Literature Review of Cost Information on Mid-Rise Mass-Timber Building Projects

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Executive Summary

Traditionally, mid-rise buildings, typically 6-12 stories in height, have used concrete and steel as structural materials. Recent advancements in engineered wood products, as well as increased concerns for environmental impacts, such as carbon emissions, are driving interest in utilizing mass timber as the primary structural system for mid-rise buildings, particularly residential projects in British Columbia. Demonstration projects like UBC Brock Commons Tallwood Building have showcased the feasibility and opportunities of mass timber structural systems, and anticipated changes to the national and provincial building codes could facilitate the development of mass timber buildings up to twelve stories in the near future.

The City of Vancouver is the regulating body for the building construction in Vancouver and as such, is developing policies that could incorporate considerations for building mid-rise mass timber buildings. While there has been a significant amount of well-documented research on the characteristics and performance of mass timber products and structural systems, there has been less on the cost implications and affordability factors of mass timber buildings above six stories. Cost is a major driver and constraint for decisions at every stage of building projects, from planning through operations, and the lack of information is an area of uncertainty in the widespread adoption of mass timber as a primary building construction material.

This study, *Literature review of cost information on mid-rise, mass-timber building projects*, was initiated by the City of Vancouver's Sustainability Department, and was undertaken in the summer of 2019 by the University of British Columbia's Sustainability Initiative. The study aims to develop an understanding of various cost indicators and the data available in the literature to identify evidential support for the benefits of mass timber construction. The results may inform the City of Vancouver on the current trends, knowledge gaps and future research identified in the literature, and serve as a starting point in collecting cost relevant information for policy and regulations.

The study was divided into four parts, starting with an overview of the literature from recognized organizations working on mass timber, such as the FP Innovations, Natural Resources Canada and the Canadian Wood Council. A full list of resources is included in Table 1 in the report, and a list of the literature reviewed in Appendix D. From here, a short list of twelve studies were analyzed in depth. This shortlist was selected based on whether the studies contained information on mass timber mid-rise buildings, quantitative and/or qualitative data on project costs, cost comparison with conventional materials, and market analysis or insights. A detailed list of the twelve studies is included in Appendix A, and copies have been provided to the City of Vancouver along with this report.

The literature review divides the information obtained from the studies into quantitative and qualitative data. The quantitative data is analyzed by extracting the numerical values from the studies, some of which compare mass timber construction costs with concrete construction costs. A summary of the quantitative data is provided in Section 3 and a breakdown of the quantitative cost analysis in Appendix B and C. The qualitative data identifies the challenges, cost-saving factors, opportunities and solutions from the literature. Section 4 of the report summarizes the qualitative information. Section 5 of the report includes further research topics identified in the literature related to mass timber construction costs for mid-rise, mass timber buildings.

Five of the twelve studies contained quantitative information on mass timber construction costs: three reports, one journal paper and one book. The literature does not reveal any significant increase or decrease in the construction cost of mass timber, mid-rise building projects compared to concrete. Overall, the cost varies from (±) 0-6%, where ' + ' indicates cost savings of mass timber compared to concrete construction, and '- ' indicates additional costs of mass timber compared to concrete construction. There are limitations to this analysis however, since all of the studies used hypothetical buildings, not actual built projects. Additionally, while the studies focused on construction costs, each one includes different types of information within that category so cost comparisons between studies are not valid. Lastly, contextual variations impact costs from region to region. To establish accurate benchmarking, additional research will be required for an accurate assessment of mass timber cost premiums and influencing factors specific to the development context of British Columbia and the Lower Mainland.

All of the studies included qualitative cost data based on anecdotal experiences, interviews, surveys, market analysis and industrial experience. The studies revealed insights into topics such as mass timber construction's cost drivers, cost-saving factors, challenges, opportunities and identified solutions and recommendations for the mass-timber building construction. Broadly, the information was organized into challenges (factors that directly drove project and construction costs), cost-saving factors (project or mass timber characteristics that reduce costs) and opportunities for cost reductions (speculative changes that should reduce mass timber costs over time). Key factors include the economic market forces that influence forestry and lumber costs, as well as supply and demand of mass timber products; expertise and availability of consultants and trades with familiarity for mass timber products and buildings; building code allowances for mass timber; construction efficiencies through prefabrication, mass production, standardization and transportation; and financial valuation of the low carbon benefits of wood products, specifically carbon sequestration.

Lastly, this literature review has summarized potential areas of future research, as identified through the studies, which may be of interest and can inform the development of future policies. The key topics that are identified for future research are:

- Cost assessment of recently built mass-timber building projects, specifically in British Columbia, Canada and the Pacific Northwest.
- Market research and analyses of manufacturing and supply chain of mass timber products in British Columbia, including prefabrication and mass-production capabilities.
- The influence that changes to the building code requirements can have on increasing or decreasing mass timber project costs.

Organizations like the Tallwood Design Institute in Oregon, WoodWorks or Canadian Wood Council may already be supporting research in this areas and could be valuable sources of information or partners.

1. Introduction

For the last century, mid-rise buildings (6-12 stories) around the globe have been predominantly built of steel and concrete, materials which have been recognized as energy-intensive, with considerable impacts to the environment and contributions to climate change. With recent advancement in design and production, wood engineered products and mass timber structural systems are gaining popularity as an alternative material to these concrete and steel structures. Wood is the best principal material available for building structures when considering total energy use, carbon emissions and water usage (Michael Green Architecture 13). The business and design rationale for wood comes from its durability, flexibility, installation efficiency and ease of use (Stantec Fast + Epp 10).

The National Building Code of Canada (NBCC) and British Columbia Building Code (BCBC) regulate built structure relative to the size and height of the building based on material selection, occupancy classification, and environment protection. In 2009, the Province of British Columbia increased the permitted building heights of combustible construction (e.g. wood) to 6-storey from 4-storey, which indicate a recognized change in the acceptable levels of risk with higher wood-frame structures (Michael Green Architecture 42).

More recently, a number of demonstration projects and initiatives have taken advantage of new mass-timber technology and regulatory accommodations. Projects like the Wood Innovation and Design Centre at the University of Northern British Columbia, Brock Commons Tallwood House at the University of British Columbia, and Origine in Montreal, Quebec demonstrated the feasibility and opportunities in using mass timber as a building construction material.

Significant market and professional interests have been identified for the use of mass timber structures in buildings above the regulated 6 stories limit. This demand establishes a need for the regulatory bodies to weigh the consequences and consider factors like safety, environmental responsibility, feasibility and affordability to upgrade the height limit of the mass-timber buildings. While there has been extensive analysis conducted on the structural strength and performance of mass timber, there has been less research into the cost implications and affordability factors of mass timber buildings above six stories. Costs are a major driver and constraint for decisions at every stage of building projects, from planning through operations, and the lack of information for mass timber costs raises questions on the feasibility of the widespread adaption of mass timber as a primary building construction material.

This research project, *Literature review of cost Information on mid-rise, mass-timber building projects*, was initiated by the City of Vancouver (Vancouver) to gain an understanding of the current information available about the cost data and cost efficiency factors for mid-rise, mass-timber building construction. Conducted by the University of British Columbia's Sustainability Initiative, this study is composed of a literature review and analysis, the results of which are contained in this report and the associated appendices. It has also identified further research topics on the affordability factors of the mid-rise, mass-timber building construction to support strategies for addressing building regulations, formulate incentives and policies for Vancouver.

1.1 Project objective

This literature study reviewed the current research and published literature on costing information for mass-timber, mid-rise building projects, in order to understand the cost implications and the costs influencing factors for mass-timber structures. Where possible, the analysis included information on construction costs compared to a traditional building material like concrete. The report summarizes the findings from the research, both quantitatively and qualitatively, and identifies current gaps in knowledge. The results can be used to inform the policy considerations and to advance and possibly incentivize strategies on the use of mass timber as a structural building material for the multi-unit mid-rise residential development while addressing the rising pressures on affordable housing in Vancouver.

1.2 Research methodology

The literature study reviewed reports, papers, journal articles and books that contain cost data on mass-timber, mid-rise buildings. The literature was sourced from a variety of resources available online, which are listed in Table 1.

A total of 51 studies were reviewed, and twelve of them were shortlisted for in-depth study in this literature study. The literature selected based on whether or not they contain information on the following key topics:

- Mass-timber, mid-rise buildings (6 to 12 stories).
- Quantitative data on building costs.
- Qualitative data on building costs.
- Cost comparisons with traditional construction building material (concrete and steel).
- Mass timber market information and insights.

Appendix D provides the full list of the literature that were reviewed, while Appendix A contains the short-list, which are also noted in Table 2 in the following section.

The selected studies contain valuable information which will be discussed in-depth in this report, divided into the following sections:

Quantitative analysis: The numerical values in the selected studies were extracted to obtain the construction cost rates of the mass-timber building construction for mid-rise buildings compared to the traditional building construction material, typically concrete.

Qualitative analysis: This section of the report identifies factors that affect and influence the construction cost of the mass-timber building construction, identified in the studies. It discusses the challenges, cost-saving factors, opportunities and solutions that are most relevant for the context of Vancouver, British Columbia

Future research: This segment discusses future research topics identified in the 12 studies, as well as upcoming research by organizations and professionals related to the cost of mass-timber, mid-rise buildings and construction.

The following table contains the list of resources that were scanned to find relevant research and literature. The majority of the resources are organizations in the forestry industry, wood industry, or educational and research sector.

S.No	Resources
1	Naturally Wood: Resources
2	FP Innovations
3	UBC Library + Articles
4	Forestry Innovation Investment
5	Canadian Wood Council
6	Natural Resources Canada
7	Mass Timber Institute
8	Ontario Ministry of Natural Resources and Forestry
9	Softwood Lumber board
10	U.S. Forest Service- Forest Products Laboratory
11	Built it with Wood A Program from New England Forestry Foundation
12	Tallwood Design Institute
13	Wood Products Council- Cost Savings
14	National Research Council Canada
15	Google Scholar Search

Table 1 List of resources that from which the literature was sourced.

1.3 Project Scope

The following topics have been included in the project scope:

- Review the current academic and professional literature on project and construction cost of building projects with mass-timber structures ranging from 6 to 12 storeys (mid-rise).
- Analyze the factors influencing the construction costs of the mass-timber, mid-rise buildings, as described in the literature.
- Review the information available in the literature on the costs associated with construction timelines and manufacturing strategies.
- Analyze the cost information related to the mass-timber construction types, major structural assemblies and other specific mass timber products used in the mid-rise buildings.

The following topics are excluded from the project scope:

- Cost information for low-rise (1-5 storey) and high-rise (above 12 storey) buildings.
- In-depth technical analysis of building codes and compliance.
- In-depth technical analysis of mass-timber construction techniques.
- In-depth technical analysis of material properties and applications.

2. Overview of the literature

The twelve studies reviewed in-depth include eight reports, two journal papers, one book and one educational article. Cost information on mass-timber, mid-rise building construction includes relevant quantitative data in five of the studies, and qualitative data in all of them. The quantitative and qualitative information will be discussed in-depth in this report in the next chapters.

The authors of these studies are from a variety of disciplines, including architecture, construction, structural engineering, forestry consultants, academic institutions and research organizations. The forestry industry sponsored seven out of twelve studies. The majority of the studies were conducted between 2015 and 2018, and apply to North America, the Pacific North West, New England or Australia regions. One study is for the New Zealand region, conducted in 2009.

The buildings studied in the literature encompass multi-unit residential, student housing, mixed-use and office building typology. Some studies also refer to building structures in general with no typology mentioned. The studies employ one or more research methodologies, including comparison and feasibility studies, market analysis, panel discussions, case studies, critical assessments, industry surveys and interviews.

The cost data specified in the studies is typically mass-timber building construction costs, which can incorporate data for materials, structural systems, manufacturing, labour, speed of construction, services or equipment costs. Each study is unique, based on specific assumptions and different methodologies, and, importantly, each study include different categories of information under the term construction costs.

The quantitative analysis in the literature explicitly outline the inclusions and exclusions used in the consideration for the mass-timber building construction costs, while the qualitative studies are often less clear. The quantitative data is either built upon an existing building with hypothetical case options or built on a hypothetical building model with hypothetical case options. The qualitative data in the studies was collected from project teams and subject matter experts, and is generally not associated with any one specific building project.

Across all of the studies, the research samples vary in building types and sizes, number of cases, and material types. However, the number of stories consistently ranges from six to twelve. The mass-timber structural material is either compared with a traditional building material like concrete or steel, or with different mass-timber products. Mass-timber products noted in the studies include cross-laminated timber (CLT), laminated veneer lumber (LVL), laminated strand lumber (LSL), glue-laminated timber (GLT), oriented strand lumber (OSL), parallel strand lumber (PSL) or nail-laminated timber (NLT).

Table 2 lists the twelve studies that were analyzed in depth, and includes information on the type of data that was extracted from each, the region it applies to and the research methodology employed by each study. Please refer to Appendix A for a detailed summary on these studies.

Given name	Title + Year	Data type	Region	Research Methodology
P1	Affordable Housing and Mass Timber: Where do Opportunities Lie for Oregon? [2017]	Qualitative	Oregon, USA	Discussion based
P2	Assessing the Wood Supply and Investment Potential for a New England Engineered Wood Products Mill [2017]	Qualitative	New England	Market Analysis
P3	CLT Feasibility Study: A Study of alternative construction methods in the pacific north-west [2014]	Quantitative + Qualitative	Pacific Northwest	Comparison Study
P4	Construction time and cost for post-tensioned timber buildings [2009]	Quantitative + Qualitative	New Zealand	Comparison Study
P5	Cross Laminated Timber Feasibility Study: A comparison between cross laminated timber and cast-in-place concrete framing for mid-rise urban buildings [2018]	Quantitative + Qualitative	Pacific Northwest	Comparison + Feasibility Study
P6	Final Report for Commercial Building Costing Cases Studies: Traditional Design versus Timber Project [2015]	Quantitative + Qualitative	Sydney, Australia	Comparison Study
P7	Mass timber construction as an alternative to concrete and steel in the Australia building industry: a PESTEL evaluation of the potential [2015]	Qualitative	Australia	Critical Assessment
P8	Mass Timber Influencers: Understanding mass timber perceptions among key industry influencers [2018]	Qualitative	British Columbia, Canada	Industry Survey + Panel Session
P9	Mass Timber Market Analysis [2018]	Qualitative	USA	Market Analysis
P10	The Business Case for Building with Wood: How wood construction can contribute to process efficiency, sustainability, and marketability	Qualitative	North America	Case Study
P11	The Case for Tall Wood Buildings: How Mass Timber Offers a Safe, Economical, and Environmental Friendly Alternative for Tall Building Structures [2018]	Quantitative + Qualitative	British Columbia, Canada	Comparison + Case Study + Industry Interviews
P12	Wood Use in British Columbia Schools [2018]	Qualitative	British Columbia, Canada	Case Study + Survey

Table 2 List of the selected studies, which were used for in-depth analysis in this literature review.

3. Quantitative analysis

As part of the literature review, a quantitative cost analysis was conducted to attempt to understand the cost implications and costing patterns of the mass-timber, mid-rise building construction in comparison with the traditional building construction system like concrete and steel, as studied in the literature. The quantitative cost data for the analysis was taken from three reports (P3, P5 & P6), one journal paper (P4) and one book (P11).

The regions covered in the quantitative studies were the Pacific North West, British Columba, Washington, Oregon, New Zealand and Sydney, Australia. The majority of the quantitative studies use hypothetical models of residential building projects, and a small portion of the data includes hypothetical models of office and mixed-use building types. None of the studies use actual cost data from real building projects.

P5, P6 and P11 explicitly compare the building construction cost of mass-timber products with concrete, while P3 and P4 also includes steel in the comparison studies. P3 compares cost of hypothetical concrete model to mass timber and steel, and P4 compares hypothetical mass-timber model to steel and concrete.

As the comparison of steel in the two studies is different and does not contain sufficient data for analysis compared to concrete options, the steel options have not been included for an in-depth analysis. Section 3.1 includes only the comparison of mass-timber building projects with concrete. Please refer to Appendix C for details on the steel option.

Of the quantitative information derived from the five studies, (P3, P4, P5, P6 and P11) each includes particular cost considerations with specific cost inclusions and exclusions. Broadly the studies analyze construction cost, but two studies, P5 and P6, specifically examine structural cost only. P6 examines structural costs as well as the costs of lift, stairs and air shafts, suspended ceilings, connectors, termite and fire engineering preliminaries. P3, P4 and P11 examine structural costs as well as exterior enclosure, architectural interiors and finishes, HVAC equipment, fire protection, MEP services and few minor cost specifications limited to each study. P11 also considers labour cost.

Because each study includes different building components in their construction costs analysis, comparisons cannot be made between the results of the individual studies. In addition, the studies present slightly varied comparisons between the construction costs of concrete, steel and different mass-timber products like CLT, LVL, charring method, encapsulated method, and a hybrid system of CLT floor levels on top of a concrete podium and foundation. In all cases, the information in the studies is specific to their region and project context. The following section summarizes the information contained in the studies, but should be understood as an overview of the current available research and not as a benchmarking or comparison analysis.

3.1 Construction cost comparison of mass timber with concrete

Construction costs are specific to a region's geographic location, material availability, market demand and supply, and the economy. The analysis below identifies the difference between the construction cost of mass timber and concrete for each region, as outlined in the studies, by calculating the percentage of cost savings or additional costs of the mass-timber construction compared to concrete. This comparison develops an understanding of the affordability factor, as described in the literature, of mass-timber construction in competition with concrete. However, due to the regional variations, comparisons of the quantitative information should not be made between different regions of the world.

A notable section of the analysis was contributed by *'The Case for Tall Buildings'*, a book by Michael Green Architecture (MGA), which communicates a detailed analysis of construction cost. The book is intended as an overview of innovation in mass-timber building construction, described through both research and built projects.

The cost information from the studies vary in both currency and value based on the year of construction. For the purpose of this analysis, all the costs in the studies have been converted to Canadian dollars as per the conversion rate of July 19, 2019.

The literature does not reveal any significant increase or decrease in the construction cost of mass-timber, mid-rise building projects compared to concrete. Overall, the cost varies from (±) 0-6%, where ' + ' indicates cost savings of mass timber compared to concrete construction, and '- ' indicates additional costs of mass timber compared to concrete construction.

Table 3 summarizes the construction cost comparison of mass timber with concrete for the relevant cases mentioned in the five studies. Please refer to Appendix B for more information on the cost considerations included in these five studies and Appendix C for detailed information on all the cases in the studies.

#	Region	Year	Project type	Structural materials	Storeys	Cost per sq.ft	Cost saving	Compared to concrete
P3	Seattle	2014	Residential	2 concrete + 8 CLT	10	-	+6.0%	Cast-in-place
P4	New Zealand	2009	Office	Post-tensioned hybrid LVL	6	$158	- 6.0%	Pre-cast
P5	Pacific Northwest	2018	Residential	CLT	10	$60	- 5.2%	Cast-in-place
P6	Sydney, Australia	2015	Office	LVL	7	-	+12.4%	Cast-in-place
P6	Sydney, Australia	2015	Residential	CLT	8	-	+2.2%	Cast-in-place

P11	Vancouver	2011	Residential	Charring method	12	$307	0.0%	Cast-in-place
P11	Vancouver	2011	Residential	Encapsulated method	12	$313	- 1.9%	Cast-in-place
P11	Northern BC	2011	Residential	Charring method	12	$338	+ 2.8%	Cast-in-place
P11	Northern BC	2011	Residential	Encapsulated method	12	$344	+ 1.0%	Cast-in-place
P11	Interior BC	2011	Residential	Charring method	12	$323	+ 2.0%	Cast-in-place
P11	Interior BC	2011	Residential	Encapsulated method	12	$329	0.0 %	Cast-in-place
P11	Fraser	2011	Residential	Charring method	12	$307	0.0 %	Cast-in-place
P11	Fraser	2011	Residential	Encapsulated method	12	$313	- 1.7%	Cast-in-place
P11	Vancouver Island	2011	Residential	Charring method	12	$323	1.7%	Cast-in-place
P11	Vancouver Island	2011	Residential	Encapsulated method	12	$329	- 0.3%	Cast-in-place

Table 3 Cost comparison of mass timber with traditional concrete building construction (costs converted in CAD as per July 19, 2019).

4. Qualitative analysis

The second part of the literature review analyzed qualitative cost information from all the twelve studies. The studies were conducted from 2009 to 2018, and are based in the regions of British Columbia, Pacific North West, New England, Oregon, United States of America, Australia and New Zealand. The research revealed insights into topics such as mass-timber construction's cost drivers, cost-saving factors, challenges, opportunities and identified solutions and recommendations for the mass-timber building construction.

For qualitative analysis section of this report, the information is divided into three broad categories: 1) challenges, 2) cost-saving factors and 3) opportunities for cost reduction. Each category discusses the key topics, as identified in the literature, which inform the mass-timber construction about the cost implications, gaps in the knowledge, current cost scenarios, and topics of further research.

4.1 Challenges

Challenges are factors directly associated with the cost drivers such as material cost, erection time-frame, site location, manufacturing location, shipping, safety measures and additional project-specific costs. The section below highlights and discusses the critical construction cost challenges pertaining to the context of British Columbia and the broader context of North America.

4.1.1 Market trends of mass timber in British Columbia

The market trend information extracted from two studies (P2 and P9) identified an imbalance between mass timber demand and supply in British Columbia. The studies measured the resources available for the production of mass-timber products in and calculated the expected demand by the building industry.

A market analysis in P9, conducted by Beck Group for the Council of Western State Foresters (CWSF- which represents 17 Western US states and 6 US affiliated Pacific Islands), showed that half of Canada's total lumber production (13.6 of 28.3 billion board feet in 2016) is produced in British Columbia, and that the majority of this output comes from interior regions. The Annual Allowable Cut (AAC) has significantly dropped due to massive tree mortality in the last decade as a result of Mountain Pine Beetle infestation. The AAC in the BC interior was around 50 million cubic meters in the late 1990s. The allowable harvest levels have increased in an attempt to salvage the dead and dying timber, but the volumes are expected to drop at around 40 million cubic meters (a drop of 20% compared to historical levels) by 2025 (The Beck Group 14).

A market analysis in P2, conducted by Poyry Management Consulting, studied the market maturity and capacity of engineered wood products like laminated veneer lumber (LVL), laminated strand lumber (LSL), parallel strand lumber (PSL), glue-laminated timber (GLT), and cross laminated timber (CLT) for the North American region. The study indicated that the engineered lumber market in Europe grows faster than construction market (supply outpaces demand), whereas in North America the engineered lumber products are being exposed to market cycles (Poyry Management Consulting

13). The study indicated that GLT and LVL are mature products in North America (ibid 12), whereas the CLT market is in an early stage of development both in Europe and North America.

This pressure on the supply of the mass-timber products to fulfill the demand of the building construction industry, and unavailability of the resources can greatly impact the fluctuation of the prices of the mass-timber products on the market. The uncertainty and variation in costs make it less competitive to concrete and steel which are widely available and relatively stable.

4.1.2 Lack of awareness and understanding

The literature identifies a lack of awareness and understanding of building with mass timber among the professionals and building stakeholders, which increases inefficiencies in the building design and construction process and tends to decrease coordination among consultants. This, in turn, leads to increases in the construction time and cost of the building project.

The P9 study by Beck Group expresses this concern and mentions that "mass timber is relatively new to the building construction industry, which lacks an understanding and awareness of the structural properties, construction techniques, interior and exterior wall coverings, plumbing, electrical and HVAC layout that can be impacted by using a new building method" (The Beck Group 7).

Gaps in the knowledge of mass-timber construction identified in the studies included: assembling engineering expertise, the impact of insurance and valuation of risk for mass timber building structures, and lack of documentation, analysis and testing of systems to demonstrate the physical properties, and performance of mass timber structures. As part of the gap in knowledge, the need to educate engineering and architecture students was also been noted. Lack of information and knowledge in these areas makes it difficult to accurately calculate the costs of mass-timber building construction.

However, awareness is growing rapidly in North America due to the initiatives of non-profit organizations such as WoodWorks and Think Wood. These organization produce informational literature, webinars, conferences, and video content to increase awareness of mass timber and address questions and concerns within the building industry (The Beck Group 7). Over time, greater awareness and familiarity with mass timber products should increase the consultants' abilities to more accurately cost mass timber projects.

4.1.3 Building codes

Wood construction policies and regulations have evolved in Canada in recent years. The *British Columbia Wood First Act* (2009) was intended to facilitate the use of wood as a primary building material in new provincially funded buildings. Currently, the *British Columbia Building Code* (2018) permits combustible construction, which includes heavy timber systems, light wood frame, and mass-timber products, in buildings up to six stories. The national and provincial building codes will be updated in 2020, and it is anticipated that changes will be made to allow for mass timber up to twelve stories, although everything over eight stories will likely need to be encapsulated. The City of Vancouver is also updating their bylaws, which may align or pre-empt the other building codes.

The literature distinguishes mass timber from other wood construction and identifies the need for separate regulations: "mass timber buildings are significantly different than light wood-frame buildings in their fire performance due to the solid nature of the timber panels and their inherent ability to resist fire without the addition of protective membrane barriers." (Michael Green Architecture 13). Currently however, the building codes do not provide regulation specifically for any one mass-timber product and do not distinguish between mass timber and light frame wood construction. Generally, the codes require third-party performance testing to demonstrate structural stability and meet the intent of the code with fire safety regulations (TallWood Design Institute 2). The code requirements and restrictions add costs to projects and can make mass-timber construction less competitive with concrete and steel-framed construction for buildings above six stories.

4.1.4 Projected lumber prices

The material costs for a building make up a significant portion of the construction and the overall project costs. The P9 study by the Beck Group developed a forecast of dimension lumber prices, which shows the forecasted pricing compared to historical prices, shown in the graph in Figure 1.

The analysis in P9 showed that the lumber prices in the United States from 2000 to 2017 varied between US$300 and US$400 per thousand board feet and rises to US$500 per thousand board feet from 2017 to 2018. The forecast predicts slightly lower lumber prices in 2019, followed by an increase in following years to meet the anticipated development demand of approximately 1.5 million units per year (The Beck Group 19).

This graph shows a rising pattern of lumber prices which in turn will drive up costs for mass timber products. The increased product costs can put pressure on the building budget and make it challenging to consider mass timber as a primary building material in competition with concrete and steel.

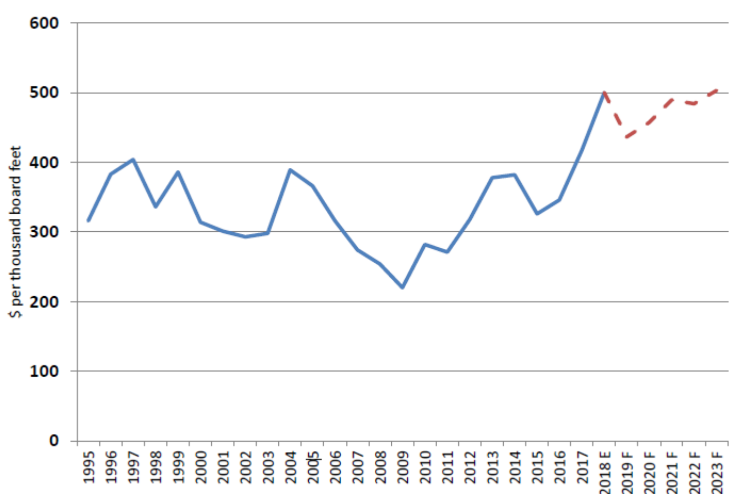

Figure 1 Dimension lumber prices in the United States of America - History and Forecast (The Beck Group 19).

4.1.5 Additional costs

Across many of the studies, there was difficulty in quantifying additional costs like construction and post-construction insurance, ongoing maintenance, out-of-town trades, features to address seismic and high wind demand, and the evolving state of mass-timber products. These costs have a direct impact on the project budget, but are highly context and project specific, and need evidential information to inform the building project costs.

4.2 Cost saving factors

The cost-saving factors described in the studies considerably highlight the following key topics: the carbon sequestration value of mass timber, future carbon taxing benefits, construction time-frame, material properties, and construction technique. The topics below discuss the important cost-saving factors within the context of British Columbia and the broader context of North America.

4.2.1 Carbon emission and sequestration value

With climate change issues, building regulations have been evolving to protect the environment and consider low carbon options for building construction. Wood as a material has holds great advantage due to the high carbon sequestration value and lower carbon emissions compared to concrete and steel.

The potential of wood in sequestering carbon and the impact of low carbon emission have been heavily discussed in the P11 study. It notes that determining the cost of carbon storage and carbon emissions, and how these affect project costs are essential components and also complex in nature. (Michael Green Architecture 193). Today, British Columbia's carbon tax impacts the energy costs used in the production of concrete, but it does not significantly impact imported construction materials like steel. Mass timber uses less energy in manufacturing and should therefore be less vulnerable to energy price fluctuation and carbon emission penalties (ibid 15).

British Columbia's carbon tax, however, does not consider carbon sequestration and there is currently no mechanism in place to gain tax benefits from choosing wood as a building material, due to this capability. Michael Green Architecture explains in their research that they have not found a carbon sequestration taxing concept that has been applied anywhere in the world to date, but stresses the importance of it in the overall cost comparison exercise and carbon tax discussion (ibid 193).

4.2.2 Construction time-frame

Reductions in construction time for building using mass timber are widely discussed in most of the studies as a cost-saving factor. The literature finds that both on-site and off-site construction time can be reduced by various techniques mentioned in the studies.

Any process that shortens the amount of time in the building stage tends to reduce the overall project costs. The ways to reduce on-site construction time mentioned in P11 include the use of large panels and faster installation systems. The P6 study by Dunn Andrew asserts that the compressed construction program saves on site infrastructure costs for scaffolding, hoists, and crane rental as well as construction site administration costs, and on-site skilled labour costs (Dunn 10). Additionally, the P10 study notes that "prefabricating components and assemblies off-site offers advantages including efficiency at every stage of the process, less disruption of building activities, and faster speed of construction" (Grable 4). The P9 study found that reduced construction time from off-site panel manufacturing can lead to a “20% reduction of the on-site construction schedule, and reduced on-site skilled labour requirements stemming from shorter construction times and off-site panel manufacturing” (The Beck Group 1).

There can also be construction time frame advantages found in the material characteristics of mass-timber products. The use of mass timber eliminates set and dry times (Kremer and Symmons 142), and the additional step of constructing falsework and formwork required by concrete (Stantec Fast + Epp 19).

4.2.3 Material properties

The literature identifies the materials properties of wood as cost-beneficial in building construction. Wood can perform well in seismic events, and is durable and lightweight. Wood buildings are also easy to renovate, expand and adapt to changing uses. The acoustic wood panels can be designed to meet the acoustic performance needs, while wood structural elements have inherent thermal qualities that can result in significant energy savings (Stantec Fast + Epp 5).

The relative weight difference between a concrete structure and a wood structure can result in cost savings through reduced foundation size and depth. A smaller or lighter foundation typically costs less, especially in poor soil areas. (Michael Green Architecture 13). The lighter weight can also bring comparative cost savings in the transportation of the material over large distances (Smith, Fragiacomo and Pampanin 137).

Relatedly, according to the literature, the smaller size floor panels can contribute to a height reduction at each floor, which can create an allowance for additional floors within the same envelope or allow buildings with poor soil conditions to have larger volume compared to heavier materials like concrete and steel (TallWood Design Institute 2).

Due to varying building project and site requirements, any potential cost benefits of the material properties of the mass timber are likely to be highly project and context specific.

4.2.4 Off-site construction technique

Off-site construction processes have been highly recommended in the literature, particularly in P10 and P11, which includes prefabrication of components and efficient assembly of the elements of the building. Prefabrication may be able to reduce the building construction cost through increased speed and improved construction efficiency which in turn reduces the labour cost on site.

"The most common categories of off-site prefabrication [of mass timber] include modular systems, panelized systems, sub-assemblies or components, and hybrid systems" (Grable 4). Off-site manufactured or prefabricated components are generally less complicated than the on-site construction and are less vulnerable to the weather conditions. On-site installation of prefabricated elements often requires only a small crew and small or limited number of cranes depending on the size of the project (Michael Green Architecture 2). Manufacturing can ensure superior quality and consistent outcomes since it is not subject to the foibles of weather and delays caused by the other on-site factors (ibid 4).

4.3 Opportunities for cost reduction

The majority of the studies have identified opportunities to reduce the mass-timber building project costs. These topics often overlap with the challenges or cost saving factors but are more speculative in the extent of their potential impacts. The essential topics derived from the studies are presented below.

4.3.1 Increasing material availability

As per the market analysis conducted in the P2 study by Poyry Management Consultants for LVL, LSL, OSL, PSL, GLT and CLT in the North American region, each mass-timber product has its own market growth, supply pattern and manufacturing units. Optimizing and standardizing the use of a mass-timber product that is highly available in a specific region can be beneficial for reduction of project costs. Using the local mass-timber products reduce the transportation costs which directly impacts both construction costs and overall project cost. Reduction in material import also reduces the carbon emission associated with transportation which can further reduces the carbon tax on the material.

In British Columbia, mass timber availability varies in the type of products and quantities. Forestry practices, climate conditions for specific tree types and the logging, milling and manufacturing infrastructure all influence product availability and associated cost. Nail laminated timber (NLT), and Glue laminated timber (GLT) are widely available in British Columbia (Stantec Fast + Epp 21). Faster growth birch and aspen used in laminated strand lumber (LSL) is a viable mass timber option in British Columbia and Canada (Michael Green Architecture 13).

CLT, in its early stages of development, is claimed to hold great potential in the construction of mid-rise and high-rise buildings. More than four-fifths of the world's CLT production is in Europe, and its manufacturing efficiencies compete with the local suppliers in North America. European suppliers are often able to provide competitive rates to the North American market, due to their capacity (Stantec Fast + Epp 21). However, the import of mass timber can increase the transportation costs and carbon emissions. CLT production in North America is concentrated in the Pacific North West region, but only one of the five producers is in British Columbia (Poyry Management Consulting 36-39).

Increased local production and greater standardization of mass timber products within the region could expand the market, meet greater demands and reduce both design and construction costs of mass timber buildings.

4.3.2 Integrating prefabrication techniques

Some studies contribute to the ideas of well-planned construction methodology which uses design and planning for prefabrication to reduce construction time and material waste, often through the use of building information modelling (BIM) for efficient communication between the project team.

A case analysis in the P4 study compared the construction times for the timber and precast concrete structures. The study mentioned that the construction method could utilize the off-site prefabrication of timber components to assist the rapidity of the construction (Smith, Fragiacomo and Pampanin 146).

Prefabrication also contributes to the mass-production potential for mass timber products with, which would “make a significant difference in affordability" (TallWood Design Institute 3). Maximizing the use of stock timber products and sizes that are readily available in the supply chain would be a cheaper solution for the mass-timber building project, while also standardizing production and reducing excess material waste. Currently most mass timber building projects are unique and non-standard sizes can generate timber waste of timber and add cost to the project (Dunn 6).

Using recycled or waste products from existing timber can potentially reduce costs and reduce environmental impact (Kremer and Symmons 139). One such example of using waste products can be witnessed in a proposal of a 40-storey mixed-use tower on the 1745 W. 8th Ave. in Vancouver designed by Perkins + Wills hopes to use cross-laminated timber and dowel-laminated timber that are manufactured in British Columbia and culled from damaged trees (Gold H4).

For some potential projects, the use of building information modelling (BIM) allows design professionals to working together from the early design stage of the building project. The computer models created through BIM directly translate into the models or documents that are used to command the CNC machine that cuts the mass timber pieces. This process enables prefabrication, which in turn enables the quick assembly of the mass-timber elements on site. This system provides cost savings by labour and material waste reduction (TallWood Design Institute 3).

4.3.3 Changing permitting allowances

Building code allowances and limitations have been identified as a challenge for utilizing mass-timber products in buildings, and leading to increases in the project costs through additional the project specific approvals.

The P1 and P2 studies stress the importance of a clear permitting pathway for mass timber building construction above 6-storeys. The P1 study by the Tallwood Design Institute notes that, as the responsiveness of mass timber to resiliency and life safety concerns in the event of emergencies and natural disasters is realized, it will be favourable to permit mass-timber building over six stories. Changes to the current building codes to permit allowances for mass timber would help to make mass timber more competitive with concrete and steel-framed construction (TallWood Design Institute 1).

Current fire resistance strategies often mean encapsulation of mass timber in drywall or similar materials, which adds additional costs. The literature indicates that costs can be reduced by allowing for fire resistance by utilizing timber’s natural char capacity. "Designing for the required fire resistance was found to be cheaper when the char capacity of timber itself was used and dependence of plasterboard was reduced" (Dunn 9).

One notable example of building code change is the allowance of 8-story, mass timber buildings in Finland in 2011. This change increased the percentage of mass-timber, multi-storey residential construction projects from 1% to 5% by 2014. The building code change also encouraged engineered wood product manufacturers to cooperate and develop concepts with construction companies (Poyry Management Consulting 14).

4.3.4 Improving trade availability

Availability of trade or skilled labour greatly impacts the building construction cost of the project. If there is not sufficient labour available in the region, the skilled labour has to be imported which constitutes to additional costs to the project.

In P12, a study conducted by Stantec on schools built of wood in British Columbia, discusses this matter and claims that wood construction offers benefits over steel and concrete due to the availability and accessibility of wood materials and trades in British Columbia. Qualified tradespersons with required skills, and engineered products for light wood frame building construction are widely available in BC. Especially in remote areas or small communities, it can be challenging to find qualified labour for concrete or steel construction, which leads to additional costs of bringing out of town trades (Stantec Fast + Epp 21).

This factor has been observed only in the study carried by Stantec for the schools in British Columbia conducted in 2018, which emphasized on the material and trade availability for wood construction including light-wood frame and mass timber, and does not specifically imply to mass-timber building construction. This may provide a training opportunity expand trade expertise from light-frame into mass timber.

4.3.5 Expanding awareness and education

Lack of awareness and education has been signified as one of the challenges of cost reductions for mass-timber building construction in most of the studies.

In the P8 study, Perkins + Will Architects suggests to improve communication of sustainability, quality, durability, aesthetic, appeal as well as tangible health, and wellness benefits of mass timber to early adopters which will develop better understanding of mass-timber construction and increase the demand of mass-timber products, eventually reducing the cost of the building project by efficient coordination and construction time" (Perkins + Will Architects 23).

In the P11 study, Michael Green Architecture recommended a public campaign aimed at re-introducing wood as building construction material and improve awareness among industry influencers and the general public. It also suggested that increased communication of research findings which is seen as important to overcome negative preconceptions that exist around the mass-timber building construction and to develop competition in the material marketplace so that more building owners and designers make use of mass-timber solutions (Michael Green Architecture 214). The P11 study additionally emphasized the importance of work by organizations such as BC Woodworks and Canada Wood Council's for developing industry understanding and expertise in new approaches to large, medium and tall wood buildings (ibid 214).

4.3.6 Exploiting intermodal transportation

Intermodal transportation refers to the movement of goods using multiple modes of transport, such as both rail and truck. The P2 study by Poyry Management Consulting establishes that transporting mass timber elements using more than one means of transportation, and prioritizing rail over truck, can be a cost effective strategy especially for long distance shipping over 800 km. In Canada there are two main rail networks, and there are nine in the US. These networks are connected on the east and the west coast across the border, making it possible to move cargo from one country to the other by train. However, the best transportation strategy might be different for each project depending on the location of the mass timber supplier and the location of the project, and needs to be assessed on a case to case basis (Poyry Management Consulting 93).

4.3.7 Incentivizing carbon sequestration

In British Columbia, carbon emission taxing of product manufacturing adds to the economic value of using mass timber in the building construction projects. However, the carbon emission taxes do not include any consideration of the potential carbon storage of materials. The P7 and P11 studies highlight the carbon sequestration value of mass timber and note that an associated question tax credit or incentives could significantly reduce the project cost in the future. "Carbon sequestration provides economic value, especially as the world moves towards a mechanism of pricing carbon" (Kremer and Symmons 138). "Future mechanisms to provide owners with carbon sequestration incentives will arguably make mass timber even less expensive than concrete in BC" (Michael Green Architecture 15).

5. Future research

This section of the report outlines future research topics identified in the literature, as well as topics identified as upcoming research by the Tallwood Design Institute. This part of the report aims to inform the policies, strategies and next steps that the City of Vancouver could consider to support the development the mid-rise, mass-timber building construction in Vancouver.

5.1 Identified research topics in literature

The list below summarizes potential future research topics identified in the literature:

1. Exploring community and consumer interests in the use of mass timber (Kremer and Symmons 145).
2. Developing an understanding of insurance cost impacts and considerations on mass timber buildings (Perkins + Wills 23).
3. Developing strategies to mitigate financial risks from associated additional costs, such as insurance (Perkins + Wills 17).
4. Identifying best practices of construction cost reduction for mass-timber building projects.
5. Developing an understanding of how building code requirements and lack of familiarity of building officials can contribute to increase the mass-timber building project costs (Mahlum, Walsh Construction Co, Coughlin Porter Lundeen 10).
6. Developing future code proposals for mass-timber construction distinct from light-frame combustible construction (Michael Green Architecture 215).
7. Cost evaluation and assessments of existing building projects, including the cost influencing factors (Michael Green Architecture 217) (Stantec Fast + Epp 11).
8. Market research and analysis of mass-timber products with associated cost implications and forest capacity in British Columbia (Michael Green Architecture 217).
9. Assessment of rapidly renewable approaches and impact of forestry on the economics and environment of British Columbia (Michael Green Architecture 217).
10. Analysis of cost comparisons of mass timber with concrete and steel from the existing building projects (Michael Green Architecture 217).
11. Collection of emerging new knowledge and cost reductions strategies from academic and industry conferences and collaborations (Michael Green Architecture 217).

5.2 Upcoming research

Tallwood Design Institute (TDI) is jointly operated by Oregon State University and the University of Oregon and aims to unite researchers focused on advancement of mass timber and structural wood products and building solutions. Through their Applied Research program, TDI has identified key research topics that aim to reduce barriers to the use of mass timber and improve performance and practice. The projects commence with an annual call and must demonstrate the results and solutions within two to five years.

The research projects are distributed into six topics:

- Fire Performance of Mass Timber
- Seismic and Structural Performance
- Durability and Adhesives
- Building Physics and Health
- Environment
- Business and Economics.

In the 2016 research plan, TDI identified the key topics for each section and announced the 2019 recipients of new research funding, which is mainly funded by the US Agricultural Research Service.

The business and economic section of this program is the most relevant for this study. However, this is one of the newer topics identified by this program and there are no published research papers yet. The following research projects have been funded, but do not yet mention the estimated date of completion:

1. The Pulse of the Global CLT Industry: Launching an Annual Survey as a Continuing Learning Tool (Project lead: Chris Knowles).
2. Establishing New Markets for CLT – Lessons Learned (Project lead: Eric Hansen).
3. Cost Comparisons of Mass Timber versus Conventional Construction (Project lead: Ingrid Arocho).

6. Conclusion

This study, *Literature review of cost information on mid-rise, mass-timber building projects*, was initiated by the City of Vancouver to better understand the information in the literature around costs for mass-timber buildings between 6 and 12 stories. It was conducted by UBC's Sustainability Initiative over the summer of 2019. The study reviewed literature from a range of sources, and selected twelve relevant studies for an in-depth analysis of both quantitative and qualitative data on cost factors and considerations.

Five of the studies contained quantitative information on mass timber mid-rise construction costs: three reports (P3, P5 & P6), one journal paper (P4) and one book (P11). The literature does not reveal any significant increase or decrease in the construction cost of mass-timber mid-rise building projects compared to concrete. Overall, the cost varies from (±) 0-6%, where ' + ' indicates cost savings of mass timber compared to concrete construction, and '- ' indicates additional costs of mass timber compared to concrete construction. There are limitations to this analysis however, since all of the studies used hypothetical buildings, not actual built projects. Additionally, while the studies focused on construction costs, each one included different types of information within that category, so cost comparisons between studies are not valid. Lastly, contextual variations also impacts costs from region to region.

All of the reviewed studies included qualitative cost data based on anecdotal experiences, interviews, surveys, market analysis and industry experience. The studies revealed insights on mass timber building costs such as cost drivers, cost-saving factors, challenges, opportunities and identified solutions and recommendations for the construction of mass-timber buildings. Broadly, the information was organized into challenges (factors that directly drove project and construction costs), cost-saving factors (project or mass timber characteristics that reduce costs) and opportunities for cost reductions (speculative changes that should reduce mass timber costs over time). Key factors include the economic market forces that influence forestry and lumber costs, as well as supply and demand of mass timber products; expertise and availability of consultants and trades with familiarity for mass timber products and buildings; building code allowances for mass timber; construction efficiencies through prefabrication, mass production, standardization and transportation; financial valuation of the low carbon benefits of wood products, specifically carbon sequestration.

This literature review has been intended as a scan of current information on costs associated with mid-rise, mass timber building projects. It is neither an exhaustive list nor a detailed analysis. However, the review has summarized potential areas of future research, as identified through the studies, which may be of interest and can inform the development of future policies. The key topics that are recommended to be considered include:

- Cost assessment of recently built mass timber building projects, specifically in British Columbia, Canada and the Pacific Northwest.
- Market research and analyses of the manufacturing and supply chain of mass timber products in British Columbia, including prefabrication and mass-production capabilities.

- The influence that changes to the building code requirements can have on increasing or decreasing mass timber project costs.

Organizations like the Tallwood Design Institute in Oregon, WoodWorks or Canadian Wood Council may already be supporting research in this areas and could be valuable sources of information.

Advancements in mass timber design and manufacturing have led to an increase interest in mass timber products as an alternative to more traditional structural materials, such as concrete and steel. Recent projects across Canada have demonstrated the feasibility and opportunities in using mass timber as a primary structural material. Cost is a major driver and constraint for decisions at every stage of building projects, from planning through operations. As jurisdictions consider changes to building codes to allow more mid-rise, mass timber projects, it is important to understand the cost influencing factors, challenges and opportunities associated with the development of these projects. The results from this literature review can be used as a starting point to inform the policy considerations and strategies on the use of mass timber in addressing the rising pressures on affordable housing in Vancouver.

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Appendices

Appendix A: Resource overview

#	Type	Given name	Title	Data	Author	Role	Sponsor	Region	Date	Project type	Research methodology	Summary	Research sample
1	Report	P1	**Affordable Housing and Mass Timber: Where do Opportunities Lie for Oregon?**	Qualitative	Tall Wood Design Institute	Interdisciplinary research collaborative	Oregon State University and the University of Oregon	Oregon, USA	Mar-17	Residential + Mixed use	Discussion based	A round table discussion hosted by the Tall Wood Design Institute on the potential contributions of mas-timber addressed the most pressing need of affordable housing in Oregon. Participants represented design, construction and development industries, and academics. A 12-storey mixed-use project combing workforce housing with ground-floor retail was the demonstration project. The project team partnered with TDI and Oregon Building Codes Division for performance testing, and hence, the lessons provided were from their experience. The panel discusses the market existence of mass-timber for affordable housing and how it can develop.	Panel discussion based on the expert's experience in the project of 12-storey Residential Mixed Use project in Oregon, USA.
2	Report	P2	**Assessing the Wood Supply and Investment Potential for a New England Engineered Wood Products Mill**	Qualitative	Pöyry Management Consulting	International Consulting and Engineering Company	New England Forestry Foundation	New England	Jul-17	General	Market Analysis	This report focuses on identifying engineered wood products introduced to the high and mid-rise construction market in the New England region of the USA. The report identifies that CLT would have the highest investment potential from wood supply and market perspective. The preliminary analysis identifies that in the New England region, the local CLT production could be competitive and holds a significant opportunity to meet the growing demand for multi-family housing and non-residential building projects. Enabling the building codes have been termed critical for growing the CLT markets in New England.	A Market Study conducted of engineered wood for the North East American Region with North America in context. Few European Countries have also been considered in the report as case-studies.
3	Report	P3	**CLT Feasibility Study** A Study of alternative construction methods in the pacific north-west	Quantitative & Qualitative	Mahlum; Walsh Construction Co.; Coughlin Porter Lundeen	Architecture, Planning & Interior Firm; Construction Company; Engineering Company	_	Pacific Northwest	May-14	Residential : Student Housing	Comparison Study	This study explores the CLT construction for the residential project as an alternative to traditional concrete and steel construction. It is a preliminary investigation to test the economic feasibility of using CLT to increase density, walkability and create an environmentally responsive built environment. The study investigated the cost competitiveness of CLT with 4% cost saving compared to the base 10-story concrete building.	The study considers an existing 7-storey student housing project and adds 3 storey to the existing 7-storey building making it a 10-storey hypothetical base model: 1.) Base Model: Concrete (10 level concrete) 2.) Metal (2 level concrete + 8 level metal) 3.) CLT (2 level concrete + 8 level CLT)
4	Paper	P4	**Construction time and cost for post-tensioned timber buildings**	Quantitative & Qualitative	Tobias Smith Massimo Fragiacomo Stefano Pampanin Andy H. Buchanan	Research students	Institute of Civil Engineers	New Zealand	Jan-09	Office	Comparison Study	This paper compares the cost and time of post-tensioned timber and steel constructions to an existing concrete construction of a six-storey office building at the University of Canterbury in New Zealand. The structure has been designed for the moderate seismic zone and abides by the New Zealand design codes in most cases. The timber structure relies on relevant international codes like Eurocode 5.	Comparison of existing 6 storey concrete office building to timber and steel alternatives.
5	Report	P5	**Cross Laminated Timber Feasibility Study** A comparison between cross laminated timber and cast-in-place concrete framing for mid-rise urban buildings	Quantitative & Qualitative	Cary Kopczynski & Company	Structural Engineering Company	_	Pacific Northwest	Feb-18	Residential + Mixed use	Comparison + Feasibility Study	This study undertakes a comparison between CLT and cast-in-place concrete as structural framing systems for a mid-rise multifamily residential building in the North American context. The objective of the structural evaluation was to compare the structural performance, constructability and cost of two systems. Building performance consideration was reviewed, which included carbon footprint, energy efficiency, fire and life safety.	A hypothetical mid-rise residential buildings was considered for the study with two structural options: 1.) CLT 2.) Cast-In-Place Concrete

Appendix A (Cont'd): Resource overview

#	Type	Given name	Title	Data	Author	Role	Sponsor	Region	Date	Project type	Research methodology	Summary	Research sample
6	Report	P6	**Final Report for Commercial Building Costing Cases Studies:** Traditional Design versus Timber Project	Quantitative & Qualitative	Timber Development Association (NSW)Researcher: Andrew Dunn	Timber industry funded association	Forest & Wood Products Australia	Sydney, Australia	Jan-15	Residential + Office	Comparison Study	This study developed cost plans for the structure of four building types:7 storey office building, 8 storey apartment building, 2 storeys aged care facility and single-storey industrial shed. Each building type was designed and independently cost for a timber option and concrete or steel-framed option. The investigation considered the elements of the building, which had significant differences and ignored the cost of elements that were the same.	Four building types with timber and traditional material options were analysed in the study 1.) 7 storey office building [Option 1: Timber - LVL; Option 2: Concrete] 2.) 8 storey apartment building [Option 1: Timber - CLT; Option 2: Concrete]
7	Paper	P7	**Mass timber construction as an alternative to concrete and steel in the Australia building industry**	Qualitative	P. D. Kremer & M. A. Symmons	_	International Wood Products Journal	Australia	Jul-15	General	Critical Assessment	The paper conceptually assesses the viability of mass timber construction as an alternative material in Australia. A business management studies tool called PESTEL model, Political, Economic, Social, Technological, Environmental and Legal, is used for analysis.	_
8	Report	P8	**Mass Timber Influencers** Understanding mass timber perceptions among key industry influencers	Qualitative	Perkins+Will	Architecture and research	Forestry Innovation Investment	BC	Aug-18	General	Industry Survey + Panel Session	This document aims to reframe the conversation around mass timber by engaging these key influencer industries to understand their current perceptions, as well as next steps needed to clarify the design and construction process and accelerate the adoption of innovative wood systems in BC.	Two approaches were taken to identify key perceptions towards mass timber within the influencer industries—an online survey and a panel session. The survey was shared with 118 stakeholders in BC including developer / owners. A total of 38 responses were received of which 30 respondents completed the full survey.
9	Report	P9	**Mass Timber Market Analysis**	Qualitative	The Beck group	Forest Products Planning & Consulting	Council of Western State Foresters	USA	Nov-18	General	Market Analysis	This report analyzes the market for mass timber within the Council of Western State Foresters (CWSF) region (17 Western US states and 6 US affiliated Pacific Islands), with a focus on the likely impact on timber demand in the region.	The scope of work included evaluation of the recent and future demand for Mass Timber in the region, the existing and planned manufacturer suppliers of mass timber products, review of existing and planned mass timber projects in the region, analysis of lumber supply and demand, and a supply/demand balance summary.
10	Article	P10	**The Business Case for Building with Wood** How wood construction can contribute to process efficiency, sustainability, and marketability	Qualitative	Juliet Grable	AIA: Continuing Education	Think Wood	North America	_	General	Case Study	This article explains how wood construction can be used to reduce construction timeframes, ensure quality, and accommodate changes in the field. It describes how wood is being used to create environments that appeal to the new generation of employees and occupants and explain how recent code changes are enabling cost-effective, high-density designs.	_
11	Book	P11	**The Case for Tall Wood Buildings** How Mass Timber Offers a Safe, Economical, and Environmental Friendly Alternative for Tall Building Structures	Quantitative & Qualitative	Michael Green Architecture	Architecture	_	BC	Jul-18	General	Comparison + Case Study + Industry Interviews	The report details how FFTT addresses cost effectiveness, durability and longevity, constructability and construction schedule, and market and consumer expectations. The report highlights the importance of Mass-Timber through factors like cost -competitiveness, economic diversification and rapidly renewable resource, forestry diversification, and market opportunities.	The cost analysis was calculated for a preliminary design model which estimates Spring 2011 costing. The comparison was carried out on three options of design model for a 12 storey and a 20 storey. - Concrete Frame - FFTT Charing method - Encapsulated method
12	Report	P12	**Wood Use in British Columbia Schools**	Qualitative	Stantec Fast + Epp	Design and Consulting Structural Engineering	Forestry Innovation Investment	BC	Nov-18	Schools	Case Study + Survey	This report addresses the opportunities and challenges for the use of wood and wood products in the construction, renovation and repair of schools in British Columbia. The report informs the development of a strategy to increase the use of wood in British Columbia schools while supporting the provincial government's priorities in education.	Four parts that will address different aspects of using wood 1. Overview of the drivers, including the widespread support for wood use in the context of schools in BC. 2. Discusses characteristics of wood use applicable to BC. 3. Presents examples of innovative wood use in schools from outside of BC to provide a comparative lens 4.Detailed examples of how wood has been implemented locally.

Appendix B: Cost Considerations

Given name	Title	Region	Date	Project type	Research methodology	Cost scope	Cost year	Currency	Research sample	Case type	Cost considerations
P3	CLT Feasibility Study A Study of alternative construction methods in the pacific north-west	Pacific Northwest	May -14	Residential: Student Housing	Comparison Study	Construction	2014	US$	The study considers an existing 7-storey student housing project and adds 3 storey to the existing 7-storey building making it a 10-storey hypothetical base model: 1.) Base Model: Concrete (10 level concrete) 2.) Metal (2 level concrete + 8 level metal) 3.) CLT (2 level concrete + 8 level CLT)	Existing building base with hypothetical options	• The 4% cost savings is a conservative estimate because of the unknowns (addition of competition and higher production rates can increase savings; little local experience; construction time to be reduced with the familiarity). • A conservative installation production rate was used to assure that a composite crew of operators, riggers and carpenters would achieve production much like the crews that install precast concrete panels. • The metal option includes cost assumptions that were derived from a current project cost estimate in a building with similar use.
P4	Construction time and cost for post-tensioned timber buildings	New Zealand	Jan-09	Office	Comparison Study	Construction	2009	NZ$	Comparison of existing 6 storey concrete office building to timber and steel alternatives.	Existing building base with hypothetical options	Some simplifications were made for the comparative analysis: removal of the basement level, removal of the atrium connection to adjacent buildings. • **Concrete option:** Load-resisting systems are made from pre-cast concrete frames and walls. Floors are pre-cast hollow core flooring units. • **Steel:** Seismic resisting floors and walls were removed and replaced with EBFs (eccentric braced frames) and the flooring is steel-concrete composite. • **Timber:** Similar to concrete structure with walls and frames changed from concrete to new hybrid LVL system.
P5	Cross Laminated Timber Feasibility Study A comparison between cross laminated timber and cast-in-place concrete framing for mid-rise urban buildings	Pacific Northwest	Feb-18	Residential + Mixed use	Comparison + Feasibility Study	Construction: Structural	2018	US$	A hypothetical mid-rise residential buildings was considered for the study with two structural options: 1.) CLT 2.) Cast-In-Place Concrete	Hypothetical building base with hypothetical options	**CLT option:** • Bearing wall system. • Wall openings are assumed to be integrated into the wall or resolved with SCL beam. • Balconies are pre-manufactured components. **Cast-in-place concrete option:** • Flat plate system. • Except for shear walls all other walls are non-load bearing. • Balconies are pre-manufactured components. **Northwest Mixed-Use Project**: • Retail on the first floor, office space on floors two through six, sixty apartments on the upper floors, and a rooftop deck. • CLT floor panels supported on glulam beams and columns. • The lateral force resisting system includes post-tensioned CLT shear walls.
P6	Final Report for Commercial Building Costing Cases Studies Traditional Design versus Timber Project	Sydney, Australia	Jan-15	Residential+ Office	Comparison Study	Construction: Structural	2015	A$	Four building types with timber and traditional material options were analysed in the study 1.) 7 storey office building [Option 1: Timber- LVL; Option 2: Concrete] 2.) 8 storey apartment building [Option 1: Timber- CLT; Option 2: Concrete]	Hypothetical building base with hypothetical options	_
P11	The Case for Tall Wood Buildings How Mass Timber Offers a Safe, Economical, and Environmental Friendly Alternative for Tall Building Structures	BC	Jul-18	General	Comparison + Case Study + Industry Interviews	Construction	2018	CA$	The cost analysis was calculated for a preliminary design model which estimates Spring 2011 costing. The comparison was carried out on three options of design model for a 12 storey and a 20 storey. - Concrete Frame - FFTT Charing method - Encapsulated method	Hypothetical building base with hypothetical options	• Concrete was used as a benchmark structure to compare costs with wood. • Location factors were applied to the numbers to further understand applications in different regions of BC. • The estimated costs were developed based on preliminary design drawings demonstrated in the document. • The estimates were taken in 2011 dollars and have taken into account then market conditions and quarter competitiveness returning to the marketplace. • A theoretical site was selected in Vancouver's West End neighborhood. • An appropriate density with residential towers typically ranging from 10 to 20 stories. • The envelope of the structure is assumed to be 70% glazing with window wall system and 30% wall cladding. • The interior construction is drywall partitions; and concrete shear walls with header beams to elevator shaft and stair core.

Appendix C: Quantitative analysis

#	Given name	Region	Study year	Project type	Cost scope	Case type	Building material	Structure	No. of storeys	Floor area (sq.ft)	Currency	Total cost	Cost per gsf	Cost conversion	Cost savings (%)	Compared to	Cost inclusions	Cost exclusions
1	**P3**	Seattle	2014	Residential	Construction	Hypothetical	Steel	2 level Concrete + 8 Steel	10	134,950	US$	–	–	–	2.0%	Base Model: Concrete	• Exterior enclosure: sheathing, weather resistant barrier, insulation, external cladding. • Backup system. • Interior partitions (metal stud with gypsum wall board) HVAC equipment	–
2	**P3**	Seattle	2014	Residential	Construction	Hypothetical	Mass-Timber	2 level Concrete + 8 CLT	10	134,950	US$	–	–	–	6.0%	Base Model: Concrete		
3	**P4**	New Zealand	2009	Office	Construction	Existing	Concrete	Pre-Cast Concrete	6	55,800	NZ$	$9,433,300	$169.06	$149.00	NA	NA	• Substructure; structural frames and walls; flooring and roofing. • Exterior walls and finishes. • Architectural interior. • Fire protection, electrical services and plumbing, heating and ventilation, vertical and horizontal transportation, drainage and external works	–
4	**P4**	New Zealand	2009	Office	Construction	Hypothetical	Steel	Steel-Concrete Composite	6	55,800	NZ$	$9,369,800	$167.92	$148.00	NA	NA		
5	**P4**	New Zealand	2009	Office	Construction	Hypothetical	Mass-Timber	Post-tensioned Hybrid LVL	6	55,800	NZ$	$10,021,300	$179.59	$158.00	(-) 6.0%	Concrete		
6	**P5**	Pacific Northwest	2018	Residential	Construction : Structural	Hypothetical : survey based	Concrete	Cast-in-place concrete	10	12,000	US$	–	$42-46	$57	NA	NA	• Prorated general conditions	• The cost of exterior enclosure systems
7	**P5**	Pacific Northwest	2018	Residential	Construction : Structural	Hypothetical : survey based	Mass-Timber	CLT	10	12,000	US$	–	$48-56	$60	(-) 5.2%	NA	• Structural frame cost only	• Exterior Enclosure • Acoustical • Fire Protection
8	**P5**	Oregon	2018	Mixed-Use	Construction : Structural	Under construction	Mass-Timber	CLT	12	90,000	US$	$5,850,000	$65	$88	NA	NA	• Structural frame cost only	–
9	**P6**	Sydney, Australia	2015	Office	Construction : Structural	Hypothetical	Concrete	Concrete	7	–	A$	$7,289,508	–	–	NA	NA	• Columns, floor, roof, lift, stair and air shafts, suspended ceiling, connectors, termite & fire engineering preliminaries	• Mechanical, electrical, plumbing, floor coverings, car parking levels, fit out
10	**P6**	Sydney, Australia	2015	Office	Construction : Structural	Hypothetical	Mass-Timber	LVL	7	–	A$	$6,387,913	–	–	12.4%	Traditional structure: Concrete		
11	**P6**	Sydney, Australia	2015	Residential	Construction : Structural	Hypothetical	Concrete	Concrete	8	–	A$	$5,126,183	–	–	NA	NA	• Columns, level 1 transfer slab, upper floors, roof, external walls, internal walls, wall finishes, ceiling finishes, termite & fire engineering, preliminaries	• Mechanical, electrical, plumbing, floor coverings, car parking levels, fit out
12	**P6**	Sydney, Australia	2015	Residential	Construction : Structural	Hypothetical	Mass-Timber	CLT	8	–	A$	$5,015,705	–	–	2.2%	Traditional structure: Concrete		

Appendix C (Cont'd): Quantitative analysis

#	Given name	Region	Study year	Project type	Cost scope	Case type	Building material	Structure	No. of storeys	Floor area (sq.ft)	Currency	Total cost	Cost per gsf	Cost conversion	Cost savings (%)	Compared to	Cost inclusions	Cost exclusions
13	P11	Vancouver	2011	Residential	Construction	Hypothetical	Concrete	Concrete frame	12	61,920	CA$	$17,550,800	$283	$307.96	NA	NA	• Fire Protection • Mechanical and electrical • HVAC (heating & ventilation only) • Mid-range level of finishes • Labour • Material • Equipment	• AC • Land costs • Legal fees & expenses • Demolition and removal of hazardous materials • Loose furniture and equipment • Off-Site works
14	P11	Vancouver	2011	Residential	Construction	Hypothetical	Mass-Timber	Exposed CLT (charring)	12	61,920	CA$	$17,518,000	$283	$307.96	0.0%	Concrete		
15	P11	Vancouver	2011	Residential	Construction	Hypothetical	Mass-Timber	Encapsulated CLT	12	61,920	CA$	$17,856,200	$288	$313.40	(-) 1.9%	Concrete		
16	P11	Northern BC	2011	Residential	Construction	Hypothetical	Concrete	Concrete frame	12	61,920	CA$	$19,832,404	$320	$348.22	NA	NA		
17	P11	Northern BC	2011	Residential	Construction	Hypothetical	Mass-Timber	Exposed CLT (charring)	12	61,920	CA$	$19,269,800	$311	$338.43	2.8%	Concrete		
18	P11	Northern BC	2011	Residential	Construction	Hypothetical	Mass-Timber	Encapsulated CLT	12	61,920	CA$	$19,641,820	$317	$344.96	1.0%	Concrete		
19	P11	Interior BC	2011	Residential	Construction	Hypothetical	Concrete	Concrete frame	12	61,920	CA$	$18,779,356	$303	$329.72	NA	NA		
20	P11	Interior BC	2011	Residential	Construction	Hypothetical	Mass-Timber	Exposed CLT (charring)	12	61,920	CA$	$18,393,900	$297	$323.19	2.0%	Concrete		
21	P11	Interior BC	2011	Residential	Construction	Hypothetical	Mass-Timber	Encapsulated CLT	12	61,920	CA$	$18,749,010	$303	$329.72	0.0%	Concrete		
22	P11	Fraser	2011	Residential	Construction	Hypothetical	Concrete	Concrete frame	12	61,920	CA$	$17,550,800	$283	$307.96	NA	NA		
23	P11	Fraser	2011	Residential	Construction	Hypothetical	Mass-Timber	Exposed CLT (charring)	12	61,920	CA$	$17,518,000	$283	$307.96	0.0%	Concrete		
24	P11	Fraser	2011	Residential	Construction	Hypothetical	Mass-Timber	Encapsulated CLT	12	61,920	CA$	$17,856,200	$288	$313.40	(-) 1.76%	Concrete		
25	P11	Vancouver Island	2011	Residential	Construction	Hypothetical	Concrete	Concrete frame	12	61,920	CA$	$18,691,602	$302	$328.63	NA	NA		
26	P11	Vancouver Island	2011	Residential	Construction	Hypothetical	Mass-Timber	Exposed CLT (charring)	12	61,920	CA$	$18,393,900	$297	$323.19	1.7%	Concrete		
27	P11	Vancouver Island	2011	Residential	Construction	Hypothetical	Mass-Timber	Encapsulated CLT	12	61,920	CA$	$18,749,010	$303	$329.72	(-) 0.3%	Concrete		

Appendix D: The list of documents scanned

A total of 51 studies were reviewed for this study. Twelve of them were shortlisted for in-depth study in this report and a detailed list of these papers is on Appendix A. The table below lists the studies that were scanned but were excluded from the scope of this review because they did not include relevant information in terms of the following criteria:

- Quantitative data on cost of mass timber mid-rise buildings (6-12 storeys).
- Qualitative data on cost of on mass timber mid-rise buildings (6-12 storeys) in North America.
- Cost data comparing mass timber with conventional building materials (i.e. concrete and steel).
- Mass-timber market information and insights for North America.

#	Title	Author	Date	Region	Publication type
1	Can Wood Become an Alternative Material for Tall Building Construction?	Jamshid Mohammadi	14 June 2017	USA	Paper
2	Cross-Laminated Timber vs. Concrete/Steel: Cost Comparison Using a Case Study	Maria Laguarda-Mallo, Omar Espinoza	August 2016	USA	Paper
3	100 Projects UK CLT	Waugh Thistleton Architects	2018	UK	Book
4	Concrete apartment tower in Los Angeles reimagined in mass timber	Matthew Timmersa, Andrew Tsay Jacobs	6 December 2017	USA	Paper
5	Cost, time and environmental impacts of the construction of the new NMIT Arts and Media building	Stephen John	January 2011	New Zealand	Report
6	Cost-Efficient Wood Framing Leads to Energy-Efficient Schools	Woodworks	June 2019 (accessed)	North America	Education material
7	El Dorado High School Students Get the 'Wow' They Deserve	Woodworks	June 2019 (accessed)	North America	Education material
8	Innovations in Wood: Emory Point	Woodworks	June 2019 (accessed)	North America	Education material
9	Designing for Durability: Strategies for achieving maximum durability with wood-frame construction	Think Wood	June 2019 (accessed)	USA	Education material
10	Designing Sustainable, Prefabricated Wood Buildings	Think Wood	June 2019 (accessed)	USA	Education material
11	Getting Down to Business: The Cost/Value Proposition of Timber Offices	Woodworks	June 2019 (accessed)	North America	Education material
12	Increasing deemed to satisfy height limits for timber construction Cost benefit analysis	Stephanie Black	June 2015	Australia	Report
13	Inspiration through Innovation: At UMass Amherst, an Exposed Mass Timber Structure is a Teaching Tool	Woodworks	June 2019 (accessed)	USA	Education material
14	Mass Timber in North America: Expanding the possibilities of wood building design	Think Wood	June 2019 (accessed)	USA	Education material
15	Mass timber – the emergence of a modern construction material	Annette M. Harte	31 August 2017	North America & Europe	Journal article
16	Mass Timber High-Rise Design Research: Museum Tower in Los Angeles Reimagined in Mass Timber	Matthew Timmers, Andrew Tsay Jacobs, Bevan Jones	2015	USA	Report
17	Maximizing Value with Mid-Rise Construction	Woodworks	June 2019 (accessed)	North America	Education material
18	Maximizing View & Value With Wood	Woodworks	June 2019 (accessed)	North America	Education material
19	Mid-Rise Best Practice Guide: Proven Construction Techniques for Five- and Six-Storey Wood-Frame Buildings	Canadian Wood Council	June 2019 (accessed)	Canada	Report
20	Mid-Rise Wood Construction: A Cost-Effective And Sustainable Choice For Achieving High-Performance Goals	Think Wood	June 2019 (accessed)	USA	Education material
21	Faster, safer, lower cost: panelized roof systems	Woodworks	June 2019 (accessed)	North America	Education material
22	Comparison of different assembling techniques regarding cost, durability, and ecology – A survey of multi-layer wooden panel assembly load-bearing construction elements	Dietrich Buck, Xiaodong Wang, Olle Hagman, and Adres Gustafsson	2015	Sweden	Peer reviewed article
23	Potential Of Cross Laminated Timber In Single Family Residential Construction	Brad Burback	-	USA	Thesis
24	Research and Education Environmental Scan for Mass Timber Institute	Catherine Cobden	June 2018	Canada	Report
25	Structural Wood Building Systems Choosing the Right Material for a Sustainable, Safe And Resilient Project	Think Wood	June 2019 (accessed)	USA	Education material
26	Summary Reort: Survey of international tall wood buildings	Perkins + Wills	May 2014	North America	Report

Appendix D (Cont'd): The list of documents scanned

#	Title	Author	Date	Region	Publication type
27	Artificial Neural Network for Assessment of Energy Consumption and Cost for Cross Laminated Timber Office Building in Severe Cold Regions	Qi Dong, Kai Xing and Hongrui Zhang	30 December 2017	USA	Article
28	The Potential of Cross Laminated Timber in North American Construction	Canadian Forest Service	January 2013	North America	Report
29	Timber in multi-residential, commercial and industrial building: Recognising opportunities and constraints	Gregory Nolan	April 2011	Australia	Report
30	Wood and Evolving Codes: The 2018 IBC and Emerging Wood Technologies	Andrew A. Hunt [Think Wood]	2018	USA	Education material
31	Wood Rises to the Occasion	Woodworks	June 2019 (accessed)	USA	Education material
32	Big Box Retail: Wood Saves Nearly $1 Million Cost and environmental studies compare wood to steel	Woodworks	June 2019 (accessed)	USA	Education material
33	Characteristics and Time Consumption of Timber Trucking in Finland	Tuomo Nurminen and Jaakko Heinonen	12 July 2007	Europe	Paper
34	Cost estimates for carbon sequestration from fast growing poplar plantations in Canada	Daniel W. McKenneya, Denys Yemshanova, Glenn Foxb, Elizabeth Ramlal	2004	Canada	Paper
35	Extending timber rotations: carbon and cost implications	Brent Sohngen & Sandra Brown	15 Jun 2011	USA	Paper
36	Feasibility of Multi Storey Post-Tensioned Timber Buildings: Detailing, Cost and Construction	Tobias J. Smith	2008	New Zealand	Thesis
37	Life Cycle Analysis and Optimization of a Timber Building	D.N. Kaziolasa, G.K. Bekasb, I. Zygomalasc, and G.E. Stavroulakisd	2015	Europe	Paper
38	Solid Wood: Case Studies in Mass Timber Architecture, Technology and Design	Joseph Mayo	2015	Global	Book
39	Tall Wood Buildings in the 2021 IBC Up to 18 Stories of Mass Timber	Scott Breneman, Matt Timmers, Dennis Richardson [Woodworks]	June 2019 (accessed)	USA	Education material