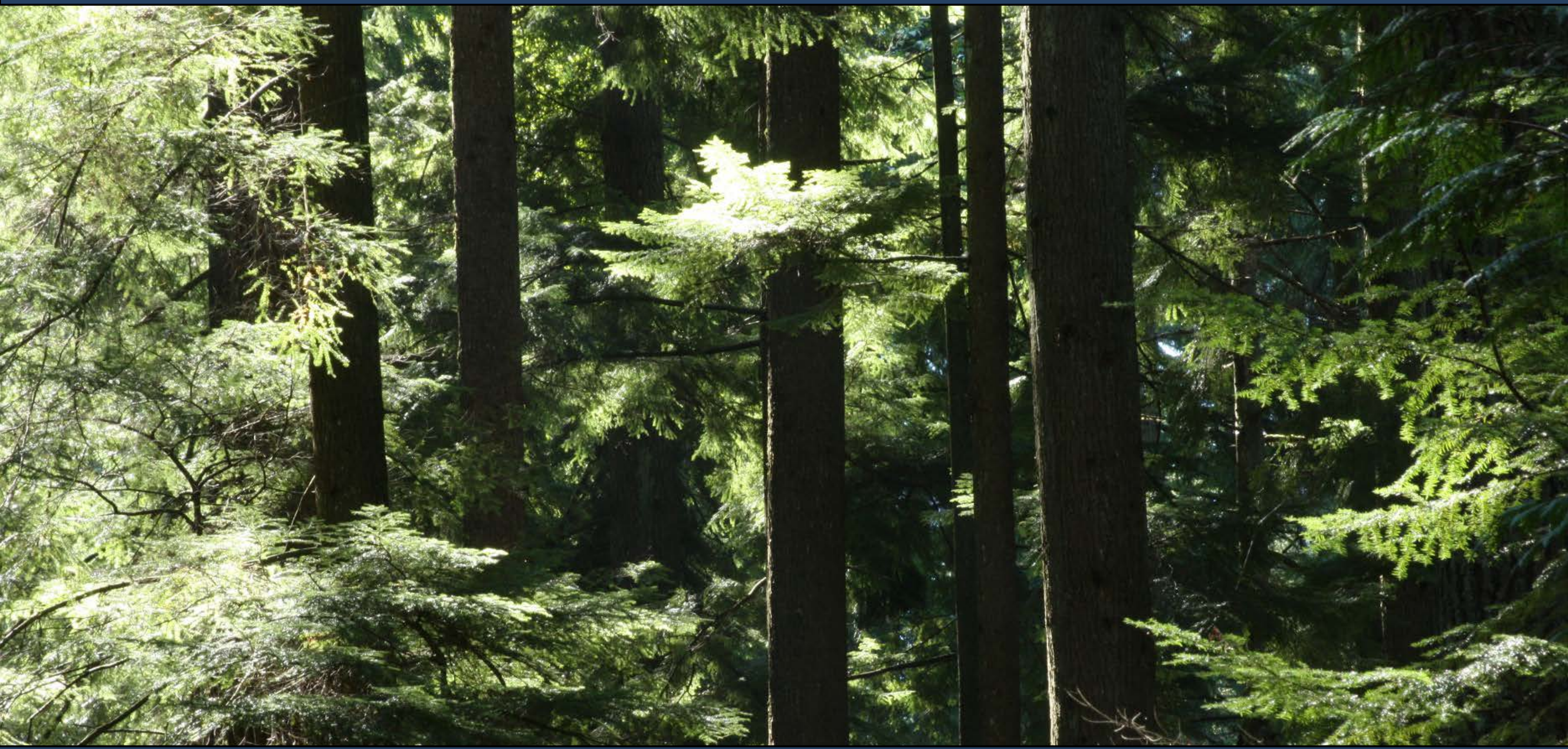
March 2020

Hem-Fir Mass Timber Research Project

Report



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Prepared for Forestry Innovation Investment

EXECUTIVE SUMMARY

Purpose and Scope of Study

The purpose of the study is to evaluate and summarize any technical or other impediments to using hem-fir in mass timber products. The different mass timber products included in the study are cross-laminated timber (CLT), glue-laminated timber (glulam), dowel-laminated timber (DLT) and nail-laminated timber (NLT).

Method of Study

Thirty-one semi-structured interviews were conducted with key informants to obtain insights regarding the suitability of hem-fir for use in mass timber projects from a variety of perspectives including regulatory, technical, supply chain and market acceptance factors. The key informants were from a variety of organizations including regulatory agencies, research organizations, mass timber manufacturers, hem-fir timber suppliers, architects, structural engineers, building contractors, industry associations and government. In addition, a detailed document and literature review was conducted to obtain the available published information on the regulatory, technical and market factors affecting the use of hem-fir in mass timber products.

Key Findings

The key study findings are:

1. **The size of the mass timber industry in BC is still small.** There currently exists only one CLT manufacturer while an additional CLT manufacturer will be operational next year. There exists only one major and one small scale DLT manufacturer in BC. There are a few glulam producers but very limited factory-built NLT production in BC.

2. **Hem-fir is not currently used to produce any mass timber products used in building construction in BC**. Spruce-pine-fir (SPF) is used primarily for CLT and DLT production while Douglas-fir is the primary species used for glulam production, although some other species are also used.

3. **There are no regulatory, product certification and technical standards that restrict the use of hem-fir in CLT, DLT, NLT or glulam production.**

4. **The key benefits of hem-fir with regard to its use in mass timber products are superior strength compared to SPF rendering it capable of long spans, and an abundant supply as hem-fir is BC's most predominant coastal species.**

5. **The major technical barrier of hem-fir for mass timber products mentioned most frequently by most key informants is the large variation in moisture content and the presence of wet pockets.** The perception is that hem-fir is difficult and costly to dry sufficiently, and the variable moisture content reduces the effectiveness of adhesives used to produce CLT and glulam.

6. **Several research studies have been undertaken that have confirmed that hem-fir is suitable for use in CLT manufacturing and that the manufacturing of hem-fir CLT is viable if appropriate adhesives are used.** Suitable adhesives can address the glue bondability issues of hem-fir in CLT and glulam production resulting from variability in the moisture content and wet pockets in hem-fir.

7. **Some research studies have also been undertaken to mitigate the variability in the moisture content of hem-fir through lumber sorting and customized drying schedules.** These studies have demonstrated that it is possible to sort hem-fir lumber by different moisture levels and to employ customized drying schedules based on the moisture content level to reduce the variability of the moisture content and to dry hem-fir to a level acceptable for the manufacture of mass timber products.

8. **Recent research involving the hydrothermal treatment of hem-fir has indicated that it is possible to eliminate the wet pockets and increase the uniformity of the moisture content of hem-fir making it suitable for use in mass timber products**. However, this research has not addressed the cost-effectiveness of the hydrothermal treatment of hem-fir for use in mass timber products, and trials to date have been limited in scale.

9. **Hem-fir is more suited to DLT and NLT production than CLT or glulam production because DLT and NLT do not use adhesives to glue component wood parts together.**

10. **The existing BC mass timber manufacturers stated that there currently exists little incentive to use hem-fir.** BC mass timber producers indicated that they would have to carry an additional inventory of another species (i.e. hem-fir), which can be costly and logistically difficult due to lack of physical storage space. In addition, there currently does not exist a supply chain capable of providing a consistent supply of hem-fir lamstock despite hem-fir being a bountiful species in BC. The limited size of the local mass timber market and competitively priced mass timber products available from Europe reduce the incentive of major BC lumber producers to increase the supply of hem-fir lamstock to BC mass timber manufacturers.

11. **The market potential for hem-fir in mass timber products is projected to increase significantly.** The market for global CLT, the most widespread mass timber product, is projected to be valued at US$2.07 billion by 2025. As a comparison, North America's demand for CLT was valued at US$119 million in 2016. This growing acceptance and expansion of mass timber should lead to a greater opportunity for variety in products, in terms of species, grade and price, challenging the species that are currently dominant.

12. **The market potential for hem-fir in CLT and DLT will likely increase as the demand for mass timber products increases.** The market potential for hem-fir NLT is more limited as only a few NLT structures are built manually in BC primarily at the construction site. The market potential for using hem-fir in glulam is likely to mirror the increase in use of hem-fir in CLT and DLT products. One reason for this is that some architects prefer to use the same species for both glulam and the wood panels made from either CLT or DLT so that the same wood species is used throughout the building.

13. **The market for industrial mats is very price competitive.** Industrial mats are used in a variety of applications such as access mats for use in construction, access roads, drilling rigs, emergency egress, access to environmentally sensitive areas, and crane mats. Because traditional bolted hem-fir industrial mats are sold at a price discount compared to bolted Douglas-fir mats, traditional bolted hem-fir mats have been able to obtain a significant share of the industrial mat market in BC. While CLT industrial mats have several advantages including being lighter and more durable, CLT mats are currently more expensive and have not captured a large share of the industrial mat market.

Recommendations

The steps required to increase the market acceptance of hem-fir in mass timber products are as follows:

1. **Conduct further research to address the constraints of using hem-fir in mass timber products.**

   The purpose of further research should be to:

   - Identify more moisture tolerant adhesives that could be used for hem-fir CLT and glulam production;
   - Determine optimum methods of drying hem-fir including research to locate and dry the wet pockets in hem-fir; and
   - Conduct additional research regarding the hydrothermal modification of hem-fir which could potentially address issues related to wet pockets, moisture content variability, and warping and twisting.

2. **Undertake further testing and demonstration of hem-fir mass timber products to encourage the use of hem-fir by BC mass timber producers.**

   Since some BC mass timber producers are currently considering the use of hem-fir, it is critical that testing and demonstration (i.e. full-scale field trials) of hem-fir timber products be facilitated to encourage use. Some testing that should be undertaken is:

   - Conduct tests to establish optimum manufacturing parameters, such as applied pressure and adhesive application rates for hem-fir CLT manufacturing, to increase panel bond quality and durability;
   - Conduct full scale field trial tests to demonstrate the feasibility of using hem-fir in CLT and DLT manufacturing; and
   - Conduct fire resistance tests of CLT and DLT hem-fir mass timber products.

3. **Promote the use of hem-fir in mass timber production to address perceived technical barriers and encourage a consistent supply of hem-fir to BC mass timber producers.**

   To develop a supply chain for hem-fir lamstock in BC, collaboration should be facilitated between BC timber suppliers and BC mass timber manufacturers. There is also a need to promote the advantages of hem-fir in CLT and DLT products which include its aesthetically visual appearance, greater strength and longer span compared to SPF. The use of hem-fir in DLT production should also be highlighted because hem-fir is suited for this type of mass timber product which can tolerate a higher moisture content.

4. **Conduct market research to assess the size of the domestic and export mass timber market to accurately determine the market potential for hem-fir mass timber products.**

   This market research is necessary to encourage BC lumber producers to provide a consistent source of supply of hem-fir lamstock to BC mass timber producers.

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I. INTRODUCTION

1. Purpose and Scope

The purpose of this study is to evaluate and summarize any technical or other impediments to using hem-fir in mass timber products. The key research questions are shown in the following table.

Table 1.1: Research Questions

Research Issue	Research Questions
Product and Research Development	• What does the current status of hem-fir use in mass timber products? • What steps or tasks will need to be completed to allow commercial use of the species in mass timber products? ➢ What testing is required to enable specification of the species as input stock for mass timber? Is there work already in progress/development? ➢ What regulatory, product certification, or technical standards need to be revised or developed that would allow hem-fir to be used for mass timber products? ➢ Does performance testing on finished mass timber products using hem-fir need to be completed (i.e. fire performance, seismic performance, etc.)? What test results currently exist? What additional work is required?
Technical and Market Issues and Requirements	• What technical barriers are limiting the use of hem-fir for mass timber products? • What market barriers may limit the use of hem-fir for mass timber products? • What can be done to overcome these barriers? • What is the potential of hem-fir mass timber by market: building construction and industrial use (e.g. CLT mats)?
Technical Support and Resources	• What (if any) range of support and resources would need to be updated or created to support the utilization of hem-fir mass timber products in the construction industry? • What (if anything) would need to be updated or changed in existing technical support documents (i.e. Tall Wood Guide, CLT Guide, NLT Guide, etc.)?

The scope of the project consists of the use of hem-fir in mass timber products. The different mass timber products included in the study are cross-laminated timber (CLT), glue-laminated timber (glulam), dowel-laminated timber (DLT) and nail-laminated timber (NLT). While the potential to use hem-fir in all of these mass timber products was examined, the primary focus of the study is the use of hem-fir in CLT due to the larger size of the market for CLT products.

2. Methodology

The following paragraphs describe the methodology that was employed to undertake the assignment.

Document and literature review

The purpose of the document review was to obtain the available information on the regulatory, technical and market factors affecting the use of hem-fir in mass timber products. Peer-reviewed literature, technical documents, and government and industry reports and websites were systematically reviewed to gain information on these topics. Information was gathered from multiple sources to capture a wide range of information and to answer the research questions. FII provided the initial relevant documents that were supplemented by pertinent information identified by Ference & Company. Each information source was reviewed for relevance with the research questions.

Key informant interviews

Thirty-one (31) semi-structured interviews were conducted with key informants to obtain insights regarding the suitability of hem-fir for use in mass timber projects from a variety of perspectives including regulatory, technical, supply chain and market acceptance factors. These key informants were from a variety of organizations including regulatory agencies, research organizations, mass timber manufacturers, timber suppliers, architects, structural engineers, building contractors, industry associations and government as shown below:

Mass timber manufacturers

- International Timberframes
- Kalesnikoff Mass Timber
- Katerra
- Structurecraft
- Structurlam
- Western Archrib

Regulatory agencies

- APA – The Engineered Wood Association
- Canada Wood Council

Research and development organizations

- FPInnovations
- University of British Columbia
- University of Northern British Columbia

Timber suppliers

- Centurion Lumber
- Interfor
- Teal Jones
- Western Forest Products

Industry associations

- BC Council of Forest Industries
- BC First Nations Forestry Council
- Canada Wood Group

Architects, structural engineers and construction companies experienced in mass timber

- Acton Ostry Architects
- Aspect Structural Engineers
- Fast + Epp Structural Engineers
- Perkins & Will Architects
- Seagate Mass Timber

Government

- BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development

3. Report Outline

The next chapter provides a brief description of the mass timber market and the current use of hem-fir in mass timber products. Chapter 3 summarizes the building standards and regulations related to the use of hem-fir in mass timber products while Chapter 4 summarizes the technical characteristics of hem-fir with regard to its suitability for use in mass timber products. Chapter 5 describes the supply chain and market factors that affect the use of hem-fir while the last chapter contains a framework to achieve market and regulatory acceptance of hem-fir mass timber products.

II. CHARACTERISTICS OF THE MASS TIMBER MARKET

This chapter describes the mass timber market and the use of hem-fir in mass timber products.

1. The Rise of Mass Timber

Wood is a natural biomaterial that is widely used for structural purposes. It has enjoyed a long history of building applications worldwide. Unlike most other building materials, wood is renewable, sustainable, bio-degradable and carbon neutral. Thus, it is the preferred building material for the next generation of green buildings. Wood construction has recently moved from traditional low-rise and mid-rise buildings to modern high-rise buildings, positioning wood as a rival to steel and concrete, materials that have dominated the construction of larger buildings for decades. Advancements in wood product technology and systems are driving the momentum for innovative buildings in Canada. Products such as such as cross-laminated timber (CLT), glue-laminated timber (glulam), and dowel-laminated timber (DLT) and nail-laminated timber (NLT) are part of a bigger classification known as 'mass timber'. Mass timber products can be formed by mechanically fastening and/or bonding with adhesive smaller wood components such as dimension lumber to form large pre-fabricated wood elements used as beams, columns, arches, walls, floors and roofs.

Recognized for the environmental and sustainable benefits of using wood in construction, the push towards mass timber has seen several government-led initiatives in Canada aimed to increase the adoption of mass timber in construction, such as the 2013 *Tall Wood Building Demonstration Initiative* by Natural Resources Canada and the 2017 Green Construction through Wood program. These initiatives have been supported by extensive research by Canadian research organizations such as FPInnovations and universities, leading to the construction of mid- and high-rise buildings made from wood.[1] The BC forest industry has endorsed a strategy to maximize the value of wood produced in BC. A recent report from the BC Council of Forest Industries, *Smart Future: A path forward for B.C.'s forest products industry*, states that:

> '*Using wood in manufacturing, resort construction, the building of institutional wood framed multi-storey buildings, and the opportunities in industrialized construction all offer promise for increasing demand for the products we make. Around the world, there is a growing interest in low-carbon, renewable products from sustainably harvested forests. This is B.C.'s strength and we should grow our opportunities*.'[2]

The report sets an industry target to increase the proportion of value-added manufacturing in BC by a minimum of 20% within 5 years, complemented by aggressively pursuing access to global markets. BC government's *Wood First Initiative* aims to advance the use of wood in the province by encouraging:

> *'The forest industry, researchers and design professionals to explore innovation in B.C.'s built environment and through value-added wood products, helping to grow local and global markets, while promoting climate-friendly construction and supporting our forest-dependent communities.'*[3]

[1] Mohammad, M., Tourrilhes, J., Coxford, R., Williamson, M. (2019). *Canadian Mass Timber Demonstration Projects Initiatives.* Modular and Offsite Construction.
[2] COFI (2019). *Smart Future: A path forward for B.C.'s forest products industry.* Council of Forest Industries.
[3] Government of B.C. *Wood First Initiative.* Accessed from https://www2.gov.bc.ca/gov/content/industry/forestry/supporting-innovation/wood-first-initiative

While there are many types of mass timber products, the scope of this assignment includes the following mass timber products: CLT, glulam, DLT and NLT. CLT, DLT and NLT are alternative ways of producing prefabricated wood panels that are used for flooring, roofing and wall construction while glulam is mainly used for wood beams and columns used in the construction of residential and commercial buildings (Table 2.1).

Table 2.1: Characteristics of Mass Timber Products

Type	Composition	Main Use	Strengths
CLT	Panel consisting of layers of lumber boards stacked crosswise at 90 degree angles, glued into place	Long spans in floor, roof and wall panels in mid- and high-rise construction	High strength, dimensional stability and rigidity
DLT	Panel consisting of softwood lumber that is stacked and friction-fit together using hardwood dowels	Horizontal spans – best suited for floors and roofs	100% wood, easy to use with computer-controlled machinery e.g. lathes, routers, mills
NLT	Panel consisting of individual dimension lumber, stacked on edge, and fastened together by nails	Floors, decking, roofs and walls	Doesn't require dedicated manufacturing facility, can be fabricated with readily available dimension lumber
Glulam	Wood laminations (dimension lumber) are positioned according to their stress-rated performance characteristics and joined end-to-end, bonded with adhesive	Beams and columns in residential and commercial building applications, also as roof panels	Stronger than steel at comparable weights. Long spans, allows for framing to be exposed timber

Source: www.thinkwood.com/products-and-systems/mass-timber

2. Cross-Laminated Timber (CLT)

CLT is heralded as the building technology that is revolutionizing the use of mass timber in construction[4]. CLT is a prefabricated multi-layer engineered wood panel, made from at least three layers of parallel boards by gluing the surfaces together using adhesive under pressure, with alternate boards placed crosswise (Figure 2.1). This gives the panels a high level of in-plane stability, and the thickness provides exceptional strength and stiffness.[5]

Figure 2.1: Illustration of a CLT Panel

Source: https://cwc.ca/how-to-build-with-wood/wood-products/mass-timber/cross-laminated-timber-clt/

[4] Gagnon, S., Pirvu, C. (eds) (2011). *CLT Handbook: Cross-Laminated Timber*. Vancouver, FPInnovations, pp. 380.
[5] Harte, A. M. (2017). *Mass timber – The emergence of a modern construction material*. Journal of Structural Integrity and Maintenance, 2:3, 121-132.

CLT production originated in Austria and Germany in the 1990s. In 2014, global CLT production was approximately 625,000 cubic metres of cross-laminated timber of which 60% came from Austria and 16% from Germany. As indicated in Table 2.2, there were 37 CLT manufacturers throughout the world in 2014 of which 81% were located in Europe while the remaining CLT plants were located in the US, Canada, New Zealand, Australia, Japan and China.

Table 2.2: Number of CLT Manufacturers in 2014

Country/Continent	Number of CLT Manufacturers
Austria	8
Germany	6
Italy	6
France	4
Rest of Europe	6
North America	3
Asia and Pacific	4
Total	**37**

Source*:* https://www.holzkurier.com/schnittholz/2015/02/brettsperrholz_waechstglobal.html

According to a market research report by IMARC Group, the global cross-laminated timber market reached a value of US$664 Million in 2018, growing at a rate of 16% per year from 2011 to 2018[6]. Another study stated that global CLT production would increase almost five-fold from 625,000 cubic metres in 2014 to 3 million cubic metres by 2025. To put this into perspective, this study stated that the achievement of this projection would require about 3% of the total annual consumption of softwood sawn wood in North America, which was nearly 91 million cubic metres in 2015.[7]

Europe has continued to dominate global CLT production as the top 5 global CLT manufacturers are all located in Europe as indicated below[6]:

- Binderholz, Austria: Wood products include glulam, timber, profiled timber, laminated timber, and single and multi-laminated solid wood panel. The company employs about 1,400 people with operations at five sites in Austria and two sites each in Germany and Finland. Binderholz CLT plants in Austria and Germany have a combined capacity of 320,000 cubic metre.

- Hasslacher, Austria: Owns eight manufacturing sites in Germany, Slovenia, Austria and Russia and is one of Europe's largest and most prominent timber industry companies. Wood products included CLT, glulam, finger jointed structural, solid timber ceiling systems and laminated beams. After a merger with Nordlam, Hasslacher became Europe's biggest producer of glulam with a 2016 production volume of 140,000 cubic metre. CLT production was around 40,000 cubic metres in 2016, but with plans to double this with a new plant.

[6] IMARC Group. (2017) *Cross-Laminated Timber Market: Global Industry Trends, Share, Size, Growth, Opportunity and Forecast 2019-2024.*
[7] Muszynski, L., Hansen, E., Fernando, S., Schwarzmann, G., Rainer, J. (2017) *Insights into the Global Cross-Laminated Timber Industry*. BioProducts Business. 2(8) pp.77-92.

- KLH Massivholz, Austria: One of the biggest producers of large-sized CLT products worldwide with more than 15,000 reference projects, as well as an annual production capacity of 125,000 cubic metres per year. Provides ceiling, structural wall, and roofing elements, floors, timber boards, crosswise laminates, and CLT panels.

- Mayr-Melnhof Holz Group, Austria: Wood products include CLT, glulam, and laminated ceiling elements. The company owns three sawmill plants in Austria, Czech Republic and Russia as well as three timber processing plants in Austria and Germany. Mayr-Melnhof Holz processing plants have an annual capacity of 200,000 cubic metres glulam and 70,000 cubic metres CLT.

- Stora Enso, Finland: A leading global forest products company with 26,000 employees in more than 35 countries with two production sites in Austria. About 75% of sales came from Europe with the rest in Asia. Stora Enso have an annual CLT capacity of 100,000 cubic metres per year which is set to increase with the addition of a third CLT production site, with a capacity of around 100,000 cubic metres annually.

The number of CLT manufacturers in North America has increased more than fourfold from three in 2014 to thirteen current and planned operations (Table 2.3). In North America, the adoption of CLT technology was first championed in Canada, where the first two production lines were founded by Nordic in Chibogameau, Quebec and Structurlam in Penticton, British Columbia. While non-structural CLT panels were produced in the US as early as 2010, the first CLT plant was established in 2016 by Smartlam in Whitefish, Montana.

Table 2.3: Mass Timber Panel Manufacturers in North America

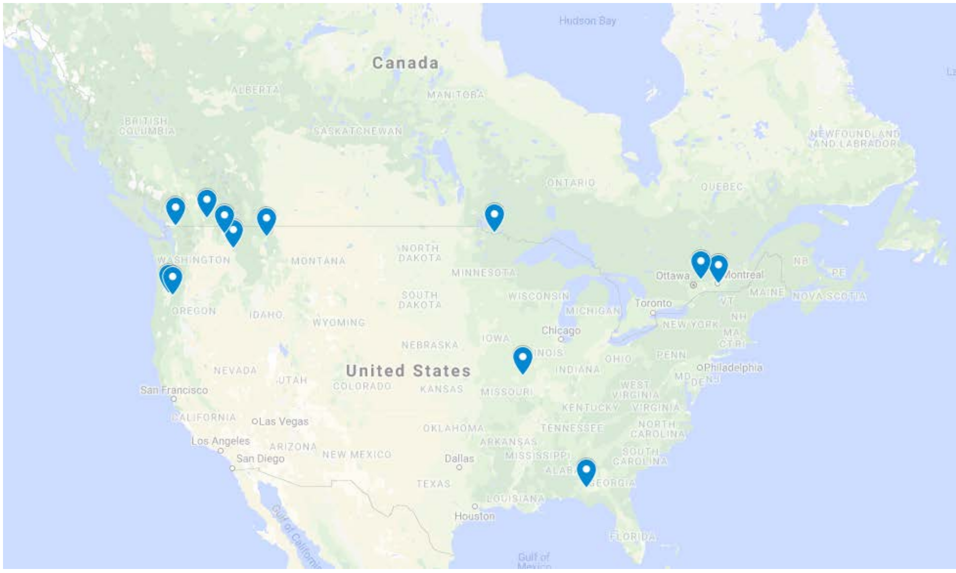
Company	City	State/Province	Lumber Demand (MMBF)	Primary Species	2019 status	Mass timber product(s)
Structurlam	Penticton	British Columbia	20-30	SPF	Operating,	CLT, Glulam, GLT
StructureCraft	Abbotsford	British Columbia	40-50	SPF	Operating	DLT (NLT recently phased out)
Leaf EWP	Devlin	Ontario	10-15	SPF	Operating	CLT, Glulam
Nordic	Chibougamau	Quebec	60-70	SPF	Operating	CLT, Glulam
Element5	Ripon	Quebec	20-30	SPF	Operating	CLT, Glulam, NLT, LVL
Katerra	Spokane	Washington	100+	SPF	???	CLT
Vaagen Timbers	Colville	Washington	40-50	Doug-Fir	???	CLT, Glulam, GLT
DR Johnson	Riddle	Oregon	60-70	Doug-Fir	Operating	CLT
Freres	Lyons	Oregon	N/A	Doug-Fir	Operating	MPP
Smartlam	Columbia Falls	Montana	20-30	Doug-Fir	Operating	CLT
Intl. Beams	Dothan	Alabama	20-30	Southern Pine	Operating	LVL
Sterling Lumber	Phoenix	Illinois	40-50	Unknown	Operating	CLT mats
Smartlam	TBA	Maine	n/a	n/a	Announced	CLT
LignaCLT	Millinocket	Maine	n/a	n/a	Announced	CLT
Sterling Lumber	Lufkin	Texas	n/a	n/a	Announced	CLT
Kalesnikoff	South Slocan	British Columbia	n/a	Multi-species	Under construction	CLT, Glulam

Source: *Mass Timber panel manufacturers operating in North America.* Updated from: The Beck Group (2018) *Mass Timber Market Analysis.* Council of Western State Foresters. Note: *MPP (Mass Plywood Panel), LVL (Laminated Veneer Lumber)*

As indicated in Figure 2.2, there exists a concentration of mass timber manufacturers in northwestern US close to the supply of timber. However, only one CLT manufacturer currently exists in BC, Structurlam in Penticton. The CLT panels produced by Structurlam typically range in size from 2.4 metres or 3 metres wide by 12.19 metres long while the panel thickness ranges from 87 millimetres to 315 millimetres. A second CLT plant is currently being constructed in BC by Kalesnikoff who recently unveiled plans for a $35 million mass timber facility in South Slocan. Kalesnikoff are producers of Douglas-fir, western larch, lodgepole pine, western hemlock, Engelmann spruce and western white pine lumber products and currently operates a multi-species mill with a capacity of 75 million fbm equipped with five state-of-the-art steam injection dry kilns.[8]

Figure 2.2: Location of Mass Timber Manufacturers in North America

[8] Information available from: http://www.kalesnikoff.com/



A 2017 market research study forecasted that the overall demand for CLT panels in the US Pacific Northwest could reach approximately 190,000 cubic metres annually.[9] The forecast demand would be almost double, 340,000 cubicmetres, if: i) the perceptions of architects, engineers and designers improve faster than projected, ii) the construction cost efficiencies of using CLT relative to traditional materials are recognized, or iii) the regulatory regime towards the use of CLT in construction were to substantially improve. The study stated that the production of 190,000 cubic metres of CLT panels would require approximately 4 medium-sized CLT manufacturing plants.

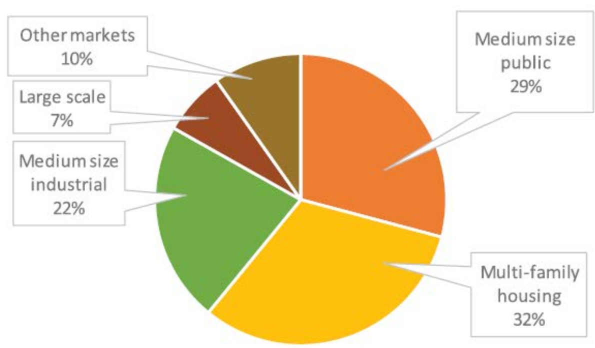
A 2018 market research study for the Council of Western State Foresters (CWSF) region (17 Western US states and six US-affiliated Pacific Islands) stated that the market for mass timber in large, multi-storey buildings is expanding rapidly, carried in part by the buzz around new products such as CLT, and by targeted educational/information campaigns[10]. The business case for mass timber is solid, with potential benefits including lower cost, strong fire and seismic performance, aesthetics, and environmental performance. Progress is being made to reduce barriers to the expansion of mass timber markets, including building code revisions, increased building industry awareness of mass timber, and expanding supplies of mass timber products. The market for CLT in the Council of Western State Foresters region is estimated to be nine million cubic feet in 2020. By 2025, the market is expected to double. Mass timber panel manufacturing is expanding rapidly to meet growing demand.

A survey of CLT manufacturers in Europe and North America indicated that over 96% of their production volume was manufactured for custom orders while only one respondent indicated production of 100% blank, non-machined panels that are sold as generic CLT products[11]. This highly customized nature of CLT production contrasts sharply with much of the North American forest industry, which generally focuses on highly

[9] Ganguly, I., Beyreuther, T., Hoffman, M., Swenson, S., Eastin, I. (2017) *Forecasting the demand for Cross Laminated Timber (CLT) in the Pacific Northwest.* Cintrafor (Center for International Trade in Forest Products) News.
[10] The Beck Group (2018) *Mass Timber Market Analysis.* Council of Western State Foresters.
[11] Muszynski, L., Hansen, E., Fernando, S., Schwarzmann, G., Rainer, J. (2017) *Insights into the Global Cross-Laminated Timber Industry.* BioProducts Business. 2(8) pp.77-92.

productive, commodity-type operations. The focus on custom projects is a result of the complex circumstances of the evolution of the CLT industry in Europe and the fact that CLT technology has been a disruption to the building environment in Europe. In order to propose a revolutionary building technology that did not rely on technologies, practices, experiences, or skill sets existing in concrete, steel, brick and mortar or even in the traditional timber structure technologies, proponents were compelled to offer a finished package: CLT-specific architectural design, engineering specifications, building materials, and a CLT-conscious construction crew. This created a strong incentive for close collaboration. In fact, close collaboration among architects, engineers, contractors and manufacturers is still commonplace today, and these functions are often vertically integrated within one company. This means that architects and engineers design with intimate knowledge of the intrinsic flexibilities of the specific manufacturing process, which allows the manufacturer to carefully optimize the product for a specific project. About one-quarter of survey respondents were involved with architectural design, half of the respondents with building engineering, and just over half with building construction. Many companies also integrated other elements of the extended CLT supply chain incorporating log harvesting, transportation, lumber processing, and other functions typical to their forest products. This study confirmed the prevalence and overall importance of integrated lumber manufacturing, log and lumber transportation for large players in the CLT industry. The survey of CLT manufacturers in Europe and North America found that respondents were focused primarily on multi-family housing, which accounted for nearly one-third (32%) of total sales (Figure 2.3). Medium-size public buildings (29%) were the second largest market segment. Large-scale buildings represented only seven percent of sales for responding companies.

Figure 2.3: Analysis of CLT Market Segments by Output Volume



Source: Muszynski, L., Hansen, E., Fernando, S., Schwarzmann, G., Rainer, J. (2017) *Insights into the Global Cross-Laminated Timber Industry.* BioProducts Business. 2(8) pp.77-92.

The small share of large projects in global CLT output is corroborated by the still small number of CLT buildings over ten storeys completed worldwide. A 2017 study indicated that 50 buildings between five and fourteen storeys tall have been completed worldwide using CLT panels. As indicated in Table 2.4, more than one half (56%) of the buildings were five or six storeys while there were only four ten-storey buildings and one fourteen-storey building constructed with CLT panels from 2005 to 2016 (Table 2.4).[12]

Table 2.4: Number of CLT Multi-Story Buildings Constructed from 2005 to 2016

[12] Harte, A. M. (2017). *Mass timber – The emergence of a modern construction material.* Journal of Structural Integrity and Maintenance, 2:3, 121-132.

Year	Number of Storeys							Total Buildings
	5	6	7	8	9	10	14	
2005	2							2
2006	1							1
2008			1	1		1		3
2009				1				1
2010		1						1
2011		1		2				3
2012	2	1		1		1		5
2013	1	4	3	1	1			10
2014	2	1	2	3		1		9
2015	3	2		1		1	1	8
2016	6	1						7
Total	**17**	**11**	**6**	**10**	**1**	**4**	**1**	**50**

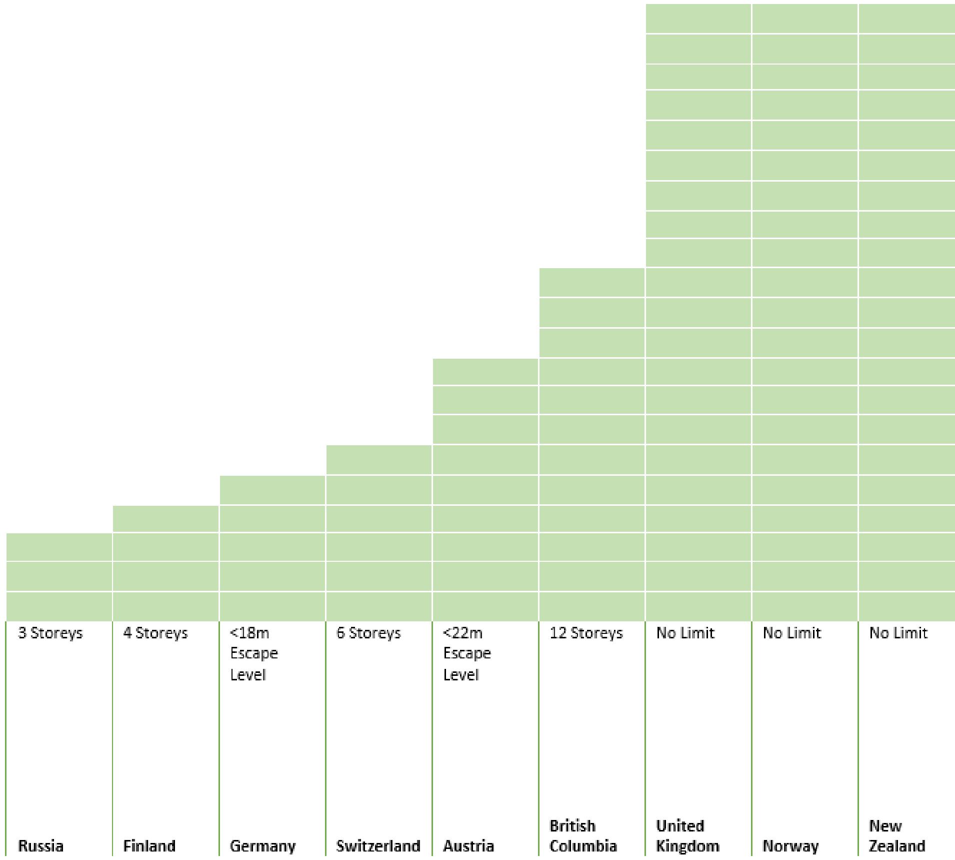
Source: Harte, A. M. (2017). *Mass timber – The emergence of a modern construction material.* Journal of Structural Integrity and Maintenance, 2:3, 121-132.

Since 2016, a number of taller buildings have been constructed with wood using CLT panels. A local example is Brock Commons, the 18-storey, 53-metre-high mass timber student housing constructed at the University of British Columbia (UBC) in Vancouver. Brock Commons consists of 16 floors of CLT floor panels, point supported by glulam columns, with a single-storey concrete podium at the base, prefabricated steel roof and two concrete cores, and at the time of completion was the tallest mass timber hybrid building in the world.[13] The residence was ahead of the building code in British Columbia, which at the time only allowed for a maximum of six storeys to be built using wood, requiring a special approvals process in the form of site-specific regulation, in consultation with the BC Standards Building Safety and Standards Branch. While BC is taking the lead in Canada in tall wood buildings, many other jurisdictions are also proceeding with the construction of tall wood buildings. The construction of Origine at Pointe-aux-Lièvres, a 13-storey building in an eco-neighbourhood in Quebec City, is the tallest wood building in eastern Canada and tallest wood condominium building in North America.[14] The title of the tallest wood building in the world, according to the Council on Tall Buildings and Urban Habitat, is held by Mjøstårnet, a mixed-use building in Brumunddal, Norway, at 85.4 metres tall and consisting of eighteen storeys.[15]

The construction of tall buildings with wood is constrained by current building codes. As indicated in Figure 2.4, the maximum number of storeys ranges considerably from country to county with some countries such as the United Kingdom, Norway and New Zealand having no limit.

Figure 2.4: Maximum Height for Wood Buildings in Different Jurisdictions

[13] Fast, P., Gafner, B., Jackson, R., Li, J. (2016). *Case Study: An 18 storey tall Mass Timber Hybrid student residence at the University of British Columbia, Vancouver.* World Conference on Timber Engineering 2016, Vienna, Austria.
[14] WoodWorks! (2018). *Brock Commons Tallwood House: University of British Columbia Vancouver Campus: The advent of tall wood structures in Canada: A Case Study.* Canada Wood Council.
[15] The Council on Tall Buildings and Urban Habitat (2019). *CTBUH Ratifies "World's Tallest Timber Building" Following height criteria update.* Accessed from: https://www.ctbuh.org/news/mjostarnet-tallest-timber-building/. Last accessed 19/11/19.



Source: *Current Trends and Future Directions for Multi-Storey Timber Buildings.*

In France, the building code has allowed mass timber structures not over three storeys tall, which was felt to significantly limit the competitiveness of CLT in the building market, particularly in cities where there is a need to build up due to land restrictions. Recently, however, the CLT France Association in collaboration with the Federation of the Wood Construction Industry has been working with French government building officials to amend the building code to allow for more CLT in larger buildings[16]. The progress of this can be seen in the announcement of the first timber towers in France under construction in Bordeaux and scheduled to be completed in 2020 – one 18-storey residential tower and a 50 metre office tower made from CLT with glulam plywood bracing.[17] A survey of CLT manufacturers in Europe and North America stated the building codes were the greatest barrier to growth while other factors were the architectural community's unfamiliarity with CLT technology, raw material costs, production costs and lack of demand.[18]

[16] Albee, R.R., Muszyński, L., Hansen, E.N., Knowles, D., Larasatie, P., Guerrero, J.E. (2018) *Recent Developments in Global Cross-Laminated Timber (CLT) Market.* World Conference on Timber Engineering. Seoul, Republic of Korea.
[17] Global Construction Review (2016) *France's first wooden towers to be built in Bordeaux.* Available from: http://www.globalconstructionreview.com/news/frances-first-wooden-towers-b7e-bu7ilt-bordea7ux/
[18] Muszynski, L., Hansen, E., Fernando, S., Schwarzmann, G., Rainer, J. (2017) *Insights into the Global Cross-Laminated Timber Industry.* BioProducts Business. 2(8) pp.77-92.

Many building codes are currently being revised to allow for the construction of taller wood buildings. BC announced in 2019 plans to increase the maximum number of storeys that can be constructed with wood from six storeys to buildings up to twelve storeys if the mass timber products (i.e. CLT and glulam columns) are encapsulated (e.g. covered with drywall). The National Building Code of Canada will be revised in 2020 to increase the number of storeys from six to twelve for buildings constructed from wood using encapsulated mass timber. In the US, provisions were approved for the 2021 International Building Code that will allow construction of mass timber buildings up to eighteen storeys.

A 2018 report of case studies of three CLT manufacturers in Europe stated that the current challenges are: consistent supply of high quality raw material; vertical integration with lumber suppliers and glulam producers; efficient and effective management of the information flow; and proper logistic and transportation operations.[19] The rate of adoption of mass timber structures in Australia is slow. A research study suggests this is, in part, due to the challenge of financing these types of projects as a result of difficulties in securing insurance for significant mass timber projects, and hesitation around perceived consumer opinions.[20] Following the Grenfell Tower fire – a residential tower block fire resulting in the deaths of 72 people– a ban has been put on the use of combustible materials in the external walls of residential buildings over eighteen metres tall in the UK. It has also been reported that since this tragic incident, the cost of insurance to construct tall wood buildings in the UK has increased significantly.[21]

The acceptance of wood and wood products as being safe and high performing construction materials is still a barrier to growth of CLT manufacturing. Some ways to overcome this require collaboration from organizations supporting wood products, such as universities, and government. Respondents in a CLT case study suggested that government support of CLT systems could be significant in incorporating wood products into new or remodelled public buildings, such as hospitals, schools, and fire stations to showcase the advantages of these products.[22]

3. Nail-Laminated Timber (NLT)

NLT is the oldest mass timber product and has been in use in heavy timber structures for over 150 years. Examples exist in the warehouse districts of many cities. Large industrial buildings like the 500,000-sq.ft., eight-story Butler Building (Minneapolis, built in 1906) used solid-sawn posts and beams with NLT floor panels to create a robust structural frame. NLT is created from dimensional lumber stacked on edge – nominal 3″, 4″, 6″, 8″, 10″, or 12″ boards which are laminated and fastened together with nails. Plywood or OSB sheathing is often added to the top side to provide a structural diaphragm (Figure 2.5).

[19] Quesada, H., Smith, R., Berger, G. (2018) *Drivers and Barriers of Cross-Laminated Timber (CLT) Production and Commercialization: A Case Study of Western Europe's CLT Industry*. BioProducts Business 3(3) pp.29-38.
[20] Kremer, P.D., Symmons, M.A. (2018) *Perceived barriers to the widespread adoption of Mass Timber Construction: An Australian construction industry case study*. Mass Timber Construction Journal.
[21] Stephen Cousins (2019) *Insight: Timber faces the heat of combustibles ban*, Construction Manager. Available from: http://www.constructionmanagermagazine.com/insight/timber-faces-heat-combustibles-ban/
[22] The Council on Tall Buildings and Urban Habitat (2019). *CTBUH Ratifies "World's Tallest Timber Building" Following height criteria update.* Accessed from: https://www.ctbuh.org/news/mjostarnet-tallest-timber-building/. Last accessed 19/11/19.

Figure 2.5: Illustration of an NLT Panel

Source: Think Wood - https://www.thinkwood.com/news/selecting-lumber-making-nlt

Heavy timber construction fell out of mainstream use with the industrial revolution and the rise of steel and concrete as primary building materials. However, this is starting to change as the construction industry realizes the importance of sustainable construction. Wood is the only primary structural material that is renewable and grows naturally. Julius Natterer, a famous Swiss timber engineer, re-introduced the concept of NLT to Europe in the 1970s. Natterer saw NLT as a mass timber product that could be produced by anyone, and encouraged manufacturing throughout Europe. However, the nails inside NLT meant that CNC machining of these panels was impossible, and manufacture by hand was laborious.[23]

There are at least 30 European companies that use specialized robotic equipment to bond massive cross laminated panels with aluminum nails. However, the output volume of plants producing NLT is small when compared to plants producing adhesive bonded CLT products.[24] As indicated in Table 2.3, there are very few NLT manufacturers in North America. Timmerman Timberworks Inc. located in New Lowell, Ontario was the first company in Canada to automate NLT production as it was previously done by hand. Structurecraft in Abbotsford, BC was also an NLT manufacturer but recently phased out production and switched to the manufacturing of DLT panels, except for custom orders of NLT. Some BC companies such as Seagate Structures do produce some NLT structures manually with simple tools and often at the construction site.

4. Dowel-Laminated Timber (DLT)

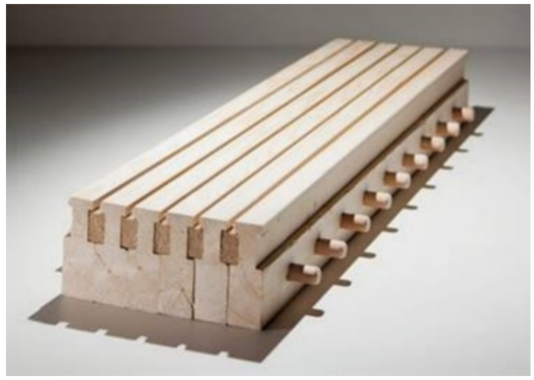
DLT panels are made from softwood lumber boards stacked like the boards of NLT, but friction-fit together with hardwood dowels instead of nails. The dowels hold each board side-by-side, forming a stiffer and stronger connection than the nails in NLT. Each board lamination in a DLT panel is finger-jointed, creating a stiffer and stronger panel than NLT as it eliminates the board splices and butt-joints which are characteristic of NLT (Figure 2.6). DLT panels may be processed using CNC machinery, unlike NLT panels (due to the nails). This creates a high tolerance panel which can also contain pre-integrated electrical conduit and other service runs. As a floor or roof deck, DLT is a highly efficient structural panel. Similar to NLT or GLT (glulam on flat), all of the wood

[23] Lucas Epp (2018). *A new mass timber product in North America.* Wood Design & Building. Available from: http://www.wooddesignandbuilding.com/dowel-laminated-timber/

[24] Muszynski, L., Hansen, E., Fernando, S., Schwarzmann, G., Rainer, J. (2017) *Insights into the Global Cross-Laminated Timber Industry*. BioProducts Business. 2(8) pp.77-92.

fiber runs in the direction of the span. This provides the most efficient use of material for floor and roof systems which are typically one-way spanning between beams or walls.[25]

Figure 2.6: Illustration of a DLT Panel



Source: https://treesource.org/news/goods-and-services/mass-timber-primer/attachment/dowel-laminated-timber/

In the early 1990s, DLT was developed by Alois Tschopp with Pirmin Jung in Switzerland. They saw this product as a superior product to NLT – it used only wood, it was CNC machinable, and production of the panel was possible with automated machinery. They proceeded to create the first automated machinery line for DLT. In Europe, DLT is a well-known and well used mass timber product. Although both products were developed around the same time, CLT has developed a larger market share in Europe, as the big glulam manufacturers saw CLT as a glued product which could be easy to expand into. DLT has remained the realm of smaller manufacturers – the largest manufacturer produces around 15,000 cubic metres per year. Interestingly, DLT is often cheaper than CLT in Europe, and is gaining more interest, due to DLT being 100 per cent wood. Recent larger and taller wood buildings in Europe have used DLT as floor and wall panels.

Of the 26 DLT manufacturers worldwide, more than three quarters are located in Europe: nine in Germany, seven in Switzerland, and four in Austria. The Austrian company, Thoma, is probably largest DLT manufacturer in Europe and produces mainly wooden single-family homes using their branded Holz100 method which focuses on the health and environmental benefits of DLT.

As indicated in Table 2.3, there are very few DLT manufacturers in North America. In 2017, StructureCraft located in Abbotsford, BC, installed the first DLT production plant in North America. This high-capacity, fully automated DLT machinery line is the fastest and has the largest capacity worldwide. The stated goal of StructureCraft is to introduce a new cost-competitive mass timber product to the rapidly growing market in North America. To produce DLT panels, hardwood dowels are connected to softwood boards for a friction-fit. The softwood species typically employed are spruce or fir while the hardwood dowels are made from European beech. StructureCraft DLT panels typically panel sizes are 8' x 20' and 10' x 60'whereas the maximum width is 12 foot and the maximum length is 60.5'. Panel thicknesses (including ½" sheathing) include 2 ¼",4", 6", 7 ¾", 9 ¾" and 11 ¾" while the lamination thickness is typically 1-1 ½" or 3".

Established in 2003, International Timberframes in Golden, BC also produces DLT panels. The company designs, manufactures and installs a 100% Wood DLT product called Wood100 DLT. International Timberframes projects

[25] Lucas Epp (2018). *A new mass timber product in North America.* Wood Design & Building. Available from: http://www.wooddesignandbuilding.com/dowel-laminated-timber/

range from full timber-frame packages for homes, decorative beams and brackets, stairs, mantelpieces, decks, gazebos and a range of specialty furniture items. The company constructs a few homes each year and produces DLT as building components for small and mid-size buildings.

5. Glue-Laminated Timber (Glulam)

Glulam is a structural engineered wood element commonly used for beams and columns in residential and commercial applications. Glulam is a highly visible form of mass timber in contemporary projects, with long spans framing signature designs that have been left exposed to take advantage of wood's natural aesthetic. Glulam is stronger than steel at comparable weights, and it is stronger and stiffer than dimension lumber. That makes the material a cost-effective choice for long, structural spans and tall columns with minimal need for additional support.

Glulam can be used in interior and exterior applications. Several manufacturers sell glulam products with adhesives that can withstand moisture and wear from use outdoors. To form a glulam component, wood laminations (dimension lumber) are positioned according to their stress-rated performance characteristics. In most cases, the strongest laminations sandwich the beam in order to absorb stress proportionally and ensure the member's longevity. The laminations are jointed end to end, allowing for long spans, and are bonded with a durable, moisture-resistant adhesive. The laminations' grains run parallel with the member's length to improve its strength (Figure 2.7).[26]

Figure 2.7: Illustration of Glulam Beams

Source: Ambista - https://www.ambista.com/de/holzleimbauteile/glulam-beams-25805

Glulam members come in standard and custom sizes. Depths range from 6 inches to 72 inches, and widths range from 2.5 inches to 10.75 inches. Components are cut to length when ordered and can surpass 100 feet. Commercial projects often require longer spans and accommodate bigger loads than residential projects,

[26] Information available from: https://www.thinkwood.com/products-and-systems/mass-timber/glue-laminated-timber-glulam

meaning custom widths and depths are often required. In addition to straight spans, glulam can also be used for curved and pitched applications.[27]

Glue laminated timber can be used in framing, floor and roof beams, columns, door headers, trusses, and many other areas. Expanding application base for the product in construction across diverse sectors such as residential, commercial, as well as industrial is projected to aid market growth. Key attributes associated with glue laminated timber, such as consistent performance, durability, and chemical resistance, are set to promote market growth. Moreover, glue laminated timber, being environment-friendly, has attracted the attention of governing authorities across the globe as a green building material. Major players in the industry are constantly striving for technological advancements to manufacture quality products with increased efficiency.

Glulam was first used in Europe in early 1890s and patented in Switzerland in 1901. The first structure using glulam in North America was the USDA Forest Products Laboratory in Wisconsin in 1934 (still used today). The addition of fully water-resistant phenol-resorcinol adhesives in 1942 sparked expansion of glulam use.

The global glulam market was valued at US$4.76 billion in 2016 and is projected to grow at an annual rate of 5.9% to 2025. Growing sustainability concerns across the globe and mounting awareness among consumers about wood as a building material are likely to be the major driving forces for the market in the coming years. Shifting consumer preference for wood-based construction owing to its durability, high thermal performance, and light weight is expected to propel market growth. Germany and Italy cumulatively accounted for about 60% of the Europe market due to the high acceptance and growing consumption of wood as a building material. Austria, is the largest producer of glulam in the world. The demand for glulam in North America was valued at US$360.1 million in 2016.[28]

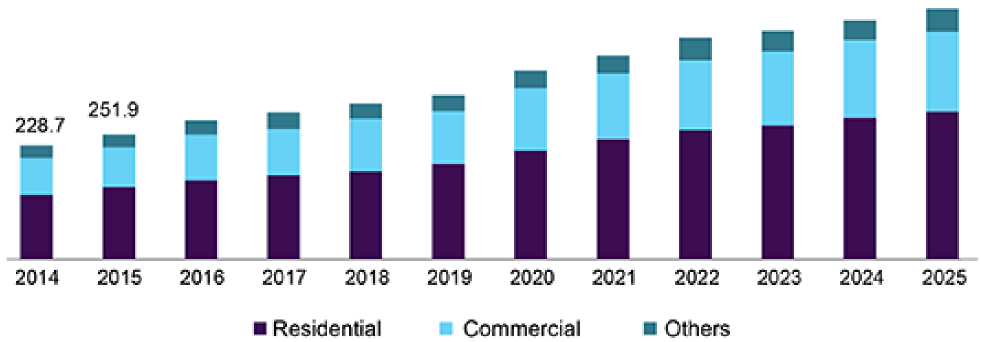
As indicated in Figure 2.8, the market for glulam in the United States is projected to more than double by 2025. The demand for glulam has observed a tremendous surge recently on account of the evolution of wood as a low-cost and sustainable alternative to steel and concrete. The growing acceptance of glulam, due to its superior strength, ease of construction, and maintenance, is likely to fuel market growth. Increasing popularity of the product and awareness regarding its benefits in regions such as North America and Asia Pacific is anticipated to positively impact the market.[29]

[27] Information available from: https://www.thinkwood.com/products-and-systems/mass-timber/glue-laminated-timber-glulam

[28] Grandview Research (2017) *Glue Laminated Timber Market Analysis, by Application (Residential, Commercial) by Region (North America, Europe, Asia Pacific, CSA, and MEA), and Segment Forecasts, 2018-2025*

[29] Grandview Research (2017) *Glue Laminated Timber Market Analysis, by Application (Residential, Commercial) by Region (North America, Europe, Asia Pacific, CSA, and MEA), and Segment Forecasts, 2018-2025*

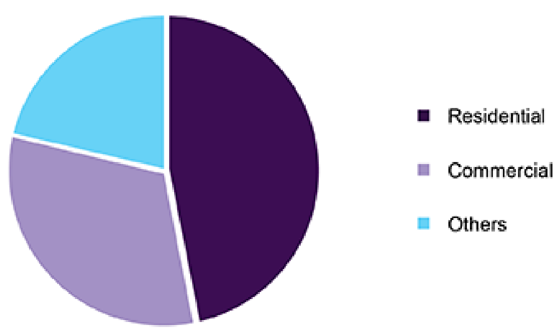
Figure 2.8: US Glulam Market Projections from 2014 to 2025



Source: Grandview Research (2017) *Glue Laminated Timber Market Analysis, by Application (Residential, Commercial) by Region (North America, Europe, Asia Pacific, CSA, and MEA), and Segment Forecasts, 2018-2025.*

As indicated in Figure 2.9, the residential market segment held the largest market share in the global glulam market in 2016. This can be attributed to increasing use in residential construction applications such as flooring and roofing systems and straight or arched beams. The favorable aesthetic qualities of glulam make it even more suitable for the residential segment, as there is a high demand for designing stylish houses. The design flexibility offered by the product is also a major factor promoting market growth. Glulam is also fire-resistant owing to which it is a safe and perfect fit for residential constructions. Residential construction is likely to be the fastest growing application segment. Glulam is also used for commercial and industrial purposes. Growing demand for the product due to its ability to span long distances, its ease of use in constructions, and favorable performance in the construction of a variety of structures such as office buildings, plants, malls, schools, colleges, and bridges is anticipated to augment the market.[30]

Figure 2.9: Glulam Market Segments by Application in 2016 (%)



Source: Grandview Research (2017) *Glue Laminated Timber Market Analysis, by Application (Residential, Commercial) by Region (North America, Europe, Asia Pacific, CSA, and MEA), and Segment Forecasts, 2018-2025.*

[30] Grandview Research (2017) *Glue Laminated Timber Market Analysis, by Application (Residential, Commercial) by Region (North America, Europe, Asia Pacific, CSA, and MEA), and Segment Forecasts, 2018-2025*

The major glulam producers worldwide are:

- B&K Structures – UK
- Binderholz GmbH – Austria
- Boise Cascade Co. – Idaho, US
- Calvert Company – Washington, US
- Canfor – Arkansas, US
- Eugen Decker Holzindustrie – Germany
- Meiken Lamwood Corp – Japan
- Mayr-Melnhof Holz Holding – Austria
- Pfeifer Holz GmbH – Austria
- Schilliger Holz – Switzerland
- Setra Group – Sweden
- Structurlam – BC

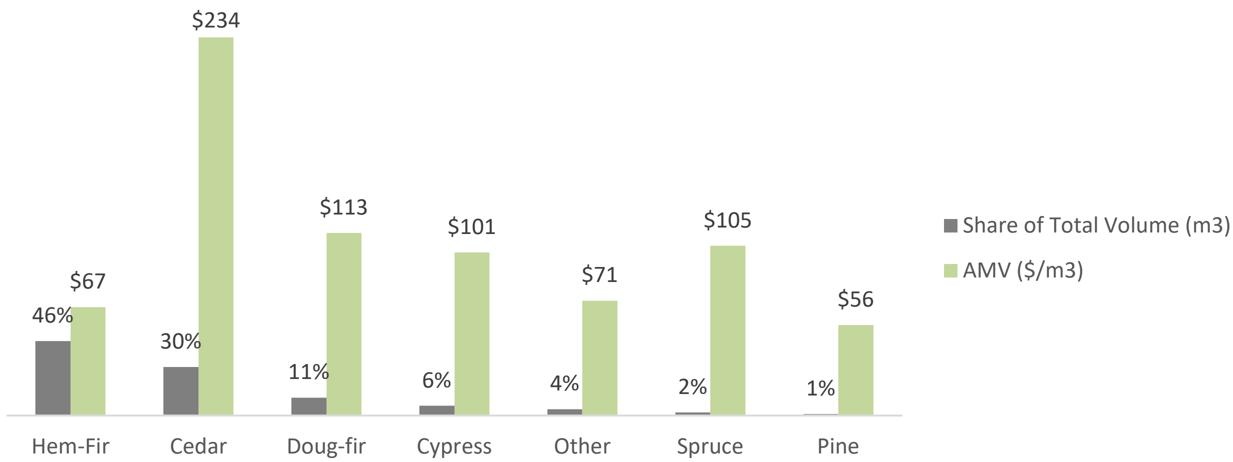
Glulam producers in BC include Structurlam, FraserWood and CutMyTimber. Some major glulam producers in the rest of Canada are Western Archrib (Alberta), Nordic Structures (QC), and Goodfellow (QC).

6. Availability of Hem-Fir in BC

Hem-fir, consisting of western hemlock (Tsuga heterophylla) and amabilis fir (Abies amabilis), are British Columbia's most abundant coastal species. Hem-fir accounts for about 60% of mature coastal forests in BC[31]. Hem-fir exists in mixed stands of timber throughout coastal and interior wet belt regions. Hem-fir is prized for its strength and stiffness, making it a preferred material for use in horizontal components and longer spans. Despite this, hem-fir is an underutilized species in BC, given relatively low value despite its attractive characteristics. Figure 2.10 indicates the significantly lower average log price for hem-fir compared to most other species harvested in coastal BC from May 1 to July 31, 2019. Hem-fir accounted for 46% of the total volume harvested but only 25% of the total value of logs harvested.

Figure 2.10: Comparison of BC Coastal Log Sales Volume and Price by Species from May 1 to July 31, 2019

[31] Coast Forest Products Association. Available from: https://www.aslchem.com/pdf/Wood/HemFir.pdf



Data source*:* https://www2.gov.bc.ca/gov/content/industry/forestry

7. Use of Hem-Fir in Mass Timber

British Columbia

Based on interviews with mass timber manufacturers in BC, hem-fir is not currently used to produce any mass timber products. Structurlam, the sole CLT and glulam producer in BC, primarily uses spruce-pine-fir (SPF) for CLT production while Douglas-fir is the primary species used for glulam production although some other species all also used but not hem-fir. However, representatives of Structurlam indicated an interest in testing hem-fir for CLT manufacturing.

While the StructureCraft website states that their DLT panels are made from a variety of wood species including SPF, Douglas-fir, hemlock, sitka spruce, western red or yellow cedar[32], the company primarily uses SPF for the production of DLT panels and purchases primarily Douglas-fir glulam from manufacturers in North America and Europe. Representatives of StructureCraft indicated that while the company does not currently use hem-fir, they are interested in testing the use of hem-fir in DLT panels. The other mass timber manufacturer in BC, International Timberframes, does not currently use hem-fir.

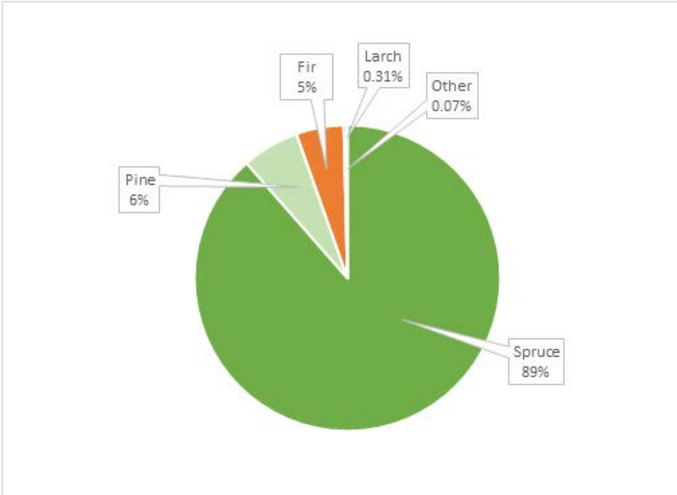
Kalesnikoff plans to commence production of CLT and glulam mass timber products in 2020 and plans to use a variety of species for these products that could potentially include hem-fir obtained from the interior of BC where the company is located.

[32] Information available from: https://structurecraft.com/

Europe and North America

A survey of CLT manufacturers in Europe and North American indicated that spruce was the most predominant species (89%) while the other two species used were pine (6%) and fir (5%). Collectively, these three species accounted for 99% of the wood species used in the manufacture of CLT products (Figure 2.11).

Figure 2.11: Wood Species Used by European and North American CLT Manufacturers



Data source: Source: Muszynski, L., Hansen, E., Fernando, S., Schwarzmann, G., Rainer, J. (2017) *Insights into the Global Cross-Laminated Timber Industry.* BioProducts Business. 2(8) pp.77-92.

As indicated in Table 2.3, SPF was the wood species used by most mass timber manufacturers. However, one American CLT producer, Smartlam, currently makes CLT panels from hem-fir in the Columbia Falls plant in Montana. The company is ANSI/APA PRG 320 certified to produce CLT panels manufactured with SPF or hem-fir, in accordance with the custom layup combination approved by APA – PR-L319. However, the hem-fir grown in the US does not have the same species combinations because Canadian hem-fir consists of hemlock and amabilis fir, whereas US hem-fir is a combination of western hemlock and five fir species: California red fir, grand fir, white fir, noble fir and amabilis fir. CSA 086 *Engineering Design in Wood* specifies that for the purposes of determining design values, US and Canadian hem-fir (hem-fir in Canada is denoted as hem-fir north) are considered equivalent. Both species combinations are marketed as hem-fir as they are considered to have similar design values. However, the American Wood Council *Design Values for Wood Construction*[33] examines the species combinations separately – hem-fir (North): amabilis fir, western hemlock, and hem-fir (US): California red fir, grand fir, noble fir, amabilis fir, western hemlock, white fir. While their design values are similar, there are some differences. For example, the specific gravity of hem-fir in the US is 0.43, as compared to 0.46 for hem-fir (north). The modulus of elasticity of hem-fir (US) is 440,000 compared to 510,000 for hem-fir (north)[34].

China

[33] American Wood Council (2018) *NDS Supplement. National Design Specification, Design Values for Wood Construction.* 2018 edition.
[34] CSA Group (2014) *CSA 086-14: Engineering design in wood.*

The Ningbo Sino-Canada Low-Carbon Technology Research Institute Co., under the guidance of a previous FPInnovations scientist, has opened a CLT plant in Ningbo, Zhejiang Province in China. The pilot plant covers 13,500 square metres and has been operating since November 2015. The operation is in line with Canadian manufacturing protocols and holds the first patent in China for its BC hemlock CLT and bamboo-wood composite CLT.[35] The company has reportedly built a few CLT demonstration houses in the province using BC western hemlock CLT panels[36].

There have recently been a number of research studies investigating the use of Canadian hem-fir with Chinese bamboo to produce CLT panels. Currently most of the dimension lumber used in CLT in China needs to be imported, increasing costs and limiting the development of China's wood construction industry. Similarly with hem-fir in Canada, Chinese proponents are seeking to add value to local resource, such as bamboo and domestic Japanese larch. China has a large population with less land, creating a bottleneck for development in wood construction as the current standards (GB 50005-2017) limit wood construction to 3 storeys. CLT construction can overcome this. There is a big push in China towards off-site construction and low-carbon building materials and methods. The market for prefabricated buildings in China is projected to reach US$375 billion per year in 10 years. A 5% market share for CLT prefabricated construction would represent a market of US$18 billion per year[37].

A study exploring CLT in China showed that the mechanical properties of CLT made of Canadian western hemlock and domestic Japanese larch were comparable or even superior to SPF.[38]
Another study explored the possibility of manufacturing Composite Cross-Laminated Timber (CCLT) from hem-fir and bamboo. The study used bamboo parallel strand lumber (PSL) and BC hem-fir to manufacture 3-layer (bamboo-wood-bamboo) CLT. The hem-fir was imported from BC at 19% moisture content, then kiln dried to 12%. It was classified into 3 grades based on strength and elasticity – E1, E2 and E3. The E2 group was used: 9,120 MPa ≤ MOE < 11,600 MPa. The conclusions were that bamboo-wood CCLT is technically feasible. It had slightly lower block shear strength and wood failure percentage than hem-fir CLT, but the average delamination rate of bamboo-wood CLT was lower. It had an acceptable bond quality and better bond durability than hem-fir CLT. The average inter-laminar shear strength of bamboo-wood CCLT was almost the same as hem-fir CLT. Failure usually occurred first in the interface of bamboo and wood.[39]

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35 Canada Wood (2017) *Pilot CLT Plant in China.* Available from https://canadawood.org/pilot-clt-plant-in-china/

36 National-provincial joint engineering research center of electromechanical product packaging (2017) *The 1st International Symposium of Engineered Biomaterials and Structural Applications.* Available from http://gczx.njfu.edu.cn/eng/class_type.asp?id=250

37 Wang, J.B., Wei, P., Gao, Z., Dai, C. (2018) *The Evaluation of Panel Bond Quality and Durability of Hem-Fir Cross-laminated timber (CLT).* European Journal of Wood and Wood Products, 76: 833-841.

38 Li, H., Wang, B.J., Wei, P., Wang, L. (2019) *Cross-Laminated Timber (CLT) in China: A State-of-the-Art.* Journal of Bioresources and Bioproducts.

39 Wei, P., Wang, B.J., Wang, L., Wang, Y., Yang, G., Liu, J. (2019) *An exploratory Study of Composite Cross-Laminated Timber (CCLT) made from Bamboo and Hemlock-fir Mix.* Bioresources, 14(1), 2160-2170.

III. MASS TIMBER REGULATORY AND PRODUCT CERTIFICATION STANDARDS

There are a number of regulatory, product certification and technical standards that govern the manufacture of mass timber products. The following paragraphs indicate whether these standards restrict the use of hem-fir in mass timber products.

1. Cross-Laminated Timber

The key product certification standard for CLT in North America is *ANSI/APA PRG 320: Standard for Performance-Rated Cross-Laminated Timber* that has been developed by the American National Standard (ANSI) and APA - The Engineered Wood Association (APA). This standard was developed by a committee made up of manufacturers, consultants, regulatory experts, academics, researchers, engineers and other experts. The standard provides requirements and test methods for the qualification and quality assurance of CLT manufactured from solid-sawn or structural composite lumber and used in construction applications. CLT products that conform to the standard may bear the stamp of an approved agency that either inspects the manufacturer or tests a random sampling of the final product in shipment. These products may be stamped with the ANSI/APA PRG 320 symbol and the CLT grade qualified for in accordance with the standard, among other identifiers. The PRG 320 standard states that:

> *'Any lumber species or species combinations recognized by American Lumber Standards Committee (ALSC) under PS 20 or Canadian Lumber Standards Accreditation Board (CLSAB) under CSA 0141 with a minimum published specific gravity of 0.35, as published in the National Design Specification for Wood Construction (NDS) in the U.S. and CSA 086 in Canada, shall be permitted for use in CLT manufacturing provided that other requirements specified in this section are satisfied.'* ANSI/APA PRG 320, 6.1.1.

The lumber standards named in PRG 320 (i.e. PS 20 and CSA 0141) are national standards for softwood lumber in the US and Canada, respectively, and used for classification and grading of softwood lumber species. Western hemlock or hem-fir is specifically named in both of these standards.

As shown in Table 3.1, below, the hem-fir grown in BC (referred to as hem-fir north) exceeds the minimum specific gravity requirement of 0.35 specified in PRG 320 because it has a specific gravity of 0.46. As a result, this table demonstrates that hem-fir grown in BC can comply with the key requirement of PRG 320.

Figure 7: Specific Gravity of Hem-Fir and Other Lumber Species

Lumber Species	Specific Gravity
Douglas Fir-Larch	0.50
Douglas Fir-Larch (North)	0.49
Douglas Fir – South	0.46
Hem-Fir (North)	0.46
Hem-Fir	0.43
Spruce-Pine-Fir	0.42
Spruce-Pine-Fir (South)	0.36

Source: *ANSI/AWC NDS-2015: National Design Specification for Wood Construction.* American Wood Council.

PRG 320 also states that the maximum moisture content at the time of CLT manufacturing shall be 12% ± 3% (PRG 320 6.1.4.). The other requirements specified in PRG 320 6.1.1 are that the lumber grades used in parallel layers of CLT shall be 1200f-1.2E MSR or visual grade No. 2 and perpendicular layers shall be visual grade No. 2. These moisture content and minimum lumber grade requirements of PRG 320 can easily be complied with by employing the appropriate kiln drying and lumber grading activities.

Interviews with representatives of APA confirmed that despite not being specifically named as an eligible species for CLT manufacturing in PRG 320, BC hem-fir currently meets the requirements for CLT manufacturing specified in PRG 320. Since these interviews, a 2020 edition of PRG 320 has been published that specifically mentions hem-fir as a species that meets the requirements for CLT manufacturing. The decision to include specific mention of hem-fir was made after complaints from multiple committee members from both US and Canada who were concerned that this major species was left out.

The Canada Standards Association (CSA) 086-14, *Engineering Design in Wood*, provides standards for the structural design and appraisal of wood structures or structural elements for building construction in Canada. These standards have been developed by a technical committee consisting of suppliers, engineers, researchers, academics, regulatory experts and consultants from around North America. However, CSA 086-14 does not provide standards for CLT manufacturing but instead contains a placeholder (Clause 8) that could eventually include CLT standards. The specific wording contained in CSA 086-14 with regard to CLT standards is as follows:

> *Clause 8 has been reserved for design provisions which will cover CLT manufactured in accordance with ANSI/APA PRG 320 standard.*

Because CSA 086-14 currently defers to PRG 320 with regard to the standards that must be met for CLT manufacturing, hem-fir complies with both CSA 086-14 and PRG 320.

2. Dowel-Laminated Timber

There are no specific standards or guides for the manufacture of DLT in North America. The reason for lack of specific standards is that DLT is not viewed as a composite building component. Consequently, the standards that must be complied with the relevant building codes and the standards for the lumber that DLT is made of. The relevant building codes include the local building codes in each province and state, National Building Code of Canada and the International Building Code in the US. In North America, the lumber standards that must be complied with include the standards for sawn lumber included in CSA 086-14 and the *National Design Specification for Wood Construction* in the US. These standards and building codes do not restrict the use of hem-fir in DLT construction.

3. Nail-Laminated Timber

Similar to DLT, there are no specific regulations or standards for the manufacture of NLT in North America, other than the relevant building codes and lumber requirements. Similar to DLT, the reason for lack of specific standards is that NLT is not viewed as a composite building component since NLT can be fabricated with readily available dimension lumber.[40] This means that hem-fir can be used in NLT, given relevant local, national or international building codes and lumber requirements are met. The *Nail-Laminated Timber: Canadian Design &*

[40] Think Wood. *Nail-Laminated Timber (NLT).* Available from: https://www.thinkwood.com/products-and-systems/mass-timber/nail-laminated-timber

Construction Guide provides the Canadian design and construction industry with support and guidance to ensure safe, predictable and economical use of NLT, offering practical strategies and advice. The guide includes architectural and structural considerations as well as envelope and fabrication details

4. Glue-Laminated Timber

The Canada Standards Association (CSA) 086-14, *Engineering Design in Wood*, provides the criteria for lumber species in glulam manufacturing and specifically includes hem-fir and Douglas fir-larch in combination, as well as Douglas fir-larch, and spruce-lodgepole pine-jack pine. The standard specifies conditions for the specific lumber species including; permissible stress grades, specified strengths and modulus of elasticity. The manufacturing of glulam must be done in accordance with CAN/CSA-O122: *Structural Glued-Laminated Timber* which provides the minimum requirements for the manufacture of glulam for the species specified in CSA 086 which includes stress grades for: Douglas fir-larch, western hemlock, hem-fir and Douglas fir-larch, spruce-lodgepole pine- jack pine, and spruce. The specific CSA minimum moisture content requirements that must be met for glulam production to are as follows:

> *6.1.1.3. The moisture content range of pieces joined in a single lamination or laminations assembled in a single member shall not exceed 5%.*
> *6.1.1.4. Moisture content of laminating stock at the time of gluing shall be between 7% and 15%.*

Given that hem-fir is kiln dried before used, hem-fir meets CSA requirements and is specifically listed as an eligible species for glulam manufacturing in Canada.

In the United States, the applicable glulam standard is ANSI/APA A190.1-2017: *Standards for Wood Products – Structural Glued Laminated Timber.* A190.1 provides requirements for the manufacture and quality control of structural glued laminated timber, and aims to establish national requirements for the production, inspection, testing and certification of glulam, and to provide material suppliers, producers, and distributors with a common understanding of the characteristics. The standard allows for any softwood or hardwood species whose stress indices and knot distributions are as described in ASTM D3737. For bonding qualifications, species are grouped into 'Basic Species Groupings' (12.1.1.1.). These groupings are as follows and hem-fir is included in one of the eligible species groupings for glulam manufacturing:

- Group 1 – Douglas-fir Larch
- Group 2 – Southern Pine
- Group 3 – Hem-Fir, Mountain Hemlock, Douglas-fir South, Sitka Spruce
- Group 4 – Softwood Species including Engelmann Spruce, Lodgepole Pine, Ponderosa Pine, Spruce-Pine-Fir and other Western Species
- Group 5 – California Redwood
- Group 6 – Alaska Cedar, Port-Orford Cedar
- Group 7 – Red Oak, White Oak

Section 5.2 of A190.1 states that the moisture content of lumber used for glulam manufacturing shall not exceed 16% at the time of bonding.

5. Summary

The previous sections demonstrate that there are no regulatory, product certification and technical standards that restrict the use of hem-fir in CLT, DLT, NLT or glulam production.

IV. TECHNICAL BARRIERS

This chapter summarizes the technical characteristics of hem-fir and the technical barriers that have constrained the use of hem-fir in mass timber products.

1. Technical Characteristics of Hem-Fir

Many key informants interviewed recognized the positive structural characteristics of hem-fir with regard to mass timber products. Some strengths of hem-fir mentioned by respondents included the following:

- Great strength and stiffness (superior to SPF)
- Good nail-holding ability (superior to SPF)
- Capability of long spans due to strength (superior to SPF)
- Consistent, abundant supply

As indicated in Table 4.1, the structural properties of hem-fir typically range between the structural properties of SPF and Douglas fir-larch for most criteria. Consequently, hem-fir is structurally superior to SPF in almost all categories which makes it suitable for use in mass timber products.

Table 4.1: Comparison of Structural Properties of Hem-Fir with Other Species

				Compression			Modulus of elasticity	
Species	Grade	Bending at extreme fibre, f_b	Longitudinal shear, f_v	Parallel to grain, f_c	Perpendicular to grain, f_{cp}	Tension parallel to grain, f_t	E	E_{05}
DF-Larch								
	SS	16.5		19.0		10.6	12 500	8 500
	No.1/No.2	10.0	1.9	14.0	7.0	5.8	11 000	7 000
	No.3/Stud	4.6		7.3		2.1	10 000	5 500
Hem-Fir	SS	16.0		17.6		9.7	12 000	8 500
	No.1/No.2	11.0	1.6	14.8	4.6	6.2	11 000	7 500
	No.3/Stud	7.0		9.2		3.2	10 000	6 000
SPF	SS	16.5		14.5		8.6	10 500	7 500
	No.1/No.2	11.8	1.5	11.5	5.3	5.5	9 500	6 500
	No.3/Stud	7.0		9.0		3.2	9 000	5 500

Source: CSA 086-14: *Engineering Design in Wood*

2. Technical Barriers

Mass timber manufacturers in BC stated that their preference was to use Douglas-fir for glulam products and SPF for CLT and DLT products. Douglas-fir is preferred for glulam manufacturing because of its superior strength characteristics compared to other species in BC. SPF is the preferred species for CLT and DLT manufacturers in BC because it is easy to dry and in plentiful supply. Most respondents stated that hem-fir does not have significantly greater technical qualities that would make it the superior choice in mass timber.

The major technical barrier of hem-fir for mass timber products mentioned most frequently by key informants is the large variation in moisture content and the presence of wet pockets. The perception is that hem-fir is difficult and costly to dry to meet the maximum moisture content requirements of CLT and glulam. Longer kiln drying times lead to increased costs. Mass timber manufacturers suggested that if they were provided with a supply of dry hem-fir economically, there would be no barriers to using the species.

> *I honestly think the issue with hemlock comes down to its drying ability. From our perspective, if they were able to dry it, there's no reason not to use it.* - **Mass timber manufacturer**

The drying of hem-fir is complicated by the existence of wet pockets which are often very high in moisture content.

> *The biggest problem is the wet pockets. When you run it through the kiln, most species dry uniformly. Hem-fir has these pockets that are hard to detect and stay wet after drying.* – **Structural engineer**

The concern with wet pockets is not only with the logistics of drying and increased drying costs, but also that the wet pockets might undermine the structural integrity of mass timber products. Because of the way mass timber products are manufactured, lack of uniform moisture levels can raise big concerns, particularly from the point of view of the structural engineers that we spoke to.

> *In the process of manufacturing CLT, you do several planings, after the last planing you pretty much want all the boards to be touching. With wet pockets they will start drying but not uniformly, this is what I would be concerned with.* – **Structural engineer**

Mass timber products often involve the process of finger jointing. In CLT, for example the boards are connected using finger joints and a structural adhesive. To dry the adhesive within the fingers, radio frequency (RF) is often used to target a precise location. When wet pockets exist, the RF can be diverted to the wettest point, the pockets of high moisture content, which can have explosive consequences, resulting in the destruction of the finger joint.

> *Many finger joint systems they cut the finger and use RF to dry glue within the fingers. If you have wet pockets, the RF is drawn to the moisture in the finger joints, it should be drawn to the glue. You can get arching, it's like lightening bolts.* – **Mass timber regulatory expert**

As a result of its high and variable moisture content, hem-fir is thought to be a species that is more likely to experience checking and gaps as well as warping and twisting once the product moisture content has stabilized. The warping and twisting of hem-fir is an issue for all mass timber products including CLT, DLT, NLT and glulam.

> *Tends to be more reactive wood species – will warp and twist a bit more, bow and cup etc. not ideal for our products.* – **Mass timber manufacturer**

> *Hemlock on the coasts depending on where it's harvested can contain a bit of compression wood, wet pockets can be pockets of compression wood so it doesn't dry consistently and will get bends or bowing.* – **Lumber supplier**

In mass timber production, boards are planed to ensure they are flat, to maximise glue bondability. If the boards are likely to warp or twist after they have been glued together, this could compromise the integrity of the adhesive.

> *Where you see these warps and twists in singular boards, you would have a problem with in then in a tightly glued material like CLT. I have no idea how it will be, it's pure speculation because I haven't glued it. My first initial reaction would be check if it can be done from a glue bondability perspective.* – **Structural engineer**

From an engineering perspective, some key informants were sceptical as to whether the glue bondability of hem-fir would be sufficient for use in mass timber and suggested that more research would be needed to overcome these doubts.

> *This is what really needs to be researched. Can we actually glue it from the standpoint of dimensional stability? The issue in CLT is that it has to be at least 80% covered in glue and then the bond must hold.* – **Structural engineer**

3. Research Regarding Suitability of Hem-Fir for CLT Production

Several research studies have been undertaken that have confirmed that hem-fir is suitable for use in CLT manufacturing and that the manufacturing of hem-fir CLT is viable.

- **A 2010 study stated that BC hem-fir can be used to successfully manufacture CLT product with distinct Modulus of Elasticity (MOE) classes (grades)**. The higher MOE hem-fir lumber can be used to make higher grade CLT. With the correlation established, the actual grade outturn of the hem-fir lumber for desired CLT products can be accurately predicted by taking into account the true MOE distribution of the hem-fir lumber. For hem-fir manufacturing, the adhesive type and applied pressure significantly affected wood failure percentage and delamination. Shear strength seemed to be relatively independent of the bonding conditions. Compared to emulsion polymer isocyanate (EPI) adhesive, polyurethane reactive (PUR) adhesive was more sensitive to pressure and yielded lower wood failure and higher delamination. For PUR adhesive, the CLT panels manufactured at 120 psi yielded significantly higher wood failure and lower delamination than those made at 40 psi pressure. For PUR adhesive, a pressure higher than 120 psi could be used to further reduce CLT delamination. The study recommended that further tests should be conducted to optimize the manufacturing parameters such as the applied pressure and adhesive application rate for CLT manufacturing to increase the adhesive bond quality and durability. Several critical manufacturing parameters were identified including lumber moisture content, lumber grade controlling characteristics (i.e. wane, shake, skip, twist, cup, etc.), adhesive type, adhesive application rate, surface aging (time elapsed since planning), assembly time, applied pressure, curing time and temperature. The study concluded that further work is needed to optimize these critical variables for manufacturing consistent CLT products and providing more technical information for developing the CLT product and plan qualification standards in North America. The study stated that further work is also needed to showcase new hem-fir CLT product and benchmark hem-fir CLT against European CLT and Canadian SPF CLT, and identify the effect of hem-fir growth traits on CLT engineering properties. **An initial economic analysis was also conducted that indicated that hem-fir CLT manufacturing is cost-competitive and that a more detailed business case study should be developed for the BC coast.**[41]

- **Another 2010 study tested the possibility of using second growth coastal hemlock to produce laminae for glulam post (on grade material) and CLT panel (fall downs) by studying the lamina recovery, adhesive performance and characteristic/performance of the products. Fifteen treatment combinations were tested using 5 types of adhesive and two wood species – hemlock and mountain pine beetle-killed (MPB) wood.** The results show that bond integrity was reasonable for all combinations. The study was conducted in light of a 90% loss of BC post exports to Japan which were replaced by European glulam posts. The study concluded that "the good structural performance of BC hemlock laminated post and beam products and the reasonable laminae recovery offer excellent product options for the BC wood industry to reposition itself in the Japanese building products market".[42]

- **A 2014 study of hem-fir CLT panels concluded that it is possible to manufacture CLT using hem-fir lumber.** Building on the manufacturing parameters identified *in Wang, B., Dai, C., Pirvu, C., Casilla, R. (2010) Development of New Coastal Hem-Fir Composite Panel Products,* the study found that the intermediate moisture content (MC) range (15-19%) was most favourable for delamination resistance, while the low MC range (11-15%) was most favourable for dry wood failure. However, the low MC range would also work for delamination resistance and there is some evidence to show that the intermediate MC range may also work for dry wood failure. Based on the study results, the authors stated that the two standards referenced by ANSI/APA PRG 320 for assessing delamination resistance are both glulam standards, and the delamination requirements for glulam are too onerous for CLT. In terms of wood-adhesive bond integrity, the utilization of hem-fir for CLT products could be realized only if the delamination and wood failure requirements specified in the existing ANSI/APA PRG 320 are relaxed. The recommendation was to adopt the delamination requirements specified in the "Seed document for proposed CLT plant qualification standard" [19] drafted by FPInnovations. This document specifies a bond line delamination of 25% and a specimen delamination of 20% for one test cycle delamination procedure, the former being much lower than that specified in the European CLT standard. The average wood failure of the block shear specimens may also need to be relaxed. For example, 75% of the block shear groups would have passed the average wood failure if the current requirement was reduced by 10%. ANSI/AITC A190.1 actually requires a minimum average dry wood failure of only 70% for quality control testing in softwood glued products. Perhaps this could also be adopted for product qualification.

  The secondary objective of the study was to conduct a manufacturing cost analysis for CLT panels made from hem-fir lumber. The analysis was carried out using KD lumber and green lumber because these prices were available. **The total cost of manufacturing CLT with KD hem-fir lumber was found to be similar to that of SPF CLT if the manufacturing plant is located close to the market.** However, it is more difficult to locate a CLT plant near the market rather than close to the resource, because the market is constantly

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[41] Wang, B., Dai, C., Pirvu, C., Casilla, R. (2010) *Development of New Coastal Hem-fir Composite Panel Products.* FPInnovations.

[42] Yawalata, D., Li, M., Lam, F. (2010) *Study of Production of Lamina and Performance of Laminated Structural Products from BC Coastal Hemlock.* Timber Engineering and Applied Mechanics (TEAM) Laboratory.

changing. Therefore, locating the CLT plant close to rail, truck, or ship transport, and minimizing the need to change the modes of transport from the plant to the customer would keep down the transportation cost and, implicitly, the manufacturing costs (delivered).[43]

- **2018 study results demonstrated that hem-fir lumber can be used for manufacturing CLT with the required panel bond quality.** The study addressed the manufacturing aspects of CLT products from hem-fir harvested from coastal British Columbia. Small CLT billets (nominal 610 mm × 610 mm) were made to examine CLT bond quality and durability through block shear and delamination tests. Two types of adhesives, single-component polyurethane (PUR) and emulsion polymer isocyanate (EPI) and two critical applied pressure parameters (0.28 and 0.83 MPa) were adopted to manufacture hem-fir CLT. It was found that the adhesive type and applied pressure significantly affected wood failure percentage (WFP) and delamination of hem-fir CLT. When PUR adhesive was used, CLT made at 0.83 MPa pressure yielded significantly higher WFP and lower delamination than that made at 0.28 MPa pressure. The study recommended that further tests should be conducted to establish the optimum manufacturing parameters, such as the applied pressure and adhesive application rates for hem-fir CLT manufacturing, to increase panel bond quality and durability. The feasibility of CLT made from hem-fir needs to be further verified by the achievement of performance requirements in the standard. Further work is also needed to showcase new hem-fir CLT products through pilot plant tests, benchmark hem-fir CLT against European CLT and Canadian Spruce-pine-fir CLT, and identify the effects of hem-fir growth traits, lumber grades and lay-ups on CLT engineering properties. [44]

- **A 2018 study testing CLT panels made of Canadian hemlock concluded that the panels performed as well as those made from SPF and Douglas-fir**, and that their results provide fundamental support for the engineering application of CLT panels made from Canadian hemlock. The study investigated the out-of-plane bending properties and compressive properties of CLT panels made from Canadian hemlock. The mechanical properties of the CLT panels in the major/minor strength directions were obtained through experimental tests, and numerical models were developed to predict bending stiffness and ultimate load resisting capacity of the CLT panels. Moreover, theoretical bending stiffness of the CLT panels was calculated according to the equations provided in different code provisions, and the calculated values were compared with the experimental data. Results show that CLT panels made from Canadian hemlock perform as well as those made from other commonly used lumber species (i.e. SPF or Douglas-fir), and the bending stiffness and ultimate load resisting capacity of the CLT panels can be predicted by the developed numerical models.[45]

4. Research to Mitigate Variable Moisture Content of Hem-Fir

High moisture content and the issues related to it – high drying costs, wet pockets, checking & gaps, warping & twisting, glue bondability – is a significant barrier to using hem-fir in mass timber. The following paragraphs summarize the research that has been undertaken to mitigate these factors to enable the use of hem-fir in mass timber products.

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[43] Pirvu, C., Casilla, R.C. (2014) *Effect of Manufacturing Parameters on Hem-Fir Cross-Laminated Timber Quality.* FPInnovations. BC Coastal Forest Sector Hem-Fir Initiative.
[44] Wang, J.B., Wei, P., Gao, Z., Dai, C. (2018) *The Evaluation of Panel Bond Quality and Durability of Hem-Fir Cross-laminated timber (CLT).* European Journal of Wood and Wood Products, 76: 833-841.
[45] He, M., Sun, X., Li, Z. (2018) *Bending and compressive properties of cross-laminated timber (CLT) panels made from Canadian hemlock.* Construction and Building Materials. 185: 175-183.

- **A 2010 study showed that Vis/NIR spectrometry can differentiate between hemlock and fir to enable sorting of these two species before drying.** A demonstration of this technology was done at Western Forest Products mill in Chemainus, BC, with a prediction accuracy of 97%. The potential benefits of separating hem-fir include the production of value-added, speciality products and improved commodity processing efficiency including enhanced treatability, greater uniformity in finishing of appearance grade products, and enhanced lumber drying efficiency. Green hem-fir is extremely difficult to dry, putting it at a disadvantage to all its competitors. The differences in density, green moisture content and permeability between the two species result in very different drying rates. Separation by species could facilitate improved drying results. After drying, the two species could then be mixed together again or, ideally, segregated for value-added applications. Visible-Near Infrared Spectrometry provides an ideal means to perform the sorting as the spectral data contains a multitude of wavelength frequency, non-destructive testing, and rapid data acquisitions that can be constructed into a portable device for at-line application or as an online application with complete automation.[46]

- **A 2010 study found that compared to unsorted hem-fir lumber, sorting hem-fir into three lumber groups can potentially reduce drying time by 1 day and increase lumber value in approximately $8/Mfbm.** Over-drying and under-drying are common causes for lower grade recovery and dimensional stability problems. In this study, a new methodology was designed and tested to optimize the kiln drying of hem-fir lumber by implementing green sorting coupled with modified drying schedules. For both the laboratory tests and the industrial validation, the 114 by 114 mm2 hem-fir lumber was sorted at a local sawmill in British Columbia using the NMI capacitance type technology. It was found that in comparison with unsorted lumber, sorting hem-fir into three lumber groups can potentially reduce drying time by 7% approximately and recover about three quarters of the under-dried lumber.[47]

- **A 2016 study found that high initial moisture content sorting of hem-fir helped to reduce the final moisture content variation.** The study stated that hem-fir has a higher and more variable moisture content than SPF, making drying more challenging and raising production and quality concerns, as remanufactured lumber with variable moisture will introduce unbalanced conditions increasing probability of surface checking and product deformations. Furthermore, BC mills tend to dry hem-fir with no green moisture content pre-sorting thus promoting high moisture differences within and between dried timbers. In this study, application of green chain moisture-based sorting, coupled with a modified drying schedule, was considered to be a potential way to improve drying times, moisture-content spreads, and lumber quality.[48]

- **A 2016 study confirmed that there are definitely advantages to using an adjustable speed drive to control fan speed during the later stages of drying hem-fir.** The benefit is an improvement in shrinkage results, degrade and the distribution of final moisture content. The study found Amabilis fir has a faster drying rate than western hemlock and usually requires shorter drying times. One other finding from this experiment is that air velocities of 5 m/ s are too fast for drying Pacific Coast hemlock and it appears to negatively affect the drying rate. The study recommended that a kiln schedule using an adjustable speed drive should

[46] Groves, K., Trung, T., Pirouz, Z., Stirling, R. (2010) *Vis/NIR Scanning for Hem-fir Species Separation at the Lumber Stage.* FPInnovations – Forintek.
[47] Elustondo, D.M., Oliveria, L., Avramidis, S. (2010) *New Methodology to Optimize Sorting in Wood Drying.* Maderas: Ciencia y Technologia.
[48] Shahverdi, M., Oliveria, L., Avramidis, S. (2016) *Kiln-drying optimization for quality pacific coast hemlock timber.* Drying Technology.

have air velocities around 3.8 m/s above the fiber saturation point and 2.5 m/s for the remaining duration of drying.[49]

- **A 2018 study of hydrothermally treated western hemlock resulted in a product of even moisture content and eliminated the wet pockets** in hem-fir which makes the wood structurally stable (less warping and twisting) after re-sawing and the low hygroscopicity, high dimensional stability, darker color, and eliminated case hardening of the wood makes it a suitable engineered wood product for most outdoor and indoor applications. This process is relatively uncommon in North America and involves heating the wood to high temperatures using steam, which alters the cell structure of the wood resulting in increased dimensional stability, durability, and resistance to natural weathering. It was found that hydrothermal treatment was effective in eliminating case hardening in kiln dried western hemlock lumber. The presence of wet pockets in western hemlock causes a permanent compression stress in the kiln-dried wood, commonly referred to as case hardening. Case hardening is a major issue because the compression stresses in the wood cause the wood to pinch and bind the saw blade when case hardened wood is cut. These results reveal that hydrothermal treatment is a promising method to expand utilization and develop value-added wood products using western hemlock. The results also revealed that the mechanical properties changed significantly as a result of the hydrothermal modification process. After hydrothermal treatment, the MOR (Modulus of Rupture) and ML (Mass Loss) MOR was decreased by 35% and the ML diminished by 38%. Larger reductions were found at higher temperatures and longer processing times. In contrast, the hydrothermal modification process improved the Modulus of Elasticity (MOE) of western hemlock by 6.4%. The decrease in MOR and ML and increase in MOE of wood after hydrothermal treatment may limit the end use application of the thermally modified wood.[50]

- **A 2019 study explored commercial heat treatment on western hemlock for potentially new applications and markets.** Flatsawn and quarter sawn kiln-dried hemlock boards were subjected to the ThermoWood® process in a commercial unit at three temperatures, i.e. 170°C, 212°C, 230°C and a 2 hour holding time. The treatment that improved dimensional stability and provided a darker color without significantly affecting hemlock strength was the 212°C/2 hour holding time combination. The study findings indicated that the development of treatment schedules for western hemlock is an opportunity for local industry to add more value to this species and help define best practices guidelines and new applications for it. The study recommended further research to fully determine the performance of thermally modified hemlock under expanded treatment combinations for interior and exterior application.[51]

[49] Wallace, J. and Avramidis, S. (2016) *Impact of airflow on hem-fir kiln drying.* Drying Technology.
[50] Song, K., Ganguly, I., Eastin, I., Dou, C., Bura, R., and Dichiara, A. (2018) *Structure-property relationships of hydrothermally treated western hemlock.* Springer Nature Switzerland.
[51] Nourian, S., Avramidis, S. (2019) *Exploratory thermal modification of western hemlock.* Wood Material Science and Engineering.

5. Research Regarding Suitability of Hem-Fir for DLT, NLT and Glulam Production

Since both CLT and glulam rely on adhesives to bond the wood components together, the above findings regarding the suitability of hem-fir for CLT production apply equally to glulam production. However, they do not apply as much to DLT or NLT because both of these do not rely on gluing component parts together. For this reason, hem-fir is more suited to DLT and NLT production than CLT or glulam production. This was confirmed by some key informants who also indicated that DLT and NLT production can accommodate a higher moisture content thereby making hem-fir a more suitable species for these two mass timber products. Some key informants indicated that allowable moisture content could be as high as 19%. In DLT, if moisture content is higher, the dowels actually expand more, giving a tighter and more secure fit. However, further research including field trials would be required to confirm the suitability of hem-fir for the DLT and NLT products.

V. MARKET POTENTIAL FOR HEM-FIR MASS TIMBER PRODUCTS

This chapter summarizes the study findings regarding the market and supply chain barriers and the market potential for hem-fir mass timber products.

1. Mass Timber Products Used in Building Construction

The size of the market for hem-fir in mass timber products in BC is currently limited due to the small number of CLT, DLT, NLT and glulam manufacturers in BC. Currently, there is only one major CLT manufacturer (another one is currently under construction) and one major DLT manufacturer in BC while there do not exist any manufacturers of factory-built NLT products for building construction. There are only a few glulam producers in BC. Stiff competition from mass timber suppliers in Europe means that often a BC building contractor can purchase glulam and CLT panels from Europe for the same or at a lower price, and superior quality.

The existing mass timber manufacturers in BC mainly use SPF for CLT and DLT manufacturing and Douglas-fir for glulam. The rationale for using SPF for CLT and DLT manufacturing is that SPF is easier to dry than hem-fir and currently SPF lamstock is available in sufficient quantities from BC timber suppliers. Douglas-fir is the standard for glulam because Douglas-fir is notably superior in strength to hem-fir and Douglas-fir lamstock is also readily available from BC timber suppliers. Most BC mass timber manufacturers stated that since hem-fir does not have technical qualities that would make it the superior choice in mass timber and the price difference between hem-fir and the other species used is not significant, there currently exists little incentive to use hem-fir. Some mass timber manufacturers indicated that a price discount of 10% to 20% from their current lamstock would be required to consider using hem-fir. Some other factors constraining the use of hem-fir by BC mass timber manufacturers are:

- There are key logistical considerations for mass timber producers when considering the utilization of hem-fir. BC mass timber producers indicated that they would have to carry an additional inventory of another species (i.e. hem-fir), which can be costly and logistically difficult due to lack of physical storage space.

- BC mass timber manufacturers also stated that they need consistency of supply; currently despite being a bountiful species, there is little hem-fir lamstock being produced in BC.

The supply chain for SPF and Douglas-fir lamstock is already well developed, so it is easy for BC mass timber manufacturers to default to these species. Because the demand for hem-fir mass timber is currently limited, a supply chain has not been developed. Not only does the supply chain need to exist, but BC mass timber manufacturers need to be confident that the supplier is reliable and able to consistently supply quality of hem-fir. Despite being a bountiful species, there is little hem-fir lamstock being produced.

> *You have to have reliability and the coastal hemlock industry is fractured somewhat. If you're going to commit to a species, you have to have an ongoing supply. If you look at the interior of BC with the Doug-fir, you have many large manufacturers; that's consistent, it's nearby, it's fairly simple for them to get material.* – **Industry Expert**

> *Currently there is not the market for hem-fir that will allow a supply chain to develop.* - **Mass Timber R&D Expert**

Some of the key constraints to developing the supply chain for hem-fir lamstock for BC mass timber production mentioned by key informants are as follows:

- Due to its higher and more variable moisture content, the costs of drying hem-fir are higher than SPF. In addition, there exist kiln capacity constraints for some hem-fir producers in BC. The quote below from a BC lumber producer shows the impact on kiln capacity of reducing the moisture content of hem-fir to 12%:

> *There is a barrier between an efficient commodity producer and producing a specialised product (e.g. hem-fir lamstock). Drying times are a major bottleneck. Kiln time is the most valuable time we have. We have kiln constraints at 2 of our 3 interior mills, even by running green product. When you produce a product with a 12% moisture content (+ or – 3%), you have these diseconomies of scale. To get to 19% moisture content, you can do it over a 17 hour kiln schedule but to get from 19% moisture content to 12%, just to get that extra 7% less will take you maybe double the time because the cell structure is compromised so you have to have a very delicate drying schedule. That would really hinder our kilns. We wouldn't have the kiln capacity to run a 12% product.* – **BC Lumber Producer**

As a means to alleviate this range in moisture content after drying, some BC lumber manufacturers employ stringent moisture sorting and have different uses for hem-fir lumber depending on the moisture content:

> *You can't just force it all into mass timber, you have to have alternate solutions. You can trim out portions of the board or leave it and let it exit the mill as a commodity board. Because we measure throughout the entire board transversely, we can work out which portion of the board is saturated.* – **Lumber producer**

Employing this kind of sorting system ensures that variable lumber is sorted to its most appropriate end-use and may ease pressure on the kilns by diverting particularly wet wood to lower value applications.

- The limited size of the local mass timber market and competitively priced mass timber products available from Europe reduce the incentive of major BC lumber producers to increase the supply of hem-fir lamstock to BC mass timber manufacturers. Often a contractor in BC can purchase CLT and glulam panels from Europe for the same or at a lower price:

> *'European supply still plays a massive factor. Even if local producers want to start incorporating hem-fir, the architect can still buy European spruce for the same price, for a superior quality.'* – **Mass timber manufacturer**

- It is unlikely that supply of hem-fir lamstock will increase until BC timber manufacturers see evidence of significant growth in the local or export mass timber market.

- The North American mass timber industry is very siloed compared to the integrated business model in Europe which makes it difficult to be competitive. Unlike Europe, most mass timber manufacturing facilities in North America do not have their own source of fibre. This siloed approach tends to increase cost and lower quality. Because the mass timber market in North America tends to be very siloed, there exists little collaboration between the big players, which can cause difficulties when trying to establish a supply chain. Europe tends to have a more integrated business model, with mass timber manufacturers often having their own source of fibre and mills. Integrated models can include anything from design, material supply, manufacturing and logistics, all the way to assembly, offering a true end-to-end service. In North America, some companies are moving toward the vertically integrated business model. As an illustration, Katerra has recently opened a fully-integrated CLT plant in Washington, spanning R&D, design, sourcing, codes and standard development, manufacturing and construction. An article in the *Architect's Newspaper* claims that:

> *'The key to Katerra's success lies in its vertically integrated business model; the company moves its project through a single pipeline and handles everything from design, to engineering, to construction.'*[52]

Katerra, however, does not have its own fibre source. Kalesnikoff is similarly promoting their new CLT plant as being 'fully integrated', and their fibre will be sourced from their own woodlands. A fully integrated model is said to have cost benefits, as well as giving the manufacturer more control.

> *In North America it's so siloed, I log or I make raw lumber. The whole spectrum increases cost and lowers quality. Everyone's trying to push their boundaries to be successful; unless you're fully integrated, you're incurring a substantial cost.* – **Mass timber manufacturer**

The emergence of integrated mass timber operations in BC such as that proposed by Kalesnikoff Mass Timber creates the potential to compete effectively with European mass timber producers.

Due to the siloed nature on the North American mass timber market, entry into the market is going to require collaboration between parties. Several lumber suppliers and mass timber manufacturers interviewed expressed interest in investigating the use of hem-fir as a species option for mass timber products. Hem-fir lumber suppliers are keen to add value to their lumber:

> *We are no longer in a volume mode. We're about selling value, volume is secondary, we have to get more value out of the forest. There's going to be more value focused product coming out.* – **Lumber supplier**

Two hem-fir suppliers interviewed have sent hem-fir samples to mass timber manufacturers to carry out CLT and DLT panel tests but these tests have not yet been undertaken. These hem-fir suppliers indicated that they need two types of partnerships to supply hem-fir lamstock to BC mass timber manufacturers: a R&D partner willing to carry out the necessary testing; and a manufacturing partner willing to add a new species.

The market potential for hem-fir in mass timber products is projected to increase significantly. As indicated in Chapter 2, innovation in the construction industry is focussing on mass timber products, creating a burgeoning market. Federal and provincial governments are starting to respond to the mass timber market by modifying building codes and encouraging the construction of mass timber buildings. Alberta and BC will become the first

[52] Hilburg, J. (2018) *Katerra acquires Michael Green Architecture as it expands into the timber market.* The Architect's Newspaper.

provinces to extend the limit to 12 storeys for tall wood mass timber buildings, ahead of the extension in the National Building Code in 2020. Several BC municipalities are revising their building codes to accommodate building construction using mass timber products. In the US, provisions were approved for the 2021 International Building Code that will allow construction of mass timber buildings up to eighteen storeys. (American Wood Council).[53] The market for global CLT, the most widespread mass timber product, is projected to be valued at US$2.07 billion by 2025. As a comparison, North America's demand for CLT was valued at US$119 million in 2016[54]. This growing acceptance and expansion of mass timber should lead to greater opportunity for variety in products, in terms of species, grade and price, challenging the species that are currently dominant.

The market potential for hem-fir in CLT and DLT will increase as the demand for mass timber products increases. The market potential for hem-fir NLT is more limited as the production of NLT is limited in BC at this time. The market potential for using hem-fir in glulam is likely to mirror the increase in use of hem-fir in CLT and DLT products. One reason for this is that some architects prefer to use the same species for both glulam and the wood panels made from either CLT or DLT so that the same wood species is used throughout the building.

Another factor contributing to an increased market potential for hem-fir is that it is an abundant and underutilized species in BC. Furthermore, the supply of SPF is projected to decrease due to the impacts of the Mountain Pine Beetle, which could increase motivation to use hem-fir in mass timber products. The reduction in Canadian lumber supply was mentioned by a number of informants, and in particular the idea that supply of SPF is going to decrease in coming years.

> *The fibre basket in the interior is being reduced over time. That puts pressure on the cost structure. There is more than enough hemlock fibre available to produce the mass timber products.* – **Lumber supplier**

There exists potential to export BC hem-fir for use in mass timber products to China. Ningbo Sino-Canada Low-Carbon Technology Research Institute built China's first CLT pilot production line and developed the world's first large-scale prefabricated CLT panel made from Canadian western hemlock lumber. The prefabricated wood construction market in China is projected to reach US$375 billion annually in 10 years.

One factor that may reduce the market potential for BC hem-fir is the growth of southern pine as a competitive species. Grown in the eastern and southern US, southern pine could compete with other dominant species, as well as hem-fir, as it is positioned as a cheap source of fibre for mass timber producers in Canada and the US. A market report notes that while timber and lumber supplies in Canada are declining, lumber capacity in the US southern pine region are booming, with fifteen new southern pine sawmills being built or announced between 2017 and 2020.[55] Structurlam has recently announced that their first mass timber plant in the US will be located in Conway, Arkansas and the plant will source softwood lumber from Arkansas-grown southern pine trees. Walmart will be the first customer of Structurlam's Conway facility. The world's largest retailer plans to use

[53] American Wood Council. https://awc.org/news/2018/12/19/awc-tall-mass-timber-code-changes-get-final-approval
[54] Grandview Research (2017) *Cross Laminated Timber Market Size, Share & Trends Analysis Report By Type (Adhesive Bonded and Mechanically Fastened), By Region (North America, Europe, Asia Pacific, South & Central America, MEA), And Segment Forecasts, 2018 – 2025.*
[55] The Beck Group (2018) *Mass Timber Market Analysis.* Council of Western State Foresters.

more than 1.1 million cubic feet of Arkansas-grown and Arkansas-produced mass timber in its new Home Office campus in Bentonville, Arkansas, making it the largest campus project in the US using mass timber.[56]

2. Industrial Mats

Some hem-fir is currently being used in industrial mats (access mats, crane mats) that are manufactured by a few producers in BC. Douglas-fir is the preferred product due to its superior strength properties. However, a considerable volume of hem-fir mats is sold at a discounted price.

Industrial mats are used in a variety of applications, such as access mats for use in construction, access roads, drilling rigs, emergency egress, access to environmentally sensitive areas, and crane mats. Traditionally, industrial mats are constructed by bolting rough green lumber together. As an example, 2x8 green lumber is bolted together to produce a typical 3 ply construction access mat. A typical crane mat is 4 feet by 20 feet, it has 4 steel rods through the cross section. Bolted industrial mats are currently produced using hem-fir or Douglas-fir. These species are preferred due to their density and strength properties and they are sometimes used in combination; SPF is not used. Because hem-fir is not as stiff and strong as Douglas-fir, hem-fir industrial mats have typically been sold at a slight price discount to industrial mats made from Douglas-fir.

Industrial mats are primarily used by large industrial construction projects such as the construction of the Trans Mountain Pipeline, Site C Dam and the Kitimat LNG facility. For these projects, it is necessary to produce and supply a large quantity of industrial mats in a very short timeframe. As an illustration, one industrial mat manufacturer we interviewed indicate that a typical order is the requirement for 10,000 mats to be produced in 2 weeks.

The key informants we interviewed indicated that the market for industrial mats is very price competitive. Because bolted hem-fir industrial mats have been sold at a price discount compared to bolted Douglas-fir mats, hem-fir mats have been able to obtain a significant share of the industrial mat market in BC.

Four bolted industrial mat producers account for the majority of bolted industrial mat production in western Canada. In addition, Structurlam produces a CLT industrial mat made from Douglas-fir. The key informants interviewed indicated the following advantages and disadvantages of CLT industrial mats versus traditional bolted industrial mats:

Advantages of CLT industrial mats
- Superior in weight and durability
- Could fit larger quantities on the truck due to more accommodating mat sizes
- Equipment tire wear would be lower because no exposed bolts which is the case for bolted industrial mats

Disadvantages of CLT industrial mats
- More expensive
- May be difficult to produce a large number of mats in a short time frame
- Potential for delamination

[56] Structurlam (2019) *Structurlam Selects Conway, Arkansas, for its first U.S. plant.* Available from: https://www.structurlam.com/whats-new/news/structurlam-selects-conway-arkansas-for-its-first-u-s-plant/

VII. RECOMMENDATIONS

The steps required to increase the market acceptance of hem-fir in mass timber products are as follows:

1. Conduct further research to address the constraints of using hem-fir in mass timber products.

The purpose of further research should be to:

- Identify more moisture tolerant adhesives that could be used for hem-fir CLT and glulam production;
- Determine optimum methods of drying hem-fir including research to locate and dry the wet pockets in hem-fir; and
- Conduct additional research regarding the hydrothermal modification of hem-fir which could potentially address issues related to wet pockets, moisture content variability, and warping and twisting.

2. Undertake further testing and demonstration of hem-fir mass timber products to encourage the use of hem-fir by BC mass timber producers.

Since some BC mass timber producers are currently considering the use of hem-fir, it is critical that testing and demonstration (i.e. full-scale field trials) of hem-fir timber products be facilitated to encourage use. Some testing that should be undertaken is:

- Conduct tests to establish optimum manufacturing parameters, such as applied pressure and adhesive application rates for hem-fir CLT manufacturing, to increase panel bond quality and durability;
- Conduct full scale field trial tests to demonstrate the feasibility of using hem-fir in CLT and DLT manufacturing; and
- Conduct fire resistance tests of CLT and DLT hem-fir mass timber products.

3. Promote the use of hem-fir in mass timber production to address perceived technical barriers and encourage a consistent supply of hem-fir to BC mass timber producers.

To develop a supply chain for hem-fir lamstock in BC, collaboration should be facilitated between BC timber suppliers and BC mass timber manufacturers. There is also a need to promote the advantages of hem-fir in CLT and DLT products which include its aesthetically visual appearance, greater strength and longer span compared to SPF. The use of hem-fir in DLT production should also be highlighted because hem-fir is suited for this type of mass timber product which can tolerate a higher moisture content.

4. Conduct market research to assess the size of the domestic and export mass timber market to accurately determine the market potential for hem-fir mass timber products.

This market research is necessary to encourage BC lumber producers to provide a consistent source of supply of hem-fir lamstock to BC mass timber producers.

BIBLIOGRAPHY

Albee, R.R., Muszyński, L., Hansen, E.N., Knowles, D., Larasatie, P., Guerrero, J.E. (2018) *Recent Developments in Global Cross-Laminated Timber (CLT) Market.* World Conference on Timber Engineering. Seoul, Republic of Korea.

American Wood Council (2018) *NDS Supplement. National Design Specification, Design Values for Wood Construction.* 2018 edition.

COFI (2019). *Smart Future: A path forward for B.C.'s forest products industry.* Council of Forest Industries.

CSA Group (2014) *CSA 086-14: Engineering design in wood.*

Elustondo, D.M., Oliveria, L., Avramidis, S. (2010) *New Methodology to Optimize Sorting in Wood Drying.* Maderas: Ciencia y Technologia.

Fast, P., Gafner, B., Jackson, R., Li, J. (2016). *Case Study: An 18 storey tall Mass Timber Hybrid student residence at the University of British Columbia, Vancouver.* World Conference on Timber Engineering 2016, Vienna, Austria.

Gagnon, S., Pirvu, C. (eds) (2011). *CLT Handbook: Cross-Laminated Timber.* Vancouver, FPInnovations, pp. 380.

Ganguly, I., Beyreuther, T., Hoffman, M., Swenson, S., Eastin, I. (2017) *Forecasting the demand for Cross Laminated Timber (CLT) in the Pacific Northwest.* Cintrafor (Center for International Trade in Forest Products) News.

Grandview Research (2017) *Glue Laminated Timber Market Analysis, by Application (Residential, Commercial) by Region (North America, Europe, Asia Pacific, CSA, and MEA), and Segment Forecasts, 2018-2025.*

Grandview Research (2017) *Cross Laminated Timber Market Size, Share & Trends Analysis Report By Type (Adhesive Bonded and Mechanically Fastened), By Region (North America, Europe, Asia Pacific, South & Central America, MEA), And Segment Forecasts, 2018 – 2025.*

Groves, K., Trung, T., Pirouz, Z., Stirling, R. (2010) *Vis/NIR Scanning for Hem-fir Species Separation at the Lumber Stage.* FPInnovations – Forintek.

Harte, A. M. (2017). *Mass timber – The emergence of a modern construction material.* Journal of Structural Integrity and Maintenance, 2:3, 121-132.

He, M., Sun, X., Li, Z. (2018) *Bending and compressive properties of cross-laminated timber (CLT) panels made from Canadian hemlock.* Construction and Building Materials. 185: 175-183.

IMARC Group. (2017) *Cross-Laminated Timber Market: Global Industry Trends, Share, Size, Growth, Opportunity and Forecast 2019-2024.*

Kremer, P.D., Symmons, M.A. (2018) *Perceived barriers to the widespread adoption of Mass Timber Construction: An Australian construction industry case study.* Mass Timber Construction Journal.

Li, H., Wang, B.J., Wei, P., Wang, L. (2019) *Cross-Laminated Timber (CLT) in China: A State-of-the-Art.* Journal of Bioresources and Bioproducts.

Mohammad, M., Tourelles, J., Coxford, R., Williamson, M. (2019). *Canadian Mass Timber Demonstration Projects Initiatives.* Modular and Offsite Construction.

Muszynski, L., Hansen, E., Fernando, S., Schwarzmann, G., Rainer, J. (2017) *Insights into the Global Cross-Laminated Timber Industry.* BioProducts Business. 2(8) pp.77-92.

Nourian, S., Avramidis, S. (2019) *Exploratory thermal modification of western hemlock.* Wood Material Science and Engineering.

Pirvu, C., Casilla, R.C. (2014) *Effect of Manufacturing Parameters on Hem-Fir Cross-Laminated Timber Quality.* FPInnovations. BC Coastal Forest Sector Hem-Fir Initiative.

Quesada, H., Smith, R., Berger, G. (2018) *Drivers and Barriers of Cross-Laminated Timber (CLT) Production and Commercialization: A Case Study of Western Europe's CLT Industry.* BioProducts Business 3(3) pp.29-38.

Shahverdi, M., Oliveria, L., Avramidis, S. (2016) *Kiln-drying optimization for quality pacific coast hemlock timber.* Drying Technology.

Song, K., Ganguly, I., Eastin, I., Dou, C., Bura, R., and Dichiara, A. (2018) *Structure-property relationships of hydrothermally treated western hemlock.* Springer Nature Switzerland.

The Beck Group (2018) *Mass Timber Market Analysis.* Council of Western State Foresters.

Wallace, J. and Avramidis, S. (2016) *Impact of airflow on hem-fir kiln drying.* Drying Technology.

Wang, B., Dai, C., Pirvu, C., Casilla, R. (2010) *Development of New Coastal Hem-fir Composite Panel Products.* FPInnovations.

Wang, J.B., Wei, P., Gao, Z., Dai, C. (2018) *The Evaluation of Panel Bond Quality and Durability of Hem-Fir Cross-laminated timber (CLT).* European Journal of Wood and Wood Products, 76: 833-841.

Wei, P., Wang, B.J., Wang, L., Wang, Y., Yang, G., Liu, J. (2019) *An exploratory Study of Composite Cross-Laminated Timber (CCLT) made from Bamboo and Hemlock-fir Mix.* Bioresources, 14(1), 2160-2170.

WoodWorks! (2018). *Brock Commons Tallwood House: University of British Columbia Vancouver Campus: The advent of tall wood structures in Canada: A Case Study.* Canada Wood Council.

Yawalata, D., Li, M., Lam, F. (2010) *Study of Production of Lamina and Performance of Laminated Structural Products from BC Coastal Hemlock.* Timber Engineering and Applied Mechanics (TEAM) Laboratory.