avoid damage to tapes, or alternatively, provide the necessary elongation strain capacity and peel resistance in order to avoid compromising airtightness design.

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Framework to Evaluate the Impact of Prefabrication of Wood-frame Structures for Low-rise Buildings

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ABSTRACT

The construction industry is shifting from traditional on-site (stick-built) to an off-site construction paradigm in which building systems are engineered, assembled in a controlled environment and shipped to site for installation. Despite the potential benefits associated with this shift, there is still a knowledge gap concerning the impact of using prefabricated building systems. This research proposes a framework to efficiently evaluate the impact of prefabricated wood-frame wall panels for residential construction by comparing different scenarios in terms of lumber waste and lumber usage. Through the use of Building Information Modeling (BIM), several scenarios taking in consideration on- and off-site methods (and the application of advanced framing techniques) are simulated and compared for a comprehensive analysis of the real impact of prefabrication on the construction industry. Applying the framework in a residential low-rise building located in Alberta (Canada) the researchers found a reduction in waste by more than 60% while providing a more efficient framing system in terms of lumber usage with a reduction of 18.39%. It is concluded that the use of prefabrication and advanced framing techniques has a significant positive impact on the construction of wood frame systems in terms of material waste and usage reductions.

Keywords: Off-site construction, Advanced Framing, Building information modeling

Introduction

The construction industry is gradually shifting from traditional on-site practices to off-site fabrication of building systems, an approach that offers superior quality, shorter construction duration, and a more efficient product (e.g. energy efficiency, material usage, etc.). In fact, Smith and Rupnik (2018) report more than 30% growth in the North American modular industry between the years 2014 and 2017 while identifying demand from the multi-family housing and hospitality sectors as main drivers for a sustained increase in the use of this construction method in the future. In the case of prefabricated wood-frame systems, panels (i.e., walls, floors and/or roofs) are designed and assembled off-site and then transported to the site for installation. Although lauded for its positive impact in terms of the efficiency of on-site operations, the success of off-site prefabrication is predicated on careful planning and design, as indicated by Barkokebas et al. (2017) and illustrated in Figure 1.

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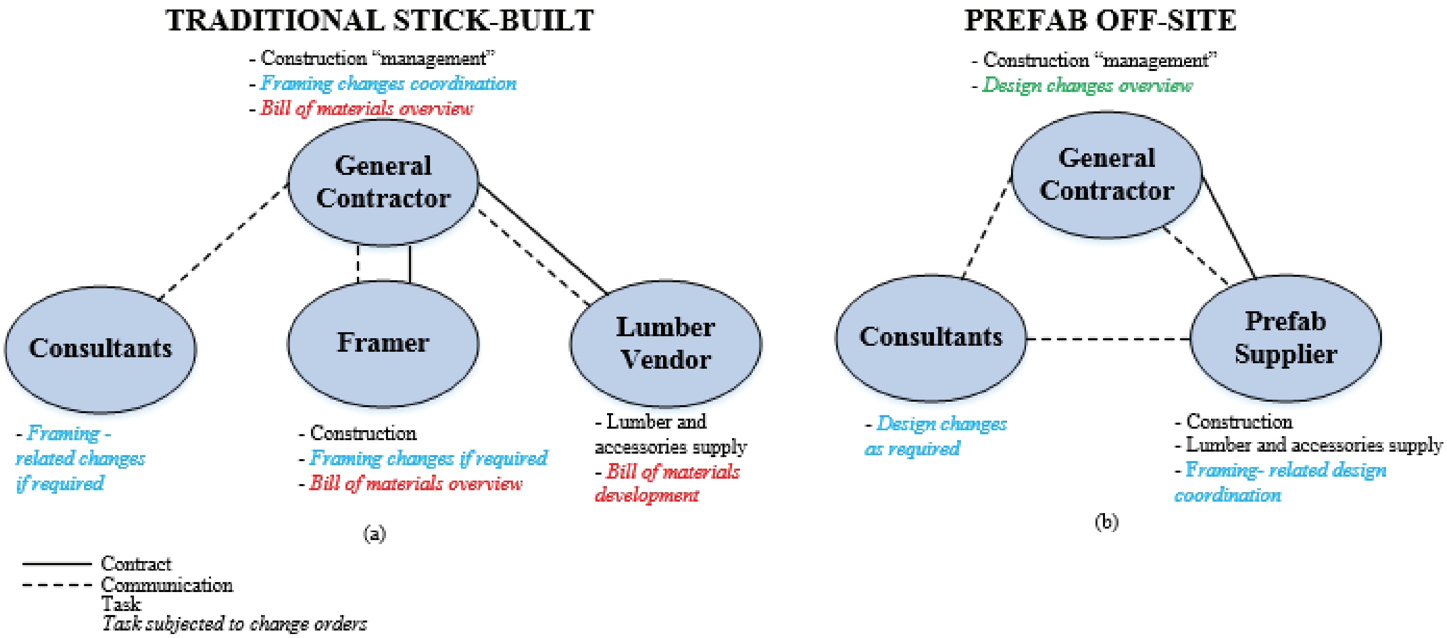

Figure 1. Traditional and off-site contractual comparisons between parties

Figure 1 demonstrates the contract and division of tasks for the framing of multi-family projects applied in traditional stick-built (on-site) and prefabricated (off-site) methods, respectively.
It can be observed in the figure that the general contractor has to spend more energy in the on-site method in order to avoid change orders with materials between the framer and lumber supplier during construction due to various reasons (e.g., higher waste than anticipated, damage due to weather, etc.) and must coordinate design changes between the framer and consultants. Furthermore, material management issues are encountered due to the nature of traditional contract arrangements, whereby the framing company (often a small company with relatively few employees) is not the buyer of the lumber and thus has no incentive to minimize material waste.
Moreover, the framer does not have the capacity to perform a thorough review of the presented design in order to identify inconsistencies and propose design changes that would improve design performance restricting himself to bid on the project as presented and leave the general contractor responsible to coordinate all framing-related design issues that may be encountered during construction. By contracting a prefab supplier, on the other hand, the general contractor can transfer the risk of material management and the design coordination effort to the prefabricator since prefabrication enterprises require low tolerance of human error and design assumptions in order to remain competitive (Alwisy et al. 2018)design assumptions and onsite interpretations of the shop drawings cannot be tolerated. Therefore, building information modelling (BIM. In fact, with the additional engineering effort and coordination associated with this construction paradigm, prefabrication of wood-frame systems opens an opportunity for design performance and waste reduction benefits for both prefab suppliers and general contractors.
The prefab supplier should lead this effort since it has the capacity within its design team to determine the optimum trade-off based on design efficiency, waste reduction, and coordination between different parties (i.e., general contractor and consultants). Toole (2016) indicates a significant waste reduction

in off-site construction due to the nature of the methods applied (e.g., panels being assembled in a controlled environment off-site compared to building on-site) and the use of alternative materials such as engineered lumber instead of dimensional lumber. Moreover, the application of advanced framing techniques to improve the design of wood frame panels (e.g., increased spacing and elimination of double-plates) is another significant driver of waste reduction that is taken under consideration in the present study. According to the U.S. Department of Energy (2000), advanced framing, or Optimum Value Engineering (OVE), consists of a variety of framing techniques to reduce the volume of lumber used and wasted during the construction process. By applying these techniques, Lstiburek (2010) indicates potential reductions of 5%-10% and 30% for lumber usage and pieces per panel respectively, while increasing space for insulation by 60%.

Despite significant efforts in the literature to demonstrate the advantages of advanced framing, these techniques are still not widely used due to the lack of information from code officials and engineers or simply because of the time required to perform an analysis and validate the actual advantages of advanced framing over traditional framing techniques (Lstiburek, 2010). To address the first problem, the APA (2014) suggests the following regulatory measures to accommodate advanced framing: (1) increased width of stud members (e.g., from 2×4 to 2×6) to increase cavity insulation in colder climate zones, (2) increase of spacing from 16″ to 24″ on center where structural codes allow, (3) incorporation of more efficient components in panels (opening and intersecting components), and (4) elimination of top double plates. Despite the information available though, the APA (2014) asserts, in order to achieve maximum savings in these techniques there must be a holistic approach to the application of these techniques.

To investigate holistically the advantages of advanced framing, this research proposes the use of Building Information Modeling (BIM) to evaluate different advanced framing techniques due to its capacity to evaluate different design solutions in a rapid and detailed manner (Gade et al. 2018) designers struggle at times to apply the different BIM-tools. In order to understand this disjoint, it is necessary to understand first the existing practices of different specialists in the building design process in order to improve future development and implementation of BIM. The aim of this article is to investigate the consequences of using BIM-tools in a collaborative building design setting consisting of different specialists. A case study was carried out to trace when BIM-tools were used (or not. An evaluation framework is developed with the objective of investigating and addressing different framing solutions quantitatively. The framework is applied in the case of a prefabricated four-storey low-rise building located in Edmonton, Alberta, Canada.

Methods

The methods applied in this research are presented in this section. As demonstrated in Figure 2 below, the BIM model containing the architectural information (e.g., location and quantity of openings, corners, intersections, etc.) is analyzed as per the available design specifications (spacing, member size, etc.) and alternative framing options such as opening components and the elimination of double top plates. The criteria used in this research for the development of Key Performance Indicators (KPIs) are also demonstrated in Figure 2, where the total waste of lumber, lumber usage, and construction methods used are selected as the criteria based upon which to determine the performance of different scenarios when planning the construction of wall panels during the fabrication stage. Still in Figure 2, for the architecture modelled in Autodesk Revit, each framing combination is generated using FrameX (an addon to Autodesk Revit) and its KPIs are automatically calculated through a Dynamo routine for the purpose of comparison between scenarios. The intent is to address the different scenarios quantitatively so that these options can later be detailed and presented to general contractors and consultants for approval.

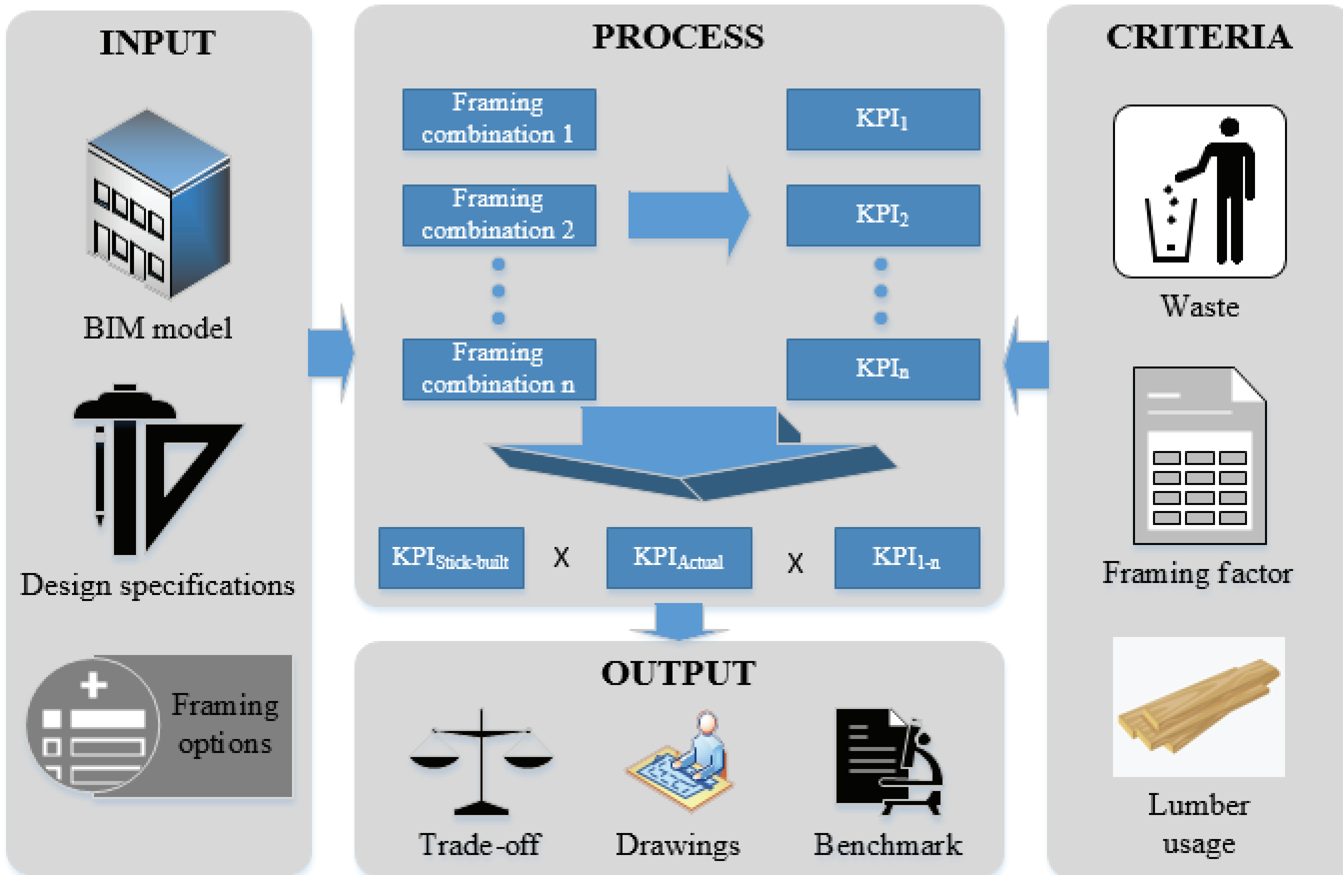

Figure 2. Overview of research methods

The scenarios evaluated in this research are presented in Table 1 below, which indicates the waste factors estimated by construction experts and allowable stud spacing in walls as per design specifications for low-rise residential buildings. Scenario SB-TRAD represents the traditional approach adopted by the industry (use of traditional framing and dimensional lumber on-site) while scenario PF-TRAD represents the same system built off-site with no changes in design. Scenarios PF-ADV1and PF-ADV2 represents the use of advanced framing with engineered lumber by prefab suppliers with double and single top plates, respectively. It can be observed that the stick-built scenario is associated with higher levels of material waste due to the dynamic and unpredictable nature of on-site work, while the prefab method allows trades to cut lumber to precise lengths as required by the design and to provide an adequate material storage area at all times. Moreover, the use of engineered lumber is a significant driver of waste reduction due to its superior quality and mechanical resistance, thus allowing greater spacing between studs and the elimination of some framing elements such as double top plates.

Table 1 Scenarios considered in analysis

Scenario	Description	Lumber Waste	Stud Spacing
SB-TRAD	Stick-built using traditional framing techniques	12%	As per Table 2
PF-TRAD	Prefab using traditional framing techniques	8%	As per Table 2
PF-ADV1	Prefab using advanced framing with double top plate	5%	24" o/c
PF-ADV2	Prefab using advanced framing with single top plate	5%	24" o/c

The stud spacing for each scenario is taken from design specifications applied to low-rise residential buildings for both dimensional and engineered lumber as demonstrated in Table 1. For dimensional lumber, the spacing varies according to the use of the wall (e.g., exterior, corridor, etc.) and the floor of the building on which the wall is located, as explained in detail in Table 2, while for engineered wood the spacing can be consistent regardless of the type of wall due to its superior mechanical properties. In assessing the performance of each scenario, the KPIs are: (1) lumber waste measured in board feet (bf) and (2) lumber usage measured in board feet per construction area (bf/sf). These KPIs are selected due to their significance in determining the total material required, and due to the relative ease with which the performance of different scenarios can be compared with other projects using these KPIs. After calculating the KPIs for each scenario, a comparison is performed by benchmarking the traditional approach (scenario SB-DB) with the alternative scenarios indicating the tradeoff between them and providing the drawings for approval. The framework is tested in a residential 4-storey building located in Alberta, Canada, with the results presented in the following section.

Case Study

In this section, the case study is presented, including a description and discussion of the results and suggestions for future research. Figure 3 provides a 3D overview of the case study project, a four-story residential building located in Edmonton, Alberta, Canada. The case study was built using components from a local prefab supplier that were fabricated using engineered lumber and employing some of the advanced framing techniques represented in

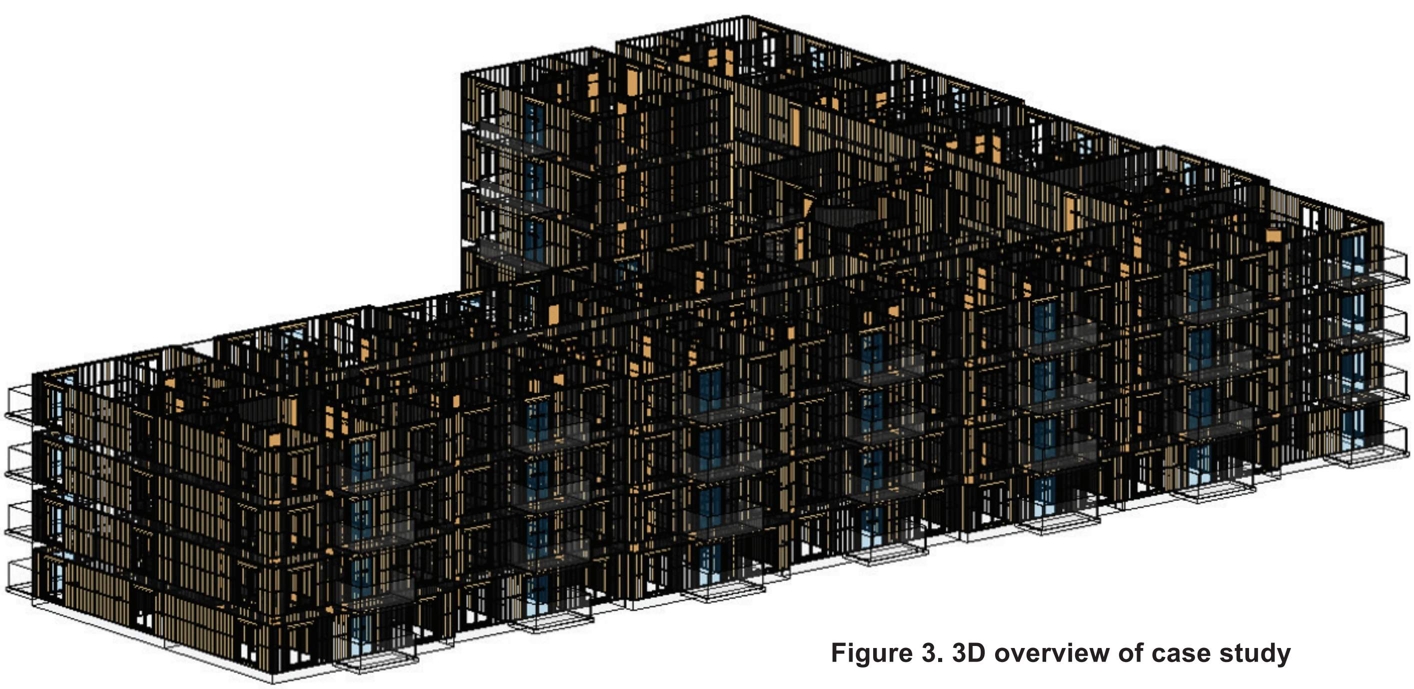

Figure 3. 3D overview of case study

scenario PF-ADV1. As mentioned above, the architecture was modeled according to architectural drawings, while the framing specifications were modelled according to structural specifications from the actual project (i.e., for a prefab construction method using engineered lumber) and from similar projects that used a stick-built method and dimensional lumber.

Tables 2 and 3 show the spacing and opening specifications for traditional and advanced framing scenarios, respectively. For traditional framing, the walls are framed with grade Spruce-Pine-Fir (SPF) 2 or better, while advanced framing uses engineered lumber (1.5E, or better, Laminated Strand Lumber). When using dimensional lumber, it can be observed that the spacing decreases, and in some cases the width of elements increases, on lower floors due to the increased load. Using engineered lumber, on the other hand, the spacing and size of elements are not affected by the load. This factor is a significant driver of lumber usage, as discussed later in this section.

Table 2 Spacing specifications for dimensional and engineered lumber

Floor	Dimensional Lumber		Engineered Lumber	
	Exterior & Interior Load Bearing[1]	Corridor[2] & Party[1]	Exterior & Interior Load Bearing	Corridor[2] & Party[1]
Main floor	2×6 @ 12" o/c	2×6 @ 8" o/c	2×6 @ 24" o/c	2×6 @ 24" o/c
Second floor	2×6 @ 16" o/c	2×6 @ 12" o/c	2×6 @ 24" o/c	2×6 @ 24" o/c
Third floor	2×6 @ 16" o/c	2×4 @ 8" o/c	2×6 @ 24" o/c	2×6 @ 24" o/c
Fourth floor	2×6 @ 16" o/c	2×4 @ 12" o/c	2×6 @ 24" o/c	2×6 @ 24" o/c

[1] 2×4 through all floors

[2] Staggered wall

Table 3 demonstrates the opening specifications for dimensional and engineered lumber for entrance doors, balcony doors, and windows; (it should be noted that the remaining interior doors are framed without any headers and consist only of one king). As with Table 2, for engineered lumber the opening specifications are consistent regardless of the floor of the building on which the opening is located or the type of opening (i.e., entrance door, balcony door, window). Once more, this is a significant driver of lumber usage, as discussed later in this section.

Table 3 Opening specifications for dimensional and engineered lumber

Members	Floor	Dimensional Lumber			Engineered Lumber
		Entrance Doors	Balcony Doors	Windows	All
King & Jack	Main floor	4-2×8	4-2×6	4-2×6	2×4+3×6
	Second floor	3-2×8	4-2×6	3-2×6	
	Third and Fourth floors	3-2×6	4-2×6	3-2×6	
Headers	Main and Second floors	4-2×10	3-2×12	3-2×10	4×10
	Third and Fourth floors	3-2×12	3-2×10	3-2×10	

After modeling all architectural and structural specifications and assigning waste factors for each scenario, KPIs are calculated using the BIM model, as demonstrated in Figure 4 below. As per Figure 4, the current practice (SB-TRAD) presents the highest waste volume and lumber usage due to its high waste factor driven by the nature of the construction method and the high quantity of material needed in order to meet structural requirements and accommodate openings. On the other hand, the actual specifications applied to this project (i.e., those associated with PF-ADV1) result in a reduction in waste of more than 60% compared to the current practice, while leading to a 18.39% reduction in lumber usage, owing to the lower number of elements required in order to satisfy the spacing and opening specifications. Scenario PF-ADV2 (prefab construction using engineered lumber and a single top plate) constitutes a refinement of the previous scenario, while PF-TRAD is considered a transitional solution between on-site and off-site operations for wood-frame wall panels.

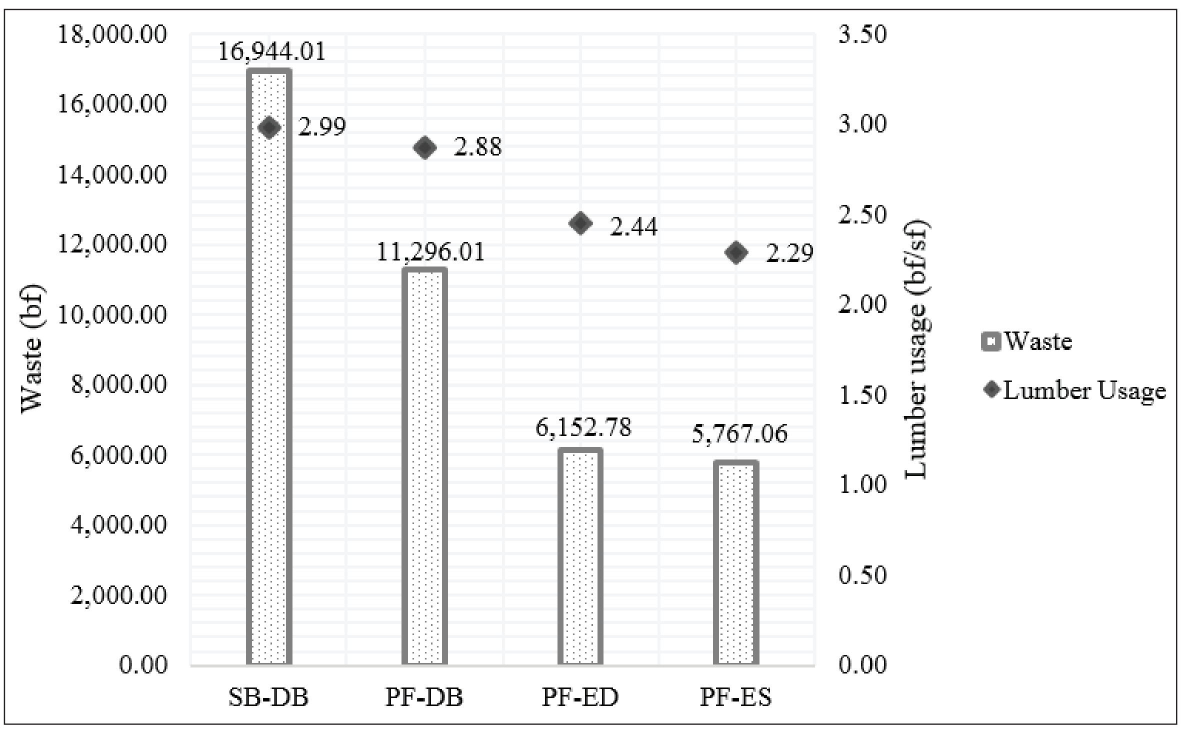

Figure 4. Waste and lumber usage for the addressed scenarios

Conclusion

The paper presents a framework to assist prefab suppliers to better communicate to general contractors the advantages of off-site construction methods and advanced framing for low-rise residential buildings. Moreover, the results of this analysis will further assist with the presentation of alternative solutions for the purpose of coordination with and approval by consultants while validating the quantitative data to support these claims. It is demonstrated that the contracting of a prefab supplier and the introduction of advanced framing techniques (scenario PF-ADV1) suggested by its team reduces significantly (by margins of 63% and 18%, respectively) the waste and lumber usage for wood-frame wall panels compared to the traditional stick-built approach (scenario SB-TRAD). By eliminating the double top plate (scenario PF-ADV2), further savings are identified, while an intermediate solution (traditional framing prefabricated off-site, as represented in scenario PF-TRAD) indicates savings of 33% in lumber waste. Although it provides interesting insights, the presented framework still does not provide a comprehensive overview of the impact of off-site methods and the use of advanced framing for the construction of low-rise buildings, given that floor and roof panels are not included in the analysis. Hence, it is recommended as a direction for future research that floor and roof systems be incorporated into this framework so that general contractors can fully grasp the impact of using prefabricated wood-frame systems. Moreover, the criteria and inputs can be modified to reflect any given context outside the one provided in this paper, while other framing options can be added as alternative solutions to the analysis. Other KPIs should be introduced in the analysis (e.g., cost, schedule, carbon dioxide emissions, etc.) in order to provide a more complete overview of the impact of each scenario during the construction phase.

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