AN ABSTRACT OF THE DISSERTATION OF

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Title: Evaluating the Feasibility of Mass Timber as a Mainstream Building Material in the US Construction Market: Industry Perception, Cost Competitiveness, and Environmental Performance Analysis.

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Ingrid Arocho

Mass timber has been considered as a promising building material because of its structural rigidity, environmental sustainability, and renewability nature. In Europe and Australia, mass timber materials have been used for many different types of construction such as residential, commercial, education, and industrial. However, the construction practitioners in the U.S. are still reluctant to consider mass timber as a mainstream building material. A limited number of case study projects make it difficult for industry personnel to evaluate the actual construction feasibility of mass timber. As a result, a significant knowledge gap has been created that is hindering the progress of mass timber material in the U.S. construction industry. To help solve the problem, this dissertation utilizes a range of research methodologies and data analysis techniques to evaluate the feasibility of mass timber building materials in the US construction industry. The dissertation focuses on four major objectives that will help the industry practitioners to adopt mass timber as a mainstream building material. The first objective of the study is to determine the existing perception of the industry practitioners regarding mass timber materials. Using industry-wide questionnaire surveys, this study determines the current awareness level among the practitioners regarding mass timber. It also identifies some of the major advantages and challenges associated with mass timber construction. Finally, the study provides several recommendations to overcome the challenges. The second objective of the study is to investigate the cost compatibility of mass timber materials compared to the other traditional building materials. A case study is used to evaluate the construction cost competitiveness of a mass timber building project with a modeled concrete building. The third objective of the study is to assess the air pollution potential of mass timber material. A mass timber building construction site, a steel building construction site, and a regular location are used to collect four different sizes of particulate matter (PM). The fourth and last objective of the dissertation is to develop a multi-criteria decision-making framework to evaluate the feasibility of mass timber material in the US market. A scientific decision-making tool named choosing-by-advantages (CBA) is used to develop the framework. The dissertation produces a total of nine peer-reviewed manuscripts summarizing the key research contributions. Findings from this dissertation will benefit both construction practitioners as well as the researchers with new knowledge on mass timber building materials. In addition to that, it will increase the acceptance of this material in the U.S. construction industry.

Evaluating the Feasibility of Mass Timber as a Mainstream Building Material in the US Construction Market: Industry Perception, Cost Competitiveness, and Environmental Performance Analysis

by
Shafayet Ahmed

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

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Shafayet Ahmed, Author

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DEDICATION

This dissertation is dedicated to my dad, who passed away eight years ago. You taught me to be humble and ambitious.

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CHAPTER 1: INTRODUCTION

1.1 STUDY BACKGROUND

For many years, wood has been considered a preferred building material because of its abundance, strength, and sustainable nature. To ensure efficient material utilization and address the inherent variability of wood products, engineered mass timber was developed. These products are manufactured to achieve several engineering properties such as strength, durability, and consistency (Mallo and Espinoza, 2015). Implementation of high-end mechanical and grading technology to the mass wood products escalates the future of wood-based construction (Canadian Wood Council, 2010). Being originated in Europe, mass timber products have been very successful in the European market since their inception (Lehmann, 2012). Nowadays, mass timber products are widely used in many different building types such as residential, commercial, education, and industrial. Although mass timber building material already has gained huge attention in Europe, Australia, and the Canadian market, in the U.S., the material is still relatively unfamiliar beyond some demonstration projects (Mallo and Espinoza, 2015). However, interest regarding this product is growing in the U.S. construction industry. Several studies have been performed on different aspects of this material. U.S. Department of Agriculture has been awarded grants to investigate mass timber products on a bigger scale (Gagnon, 2011; Mohammad et al., 2012; APA, 2013).

An important element of adopting a new material is to analyze the market potential of that product. In the U.S. construction market, this area has received relatively small consideration compared to other technical features of this product. The perception, awareness, and motivation among the industry practitioners to adopt a new material can play a substantial role in the growth of that product. Analyzing the cost competitiveness of mass timber products is another substantial parameter to assess the future of mass timber. Unlike many other building materials, the cost information of mass timber building construction is still relatively uncommon. An experimental, thorough, and reasonable correlation between the cost of buildings utilizing different construction materials will aid during the major monetary decisions regarding mass timber. Being known as a green and sustainable building material, mass timber products are believed to have less air pollution potential during construction. However, there are not enough evidence, thus, it is important to evaluate the actual air pollution potential of mass timber building construction.

1.2 RESEARCH OBJECTIVES

The overreaching goal of this study is to evaluate the feasibility of mass timber products as a mainstream building material in the U.S. construction industry. The goal is developed based on four distinct objectives that will provide ground for the assertion. Figure 1.1 illustrates the summary of research. The major objectives of this research are:

- Evaluate the existing awareness level, barriers, and recommendations to adopt mass timber products by the U.S. industry practitioners
- Analyze the construction cost competitiveness of mass timber building with traditional materials such as concrete and steel
- Identify the air pollution potential of mass timber building construction compared to traditional concrete and steel building construction

- Develop a multi-criteria decision-making tool to identify the feasibility of mass timber material in the U.S. construction industry

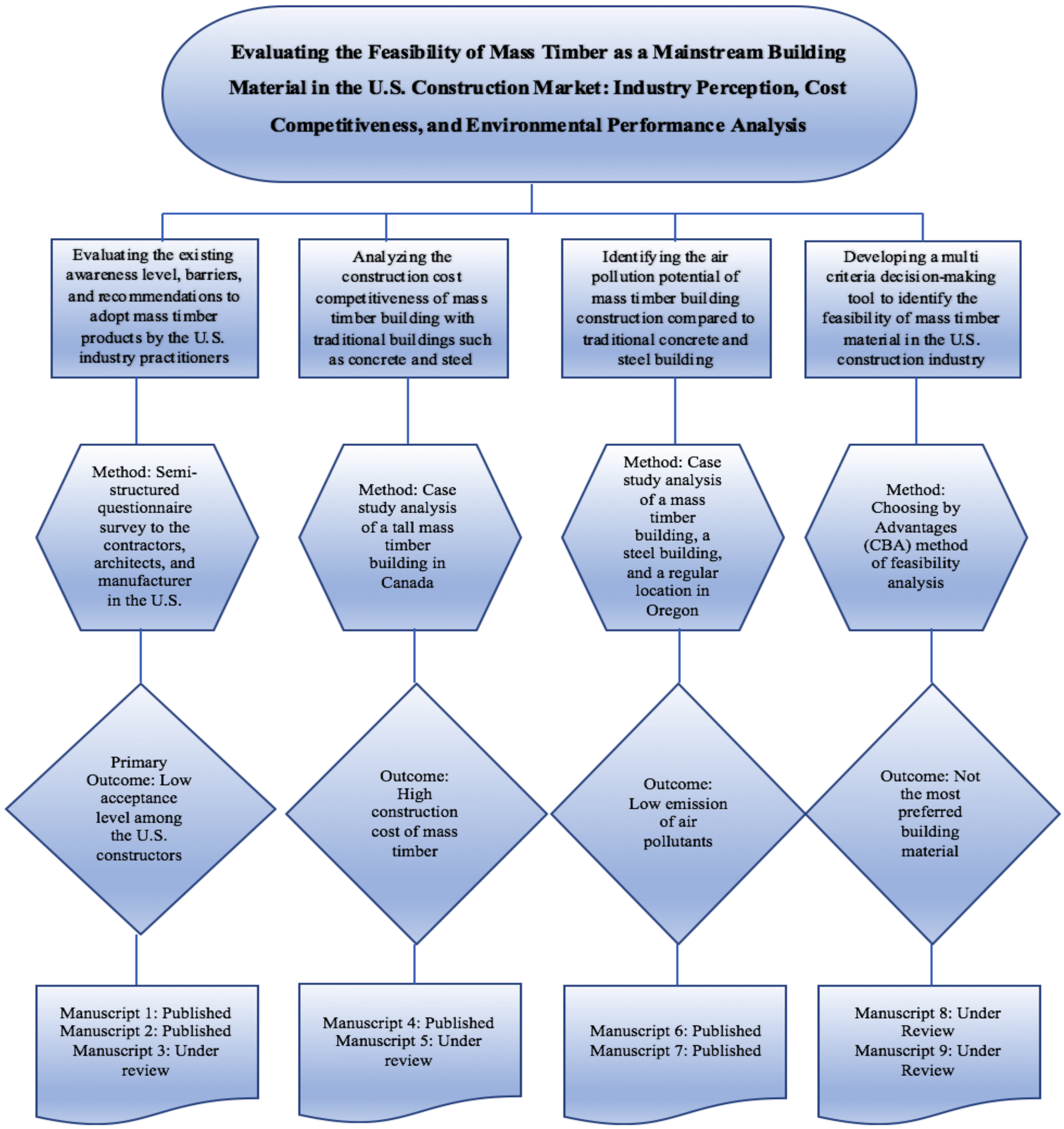

Figure 1. 1 Summary of the research

1.3 DISSERTATION OUTLINE

This document is composed of seven chapters including a general introduction and conclusion. Chapter 1 consists of the general introduction that focuses on the study background, main research objectives with summary, and orientation of the dissertation. Chapter 2 consists of a brief literature review of the study that is fundamental to achieve the goal of this dissertation. This chapter discusses the definition of mass timber building materials, its implication in the US construction market, the innovativeness of mass timber products, and some of the existing challenges associated with mass timber construction.

Chapter 3 presents the first objective of the study modified from Manuscripts 1, 2, and 3. This chapter shows the outcomes of the existing industry perception, advantages, and challenges, and recommendations to adopt mass timber as a mainstream building material in the US construction industry. The study is developed by industry-wide questionnaire surveys and shows the current perception of the industry practitioners regarding mass timber building materials.

Chapter 4 comprises a construction cost competitiveness study of mass timber materials. The study is developed based on a case study project located in Canada. The study analyzes the construction cost of a mass timber building project compared to its concrete counterpart.

Chapter 5 contains an air pollution study of a mass timber building construction project. Similar to Chapter 4, this study is also developed with a case study that includes a mass timber building construction project, a steel building construction project, and a regular area. On-site data collections are performed from all three locations for a certain period. Later, data are statistically analyzed to determine the air pollution potential of mass timber compared to steel and the regular location.

Chapter 6 incorporates a multi-criteria decision-making framework named choosing-by-advantages (CBA) to determine the feasibility of mass timber building materials in the US market. Knowledge created in previous chapters is utilized to develop the framework for the study. This study was also performed by an industry-wide questionnaire survey to allow the practitioners to participate in the CBA study. This study concludes the actual feasibility of mass timber materials in the US compared to concrete and steel.

Finally, Chapter 7 discusses the major findings and key contributions of the study to the body of knowledge. It also discusses the limitations of the current research along with potential future avenues to address and enhance the work performed for this study.

CHAPTER 2: LITERATURE REVIEW

2.1 MASS TIMBER BUILDING MATERIALS

Mass timber buildings refer to buildings that are generally constructed with large-volume of composite wood. It is a type of building material that utilizes large solid wood panels for wall, floor, and roof construction (reThink Wood). Mass timber products provide several advantages compared to the traditional concrete and steel buildings such as improved aesthetics, increased carbon capture, superior resilience to earthquakes, and improved indoor and outdoor environmental performance (ECONorthwest 2018). Because of several limitations in strength and fire resistance, typical wood-framed buildings were initially limited only to low-rise construction that are smaller than eight story (Kordziel et al. 2019). However, the increasing popularity of mass timber products such as Cross-Laminated Timber (CLT) and Glued-Laminated Timber (Glulam) has been expanding the wood construction market to larger-scale commercial building applications (Gagnon and Pirvu. 2011). Because of aesthetic appeal and ease of construction, mass timber products are now considered as an alternative by many developers (Mohammad et al. 2012).

Several innovative mass timber building products are currently available in the market. Major types of mass timber products include Cross-Laminated Timber (CLT), Glue-Laminated Timber (Glulam), Nail-Laminated Timber (NLT), and Dowel-Laminated Timber (DLT). One of the most prominent types of mass timber products is CLT that consists of layers of dimension lumber oriented at right angles to one another and glued to form structural panels with exceptional strength, dimensional stability, and rigidity (reThink Wood). CLT panels typically consist of three, five, or seven layers of timber plies where each layer can vary from 5/8" to 2" thick and are glued together with polyurethane, melamine, and phenolic based adhesives (Kordziel, 2018). Fabricated CLT panels can reach a maximum size of 10 feet by 60 feet (FPInnovations, 2013). CLT panels are mostly used for major structural components such as wall, roof, and floor slabs (Kordziel et al. 2019). Figure 2.1 shows a typical CLT panel.

Another common type of mass timber product is Glue-Laminated Timber (Glulam). Glulam products consist of individual layers of wood that are placed parallel to each other (Kordziel, 2018). Similar to CLT, Glulam products are also composed of dimension lumber that are selected based on their structural performance characteristics and bonded together using durable and moisture-protected adhesives (reThink Wood). Glulam provides excellent structural strength that allows the developers to use that product for floor and roof decking, besides typical beams and columns (reThink Wood).

Nail-Laminated Timber or NLT is another very common type of wood product that has been used for more than a century. However, in recent days, NLT is undergoing a resurgence as a part of the current development of mass timber products. NLT is developed from individual dimension lumbers, stacked on edge, and fastened with nails or screws to create a larger structural component (reThink Wood). Besides being used for floor, decks, and roofs, NLT has also been used in elevator and stair shafts in mid-rise wood frame buildings (reThink Wood). NLT provides great advantage on roof form over other mass timber products because of its panels that are comprised of individual boards spanning in a single direction (reThink Wood).

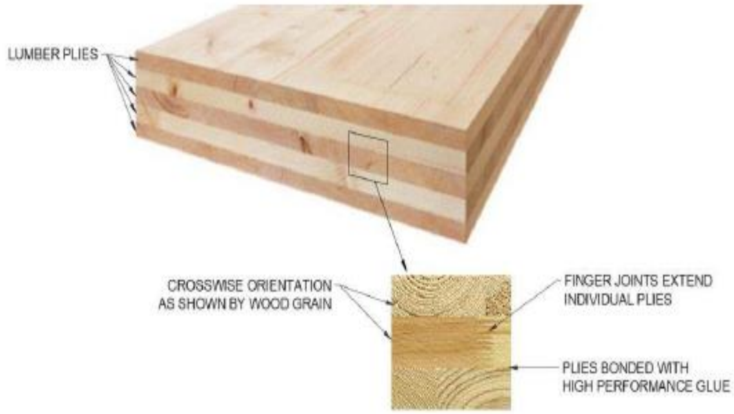

Figure 2. 1 Schematic of CLT panel (Kordziel, 2018)

2.2 MASS TIMBER BUILDINGS IN THE U.S. CONSTRUCTION MARKET

In the U.S. market, the concept of mass timber building has been progressed by demonstrating a few pilot projects, although a lack of well-defined code has always remained a key concern (Pei et al. 2016). The first performance-based standard for mass timber building in North America was developed by a shared exertion between APA-The Engineered Wood Association and FPInnovations (Borjen et al. 2012). Leading North American mass timber manufacturers such as DR Johnson Lumber Company, Nordic, and Structurlam have obtained American Plywood Association (APA) certification. A handbook developed by FPInnovations provides direction to the contractors and architects to design mass timber buildings (Karacabeyli and Lum, 2014). However, the number of mass timber buildings in the U.S. is still significantly low, and many of those buildings have witnessed challenges with meeting building codes and cost (Juntunen et al. 2018). The construction cost of mass timber building has prevailed as a primary concern among the stakeholders as previous research has found a high cost of mass timber building projects, compared to concrete and steel. Ahmed and Arocho (2021) found that the construction cost of a mass timber building is 6.43% higher than a similar building designed with a concrete option. Burback and Pei (2017) showed that the construction cost of CLT residential buildings can be 23% higher than using the traditional light-framed wood option. Thus, to increase the acceptability of mass timber products, these cost-related issues need to be resolved.

2.3 INNOVATIVENESS OF MASS TIMBER MATERIALS

In the context of rapid urbanization with the enormous demand for housing and shelter, it is important to utilize building materials having a relatively lower impact on global climate change compared to traditional high energy-intensive materials. The construction process of buildings consumes up to 40% of global energy use and produces one-third of the total greenhouse gas emission (Crampton, 2017). Traditional building materials such as concrete and steel have a significantly large carbon footprint and the manufacturing operation of concrete and steel contributes 5% of total carbon emission (Yale Environment360, 2019). To help solve the problem, the innovation of mass timber products can play a crucial role to integrate urban built environment with the natural system. Wood-based products are known for their high carbon sequestration and low carbon emission (NCSU, 2018). When trees are sustainably harvested as wood products, 50% weight of the wood transforms into carbon that increases the sequestration capacity of wood (Crampton, 2017). Thus, more wood-based structures assure more inherent carbon storage capacity that eventually helps to reduce the carbon footprint on the atmosphere. The prefabricated nature of mass timber panels increases project success by reducing the project completion time and crew size. The timber construction process requires relatively low labor input, which helps to solve the problem of a limited supply of available construction workers in booming development locations with high labor demand. Mass timber products also have a high potential for local benefits by establishing timber manufacturing plants that could provide more employment and economic growth in a particular location. By integrating the wood-based natural system with the urban built environment, mass timber will play an innovative role in achieving sustainable development.

2.4 CHALLENGES ASSOCIATED WITH MASS TIMBER MATERIALS

Despite having substantial movement, mass timber building materials are still experiencing several challenges. Mass timber panels use three times more wood than a wood-frame system solution (Mallo and Espinoza, 2015) that makes the material more expensive than the traditional construction materials. Installation inefficiency of mass timber panels causes considerable acoustic problems (Mallo and Espinoza, 2015). Since the concept of mass timber building is still growing in the U.S., the level of awareness among the industry practitioners is questionable. Locations with more traditions in wood-based construction (e.g. Pacific Northwest), have higher level of awareness compared to other locations with less tradition of wood-based construction. Lack of sufficient design codes and specifications makes the product not being adopted by many developers. The presence of excessive moisture can cause significant damage to mass timber panels. In the U.S., the number of mass timber manufacturing facilities is still small, as a result, material delivery becomes inconvenient and the transportation cost of the product goes high.

CHAPTER 3: INDUSTRY PERCEPTION OF MASS TIMBER BUILDING MATERIAL

Modified from:

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3.1 INTRODUCTION

Due to rapid urbanization and increasing housing demand, construction materials are now one of the cardinal factors to assure green and sustainable development. The construction industry is considered a resource-intensive industry because of its diverse characteristics of work and pollution potential. Crampton (2017) found that building construction processes can consume up to 40 percent of total global energy and produce one-third of total greenhouse gas emissions. Typical building materials such as concrete and steel have a relatively large carbon footprint, which contributes to global warming. In the given context, it is important to look for an innovative and sustainable building material that has a low carbon footprint and embodied energy.

Among various other construction materials, mass timber has the potential to be used for green design and zero-waste production (Mohammadi and Ling, 2017). It was found that construction sites that utilized mass timber building material experienced a low-level of air pollution compared to concrete and steel building materials (Ahmed and Arocho, 2019). Mass timber is a type of building material that consists of a large volume of composite wood panels placed on top of each other either in an orthogonal right angle or parallel direction, depending on the type of structural application. The most prominent types of mass timber products include cross-laminated timber (CLT) and glue-laminated timber (GLT) (Kordziel et al. 2019). Mass timber products have several clear advantages over other traditional building materials in terms of aesthetics, seismic resiliency, and carbon sequestration (ECONorthwest 2018). Earlier, mass timber products were only limited to low-rise construction but the development of new engineered wood products with increased durability and strength helped this product to gain more propulsion in recent years.

Introduced in Europe back in the 1990s, mass timber is considered as an effective building material because of its structural rigidity, environmental sustainability, and renewability (Mahamid and Tora-Bilal, 2019). However, in the U.S., the concept of mass timber buildings is still evolving and limited beyond some demonstration projects (Mallo and Espinoza, 2015). Lack of sufficient mass timber construction projects, availability of skilled workforce, and lack of awareness and knowledge have created skepticism among the stakeholders to adopt this material on a greater scale. Also, market analysis received little to no consideration compared to the other building materials such as concrete and steel. A thorough investigation regarding the current awareness level and challenges associated with mass timber products will play an important role to establish this material in the U.S. It will also provide a roadmap for the stakeholders to streamline the adoption process.

In the given circumstance, this study has aimed to identify the existing awareness and involvement level on mass timber building construction, challenges and difficulties associated with mass timber products, and provide recommendations to overcome the existing challenges and increase the acceptability of this product among the construction practitioners in the U.S. The study included building constructors, architects and designers, and mass timber manufacturers in the U.S. Three different questionnaire surveys were developed and distributed among 1200 building constructing companies, 300 architecture companies, and 55 mass timber manufacturing companies. The questionnaire surveys were semi-structured in nature, meaning it has both close-ended and open-ended questions for the participants.

The research focused on three distinct objectives. The first objective of the study was to identify the current awareness and involvement level among the construction practitioners regarding mass timber materials. The second objective of the study was to determine the construction, design, and manufacture related challenges and difficulties of mass timber products. The third objective of this study was to provide recommendations to tackle the challenges and difficulties related to mass timber building construction and grow its admissibility among the stakeholders. The research team has found three distinct contributions to this study:

- Identify the existing awareness and involvement level regarding mass timber materials among the U.S. construction practitioners.
- Determine specific construction, design, and manufacture related challenges and difficulties associated with mass timber materials based on the experience of the study participants.
- Provide recommendations to overcome the challenges and difficulties of mass timber products and increase the acceptability of this product among the U.S. building developers and owners.

3.2 LITERATURE REVIEW

This section summarizes the overview of mass timber in the U.S. construction market, and existing barriers of using mass timber products.

3.2.1 Overview of Mass Timber in the U.S. Market

Europe has experienced double-digit growth rates in last two decades of the use of mass timber products (Crespell and Gagnon, 2011). However, in the U.S., this material is still gaining momentum. Since the introduction of mass timber materials into North America in the mid-2000s, some advancement has been made to empower pilot building projects in the U.S. and Canada using this new material, despite a lack of comprehensive streamlined building code adoption (Pei et al., 2016). SmartLAM in one of the U.S. manufacturers that has been producing locally sourced mass timber panels since 2012. Pacific Northwestern states such as Oregon and Washington have demonstrated extraordinary enthusiasm for mass timber production that could ultimately contribute to the development of the local economy. At the same time, numerous research projects are currently ongoing to investigate local wood species and analyze the market.

The development of a product standard is one of the first steps needed to introduce a new product (Pei et al., 2016). While CLT manufacturers in Europe adopted a proprietary approach for panel mechanical properties, the first performance-based CLT material standard for CLT in North America was developed through the collaboration of APA-The Engineered Wood Association and FPInnovations (Borjen et al. 2012). North American CLT manufacturers have been gradually adopting this standard, with Structurlam, Nordic and the DR. Johnson Lumber Company being the first North American CLT manufacturers to obtain the APA certification (Pei et al., 2016). FPInnovations have developed a handbook for the design of timber building and provided directions needed for the design of wood buildings in terms of plans and specifications (Karacabeyli and Lum, 2014). Because of all these efforts, the number of mass timber building construction has significantly increased in last five years.

3.2.2 Existing Barriers to Adopt Mass Timber as a Building Material

There are a number of factors that hinders the widespread use of mass timber material. Because of the limited number of timber building projects, experimental data on a full-scale design model is not available (Mohammadi and Ling, 2017). More specifically, data on timber connection performance is a major concern among the designers and more data is necessary to assess the structural rigidity of mass timber materials. Fire hazard is an important drawback of timber materials and fire testing has been performed on a very limited basis for timber joints. Thus, the fire performance of timber joints needs to be validated through comprehensive fire hazard tests and computer simulation studies (Ling 2014). Mass timber panels require extensive use of chemical adhesives during the lamination process and the study showed that adhesives are responsible for delamination when timber panels are subject to fire (Mohammadi and Ling, 2017). Also, the volatile organic compounds (VOCs) emitting from the adhesives are hazardous to indoor air quality (Sun et al. 2020). The acoustic performance of mass timber is also questionable as research shows that the installation inefficiency of mass timber caused considerable acoustic problems (Mallo and Espinoza, 2015). However, recent research demonstrates that mass timber built with proper insulation can achieve preferred (50 dB) and targeted (55 dB) sound insulation thresholds (Kremer and Symmons, 2015).

The level of awareness among the industry practitioners is another issue as the concept of mass timber is still growing in the North American construction market. Locations having more traditions in wood-based construction (e.g. Pacific Northwest) have a higher level of awareness compared to other locations with less tradition of wood-based construction.

3.3 RESEARCH METHODOLOGY

The study was developed based on both quantitative and qualitative research methods. To evaluate the current industry perception regarding mass timber, three different sets of questionnaire surveys were developed and distributed among the building contractors, architects, and mass timber manufacturers in the U.S. The aim of including different parties into the study is to collect and analyze their opinions and evaluate the findings in a collective framework.

3.3.1 Development of Questionnaire Surveys

The research team performed both quantitative and qualitative data analysis for the study. Three different questionnaire surveys have developed that emphasized industry perspectives of mass timber building material. All three sets have different question pattern and size based on the receivers' profession. The questionnaire survey for the building contractors have 25 questions whereas the questionnaire surveys for the architects and manufacturers have 16 and 9 questions respectively. The architects and designers responded if they are familiar with mass timber to identify the existing level of awareness among themselves. They were further asked about the advantages and disadvantages of using mass timber, code and specification sufficiency, most suitable building types for mass timber material, current social acceptance, and the future of mass timber building in the U.S. construction market. The building contractors were questioned on the availability of mass timber in the U.S., construction cost, and schedule competitiveness of mass timber buildings compared to steel and concrete options, safety and health-related issues during construction, workers efficiency, and construction-related difficulties. The timber manufacturers were asked about the advantages and disadvantages of the current timber manufacturing process, health-related issues, and the future of timber manufacturing in the U.S.

The questions were developed in such a way so that the participants can demonstrate their knowledge in the most efficient way. The quantitative part of the surveys provided information regarding participants' demographics, level of awareness, and work experience. On the other hand, the qualitative part of the survey allowed participants to provide their open-ended perceptions of the existing challenges and their potential solution processes regarding mass timber. The research team developed the surveys using Qualtrics. Qualtrics is cloud-based software to create and conduct research surveys, evaluations, and other data collection activities (CSULB, 2020). It allows the user to create and distribute the survey using a simple web link. The responders of the survey remained anonymous.

3.3.2 Sample Selection for the Study

After developing the surveys, the study team submitted the research to the Institutional Research Board (IRB) of Oregon State University for review. IRB works to protect the rights and welfare of human subjects who participate in the research; promoting the ethical principles of respect for persons, beneficence, and justice. After completing the review process and getting the approval from IRB, the research team selected the samples used for the study. A total of 1,200 general contractor and specialty subcontractor companies, 300 architecture firms, and 55 mass timber manufacturers were contacted to participate in the study. Since the study especially focused on the U.S. construction market, surveys were distributed only to U.S. practitioners. The list of general contractors and subcontractors was extracted from a repository of Oregon State University Department of Civil and Construction Engineering. The list of architects and designers was prepared from ArchDaily "Top 300 Architectural Firms in the U.S." The list of manufacturers was obtained from APA-The Engineered Wood Association, which is a nonprofit trade association that works with its members to create structural wood products. While selecting the participants, heavy civil contractors were excluded from the study due to their different work dynamics. The samples were selected from all parts of the country to ensure a nation-wide representation of the participants. Furthermore, the samples were selected regardless of company size and budget to allow consistency among the participants.

3.3.3 Survey Distribution and Data Collection

The study team used a double round of survey distribution policy to allow ample time for the participants to answer the surveys. It also helped to increase the number of participants of the study. The survey links were distributed to the participants through their publicly available emails. Their responses were stored anonymously in the Qualtrics that are used later for data analysis. After the first round of survey distribution, the research team received 69 responses from the contractors, 18 responses from the architects, and 7 responses from the manufacturers. Two months later, the team redistributed the surveys and received 31 more responses from the contractors, 14 responses from the architects, and 8 responses from the manufacturers. The study team kept the survey window open for another two months to ensure maximum response rate. Finally, 100 contractors responded with a return rate of 8.3%, 32 architects responded with a return rate of 10.7%, and 15 timber manufacturers responded with a return rate of 27.3%. Although the return rates are low, it was sufficient to conduct data analysis and draw statistical conclusions. Figure 3.1 shows the road-map used for research method.

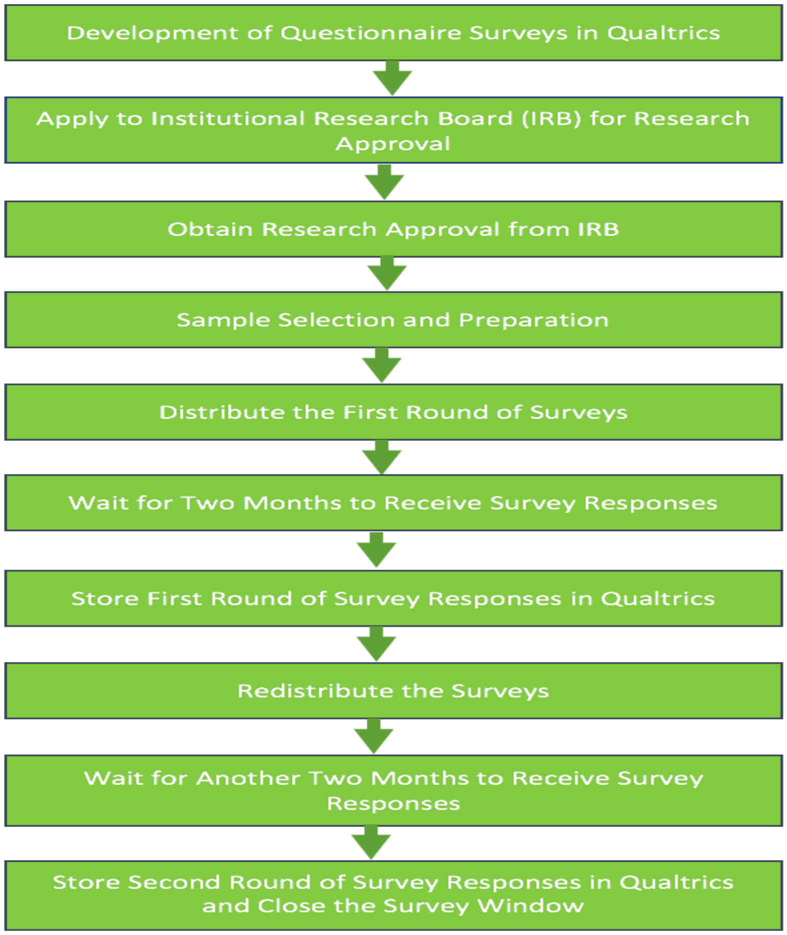


Figure 1.1 Road-map of research method

3.4 RESULT

This section summarizes the findings of the study. The result section is developed based on five emphases. The first part describes the demographics of the participants with their experience and awareness level on mass timber building projects. The second and third part summarizes the advantages and disadvantages of mass timber products from constructors, architects, and manufacturers points of view. The fourth part covered the importance of the geographic location of mass timber construction sites. In the last part, major recommendations derived from the surveys will be listed which will provide insights on how to increase the current acceptability level of mass timber materials.

3.4.1 Company Demographics and Involvement in Mass Timber Building Projects

The research focused on company demographics and their involvement level in mass timber building projects to determine the diversity of the participants and the degree of awareness among the industry practitioners regarding mass timber materials. The number of employees, average annual budget, and years of experience in mass timber building construction are the major factors considered in this part.

The building contractors who participated in the study exhibited a diverse background in terms of their annual budget and number of employees, which indicates that the majority of the participants were from mid-size to large construction companies. Among the participants, 27% responded that they have an employee size of 50-250 followed by the companies with an employee size of over 1000 (21%). Statistics of average annual budget demonstrated that 41% of the participating companies have an average annual budget of over 400 million dollars, 23% of the participants said their company budget is 50-150 million dollars. Figure 3.2 shows the company demographics of the building contractors.

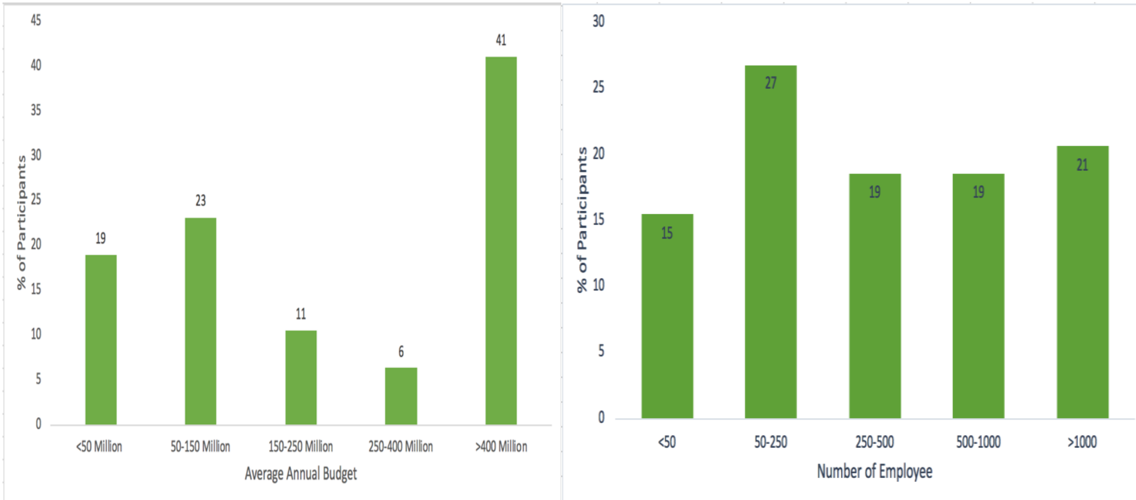


Figure 3.2 Company demographics of the building contractors (n=100)

Although the participating building contractors showed diverse demographics, their involvement level in mass timber building construction project was significantly low. Among the participants, 45% of the respondents said they were involved in mass timber construction, however, 56% of them said that their experience level is less than a year, which indicates a low level of involvement and experience among the contractors. Participants having five to ten years of experience represented only 7% of the total respondents, saying that the concept of mass timber building in the U.S. is still evolving. Figure 3.3 shows the building contractors' level of involvement in mass timber construction.

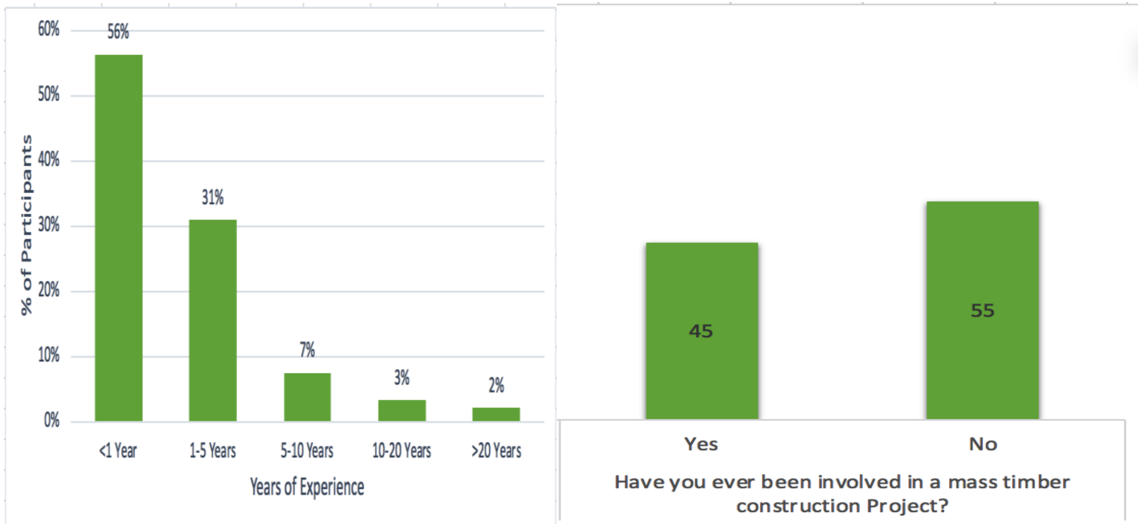


Figure 3.3 Experience and involvement level of the building contractors (n=100)

The designers and architects who participated in the survey showed a slightly different demographics than the building constructors. The majority of the participants mentioned that they have an annual company budget of less than 50 million dollars, 25% of participants indicated that their company budget is 50-150 million dollars. While answering the question of employee size, 60% of the respondents said that their employee size is 50-250 and 30% of participants mentioned an employee size of less than 50. These numbers indicate that the majority of the participating companies were mid-size to small. Figure 3.4 shows the company demographics for the architects.

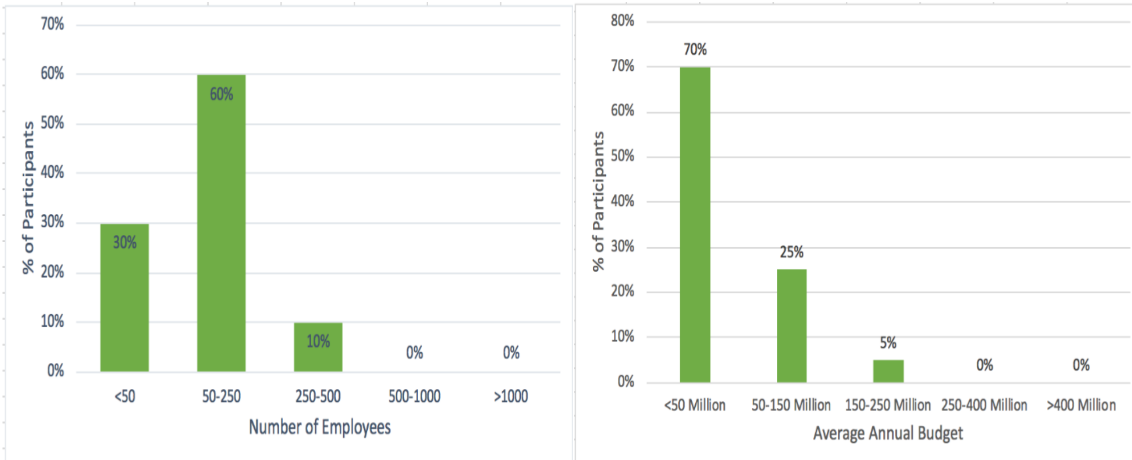


Figure 3.4 Demographic information of the architects (n=32)

The architects demonstrated a similar trend like the contractors for the involvement level in mass timber construction projects. Although 70% of the participating architects mentioned that they were involved in mass timber building projects, 45% of those who were involved indicated that they have less than a year of work experience in timber projects and 40% of them exhibited an experience level of 1-5 years. Figure 3.5 shows the involvement and experience level of the architects who participated in this study.

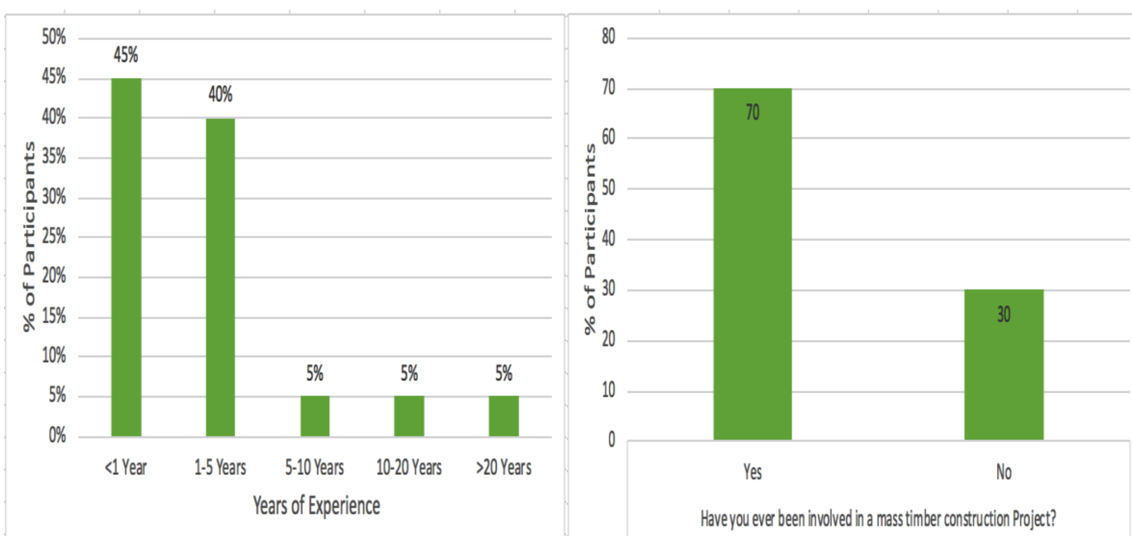
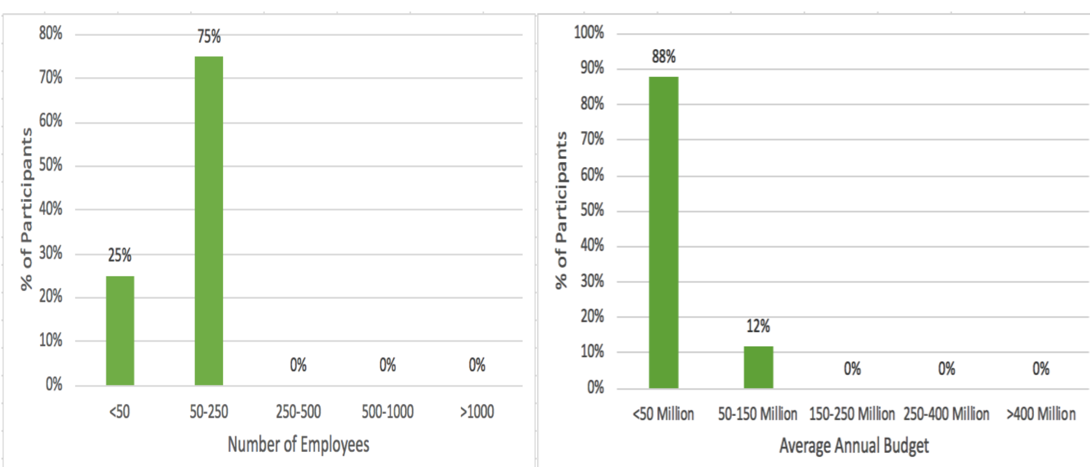


Figure 3.5 Work experience and involvement level of the architects (n=32)

For mass timber manufacturers, although the study received only 15 responses, it still showed some important aspects of mass timber in the U.S. industry. Since there are not many timber manufacturing plants available in the U.S., the result would still be sufficient to depict the current situation of the manufacturers. Unlike the architects and constructors, manufacturers showed a much higher level of experience and involvement in mass timber materials. While answering the question about the experience level, 64% of the respondents said they had 1-5 years of experience. Surprisingly, 36% of respondents mentioned an experienced level between 5-20 years, which illustrates that although the builders and designers are not quite familiar with the product, timber manufacturing plants are operating in the U.S. for a relatively long time. However, it is unknown who were the early customers of these manufacturing plants. It was also found that a typical timber manufacturing plant operates with relatively a smaller number of employees and annual budget compared to building contractors and architects. Figure 3.6 exhibits the demographics and experience of timber manufacturers.



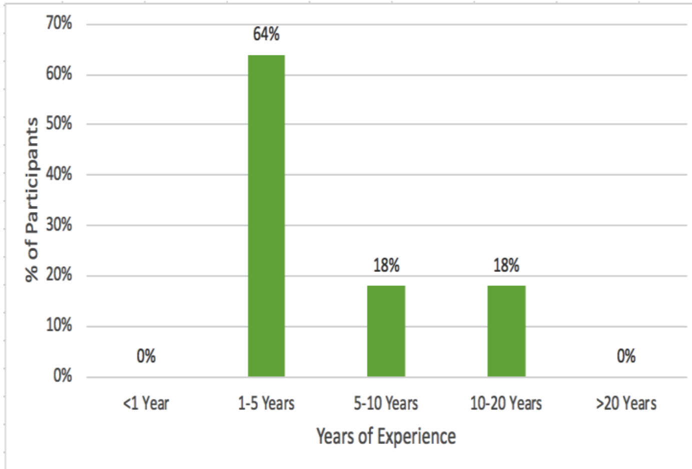


Figure 3.6 Demographics and work experience of timber manufacturers (n=15)

3.4.2 Advantages of Using Mass Timber Materials

The participants were explicitly asked about the advantages of using mass timber products in the design and construction of building projects. Respondents from all three participating groups (constructors, architects, and manufacturers) provided their opinion that helps the researchers summarize the main positive factors of mass timber in the construction industry. It will further aid the decision-makers and other stakeholders to adopt mass timber products on a more frequent basis.

Since the participants answered multiple open-ended qualitative questions to identify the advantages of mass timber, the qualitative content analysis method was used to statistically derive the responses. It is a popular method of analyzing qualitative survey data that transform each response from the participants into a relevant theme or code and draw an interpretation of the results by developing the frequency distribution table (Bengtsson, M. 2016). In this study, all the responses for the question of mass timber advantages were transferred into an excel spreadsheet and for each response, a keyword was generated that defined the original meaning of that response. As an example, any response from the participants related to prefabrication of timber panels were fall under "Prefabricated" keyword. Figure 3.7 illustrates the development process of the qualitative content analysis method.

Construction-Related Advantages of Mass Timber Material	Keyword
Prefabricated for assembly on site	Prefabricated
Installation, level of care given by the Specialty Trade that is installing it. Cleanliness of activities. Less welding activities overhead.	1. Small Manpower 2. Short Installation Time
We utilize the same basic safety principles while building with mass timber, but the advantage with timber is that the decks can be safe to walk on sooner that with a steel structure.	Prefabricated
1. Prefab 2. easy installation 3. Less workers	1. Prefabricated 2. Small Manpower 3. Easy Installation
Pre-fabrication process of the panels Smaller crew size to install Seismic protection	1. Small Manpower 2. Short Installation Time 3. Seismic Protection
Easy installation, factory fabrication, small crew	1. Prefabricated 2. Small Manpower 3. Easy Installation
Never been involved in a mass timber project so not exactly sure. However, a major leading indicator would be prefabricated nature of timber panels which is safer than the other options.	Prefabricated
Prefab nature Small crew size Less variables	1. Prefabricated 2. Small Manpower 3. Easy Installation
The installation process is much leaner than the other types of construction. Less labor work as panels are lifted by crane or any other mechanical instrument. All panels are prefabricated that reduces the work load.	1. Prefabricated 2. Small Manpower 3. Easy Installation
All panels are prefabricated that reduces work time and improve safety. Timber panels are easy to install. Installation process requires less workforce	1. Prefabricated 2. Small Manpower 3. Easy Installation
It has shown to have the required strength for the applications it's used in, It is flexible to withstand more movement, don't have a third.	Structural Strength

Figure 3.7 Data processing in the quantitative content analysis method

The qualitative content analysis method revealed several positive factors of using mass timber materials in construction projects. The contractors concluded that the requirement of small Labor for the installation and erection process is the most prevalent factor of mass timber materials that have the highest frequency percentage (35%). The participants indicated that smaller labor needs smaller on-site work areas and less equipment that eventually reduces the complexities of the construction process. The prefabricated nature of mass timber panels is another factor that respondents identified as an advantage with the second-highest frequency distribution percentage (22%). Prefabricated timber panels require a much simpler sequence of construction work that reduces the onsite work duration. As a result, project completion time becomes faster. Easy and short installation and erection process of timber panels are also found as a major advantage of using mass timber building materials in the construction site. Table 3.1 listed the major construction-related advantages of mass timber building materials.

Table 3.1 Construction-related advantages of mass timber materials

Factor	Frequency	Frequency Percentage
Prefabrication	14	22%
Small Labor	22	35%
Easy Installation/Erection	12	19%
Fire Protection	2	3%
Short Installation and Erection	9	14%
Product Simplicity	1	2%
Seismic Protection	1	2%
Structural Strength	1	2%
Environmental Protection	1	2%

The architects also mentioned several advantages of mass timber materials, although they focused more on design and sustainability parts of this material. The highest percentage of frequency was obtained for aesthetics as 23% of the respondents indicated that mass timber is aesthetically preferable than the other materials. The second highest percentage was for the low-carbon footprint of mass timber and 15% of participants concluded that the low-carbon footprint of mass timber helps to reduce the global carbon emission, which is an important factor of green and sustainable engineering. Fast project completion time was mentioned by 13% of the respondents that allows the project parties to complete the project on time. Other important advantages were prefabricated characteristics of timber panels, renewable material, easy and short installation/erection process, and design simplicity. Table 3.2 shows the major advantages of mass timber from the designer's perspective.

Table 3.2 Design-Related advantages of mass timber products

Factors	Frequency	Frequency Percentage
Renewable Material	3	6%
Aesthetics	12	23%
Design Flexibility	4	8%
Fast Project Completion	7	13%
Sustainable Material	4	8%
Seismic Performance	1	2%
Large Scale Development	1	2%
Rapid Growth	1	2%
Low-Carbon Footprint	8	15%
Prefabrication	4	8%
Easy Installation	4	8%
Natural Resource	2	4%
Lightweight	2	4%

Finally, the manufacturers of timber panels were asked about the advantages of mass timber products including its production process. Low-carbon footprint and prefabricated nature of timber panels were identified as two major advantages of mass timber by the manufacturers. They concluded that mass timber is a natural and sustainable product that has the potential to be an alternative building material. They further indicated that the production process needs a very small labor requirement and it does not need a huge area to produce timber panels. Table 3.3 shows the major advantages of the timber manufacturing process.

Table 3.3 Advantages of timber production process

Factors	Frequency	Frequency Percentage
Low-Carbon Footprint	6	22%
Sustainable Material	3	11%
Aesthetic	1	4%
Prefabricated Panel	6	22%
Small Labor	5	19%
Small Space	3	11%
Natural Resources	3	11%

3.4.3 Existing Challenges of Mass Timber Materials

Since the concept of mass timber building construction is still evolving in the U.S. industry, this research especially emphasized on identifying the existing challenges associated with mass timber materials. All the participants were asked to list construction, design, and manufacturing-related drawbacks of mass timber that they have experienced.

The contractors identified some of the major construction-related drawbacks of mass timber products. Inexperience in timber construction was identified as the most challenging factor in the U.S. industry. Among all, 29% of the participants stated that the majority of contracting companies including subcontractors and trades do not have sufficient work experience in mass timber building construction projects. As a result, an industry-wide gap of knowledge and awareness has been created which is hindering the progress of mass timber materials. Lack of coordination among the project parties is another vital flaw of mass timber as 14% of respondents mentioned that they have experienced the absence of effective coordination with other trades during the construction process that significantly dropped the productivity rate of construction. A significant percentage of respondents (13%) talked about the installation difficulties of the timber panels as most of the workers are still not familiar with the proper installation process of mass timber panels. In addition to that, the high cost of engineered wood, lack of skilled workforce, risk of fire hazard, insufficient code, and presence of moisture in the timber panels are some of the other concerns that came from the constructors. Table 3.4 listed the major construction-related challenges of mass timber products.

Table 3.4 Major construction-related disadvantages of mass timber materials

Factors	**Frequency**	**Frequency Percentage**
Inexperience	34	29%
Long Delivery Time	11	9%
Lack of Manufacturers	3	3%
Cost	12	10%
Coordination	17	14%
Design Difficulty	16	13%
Unskilled Labor	5	4%
Code	3	3%
Fire Hazard	6	5%
Moisture	10	8%
Change Orders	1	1%
Equipment	1	1%

The designers also have stated some disadvantages of mass timber products from their work experience. According to their observation, lack of awareness is the most prevalent challenge of mass timber. The majority of participants indicated that this material is fairly new in the U.S. context and the stakeholders are reluctant to use this product because of lack of case study and previous experience. The high cost of engineered wood and timber panels are another important factor that restricts the owners to adopt more mass timber building projects. A significant number of participants talked about design difficulties as they mentioned that mass timber is not suitable for all types of design due to code limitations and material unavailability. They further noted that fire safety is a major concern of mass timber buildings and a well-defined code is needed to avoid fire hazard. Table 3.5 shows the major design-related difficulties of mass timber materials.

Table 3.5 Major design-related difficulties of mass timber materials

Factor	**Frequency**	**Frequency Percentage**
High Cost	19	20%
Awareness	20	22%
Fire Hazard	10	11%
Material Unavailability	13	14%
Design Difficulties	16	17%
Impact of Forest	3	3%
Code Limitation	7	8%
Coordination	3	3%
Moisture Content	1	1%
Insulation	1	1%

The study identified some of the major challenges associated with the timber manufacturing process. The manufacturers of mass timber listed multiple challenges of current timber production technology. The majority of the respondents said that the timber production process vastly depends on the local forest. In absence of ample supply line of wood from the local forest, it is hard to continue the production. As a result, timber materials become unavailable to the local developers. Timber manufacturers emphasized on developing the current production technology and urged for implementing research and innovation for this sector to increase the current production rate. They indicated the high cost of wood as a barrier to develop mass timber products. Also, since the timber production needs significant utilization of lumber and wood, it is important to quantify the negative impacts on forestry and environment. Table 3.6 shows the major manufacturing-related challenges of mass timber materials.

Table 3.6 Major manufacturing-related challenges of mass timber materials

Factor	Frequency	Frequency Percentage
Lack of Manufacturing Plants	4	14%
Development of Production Technology	5	17%
High Cost of Timber	4	14%
Material Unavailability	5	17%
Lack of Skilled Labor	5	17%
Awareness	2	7%
Impact on Forest	4	14%

3.4.4 Importance of Geographic Location of Timber Construction Site

The construction industry is a highly resource-intensive sector that vastly depends on geographic location. Due to climate conditions, local jurisdiction, and material availability, the overall success of a construction project might fluctuate. Since mass timber materials are relatively new, it is important to determine the geographic impacts on mass timber building construction projects. This will also aid local developers to identify the main location-related factors associated with mass timber buildings.

All of the participants of this study explained the importance of geographic location on project success. Especially for mass timber buildings, the participants identified several factors that alter the overall quality of the project. The availability of timber material is identified as the most important geographic factor as 30% of the respondents said that locations having more timber manufacturing plants experience a higher quality. As an example, it was found that the Pacific Northwest region has more manufacturing facilities, so it is relatively easy to build timber buildings compared to other parts of the country. Also, many projects call for materials to be from the close region compared to other projects, thus cannot reasonably get the required materials.

The impact of weather is another important factor mentioned by the participants. Mass timber structures are very susceptible to moisture and hard to keep them protected in geographic areas with high rainfall rate. Excessive rainfall is also responsible for causing mold and delamination of timber panels. The participants also stated the availability of workforce and mentioned that remote projects may have less access to skilled labor that can impact the overall quality of a project. The high cost of transporting the timber panels, seismic vulnerability, and soil conditions are also some of the major geographic impacts that participants indicated. Table 3.7 listed the major factors.

Table 3.7 Major geographic factors of mass timber building projects

Factor	Frequency Distribution	Frequency Percentage
Weather Impact	27	29%
Product Availability	28	30%
Labor Availability	22	23%
Transportation Cost	13	14%
Seismic Vulnerability	2	2%
Soil Condition	2	2%

3.4.5 Recommendations to Increase the Acceptability of Mass Timber Materials

The participants recommended several action plans to overcome the current challenges associated with mass timber materials and to increase the acceptability of this material among the stakeholders. The recommendations from the industry practitioners will help the stakeholders as well as policymakers to develop a roadmap to adopt mass timber as a mainstream building material.

The building constructors provided several recommendations to streamline the construction operation process of mass timber buildings. However, the highest percentage of participants raised the importance of more mass timber building construction projects in the U.S. According to them, lack of sufficient timber building projects has created a knowledge gap among the contractors and only more construction projects could solve this problem to develop an acceptable level of expertise in this field. Establishing more timber manufacturing facilities is a key factor to increase acceptability. At present, the majority of timber manufacturing facilities are located in the Pacific Northwest region which obstructs the progress of timber construction in other parts of the country. A nation-wide establishment of timber manufacturing plants will ensure material availability and reduced transportation cost. It will further decrease the cost of engineered wood. All parties involved in a typical construction project must exhibit increasing collaboration. Pre-planning and early involvement of all project parties will secure project success by reducing any design and construction-related errors at an early phase of the project. Besides, the development of a skilled workforce is also an essential part of streamlining the construction process of mass timber buildings. Table 3.8 shows the recommendations from the building constructors.

Table 3.8 Recommendations from the building constructors

Factors	Frequency	Frequency Percentage
More Timber Construction	14	22%
More Manufacturing Facilities	13	20%
Code Sufficiency	4	6%
Increasing Coordination	13	20%
Cost Optimization	8	13%
Material Delivery	1	2%
Experienced Designer	1	2%
Increasing Fire Safety	2	3%
Owner's Interest	2	3%
Skilled Labor	6	9%

The architects and developers focused more on creating an industry-wide awareness to increase the current acceptability of mass timber products. They also indicated the insufficiency of codes and standards and urged for well-developed code and specification. Many of the participants denounced defective diaphragm, connection, and lamination settings of mass timber panels and recommended to solve these issues. There are not many different types of timber panels available in the market. For better performance, manufacturers need to make panels with many different sizes. Furthermore, they also pointed out a comprehensive fire testing process of timber buildings. Table 3.9 summarizes the recommendations presented by the architects

Table 3.9 Recommendations from the Architects

Factors	Frequency Distribution	Frequency Percentage
Code Development	9	31%
Awareness	9	31%
Design Development	7	24%
Fire Testing	4	14%

Finally, timber manufactures also outlined a few driving factors to increase the current timber production process. The most important factor that they mentioned is to establish more timber manufacturing plants in the country. Increasing awareness, cost optimization, and innovative timber production technology are some of the other major factors. Table 3.10 summarizes the findings from the manufacturers.

Table 3.10 Recommendations from the timber manufacturers

Factor	Frequency Distribution	Frequency Percentage
More Manufacturing Facilities	8	40%
Innovative Production Technology	2	10%
Support from Local Authority	2	10%
Awareness	3	15%
Code Development	2	10%
Cost Optimization	3	15%

3.5 DISCUSSION

The study assessed the feasibility of mass timber building materials in the U.S. by identifying the current involvement and awareness level and construction, design, and manufacturing-related challenges associated with mass timber products. The study further provided several recommendations to overcome the existing challenges to increase the acceptability of mass timber among U.S. construction practitioners. The building constructors, architects, and mass timber manufacturers in the U.S. were the participants of the study.

The study involved semi-structured quantitative and qualitative questionnaire surveys that were distributed among 1,200 building constructors, 300 architects, and 55 manufacturing companies in the U.S. Quantitative data analysis was used to determine the participant's awareness and involvement level in mass timber building projects.

Demographic information of the participants suggested that the majority of building construction companies participated in this study were mid-size to large based on their number of employees and average annual budget. However, the architecture companies that participated in the study came from small-size to mid-size. It was also found that the majority of mass timber manufacturing companies have an average annual budget of less than 50 million U.S. dollars and an employee size of 50-250. Demographic information helped to identify the work scopes and range of the participating companies.

Quantitative data analysis further demonstrated a low involvement level among the industry practitioners regarding mass timber building construction projects. The building constructors who participated in the study said that 56% of them have less than a year of work experience in mass timber construction. Only 7% of the constructors have 5-10 years of work experience in mass timber. The architects who participated in the study showed a similar trend as 40% of the participants have less than a year of work experience in designing timber building and 5% of the architects have experience level between 5 to 10 years. However, timber manufactures exhibited a different experience level as 64% of the respondents have work 1-5 years of work experience and 18% of the respondents have 5-10 years of experience in timber manufacturing. It indicates that although the concept of mass timber building is new, mass timber products have been manufactured in the U.S. for a long time. However, the previous sources of utilization of mass timber is mostly unknown because of lack of previous studies and supporting literatures. As a result, it is assumed that mass timber products were mainly utilized for small-scale residential building projects.

A large part of the study involved multiple open-ended qualitative questions. To analyze the open-ended responses from a statistical standpoint, the qualitative content analysis method was used. This method transformed all the qualitative answers of the participants into quantitative numeric values. The participants were asked to put their opinions on the advantages and challenges of using mass timber, the importance of geographic locations on mass timber construction, and recommendations to improve current challenges and difficulties associated with mass timber materials. While answering the advantages of mass timber products, 35% of the building constructors indicated that the requirement of small labor is the biggest construction-related advantage of using mass timber material. They mentioned that small labor allows the constructors to optimize the construction cost and equipment usage. It also reduces the chance of accidents. The prefabricated nature of the timber panel was also identified as a major advantage of mass timber. The architects, however, stated that aesthetics is the biggest design-related advantage of mass timber followed by its low-carbon footprint. The manufacturers concluded that low-carbon footprint and prefabricated nature of timber panel as the biggest production-related advantage of mass timber.

The participants identified some major disadvantages of mass timber material in terms of construction, design, and production. Lack of experience and knowledge in timber construction is the main construction-related drawback of this product in the U.S as 29% of the building constructor said timber material is still not familiar among them and a more skilled workforce is needed. Poor coordination among the project parties is another major disadvantage identified by the constructors. The architects suggested that lack of awareness among the owners is the main downside of this product. They further mentioned about the high cost of engineered wood delamination of timber panels. The manufacturers pointed out that timber material is not available all over the country, which caused complications in the production process. They also suggested that a skilled workforce is important, and the current production technology needs innovation and research to flourish the industry.

The majority of the participants accepted the fact that geographic location has a major role in the future of mass timber materials. In many parts of the country, timber material is not available because of insufficient manufacturing facilities. As a result, stakeholders of those locations remain uninterested to adopt mass timber as the main structural component of the project. The weather has a substantial role in construction work and for mass timber projects, it is even more important. Mass timber materials become wet during rainfall and produce a significant amount of moisture in the timber panels that degrades the quality of the products. Labor availability is another concern as only some major cities have sufficient labor with experience with timber construction. Also, construction sites that do not have local timber supplies, have to bear additional cost for transporting the timber panels from other parts of the country.

The participants provided recommendations to streamline the construction, design, and production process of mass timber materials. The constructors focused on undertaking more timber construction projects to get proper work experience. They also recommended increasing the amount of timber manufacturing facilities in the U.S. The architects concluded that the owner needs to be unbiased about this material and should accept timber as a mainstream building material. They further indicated that the current codes and standards need to be revised and elaborated that will allow more flexibility to design mass timber buildings. The manufacturers recommended establishing more timber manufacturing plants all around the country to make this material available to everyone.

This research has two major limitations. First of all, the survey return rate was significantly low (8.3-27.3%). According to Lindemann, N. (2019), the average survey return rate is 33%. However, survey distribution methods play an important role on survey response percent as Yan and Fan (2010) found that response rate for the web-based survey is approximately 11% lower than that of other survey modes. Since the study involved fully web-based survey, the response rate was decreased. The research team used double round of survey to increase the rate. Despite the low response rate, based on the consistency of data, the research team is still convinced that this nation-wide survey represents the actual perception of the U.S. construction practitioners regarding mass timber material. For future extension, the return rate needs to be at least 33% or more. In person distribution of surveys will help to increase the response rate. The study also failed to incorporate all types of companies in terms of their size. Future research should include small, medium, and large sizes of construction companies, architectural firms, and timber manufacturers to get the strongest industry insight regarding mass timber materials.

3.6 CONCLUSION

The study shows that a significant percentage of U.S. construction practitioners are still hesitant to use mass timber building materials, despite having several structural and environmental advantages. There is a lack of awareness about mass timber materials that obstructs the practitioners to adopt this material on a more frequent basis. The study will work as a source of reference as it identifies the current industry awareness level, advantages, and disadvantages of using mass timber products. Also, it develops a set of recommendations to overcome the existing challenges of mass timber products. Since the study is completely based on industry surveys, it will work as an actual representation of the industry. Besides, the study occupies the perception of building constructors, designers, and timber manufacturers. As a result, it will be easier to find the insights of three specific parties involved in a typical mass timber building construction project. Overall, the research team is convinced that the findings of this study will create new knowledge of mass timber materials that will help industry practitioners as well as the building owners to adopt this innovative and sustainable material more often than before.

CHAPTER 4: COST COMPETITIVENESS OF MASS TIMBER MATERIALS

Modified from:

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4.1 INTRODUCTION

The construction industry is considered one of the most resource-intensive industry sectors in the global economy and is often exposed to several risks such as resource scarcity, availability, and prices of globally traded commodities (Jones et al. 2016). Decreasing the power of assets used in construction is, in this way, critical for expanding industrial and economic resilience (European Union 2014). A move towards resource-efficient construction will require the selection of novel procedures and practices. To achieve the objective of green and sustainable construction practice, building materials are becoming a vital component. Among various other construction materials, timber has been gaining momentum in recent years because of its contribution to green design and less energy consumption (Mohammadi and Ling 2017). A favorable strength-to-density ratio, versatility, and flexibility, as needed in architectural design, may make timber a compatible material with concrete and steel in certain tall building applications (Mohammadi and Ling. 2017). Although the concept of mass timber building has been successful in the European market, it has not been adopted properly into the North American market, especially in the United States (Structurlam 2019). Research has demonstrated that the long-term success of CLT is highly reliant on potential adopters' impression of the item characteristics. Because of that, the investigation of perceptions plays an important role in understanding and analyzing the adoption potential of a new product or technology (Mallo and Espinoza 2015).

An important parameter to assess the future success of a product is to determine its cost competitiveness. Initial construction cost is invariably perceived as being critical and the total on-going cost of operating a building over its whole life is increasingly being recognized (John and Buchanan, 2012). Unlike many other building materials, the cost information of mass timber building construction is still relatively uncommon. An experimental, thorough and reasonable correlation between buildings utilizing distinct construction materials will aid on the major monetary decisions regarding the CLT and their outcomes.

The research presented here was accomplished focusing on three major objectives. The first objective of this study was to compare the construction cost of a mass timber building with a concrete option. A wood hybrid 18-story residential building was selected for the study and all construction activities characterized into 17 major categories that were analyzed and compared with the same building modeled using concrete. Both estimated and actual cost of the project was included in the analysis process to get a better idea on the comparison. The second objective of the study was to determine the factors affecting the construction cost of that mass timber building project. The actual construction cost of mass timber building was analyzed and profiled based on their expenditures. The third objective of the study was to determine the leading causes of change orders in that project and determine how mass timber-related change orders affect the overall construction cost of the project. The past study revealed that the change orders have detrimental effects on cost and schedule growth of construction projects (Shrestha and Maharjan 2018). According to Du et al. (2015), change orders are very common to most construction projects and determine many performance factors such as productivity, project delays, and cost overruns. Hanna et al. (1999) revealed that change orders lead to the increasing frequency of planning, supervision, scheduling compression, and overmanning in construction projects. Chen (2008) found that change order causes difficulties while determining the proper compensation for the parties involved that eventually results in adversarial relationships among the stakeholders. Considering these factors, the study team was convinced to analyze the change order and its impacts on construction.

The research team identified two major contributions of this study towards the mainstream construction cost estimation research. The unique contributions of this study are:

- Identifying the main causes for high construction cost of a mass timber building compared to a concrete building.
- Identifying the major sources of change orders and determining the impact of mass timber material on change order costs.

4.2 LITERATURE REVIEW

Wood-based construction is gaining momentum during the last few years in the United States construction industry. Different types of wood-based materials are now used as Engineered Wood Products (EWPs). One of the most common forms of EWPs is the Cross-Laminated Timber (CLT). Because of the improved rigidity, stability, and mechanical properties, CLT panels are becoming more common as a building material. The construction project used for this study utilized CLT as the primary wood material. This section will briefly discuss CLT and its cost competitiveness compared to other building materials. Furthermore, this section will also discuss the major causes of construction cost overruns and change orders.

4.2.1 Definition of Cross-Laminated Timber

Cross-laminated timber (CLT) was developed around 15 years ago in Central Europe (Van De Kuilen et al. 2011). CLT boards are made by sticking timber planks to each other aligning the fibers transversely and applying high compression (Mohammadi and Ling 2017). Figure 4.1 shows the schematic of the CLT layer configuration. The regular thickness of a CLT panel can be 1-1.6 inches and boards are sometimes fastened together utilizing mechanical fastenings alternating 90 degrees (Mallo and Espinoza 2014). In some special configurations, layers of the panels can be put together in a similar way giving a double layer to accomplish certain structural strength (Mohammad et al. 2012). CLT panels are available in 3, 5, 7 or more layers of panels depending on the purpose and static requirements. The double bearing of the CLT boards shows more structural stability, enhanced unbending nature, and mechanical properties (Evans 2013). The CLT panels can be built in large dimensions up to 18.3 m (60 ft.) long and 0.5 m (20 in.) thick

(FPInnovations 2013). CLT Panels are jointed together using structural adhesive and the lumbers are machine stress-rated and kiln-dried. All the CLT panels are pre-assembled and can be gathered onsite rapidly (Burback and Pei 2017). The erection of the CLT panels can be performed by even non-skilled manpower. The previous investigation presents the fast-on-site construction that might be as short as three to four days per 10 ft. of vertical height (WoodWorks 2013) compared to twenty-eight days per 10 ft. of vertical height for typical concrete construction (Wilson and Kosmatka, 2011). Construction work may take as little as three to four months for buildings of up to nine stories, a fraction of the time contrasted with traditional construction techniques, for example, concrete (Hamilton and Lehmann, 2011). According to a study by Patterson in 2013, a decrease of eleven to twelve months in construction time could be accomplished by choosing CLT instead of concrete (Mallo and Espinoza, 2015).

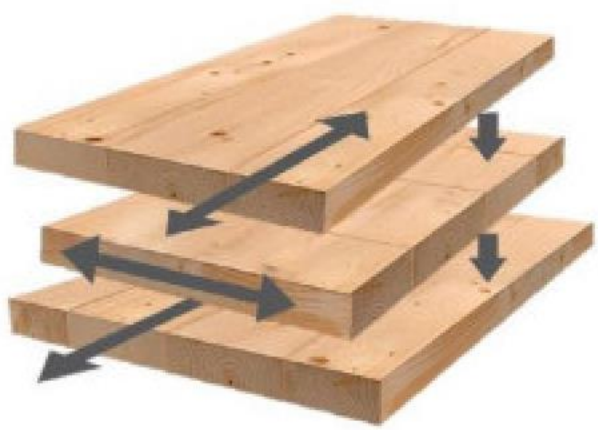


Figure 4. 1 Schematic of CLT layers (Mallo and Espinoza, 2014)

4.2.2 History of Tall CLT Buildings

The first 9-story tall CLT building was constructed in London, in the year of 2009, named as Stadhaus Building (Mohammadi and Ling, 2017). With practically no columns used, a cellular structure was formed to resist gravity and lateral loads. The building has a one-hour fire-resistance rating from the potential charring effect of the timber and a one-half hour fire-resistance rating from plasterboards that meet the local fire code requirement (TRADA 2009). Later in 2012, the LCT One Building was constructed in Austria using CLT, eight-stories high. Skidmore, Owings& Merrill, LLP (SOM) introduced a precedent of a hybrid concrete-timber application in a tall-building-concept design (SOM 2013). Called the prototypical working of Dewitt-Chestnut Apartments, the ideal configuration is 42 stories high and is a case of a tall building that can be developed in urban areas, for example, Chicago (Mohammadi and Ling, 2017)). Green and Karsh (2012) reported another tall timber building that used a “strong column-weak beam” design concept with timber panels providing for vertical members, shear walls, and floor slabs. The potential maximum number of stories can be 12, 20, or 30, depending on the type and combination of the resisting system adopted, with a cost comparable to that of a concrete building with a similar configuration (for 12- and 20-story buildings) (Mohammadi and Ling, 2017). To show the capacity of wood-based frameworks in seismic vulnerability conditions, the NEESWood Capstone Test Project was directed in 2009 through the sponsorship of the National Science Foundation (NSF). The building, seven stories tall with a 12 m by 18.3 m dimensions, made up of a steel moment frame in the first story and wood frames in the second to seventh levels, was subjected to 180% of the 1994 Northridge earthquake (Van de Lindt et al. 2010). Despite no major failure in the structure, an appearance of a minor crack in the drywall was observed and a negligible removal of fasteners (nails) was determined after the test.

4.2.3 Factors Affecting Cost Overruns of Construction Projects

There are multiple factors that directly affect the overall cost performance of a construction project. Cost overrun occurs when the final cost of the project exceeds the initial estimate or budget (Khabisi et al. 2016). The factors that influence the cost performance of the project and cause cost overruns are present from the estimating stage to the completion stage of the project (Baloi and Prince 2003). According to Doloi (2013), regardless of management competence and the financial strength of the contractor, accurate cost estimation at an early stage is the key to avoid cost overrun in projects. Poor site management and supervision, low speed of decision-making, and client-initiated variations have been considered as some of the most significant causes of cost overruns (Trost and Oberlender 2003; Iyer and Jha 2005). Winch (2010) identified a lack of clear links between the project and the organization's key strategic priorities and lack of skills and proven approach to project management and risk management as the driving factors of cost overruns. Memon et al. (2010) identified the most severe factors that affect cost overruns in Malaysia are cash flow and financial difficulties faced by contractors, contractors' poor site management and supervision, inadequate contractor experience, shortage of site workers, and incorrect planning and scheduling by contractors. Fugar and Agyakwah-Baah (2010) revealed the causes of cost overruns in Ghana as the following: delay in honoring certificates, underestimation of the costs of projects, underestimation of the complexity of projects, difficulty in accessing bank credit, poor supervision, underestimation of time for completion of projects by contractors, shortage of materials, poor professional management, fluctuation of prices or rising cost of materials, and poor site management. Mukuka et al. (2014) found the major causes of cost overruns in South Africa that include: contractors' project inexperience, poor project management, inadequate planning, contractors' inefficiency, inadequate financial provision, a shortage of skilled site workers, poor workmanship, inaccurate estimates, project complexity, and site conflicts.

4.2.4 Effects of Change Orders on Construction Projects

Change orders (CO) in construction projects are an inevitable incident that happen mostly during the construction phase of the project. Change orders are usually issued to cover variations in the scope of work, material quantities, design errors, and unit rate changes (Alnuaimi et al. 2010). The magnitude of the COs is a major concern for the owners because they can have a detrimental effect on the project's cost and schedule growth and quality as well as the morale of the project participants (Shrestha and Maharjan 2018). As a result, change orders are considered as an important aspect among the project entities. Change orders in the project need to be controlled in such a way so that they have minimal impacts on the cost, schedule, and productivity of the project. Several reasons were identified as the main causes of change orders. Halwatura and Ranasinghe (2013) identified five major causes of change orders in public projects based on a survey conducted over 50 respondents who had experience in road construction projects in Sri Lanka. According to this study, the five major causes of change orders are poor estimation, unforeseen site conditions, political pressure during the construction phase, poor soil conditions, and client-initiated variations. Dickson et al. (2015) identified land acquisition, differing site conditions, change in scope, change in schedule by the client, and lack of coordination as the top five important causes of change orders. Serag et al. (2010) found that change order growth was significantly correlated to the timing of the change orders and unforeseen conditions. Impacts of change orders can cause significant cost and schedule overrun of a project. Jawad et al. (2009) found that cost overruns due to change orders were in the range of 5–10% of the original contract cost. Similarly, its effects on schedule growth were less than 10% of its original contract duration. Ibbs (2012) determined that the construction cost of industrial building projects could go up to 42% because of change orders. The study also found that change orders increased the project duration by 16% in 50% of the projects analyzed and because of change orders, the overall productivity of the project decreased by 20%. Other researchers also found the loss of productivity because of change orders (Thomas and Napolitan 1995; Ibbs 2008; Hanna et al. 1999; Vandenberg 1996).

4.2.5 Cost Competitiveness of CLT Buildings

An important parameter of the success of CLT in the U.S. construction industry is its cost competitiveness. There are not many studies available that addressed the cost performance of timber buildings, which created a significant research gap in current CLT research. Although the advantage of large CLT buildings has been recognized by the investors and the public resulting in a significant number of tall buildings around the world, there are still considerable stagnations that are obstructing the progress of CLT as a mainstream construction material in the U.S. market. A decisive factor to curtail the trend could be establishing CLT construction as an economically feasible alternative to traditional construction materials. However, the majority of the previous studies revealed that CLT construction is relatively more expensive compared to concrete and steel construction because of its high material cost. A study by Burback and Pei (2017) shows that, for a single-family residential building in the U.S., the construction cost of using CLT can be 23% higher than using traditional light-framed wood options. Another study conducted by John and Buchanan (2012) on a three-story commercial building in New Zealand concluded that construction cost of the building using timber as the main structural can go up to 4% higher than the cost of using concrete. A similar study by Smith et al. (2014) on a six-story office building in New Zealand showed that the predicted construction cost of the timber building is approximately 6% higher than both the steel and concrete options. Cazemier (2017) analyzed the cost information of two buildings in Australia, one used concrete and steel and the other one was theoretically modeled CLT using the same structural design. According to his study, the construction cost of a theoretically developed model of CLT building was 2.64% higher than the cost of the actual building being developed by concrete and steel. According to a report on solid timber construction published by The University of Utah in 2015 which covered 18 functionally different CLT projects in Europe, Australia, and North America, overall cost saving was 4% compared to similar types of concrete and steel buildings. Another report published by the Forest and Wood Products Australia which covered 4 functionally different buildings (office, residential, healthcare, and industrial), cost of CLT structural solution was determined 2.2-13.9% cheaper than the traditional structures.

Although in most cases, the CLT option as a primary construction material was found more expensive than the traditional options, there is room for optimizing the cost of CLT construction. CLT buildings can be a better option for the designers, constructors, and the end-users because of its clean, easy, and faster installation, reducing the on-site overheads, less on-site workers, and reducing the construction delay (100 Projects UK CLT, 2018). CLT buildings in Oregon achieved a high lease rate and sales value compared to other buildings (ECONorthwest, 2018). Panels of the CLT are mostly pre-fabricated and built-in factories thus it reduces the cost of additional workers to erect scaffolding, weld steel girders, and pour and set concrete slabs. In the long term, as contractors dial in their mass timber construction methods, suppliers increase their efficiency, and the mass timber market continues to grow, there is an opportunity to continue to shrink mass timber development costs (ECONorthwest, 2018).

4.3 RESEARCH METHOD

The research was focused on comparing the construction cost of two different building materials: wood and concrete. A residential building project in Canada was used for the study. The project name and stakeholders' details remained unrevealed because of confidentiality purposes. After receiving the cost information from the owner, the research team started the analysis process and listed 17 distinct categories of activity throughout the life cycle of construction. The research solely focused on the construction cost of the project, including construction-related change orders. The initial cost estimate of the building was done in 2015. The initial estimation process involved both wood and concrete options. The project, however, was finally built using the wood option in 2017. The actual cost of the wooden building was then calculated. At the same time, a modeled cost of the same building designed by concrete material was also developed. The project team estimated the price of each line item by estimating the unit price and quantity. Then they added all the divisions to estimate the total cost. The virtual design and construction model also played a significant role in quickly estimating the quantities. The model cost was developed by the construction manager of the project based on his previous experience with concrete projects and with the input from the other design and trade team members. After completing the construction, the project team listed all the change orders that occurred during the construction process. The project team listed a total of 205 change orders for that project. Some of the change orders were very specific to mass timber thus the cost related to those change orders was added with the actual cost of the project. However, some of the change orders that the project team found would have occurred to any construction process, regardless of the structural component of the project. Those change orders and their associated costs were added to both actual cost of the mass timber building as well as the model cost of concrete building.

The owner of that project wanted to develop a landmark building that is structurally rigid, environmentally friendly, aesthetically soothing, and will enhance the current perception regarding the mass timber building in the North American construction market. Another reason for constructing that building was to encourage the other owners of the North American region to undertake more mass timber building projects.

4.3.1 Project Description

The project selected for this study is a residential mass timber tall building located in Canada. Mass-timber hybrid was used as the major structural component of the building. However, the foundation, ground floor, second floor, slab, and elevators cores were built out of concrete. The superstructure of the building was composed of prefabricated cross-laminated timber (CLT) panel floor assemblies supported on glue-laminated timber (GLT) and parallel strand lumber (PSL) columns with steel connections. The building envelope used prefabricated, steel-stud frame panels with a wood-fiber laminating cladding and a traditional styrene-butadiene-styrene (SBS) roof assembly on metal decking. In this project, on-site construction activities were divided into three major phases: concrete, mass-timber structure, and building envelope. The concrete work was finished before the beginning of the mass-timber structure. This resulted in better site coordination because concrete forms and mass-timber assembly required constant use of a crane and the narrow site was too restrictive for multiple cranes and construction crews. The timber panels were produced locally delivered on-site by using heavy duty multi-axle lorry. The manufacturing plant was approximately 263 miles away from the construction site and each lorry carried 47,500 lbs. of weight. An Environmental Building Declaration (EBD) was prepared for the project. However, EBD addressed the environmental impacts associated with building materials, not the building operations. The data used for EBD was collected from the project manager’s bill of materials and project documents. The project team also used Integrated Project Delivery (IPD) method enhanced by the use of virtual design and construction (VDC) modeling. Broad construction planning and sequencing, highly controlled prefabrication of the building structure and envelope, and itemized coordination of on-site erection and installation activities all added to successful completion of the project. Table 4.1 shows the detailed background of the project.

Table 4.1 Details of the project

Storeys	18
Height	53 m
Site Area	2,315 m^2
Gross Area	15,120 m^2
Typical floor-to-floor height	2.81 m for upper floors, 5 m for ground floor
Duration	21 months

4.3.2 Analysis Process

This study compiled 17 different categories of construction activity for the analysis process. Major categories included earthwork, masonry, interiors, mechanical and electrical installation, and exterior improvement. Cost breakdown was developed for four different parts:

- Budgeted cost of mass timber building
- Budgeted cost of concrete building
- Actual cost of mass timber building including change order cost
- Modeled cost of concrete building including change order cost

The construction cost of the project was calculated for all four parts mentioned above that provided an idea of the most and least expensive method of construction. The study team used the actual cost of wood building and the modeled cost of concrete building to compare the cost variances for each of the 17 activity categories. That comparison process brought the most and least expensive construction activities for both methods. Based on that, a fish-bone diagram was developed that showed the major sources of positive cost variance for wood option. For change order analysis, all the change orders were categorized into ten different types. For each specific type of change order; frequency, cost, and percent contribution to the total change order were calculated. Based on that calculation, another fish-bone diagram was developed to represent the major sources of change orders during the construction process.

4.4 RESULT AND ANALYSIS

This section provides a detailed breakdown of the construction cost of the project. The research team performed data analysis to determine the cost competitiveness of both materials. Table 4.2 illustrates the details budgeted and actual cost estimation of the project for four different categories.

Table 4.2 Construction cost breakdown of the project

	Budgeted Cost (Concrete)		Budgeted Cost (Wood)		Modeled Cost (Concrete)		Actual Cost (Wood)	
Cons. Phase	**Budget**	**Cost/GSF**	**Budget**	**Cost/GSF**	**Budget**	**Cost/GSF**	**Budget**	**Cost/GSF**
General Condition	$2,608,637	$16.03	$2,398,010	$14.73	$3,374,663	$20.74	$3,661,566	$22.50
Concrete	$6,444,569	$39.60	$3,621,537	$22.25	$6,628,694	$40.73	$3,694,268	$22.70
Masonry	$105,671	$0.65	$105,671	$0.65	$105,761	$0.65	$84,400	$0.52
Metals	$388,918	$2.39	$503,920	$3.10	$432,487	$2.66	$910,565	$5.59
Wood and plastic	$714,259	$4.39	$5,103,689	$31.36	$746,563	$4.59	$3,731,316	$22.93
Thermal/ moisture protection	$5,030,933	$30.91	$5,056,139	$31.07	$5,131,827	$31.53	$5,253,529	$32.28
Doors and windows	$1,995,590	$12.26	$1,824,190	$11.21	$2,076,157	$12.76	$2,053,890	$12.62
Finishes	$3,736,954	$22.96	$4,589,581	$28.20	$3,860,899	$23.72	$4,979,374	$30.59
Specialties	$260,053	$1.60	$260,053	$1.60	$260,053	$1.60	$100,436	$0.62
Equipment	$638,101	$3.92	$638,101	$3.92	$643,471	$3.95	$580,750	$3.57
Furnishing	$1,438,360	$8.84	$1,438,360	$8.84	$1,475,266	$9.06	$2,130,925	$13.09
Elevators	$815,000	$5.01	$815,000	$5.01	$673,475	$4.14	$658,475	$4.05
Mechanical	$5,878,880	$36.12	$6,316,780	$38.81	$5,966,830	$36.66	$6,304,947	$38.74
Electrical	$3,035,000	$18.65	$3,325,000	$20.43	$3,135,210	$19.26	$3,510,015	$21.57
Earthwork	$636,675	$3.91	$547,875	$3.37	$637,882	$3.92	$608,922	$3.74
Exterior improvement	$700,492	$4.30	$700,492	$4.30	$710,516	$4.37	$465,097	$2.86
Utilities and road work	$884,140	$5.43	$884,140	$5.43	$1,250,810	$7.69	$1,250,802	$7.69
Total	**$35,312,231**	**$216.97**	**$38,128,537**	**$234.27**	**$36,186,180**	**$222.34**	**$38,674,294**	**$237.63**

4.4.1 Cost Assessment of the Project

Table 2 illustrates a significant difference between the budgeted cost and the actual cost of the project. For the wood option, the actual construction cost was found 1.4% higher than the budgeted cost. The modeled cost of the concrete option, although, was not used for the final construction, was found 2.4% higher than its budgeted cost. A comparison between two different options suggested that the budgeted cost of wood construction option was 7.4% higher than the budgeted cost of concrete construction. The final cost of wood construction was 6.4% higher than the modeled concrete option. The actual cost of wood construction per gross square foot of the building was $237.63, which was the highest among all other options. Figure 4.2 shows the budgeted and actual costs for both construction options.

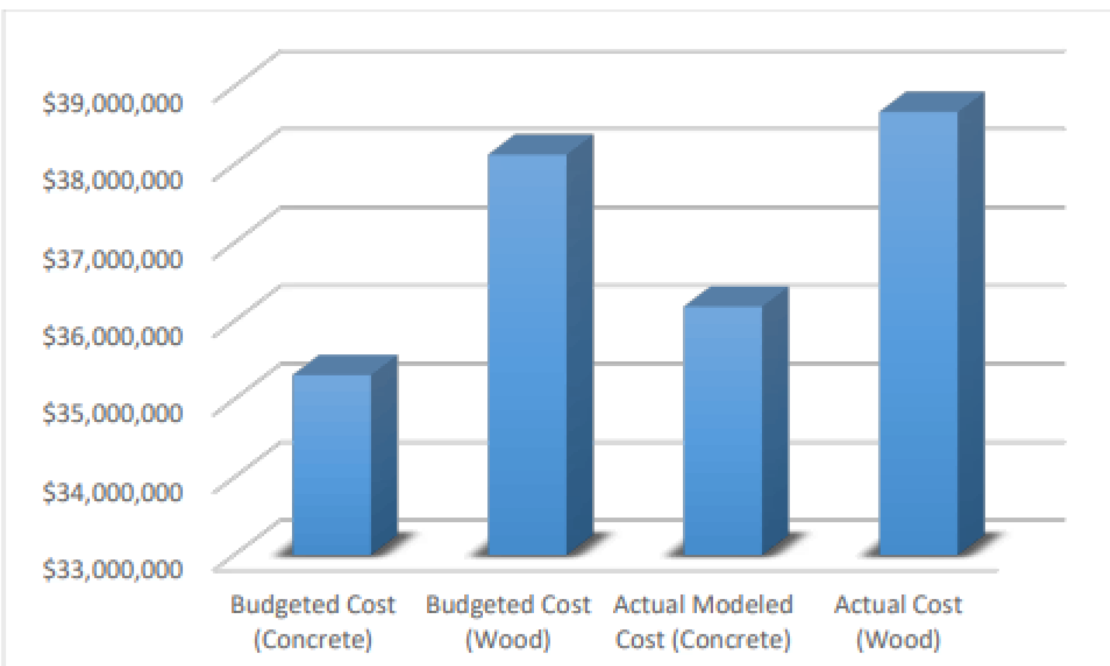


Figure 4. 2 Budgeted and actual construction cost of concrete and mass timber

Comparing the modeled cost of concrete building and the actual cost of wooden building demonstrated several sources of cost variance. Three major sources of positive cost variance for the wood option compared to a concrete option were specialties wood and plastic (399.8%), metal (110.5%), and furnishing (44.4%). The cost of wood per gross square foot of modeled concrete building ($4.6) was found reasonably lower than the wooden building ($22.9). Similarly, the cost of concrete per gross square foot of actual wooden building ($22.7) was found lower than the modeled concrete building ($40.7). This cost contrary occurred because, in a wooden building, concrete was used only in a small portion of the total building area, thus the unit cost of concrete for the wooden building went lower compared to the unit cost of wood per gross square foot of the building area. Similarly, in the modeled concrete building, wood was utilized in a small area. Three major sources of negative cost variance for the wood option compared to a concrete option were specialties (-61.4%), concrete (-44.3%), and exterior improvement (-34.5%). Figure 4.3 shows the major positive and negative cost variances between both options.

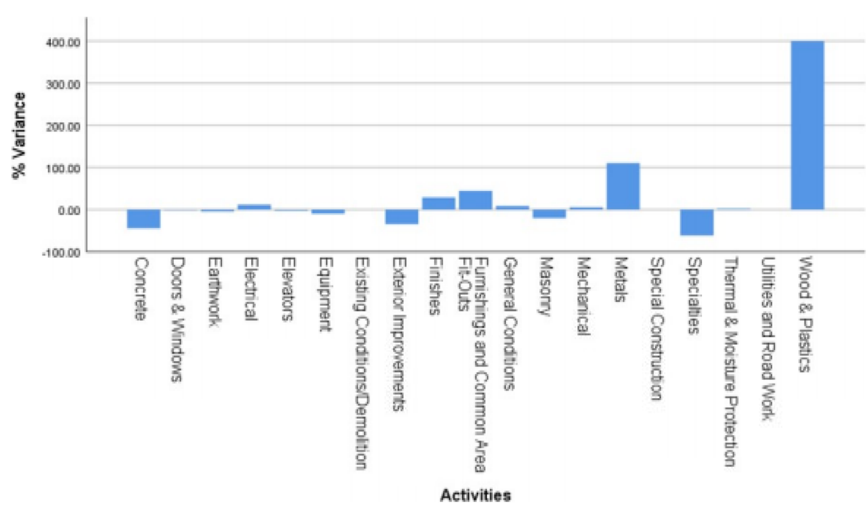


Figure 4. 3 Percent variances of timber option compared to concrete option

Analyzing construction activities that resulted in the positive cost variance of the wood option suggests that the cost of engineered wood and cost of wooden structure installation are two major sources of positive cost variance that fall under the wood and plastic category. Three major activities were observed in the metal category such as the cost of aluminum stair rails, cost of miscellaneous steel, and cost of structural steel. The third highest positive cost variance category was found furnishing and common area fit-outs and two most expensive activities found in this category were the cost of kitchen cabinets and cost of plastic laminate countertops. Besides the top three categories, finishing category cost was 29% higher for the wood option and a major source of the cost was found in vinyl wood flooring. Electrical activities resulted in a 12% cost increase for wood option and the major source of this variance was identified as the cost of the electrical trade. Finally, the cost of general condition was increased by 8% due to wood construction and cost associated with the project staffing was observed as the major source of cost in this category. Figure 4.4 illustrates the major categories and their related activities that caused the positive cost variance of this project.

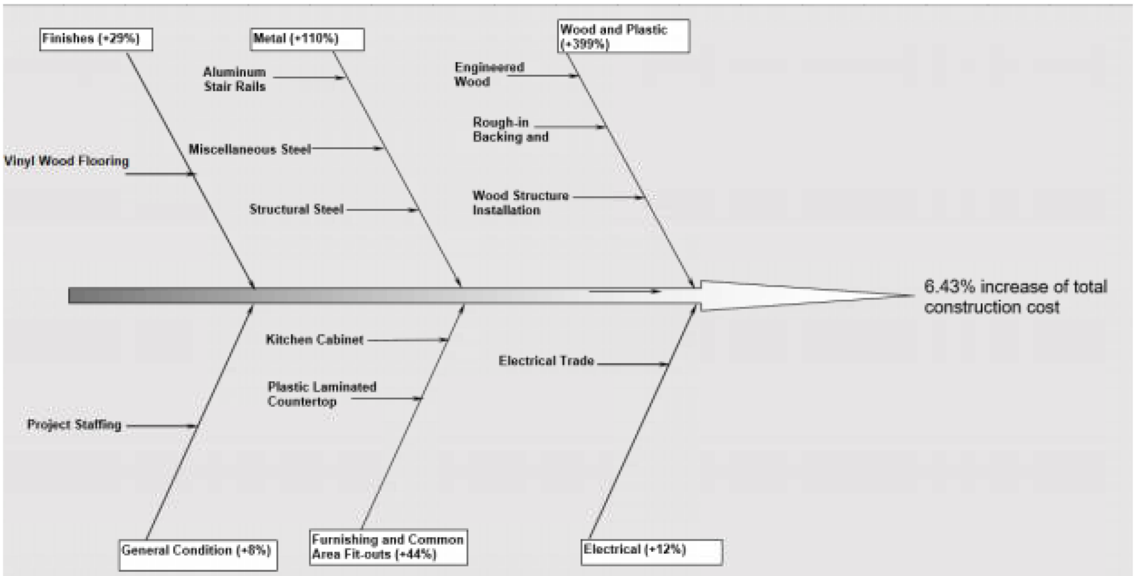


Figure 4. 4 Major sources of positive cost variance

4.4.2 Change Order Analysis

The project experienced several scope changes that cost an additional $2,155,549 throughout the construction time. The research team identified a total of 205 change orders. Table 4.3 shows the descriptive statistics of major change order sources.

Table 4.3 Descriptive statistics for change order sources

Reasons	Frequency	Cost of CO ($)	%Contribute in Total Change Order Costs
Unforeseen site conditions-unrelated to mass timber	15	$98,623.92	4.58
Unforeseen site conditions-related to mass timber	12	$94,421.92	4.38
Requested by project manager	3	$1,235.92	0.06
Requested by owner	15	$172,217	7.99
Requested by Architect	32	$173,472.86	8.05
Requested by Consultant	49	$631,044.07	29.27
Requested by other consultant and off-site	9	$393,137.45	18.24
Trade performance issues not recoverable	16	$158,711.75	7.36
Miscellaneous	38	$255,963.51	11.87

Owner inspector	16	$176,720.75	8.19
Total	**205**	**$2,155,549.15**	**99.99**
F-Value		**22.12**	**22.11**
P-Value		**0.044**	**0.044**

*CO= Change Orders

The descriptive statistics show that change orders by the consultant has the highest frequency, occurring 49 times among all observed change orders. It also has the highest cost in dollar amount, contributed 29.27% of the total cost of change orders. Miscellaneous changes have the second highest frequency, occurring 38 times, yet this category has the third highest cost in dollar amount 11.87% of the total cost of change orders. Change orders by the architect has as the third highest frequency with a total occurrence of 32 times. However, the contribution of that category towards the total change order cost was fifth highest, indicating that the cost associated with the change orders is not a function of frequency rather the cost is more dependent on specific activity. Change orders requested by off-site consultant occurred only nine times, ranked ninth out of ten options in terms of frequency, and contributes the second highest dollar amount, resulted in 18.24% of the total change order cost. Change orders related to mass timber occurred 12 times throughout the construction time, was eighth highest in terms of frequency, and contributes only 4.38% of the change order cost, ranked also eighth with regards to dollar amount. Lowest number of change orders were from the project manager for both frequency and dollar amount options. The F-value for the cost and percent change was calculated 22.12 and 22.11 respectively, indicating that the observed differences in the dollar amount by the sources were statistically significant. In addition, low P-value indicated that the results are not random, and probability of data set happened by chance is statistically insignificant. Figure 4.5 shows the major categories of change orders.

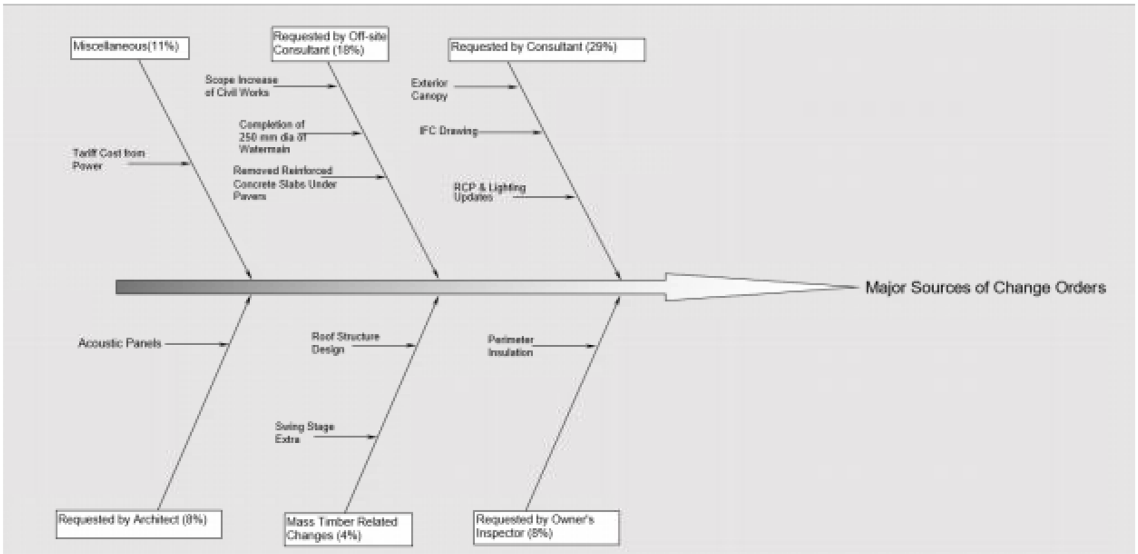


Figure 4. 5 Major sources of change orders

An interesting observation regarding construction cost and change orders related to mass timber indicated that although timber is responsible for a 6.4% increased construction cost compared to concrete option, no significant correlation exists between timber related construction cost and timber related change orders. To determine the correlation between both variables, Pearson coefficient test was performed. This test measures the strength of linear relationship between the variables. The Pearson coefficient r can take a range of values between +1 to -1. A perfect linear relationship is considered as r=1. A value of 0 indicates no significant correlation between the variables. Pearson coefficient factor r>0 indicates a positive correlation and r<0 indicates a negative correlation between the variables. In this study, the coefficient factor was found -0.315, indicating that both variables are negatively correlated and there is no significant correlation between timber related construction cost and change orders. Result of this test statistically indicates that change orders do not alter the timber related construction cost, and majority of the costs were involved in engineered wood purchase and its installation process. Table 4.4 shows the result of Pearson correlation test.

Table 4.4 Correlation Analysis between Construction Cost and Change Orders Related to Mass Timber

		CC	COC
CC	Pearson Correlation	1	-0.315
	Sig. (2-tailed)		0.375
	N	12	10
COC	Pearson Correlation	-0.315	1
	Sig. (2-tailed)	0.375	
	N	10	10

* CC = Construction Cost
*COC = Change Orders Cost

4.4.3 Non-Construction Related Cost Factors for Mass Timber Buildings

Cost analysis of this study suggests a similar trend of cost variance between mass timber and other construction options such as concrete and steel. The majority of previous studies identified that the construction cost of mass timber building is 2-6% higher than the traditional construction cost whereas, in this study, the construction cost of timber project was found 6.4% higher than the concrete construction option, which supports the findings of previous studies. Cost variance between mass timber and other options was observed much lower for high-rise buildings (building over 6 stories high) projects compared to residential building projects as for single-family residential building construction, the cost of using mass timber can be 23% higher than using traditional light-frame wood option. A construction project typically consists of numerous cost components such as material, labor, soft costs, developer fee, and land. In a small project with a relatively short time, many of these components are more expensive or time consuming for mass timber buildings compared to concrete and steel buildings. For example, insurance for construction may be more expensive as the insurance agencies might have fewer data to predict the potential risk of underwriting a mass timber project. The entitlement process can be complicated, time-consuming, and costly because of the reluctance of the city staff and building code department to permit a new mass timber building. The number of manufacturers of mass timber system in the United States is still very few with limited capacity and lack of efficient production process, which enable mass timber to be overpriced in the U.S. construction market. Besides, the cost of wood, prefabrication of mass timber panels in the built environment, and transportation cost of prefabricated panels to the job site escalate the final cost of mass timber projects.

4.4.4 Qualitative Measures to Avoid Change Orders

According to Chen (1992), the later a project change occur, the greater the impact of the change on project cost and schedule performance. In this study, the major source of change orders was identified as the change orders from miscellaneous sources such as from the owner, consultants, and designers suggest that there was a lack of proper communication between different project parties. The project was developed under the Integrated Project Delivery (IPD) method where all the project entities worked together at the same time to accomplish the project. A significant amount of change orders from different parties indicates a poor implementation of the IPD method. To improve the quality of a project, all the project participants need to work collaboratively in an efficient manner.

Improved planning during the project planning and design phase can significantly eliminate the change orders. Taylor et al. (2012) identified the importance of early planning through a structured questionnaire survey where the respondents pointed on several key factors such as constructability reviews, better design, more upfront work, and conducting value engineering during the design phase of the project. Front end planning has been gaining more acceptance in recent days especially in public and private industrial and non-transportation infrastructure construction (Gibson et al. 2010a). Front end planning, which is also known as pre-project planning, involves a structured and systematic process that helps owners define a project to a suitable level of development before authorization (Taylor et al. 2012). This is achieved by fully defining the parameters of a project, such that a project is most likely to meet its cost and schedule objectives (Gibson and Dumont 1996). The previous study indicates projects that utilized front end planning were able to minimize the total design and construction cost by 20% and total design and construction schedule by 39% (Dumont et al. 1997). Several other studies revealed that projects with a structured front-end planning process resulted in significant improvement in terms of cost, schedule, and change order performance relative to projects that received little to no structured front-end planning (Ray et al. 2006; Irons and Gibson 2006). Hanna et al. (2002) summarized several factors causing change orders such as large project size, design problems, architect-engineer coordination, manpower ratio and suggested that pre-project coordination among the project parties can help reduce these factors. Gunhan et al. (2007) recommended some preventive measures to avoid change orders such as choosing the right construction management firm, emphasizing the definition of project scope early in the project, and effectively managing the pre-contract activities by conducting value engineering and constructability reviews.

4.5 CONCLUSION AND RECOMMENDATIONS

This study centers on assessing the cost of a mass timber high-rise building project and compare the construction cost with the modeled cost of the same building designed by concrete option. Outcomes of cost study suggest that the construction cost of mass timber building is 6.43% higher than the modeled concrete option, which supports the findings of previous studies where timber construction costs were ranged 2-6% higher than the traditional concrete and steel construction. For mass timber residential hybrid building option, previous study showed that the life cycle cost of timber and concrete hybrid buildings is 4.4% higher than timber-steel hybrid buildings (Balasbaneh et al. 2018). Another study showed that the life cycle cost of single-story timber-concrete hybrid residential building is 4.4% higher than the same building using timber-steel material (Balasbaneh et al. 2018). The study summarized all the construction activities into 17 distinct categories and determined that the cost of engineered wood is the main factor responsible for cost increment. The installation cost of the timber structure was also found relatively high. Mass timber panels need extensive use of crane to fly and install the panels, indicating that high installation cost is related to the high usage of crane. Another notable cost source was identified as the cost of project staffing and indicates that the operation cost of manpower specialists in mass timber construction is higher than the traditional workforce. Although metals and furnishings also comprised a good portion of overall cost increase for the mass timber building, the research team was convinced that these are not directly related to timber construction and could be optimized by using different materials. For example, the principal cost of metal was from aluminum stair rails, which could have been replaced by any other material that is less expensive. Similarly, major cost related to furnishing was the cost of manufactured cabinets that could have also be replaced by less expensive materials.

The research team also analyzed the change orders occurred in this project and identified a total of 205 change orders that increased the final construction cost by 5.6%. Change orders were characterized in ten different categories and analysis determined that request from the consultant is the primary source of change order for this project in terms of frequency and dollar amount. Descriptive statistics of the change orders suggests that the cost associated with change orders is not frequency dependent but rather it depends on the type of activity. An interesting observation regarding the change order is that although the building was constructed by mass timber, its impact on change orders is insignificant. Mass timber related change orders were observed 12 times which consisted only 4.4% of the total change order costs.

The study identified several qualitative and quantitative approaches to reduce the construction cost of mass timber buildings. According to this study, the cost of engineered wood is very high, which is the biggest concern of mass timber construction. The cost of engineered wood needs to be reduced in order to increase the economic feasibility of mass timber construction projects. Equipment operation needs to be optimized to reduce the installation cost, and qualified workforce expert on timber construction needs to develop to decrease the cost of project staffing. Since mass timber panels are prefabricated in a separate built environment, the cost of millwork needs to be reduced as well. Finally, the number of mass timber manufacturing factories is required to be increased in the U.S. so that the transportation cost of prefabricated timber panels will decrease. Currently, the majority of the manufacturing facilities are located in the Pacific Northwest region of the country; as a result, transportation costs would extremely increase if a project is located in other parts of the country. More mass timber buildings will eliminate the uncertainties among the insurance and city authorities and will potentially reduce the planning cost of mass timber buildings.

The study also suggested some remedies to avoid change orders during the construction phase of the project. The findings of the study demonstrate that coordination between the project parties is extremely important so that any type of error during construction can be avoided. Project pre-planning is an effective action to detect the design deficiencies at the early phase of the project. Hiring an experienced project management team can also play a vital role to reduce the change orders and increase the value of the project. Incorporation of virtual design and building information modeling (BIM), and developing an integrated project delivery (IPD) method would also be a helpful pathway to avoid change orders.

The current research has multiple limitations. First, the study was conducted based on a single building construction project, thus it is difficult to generalize the findings of the study for other projects. The price of building materials can be different and different countries have different construction practices. Also, the type of building is another important factor to consider as cost variance might fluctuate depends on the type of building. Small sample size also compromised the statistical validation of the study. Second, the remedies of change orders were based on previous studies, as the study team was unable to interview people involved in the project. A structured survey among the workers would have provided a better insight regarding the root causes of change order and their potential impacts on the project. Third, in this study, only construction cost was compared. If the total life cycle costs are compared, then there might be an offset for mass timber buildings. Finally, the study excluded the schedule information of the project because of data unavailability. Future research should address all these issues to analyze the cost and change orders of the building construction projects.

CHAPTER 5: ENVIRONMENTAL POLLUTION POTENTIAL OF MASS TIMBER MATERIALS

Modified from:

Ahmed, S.; Arocho, I.; (2019). "Emission of particulate matters (PM) during construction: A comparative study on a cross-laminated timber (CLT) and a steel building project. *Journal of Building Engineering*, 22: 281-294. https://doi.org/10.1016/j.jobe.2018.12.015

Ahmed, S.; Arocho, I.; (2019). "Characteristics of the emission of particulate matters in construction site: A comparative study on a timber and a steel construction project". Proceeding of the 7th International Construction Conference (Jointly with Construction Research Congress), June 2019, Canada.

5.1 INTRODUCTION

On account of the extensive variety of industrial activities, construction have been considered as a powerful piece for accomplishing sustainable development (Wetheril et al. 2007; Pinkse and Domisse 2009; Pitt et al. 2009). Generating significant amount of waste and causing several public health problems make the construction operation even more risky and threatening than any other production process (Holton et al. 2008). Air pollution is one of the key environmental effects that come about because of construction work. Emission of particulate matter (PM) of different sizes are predominantly responsible for pollution on the construction sites (Chang et al. 2014). As a result, construction sites are considered as a major source of urban dust emissions (Chang et al. 2014). Construction workers are uniquely recognized under certain health hazard for PM having a diameter of 10 micrometers and 2.5 micrometers, commonly known as PM_{10} and $PM_{2.5}$ respectively (Ketchman and Bilec 2013). For this reason, it is crucial to evaluate the concentration of PM, especially during construction (Moraes et al. 2016). In order to do that, some global organizations have endeavored to enhance measurements for construction activities such as the Building Research Establishment (BRE), the American Economic Association (AEA), the Greater London Authority (GLA); and the UK Department for Environmental, Food, and Rural Affairs (DEFRA) (Sadler 2005).

This research centers around the emissions of PM from an emerging construction material, cross laminated timber (CLT). In spite of having some beneficial effects, cross laminated timber has also been addressed for its negative effects on air quality and human health. This study aimed to determine the concentration of PM on a construction site using CLT panels. PM concentration was also measured on a steel building construction site. This study also compared the emission of the construction sites with a relatively clean atmospheric location to determine how the emission from the construction sites differ from typical PM levels of emission. While measuring the emission, four different PM sizes ($PM_{2.5}$, PM_4, PM_7, PM_{10}) were monitored.

This study was accomplished focusing on three objectives. The first objective of the study was to determine the emission of PM during construction. Two construction sites were selected for the study using different construction materials. To compare the emission level from the construction sites, a reference location was also used. The second objective of the study was to use the United States Environmental Protection Agency (EPA) published data on national PM_{10} and $PM_{2.5}$ to compare with construction site measurements. This study also measured and analyzed the concentration level of $PM_{1.0}$ and $PM_{4.0}$ in all three locations. The research team found that $PM_{1.0}$ and $PM_{4.0}$ are mostly absent in most of the related previous studies and there is no standard set for $PM_{1.0}$ and $PM_{4.0}$ by any regulatory agencies. In this study, both PM sizes were extensively analyzed in terms of their emission levels and correlated with $PM_{2.5}$ and PM_{10}. Since there was no prior study found on the emission level of $PM_{1.0}$ and $PM_{4.0}$, this study believes to be a good source of analyzing the characteristics of both PM sizes. Finally, PM data obtained from the different locations were compared with EPA standard for PM emission.

The third objective of this study was to characterize the construction sites regarding their PM emissions. Since both construction sites were using two completely different materials (CLT and steel), it has drawn the attention of the research group to observe PM emission level and analyze which construction material is more susceptible to PM emission. EPA national average concentration data and standards were also included to compare the pollution level.

The research team identified several contributions of this study towards the mainstream construction air pollution research. The unique contributions of this study are:

- Measuring and comparing the emission of PM in construction site using different materials.
- Determining the difference of PM emission level between construction sites and regular areas.
- Analyzing the compatibility of PM concentration between different construction sites and EPA standard.
- Correlation between four different PM sizes.

5.2 LITERATURE REVIEW

Air pollution is an obvious outcome of construction activities and PM is one of the common sources of air pollution. PM is responsible for human illness and even mortality (Lorenzo et al. 2006). This section will review the relevant literature on the definition of PM, PM pollution especially in the construction sites, and its health hazard. Also, a general discussion will be presented on CLT and its potential advantages and disadvantages as construction material.

5.2.1 Particulate Matters (PM) in the Air

Particulate Matter (PM) is a group of polluting agents consisting of dust, smoke, and all types of solid and liquid materials that remain suspended in the air because of their small size (USEPA 2017). Some particles of this group such as dust, dirt, soot, and smoke are big enough to be seen with the naked eye. Others are relatively small and need electron microscope to be detected. There are two main sources of particulate matters: primary, and secondary. Pollution from primary sources is produced by their own processes such as wood stoves and forest fires. Secondary sources are those that let off gases that can form particles in the atmosphere (CDC 2016). The majority of the particulate matters are the byproduct of sulfur dioxide (SO_2) and nitrogen oxide (NOx) (USEPA 2017).

In general, PM is distinguished by its size and the common classifications are:

- $PM_{1.0}$: Particulate matters with a diameter less than 1 µm
- $PM_{2.5}$: Particles with diameters generally 2.5 µm or less
- PM_4: Particulate matters with diameter 4 µm or less
- PM_{10}: Particulate matters 10 µm or less in diameter

Particles which are 2.5 μm to 10 μm in diameter are called coarse particles. Particles less than 2.5 in diameter are called fine particles and include ultra-fine particles of less than 0.1 μm ($PM_{0.1}$) (CITEPA 2017).

5.2.2. Particulate Matter Air Pollution in Construction

As mentioned before, PM has been considered as one of the major sources of air pollution. Yan et al. (2018) showed that the PM_{10} concentration at the construction site exceeded the local standard of China. Also, the concentration level produced by the dust at the construction site has a certain degree of impact on the surrounding air. According to Zhao et al. (2007), the average monthly contribution of construction dust to the overall PM10 pollution was approximately 10% in Beijing, and this phenomenon is widespread in China. Because of the increasing trend of the number of construction and demolition activities, it is predicted that construction dust pollution will become more serious in the future (Wu et al. 2016). Because of a series of different activities and equipment, construction sites are in a very high exposure of different air pollutants including PM. Sources of PM in construction activity are different than any other PM sources in terms of the direct estimation and control of its emissions (Moraes et al, 2016). According to Arocho et al. (2014), the concentration of PM during the beginning of a construction project is much higher than the concentration of the other pollutants because of the excess use of construction equipment such as bulldozers, roller, and loader. Reddy and Arocho (2018) showed that construction equipment like cranes is responsible to produce up to 2,450 grams of PM_{10} during construction operations. Construction activity of the city of Pittsburgh increased 48% from 2010 to 2011, which listed this city in the most polluted U.S. cities in terms of PM emissions (Ketchman et al. 2013). A study performed during the construction of King's Cross Depot in London, England, demonstrated that the wards of Somers Town and St. Pancras and those close-by frequently experienced high concentrations of PM because of construction activities (Haynes and Savage 2007). Construction equipment such as backhoes, motor grades, front-end loaders, trucks, and cement mixers also been investigated for PM and considered as an impact factor for high construction PM emissions (Frey and Kim 2009). Different sizes of PM can be produced during the construction work that affects the workplace and surrounding areas (Resende 2007). Impacts of PM emissions can be noxious to the construction sites themselves including damage to the workers and threats to the safety and well-being of the surrounding areas (Moraes et al. 2016).

5.2.3 Adverse Health Impacts of Particulate Matters

PM are considered responsible for causing several human health problems. Several studies suggested that they are responsible for increasing human mortality and illness rate (Mastalerz et al. 1998, Shi et al. 2003, Mueller-Anneling et al. 2004). Most common health effects of particulate matters include heart and lung diseases, eye irritation, respiratory problem, and low birth weight of newborn babies etc. According to the World Health Organization, PM causes approximately 800,000 premature deaths around the world each year and ranks as the 13th leading cause of mortality (Anderson et al. 2012). More specifically, PM is believed to contribute to cardiovascular and cerebrovascular diseases and research shows that long term exposure of PM is responsible for significantly high cardiovascular incident and mortality rate (Samet et al. 2000). Particulate matters are emphatically connected with death from lung growth and cardiopulmonary ailments. The

“Harvard Six Cities Study”, conducted on six U.S. cities showed an increasing mortality rate of 29% when comparing to the most polluted cities to the least polluted (Dockery et al. 1993). Another study performed among 1.2 million participants in 151 U.S. metropolitan areas using the American Cancer Society’s Cancer Prevention 2 database (ACS CPS 2) demonstrated that an average increase of 10 $\mu g/m^3$ in PM caused 18% increase of cardiovascular mortality (Pope et al. 2006). Similarly, research shows that reduction in PM concentration in the air reduces the mortality rate (Laden et al. 2006).

Several studies also investigated the association of PM exposure with respiratory diseases. A study in southern California suggested that 19 $\mu g/m^3$increase of PM_{10} was responsible for a 40% increase of the risk of bronchitis syndromes among the asthmatic children (McConnell et al. 1999). Because of the indoor biomass burning in the developing countries, concentration of PM inside house can exceed 200 $\mu g/m^3$ which can cause lung infection and impaired lung function (Grigg 2009). An investigation of 12 million Medicare participants in 108 counties exhibited a huge increment in respiratory hospitalizations for the increases in $PM_{2.5}$ in the eastern USA (Peng et al. 2009).

5.2.4 Concept of Cross-Laminated Timber in Building Construction

Nowadays, Cross Laminated Timber (CLT) has been recognized as an attractive material for the sustainable construction industry. An engineered wood product, although incepted in Europe, now is also gaining momentum on the North American market (Shiling et al. 2016). The large amounts of forest in North America provide savings in the cost of mass CLT production. CLT has been considered as a sustainable material due to the renewable characteristics of timber, its major component. CLT also has the ability to turn lower value wood stocks into high-value product and foster economic development in rural communities (Shiling et al.2016). Apart from that, there are several other aspects that has been identified as significant advantages of CLT over conventional concrete and steel structure such as high thermal insulation properties, cost effectiveness, environmental friendliness, design flexibility, and production of less waste during construction (WoodWorks, 2016). Another important aspect of CLT is its ability to serve as carbon dioxide storage, otherwise known as a carbon sink (University of Pittsburgh, 2017). Although, there are numerous challenges associated with the implementation of the CLT in mass construction especially in North America, it is very much possible to establish CLT as a potential alternative source of sustainable construction material.

A panel of CLT typically consists of multiple layers of structural lumber board glued together in the wide faces. A cross-section of a CLT element has at least three glued layers of boards placed in orthogonally alternating orientation to the neighboring layers (Mohammad et al. 2012). Dimensions of the CLT panel greatly varies, however typical width size are between 0.6m-1.2m. The length of the panel can be up to 18m and the thickness can be up to 508 mm (Mohammad et al. 2012).

5.3 RESEARCH METHODOLOGY

The research was concentrated both on field study and extensive statistical analysis. Field study included going to construction sites, meeting with the project engineers to identify the activities, and measuring PM for a particular timeframe, following similar data collection methods for the site utilized for comparison. Statistical analysis was performed based on the collected data and covered sample analysis and comparative data analysis.

5.3.1 Site Selection

For this study, College of Forestry Building (known as Peavy Hall) of Oregon State University was selected as one of the construction sites. The old building has been torn down for the construction of a new learning facility that will be part of OSU's $65 million Oregon Forest Science Complex. The total available area of the project was 114,000ft^2 where 80,000 ft^2 was utilized for the construction of a three-story CLT building. The remaining area will be used for the Advanced Wood Products Laboratory. During the data collection time, the construction team was flying and installing CLT panels.

Another construction site was evaluated in terms of PM emission to compare with emission at Peavy Hall. The New Corvallis Museum building, a $9.5 million project with an area of 19,000 ft^2 was analyzed for the study. The project was being constructed out of steel structure. While collecting data, multiple truckloads were delivering the steel and the crews were installing the frames. A few wielding machines were observed running on the construction site.

In order to compare the PM concentration from two different construction sites, Oregon State University Library (known as Valley Library) entrance premise was used as a reference site for this study. The area was believed to be a clean air zone and same data collection procedure was followed. Figure 5.1 shows the sites selected for the study.

Figure 5. 1 Selected sites for the study (L-R: Peavy Hall, Museum Building, and OSU Valley Library)

5.3.2 Equipment Used for the Study

To monitor the PM of the selected sites, TSI DustTrak II 8530EP was used. It is an aerosol monitoring device that provides the real-time aerosol mass reading. The model is a standard desktop model that comes with USB, Ethernet, and analog alarm outputs that allows remote access to the data. Some of the unique features of the device include measuring high concentration aerosol, gravimetric sampling capacity using a 37-mm filter cassette for custom reference calibration, STEL alarm for tracking 15-minute average mass concentration for fugitive emissions at hazardous waste sites, environmental protection and tamper-proof security. Lightweight and portability make the device an easier solution of carrying. The program is easy to install in Windows computer and provides sufficient statistical and graphical data.

The device consists of four different diameter inlets representing four different sizes of particulate matters (PM_1, $PM_{2.5}$, PM_4, PM_{10}). Before testing, specific inlet needed to be connected to the bottom part and an impaction plate. Once everything is connected, the inlet needs to be connected with the device. Figure 5.2 shows the device setup. The device also recommends performing zero calibration before every use. Zero calibration can be performed by using a zero-filter provided with the device package. Although µg/m^3 was used as the typical unit of expression for PM, the device measures the concentration in mg/m^3 using the following equation.

$$Concentration\left(\frac{mg}{m^3}\right) = \frac{Filter\ Post\ Weight\ (mg) - Filter\ Pre\ Weight\ (mg)}{\frac{\left(\frac{2}{3}\right)(Flow\ Rate\ of\ the\ Filter)\left(\frac{L}{\min}\right)}{1000}} \times$$

$Total\ Sample\ Time$ (min)

Figure 5. 2 Components of the device

5.3.3 Data Collection Method

In this study, data collection aimed to measure the emission of particulate matters from two different construction sites. To compare the data obtained from both construction sites, data was collected from a reference location that provided a notion regarding the variation of PM concentration from the construction sites with respect to an off-site location. For all the measurements, TSI DustTrak II 8530EP was used. The measurements were not conducted at exactly the same time of the day as the priority was given to the construction activities, not the specific time of a day. The research team identified the weather-related factors; thus, temperature, relative humidity, and wind speed were recorded during the sampling periods. However, the team did not find any significant correlations between weather factors (e.g. temperature, humidity, and wind speed) and the measured data.

The research team selected two construction sites using different primary materials for the process: Cross-laminated timber (CLT) and steel to measure and compare the emission of PM. A reference site was also used to compare the emission level of construction sites with a normal location. Before starting data collection, the research team talked to the project engineers of both construction sites to identify major construction activities of each site. For CLT project, main activities were found flying CLT panels, installing CLT panel to the positions, moving CLT panels using scissor lift from one point to another point of the building. For the steel building site, major activities were determined unloading trucks, cutting metal frames, welding, and installing metal columns and beams to the positions. The sampling material (DustTrak) was placed in a close proximity (350 ft.) from all the identified activities in both construction sites to measure the PM concentration. The DustTrak was placed at a height of 5 ft. from the ground in order to maintain the consistency of data. At the reference location, the research team focused on measuring PM in a relatively quiet area. Similar to the other locations, the DustTrak was placed at a height of 5 ft. from the ground. There was no significant activity observed other than the movement of nearby students. After each measurement, the impaction plate, PM size caps, and bottom plate of the measurement were cleaned properly. The first measurement was $PM_{1.0}$ for all the locations followed by $PM_{2.5}$, $PM_{4.0}$, and PM_{10}. The data collection was started when all the identified activities were observed in the construction sites. The research group spent 3hr./day in three different locations (1hr./day each) for 5 days. The one-hour time frame was divided equally into four parts to collect PM concentration of four different diameter particles (15 minutes for each size) with a log interval of 59 seconds and a time constant of one second. Right after beginning the data collection, $PM_{1.0}$ concentration was measured for 15 minutes. After 15 minutes, the inlet of $PM_{1.0}$ was cleaned and replaced by $PM_{2.5}$. Similarly, after 30 minutes, the $PM_{2.5}$ inlet was replaced by $PM_{4.0}$ inlet and finally, after 45 minutes, $PM_{4.0}$ inlet was replaced by PM_{10} inlet. During each replacement, inlets and the plate were cleaned with a piece of cloth to remove any other external particulate. Zero calibration performed, and two drops of oil was applied before every use. Same procedure was followed in all locations to keep the consistency of data collection method. After completion, data were processed and transferred from the device to the computer where collected data were saved for the statistical analysis. The authors attempted to collect a significant amount of data points on which extensive statistical analysis can be performed. Based on that, a total of 900 data points was obtained from all three locations (300 data points from each site) for a period of 5 days. The 900 data points included different PM sizes (PM_1, $PM_{2.5}$, PM_4, and PM_{10}). Individually, each size had 225 data points.

5.4 RESULTS

This section provides the detailed statistical analysis of the collected data from three distinct locations. PM were categorized based on their sizes and locations; assessment was made accordingly. In the meantime, a comparison was drawn among different data collection locations to determine the impacts of PM on each individual site. In this study, SPSS was used to perform all necessary analyses to statistically validate the research.

SPSS is a widely used software program to perform extensive statistical analysis, data mining, text analytics, and data collection.

5.4.1 Location 1 (Peavy Hall)

Since Peavy Hall was using cross laminated timber as the primary building material and the concept of cross laminated timber is still new in the U.S. construction market, it is pivotal to know its emission level. Table 5.1 shows the characteristics of different particulates matters obtained from the construction site.

Table 5.1 Characteristics and concentration (µg/m3) of particulate matters

Mass Conc.	25th Percentile	50th Percentile	75th Percentile	90th Percentile	Mean	Median	Std. Deviation	Max.	Min.	Std. error
$PM_{1.0}$	3	8	9	11.4	6.61	8	3.49	12	2	0.40
$PM_{2.5}$	4	8	10	10	7.17	8	2.95	17	2	0.34
$PM_{4.0}$	4	10	12	15.4	9.05	10	6.43	44	2	0.74
PM_{10}	4	9	17	22	11.39	9	7.98	32	2	0.92

From Table 5.1, it is noticeable that the concentration levels of $PM_{1.0}$ and $PM_{2.5}$ were relatively similar. The mean concentration of $PM_{1.0}$ was 6.61 µg/m^3 with a standard deviation of 3.49 and a standard error of 0.40. Highest and lowest concentration level were 17 µg/m^3 and 2 µg/m^3 respectively. For $PM_{2.5}$, the mean 7.17 µg/m^3 which was close to $PM_{1.0}$ concentration. Maximum and minimum concentration level were 12 µg/m^3 and 2 µg/m^3 respectively. The standard deviation of 2.95 for $PM_{2.5}$ indicated a relatively less spread set of concentration levels.

Unlike $PM_{1.0}$ and $PM_{2.5}$, the concentration level of $PM_{4.0}$ and PM_{10} was found higher and more widely scattered. The mean concentration level of $PM_{4.0}$ was 9.05 µg/m^3 with a standard deviation of 6.43. Maximum concentration level was 44 µg/m^3 which was significantly high. PM_{10} exhibited an even higher mean concentration of 11.39µg/m^3 with a standard deviation of 7.98 that means PM_{10} showed more spread set of concentration levels. Highest and lowest concentration was 32 µg/m^3 and 2 µg/m^3 respectively. Figure 5.3 shows the histograms of the PM concentrations.

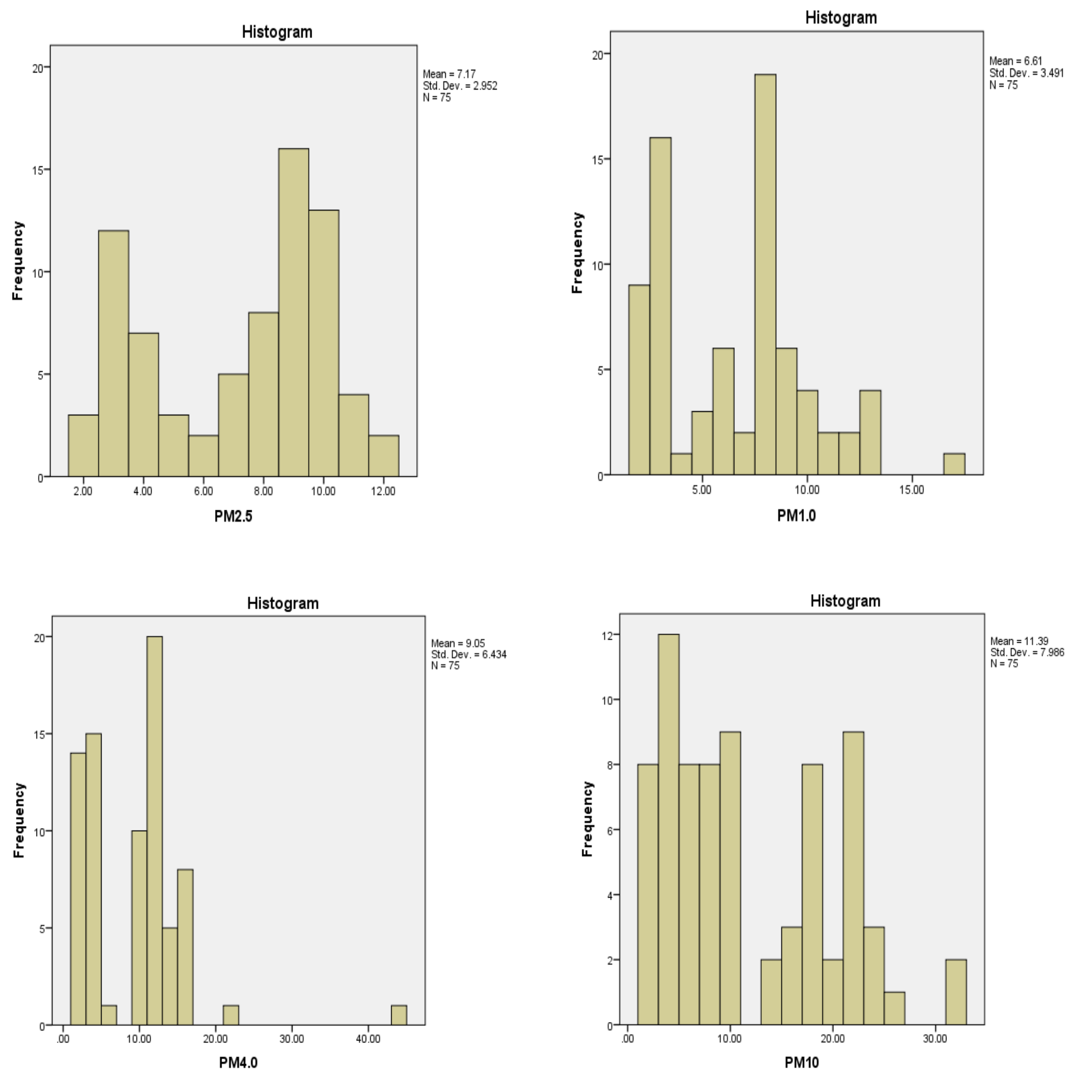


Figure 5. 3 Histograms of PM concentrations collected from Peavy Hall

In order determine the correlation between different PM sizes, Pearson coefficient factor was used. This factor measures the strength of linear relationship between the variables. The Pearson coefficient r can take a range of values between +1 to -1. A perfect linear relationship is considered as r=1. A value of 0 indicates no significant correlation between the variables. Pearson coefficient factor r>0 indicates a positive correlation and r<0 indicates a negative correlation between the variables. In this study, result of Pearson correlation analysis revealed a moderate correlation among the different sizes of particulate matters. $PM_{1.0}$ showed a correlation of 0.704, 0.584, and 0.500 respectively to $PM_{2.5}$, PM_4, and PM_{10}. $PM_{2.5}$ also showed a moderate correlation of 0.704, 0.685, and 0.666 to $PM_{1.0}$, PM_4, and PM_{10}. PM_4 and PM_{10} also exhibited similar trend of correlation to other particulate matters. Result of this correlation indicated that the particulate matters emitted mostly from the similar emission sources. Table 5.2 shows the details of the correlation data.

Table 5.2 Details of the Pearson's correlation analysis

Correlations

		PM1.0	PM2.5	PM4.0	PM10
PM1.0	Pearson Correlation	1	.704**	.584**	.500**
	Sig. (2-tailed)		.000	.000	.000
	N	75	75	75	75
PM2.5	Pearson Correlation	.704**	1	.685**	.666**
	Sig. (2-tailed)	.000		.000	.000
	N	75	75	75	75
PM4.0	Pearson Correlation	.584**	.685**	1	.704**
	Sig. (2-tailed)	.000	.000		.000
	N	75	75	75	75
PM10	Pearson Correlation	.500**	.666**	.704**	1
	Sig. (2-tailed)	.000	.000	.000	
	N	75	75	75	75

**. Correlation is significant at the 0.01 level (2-tailed).

In order to compare the means of the collected samples from the Peavy Hall, one sample t-test was performed that explained the scenario of PM emissions in the construction site in comparison to the nation average. EPA conducted a research to determine the national average concentration of $PM_{2.5}$ and PM_{10}. For $PM_{2.5}$, they published 17 years of data (2000-2016) that covered 455 locations in each year and according to that research, the average national concentration of $PM_{2.5}$ was 10.78 µg/m^3. Similarly, for PM_{10} concentration, they published 27 years of data (1990-2016) that covered 149 testing in each year and as per that study, the average national PM_{10} concentration was 63.64 µg/m^3. Since there was no previous data found for $PM_{1.0}$ and $PM_{4.0}$ thus in this study only $PM_{2.5}$ and PM_{10} comparison was performed. Table 5.3 shows the result of one sample t test for both $PM_{2.5}$ and PM_{10}.

Table 5.3 Result of one sample t test for $PM_{2.5}$ and PM_{10}

One-Sample Test

	Test Value = 10.8					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
PM2.5	-10.640	74	.000	-3.62667	-4.3058	-2.9475

One-Sample Test

	Test Value = 63.6					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
PM10	-56.620	74	.000	-52.21333	-54.0508	-50.3759

Table 5.3 illustrated that the two-tailed p-value for both $PM_{2.5}$ and PM_{10} are smaller than 0.001 which detrmined that the means of the PM are significantly different than the national average. Negative value of test statistics (t) indicated that the PM means collected from Peavy Hall are lower than the national average. Result of 95% confidence interval also supported the same finding since in both cases, the lower and the upper value did not include zero. EPA also established daily and yearly standard for $PM_{2.5}$ and PM_{10}

concentration and according to that, daily standard was set to 35 µg/m^3 for $PM_{2.5}$ and 150 µg/m^3 for PM_{10}. However, PM_{10} standard was revoked later because of the lack of sufficient evidence. PM data collected from the construction site satisfied the EPA standard as well.

5.4.2 Location 2 (Corvallis Museum Building)

As specified previously, The Peavy Hall project utilized cross laminated timber as the principal construction material. On the other hand, Corvallis Museum Building has used steel as the primary building material. Additionally, different types of work were observed during the data collection period in both sites. As an example, in the Peavy Hall, CLT panels were flying and installing during the data collection time whereas in the museum building project, installation of metal frames, welding, delivery trucks were found. Based on functional differences of both projects, it was assumed that the emission level of particulate matters will be different. Table 5.4 shows the characteristics of the particulate matters emitted from the museum building construction site.

Table 5.4 Characteristics and concentration (µg/m^3) of particulate matters from Corvallis Museum Building Site

Mass Conc.	25th Percentile	50th Percentile	75th Percentile	90th Percentile	Mean	Median	Std. Deviation	Max.	Min.	Std. error
$PM_{1.0}$	10	10	23	85	29.65	10	51.71	248	3	5.97
$PM_{2.5}$	5	7	15	53	18.63	7	29.26	136	2	3.38
$PM_{4.0}$	6	14	32	98	30.44	14	42.68	209	3	4.93
PM_{10}	4	6	17	32	25.05	6	105.74	914	3	12.21

Unlike Peavy Hall, Museum Building project showed a significantly higher concentration of particulate matters. As mentioned before, during data collection, wielding and metal frame installation works were observed, and it was assumed that because of the types of work, concentration level significantly arose. Four different sizes of PM showed a very discrete level of emission trend. The mean concentration level of $PM_{1.0}$ was 29.65 µg/m^3 with a standard error of 5.97. The standard deviation of 51.71 indicated a very spread level of concentration during data collection period. However, the median concentration value of 10 µg/m^3 showed that the concentration level was below the EPA standard, however, the highest concentration obtained for $PM_{1.0}$ was 248 µg/m^3. $PM_{2.5}$ exhibited a relatively lower concentration level than $PM_{1.0}$. Mean concentration was found 18.63 µg/m^3 with a standard deviation of 29.26. Median concentration level was 7 µg/m^3 with the highest concentration level of 136 µg/m^3 and lowest concentration level of 2 µg/m^3.

Among all of the mass concentrations, $PM_{4.0}$ displayed the highest level of emission. Mean concentration level for $PM_{4.0}$ was 30.44 µg/m^3 which was highest among all the mass concentrations. Although median concentration level was found 14 µg/m^3 but the maximum concentration level of 209 µg/m^3 indicated an alarming increase. The concentration of PM_{10} was also found very high in the construction site. Mean value of concentration was determined 25.05 µg/m^3 with a standard deviation of 105.74. Among all, PM_{10} exhibited the highest concentration level of 914 µg/m^3 which was significantly higher than the national average and the standard concentration level set by EPA. Figure 5.4 shows the histograms of the PM concentrations collected from the museum building construction project.

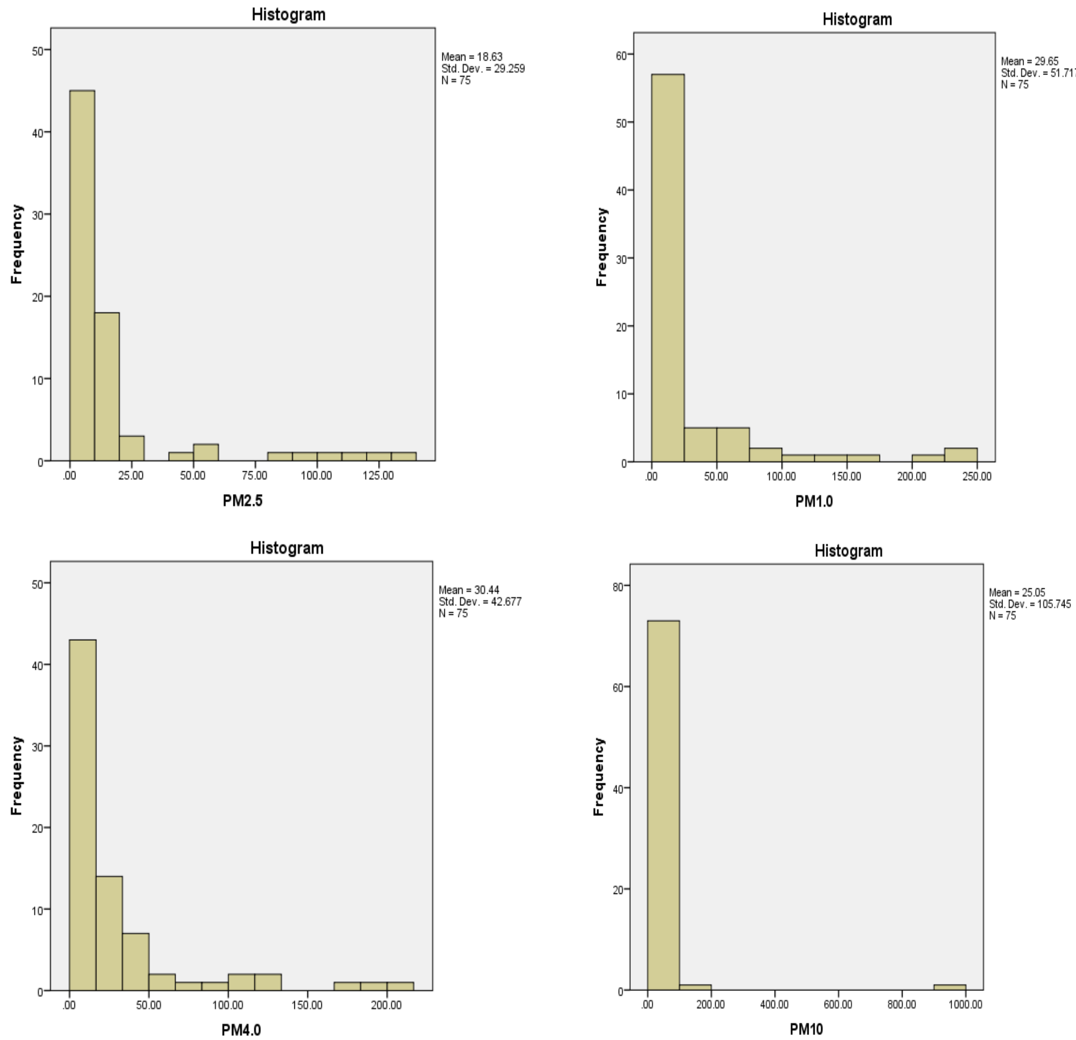


Figure 5. 4 Histograms of PM concentrations collected from museum building

To determine the correlation among the particulate matters, Pearson correlation analysis was performed (Table 5.5). From the analysis, it was found that $PM_{1.0}$ and PM_4 are not significantly correlated to each other as the correlation factor between these two particulate matters was found close to zero (0.009). $PM_{1.0}$ also showed a poor correlation with $PM_{2.5}$ and PM_{10}. The correlation factors were obtained 0.068 and -0.074 respectively. Likewise, as $PM_{1.0}$, other particulate matters also showed relatively less significant correlations with each other's. Poor correlations among the particulate matters indicated the wide variance of data collected from the job site. Table 5.5 illustrates the scenario and Pearson's correlation analysis showed more statistical evidence of that.

Table 5.5 Pearson's correlation analysis of collected data from the museum building project

Correlations

		PM1.0	PM2.5	PM4.0	PM10
PM1.0	Pearson Correlation	1	.068	.009	-.074
	Sig. (2-tailed)		.560	.941	.526
	N	75	75	75	75
PM2.5	Pearson Correlation	.068	1	-.074	-.064
	Sig. (2-tailed)	.560		.531	.586
	N	75	75	75	75
PM4.0	Pearson Correlation	.009	-.074	1	-.005
	Sig. (2-tailed)	.941	.531		.965
	N	75	75	75	75
PM10	Pearson Correlation	-.074	-.064	-.005	1
	Sig. (2-tailed)	.526	.586	.965	
	N	75	75	75	75

One sample t-test was also performed to compare the mean values of $PM_{2.5}$ and PM_{10} with the U.S. national average values. It was aforementioned that there is no national database available for $PM_{1.0}$ and $PM_{4.0}$ thus only $PM_{2.5}$ and PM_{10} concentrations were compared with the national average. Table 5.6 shows the detail outcomes of the one sample t-test for museum building project.

Table 5.6 The result of one sample t-test for $PM_{2.5}$ and PM_{10}

One-Sample Test

	Test Value = 10.78					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
PM2.5	2.323	74	.023	7.84667	1.1148	14.5785

One-Sample Test

	Test Value = 63.64					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
PM10	-3.160	74	.002	-38.58667	-62.9163	-14.2570

Outcomes of Table 5.6 suggested that the mean of $PM_{2.5}$ collected from the project site was not significantly different than the national average (P>0.001). Positive test statistics (t) value of 2.323 indicated that the mean $PM_{2.5}$ was higher than the national average. Upper and lower value of 95% confidence interval also supported the same outcome. However, PM_{10} means of the construction site was found slightly different than the national average (P=0.002 which is greater than 0.001) and t value said the mean was lower than the national average which was finally supported by 95% confidence interval.

5.4.3 Location 3 (Reference Site: OSU Library Complex)

In this study, two construction sites were incorporated to analyze the concentration of particulate matters. To look at the outcomes of those two construction sites, a reference site was additionally analyzed to determine how the concentration levels alter because of construction activities. To do that, the library complex of Oregon State University was chosen as the reference site. The library complex is situated in an area anticipated cleaner and safer in terms of PM emissions. Same data collection methodology was applied as before, and the same amount of data points were obtained from the reference location to analyze the comparison with other locales. Table 5.7 summarizes the major characteristics of the reference site.

Table 5.7 Characteristics and concentration (µg/m^3) of particulate matters

Mass Conc.	25th Percentile	50th Percentile	75th Percentile	90th Percentile	Mean	Median	Std. Deviation	Max.	Min.	Std. error
$PM_{1.0}$	2	4	7	11	5.4	4	4.86	36	2	0.56
$PM_{2.5}$	3	4	6	13	5.83	4	4.24	22	2	0.49
$PM_{4.0}$	3	4	5	12	5.13	4	3.53	12	2	0.41
PM_{10}	3	3	5	12.4	5.12	3	3.77	13	2	0.44

Table 5.7 recapitulated that the concentration of particulate matters in the library complex was less than both of the construction sites, as anticipated. Average $PM_{1.0}$ concentration was found 5.4 µg/m^3 with a standard deviation of 4.86. Maximum and minimum concentration level was found 36 µg/m^3 and 2 µg/m^3 respectively. For $PM_{2.5}$, the mean concentration was found 5.83 µg/m^3 with the standard deviation of 4.24. $PM_{4.0}$ and PM_{10} concentration levels were also found very similar. Table 7 also shows that the average concentration of $PM_{1.0}$ and $PM_{2.5}$ in location 3 is slightly higher than the average concentration of $PM_{4.0}$ and PM_{10}. Characteristically, PM_{10} and $PM_{4.0}$ are similar and different than $PM_{2.5}$ and $PM_{1.0}$ because of their size. Components of $PM_{1-2.5}$ are relatively finer than $PM_{4.0-10}$. $PM_{1.0-2.5}$ are combustion particles and organic compounds while $PM_{4.0-10}$ are more likely dust, pollen, and mold. Since location 3 was covered by grass, there is a high chance that the grass concentrates organic compounds that can reasonably increase the emission level of $PM_{1.0}$ and $PM_{2.5}$, compared to $PM_{4.0}$ and PM_{10}. Figure 5.5 illustrates the histograms of the collected data sets.

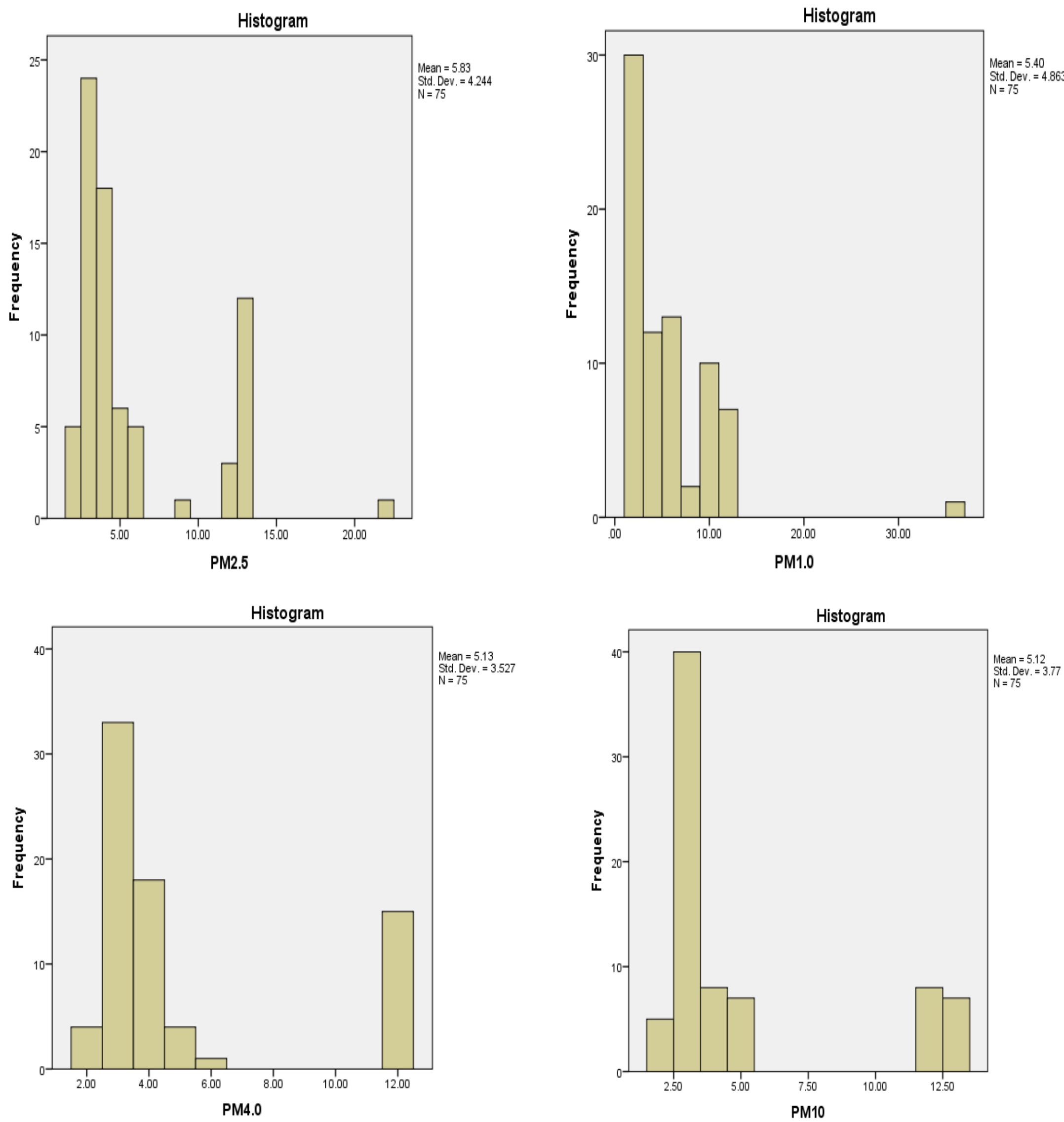


Figure 5. 5 Histograms of PM concentrations collected from Valley Library complex

Particulate matters collected from the OSU library premise showed moderate correlation among each other's. $PM_{1.0}$ exhibited a correlation range of 0.511-0.584 to the other mass concentrations. For $PM_{2.5}$, the range was varied between 0.584-0.810. Similarly, $PM_{4.0}$ also showed a moderate to good correlation to others, especially $PM_{4.0}$ revealed almost perfect correlation of 0.984 to PM_{10}, although the range varied between 0.558-0.984.

Finally, PM_{10} displayed the similar correlation trend as well. Details of the Pearson's correlation test result provided in table 5.8.

Table 5.8 Pearson's correlation analysis of collected data from OSU library premise

Correlations

		PM1.0	PM2.5	PM4.0	PM10
PM1.0	Pearson Correlation	1	.584**	.558**	.511**
	Sig. (2-tailed)		.000	.000	.000
	N	75	75	75	75
PM2.5	Pearson Correlation	.584**	1	.827**	.810**
	Sig. (2-tailed)	.000		.000	.000
	N	75	75	75	75
PM4.0	Pearson Correlation	.558**	.827**	1	.984**
	Sig. (2-tailed)	.000	.000		.000
	N	75	75	75	75
PM10	Pearson Correlation	.511**	.810**	.984**	1
	Sig. (2-tailed)	.000	.000	.000	
	N	75	75	75	75

**. Correlation is significant at the 0.01 level (2-tailed).

Outcomes from one sample t-test exhibited the similar tendency determined in previous analyses. Analysis of $PM_{2.5}$ and PM_{10} revealed a significant relationship with the national average value. Also, result of one sample t-test showed that the mean concentration of $PM_{2.5}$ and PM_{10} are significantly less than the national average. Table 5.9 shows the result of one sample t-test.

Table 5.9 Result of one sample t-test for $PM_{2.5}$ and PM_{10} analysis

One-Sample Test

	Test Value = 10.8					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
PM2.5	-10.149	74	.000	-4.97333	-5.9497	-3.9969

One-Sample Test

	Test Value = 63.6					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
PM10	-134.327	74	.000	-58.48000	-59.3475	-57.6125

5.4.4 Comparative Study

Figure 5.6 represents the concentration level of PM in all three locations through Box-and-Whisker Plots. Among all three locations, location 2 exhibited a relatively higher concentration level followed by Location 1. As Location 3 was not a construction site, it was assumed that the concentration level will be lowered and from the figure, it was found that PM emission at Location 3 was significantly lower than the other locations. The research team concluded that activities observed in Location 2 such as welding, installing metal frames were the reason behind the high concentration of PM emission. Findings of Box-and-Whisker plots suggested that although Location 2 revealed a much higher concentration of emission, median concentration level of Location 1 for $PM_{2.5}$ and PM_{10} was higher than Location 2 and 3.

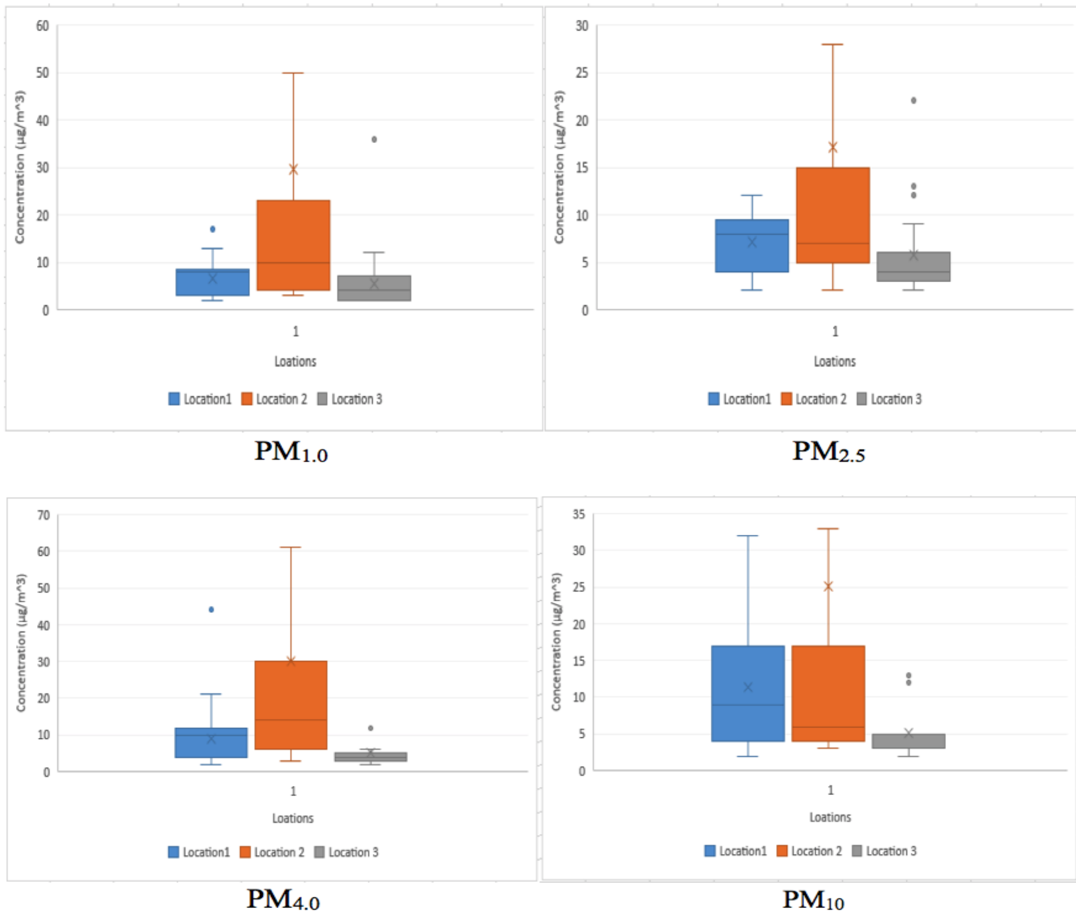


Figure 5. 6 Box-and-Whisker plots of PM concentrations

Pearson's correlation analysis was performed to determine the correlation of the same PM size collected from different locations. The purpose of this analysis was to determine any significant correlation among the PM data of different locations and the result of the analysis suggested no significant correlations among the particulate matters of different locations. This outcome indicated that the sources of PM emission were different in different locations. Figure 5.7 illustrates the result of Pearson's correlation test of PM emission.

Correlations

		L1PM1	L2PM1	L3PM1
L1PM1	Pearson Correlation	1	-.018	.371**
	Sig. (2-tailed)		.879	.001
	N	75	75	75
L2PM1	Pearson Correlation	-.018	1	.491**
	Sig. (2-tailed)	.879		.000
	N	75	75	75
L3PM1	Pearson Correlation	.371**	.491**	1
	Sig. (2-tailed)	.001	.000	
	N	75	75	75

Correlations

		L1PM2.5	L2PM2.5	L3PM2.5
L1PM2.5	Pearson Correlation	1	-.225	-.275*
	Sig. (2-tailed)		.052	.017
	N	75	75	75
L2PM2.5	Pearson Correlation	-.225	1	.466**
	Sig. (2-tailed)	.052		.000
	N	75	75	75
L3PM2.5	Pearson Correlation	-.275*	.466**	1
	Sig. (2-tailed)	.017	.000	
	N	75	75	75

Correlations

		L1PM4	L2PM4	L3PM4
L1PM4	Pearson Correlation	1	-.207	-.356**
	Sig. (2-tailed)		.075	.002
	N	75	75	75
L2PM4	Pearson Correlation	-.207	1	.184
	Sig. (2-tailed)	.075		.113
	N	75	75	75
L3PM4	Pearson Correlation	-.356**	.184	1
	Sig. (2-tailed)	.002	.113	
	N	75	75	75

Correlations

		L1PM10	L2PM10	L3PM10
L1PM10	Pearson Correlation	1	.283*	-.475**
	Sig. (2-tailed)		.014	.000
	N	75	75	75
L2PM10	Pearson Correlation	.283*	1	-.129
	Sig. (2-tailed)	.014		.270
	N	75	75	75
L3PM10	Pearson Correlation	-.475**	-.129	1
	Sig. (2-tailed)	.000	.270	
	N	75	75	75

Figure 5. 7 Pearson's correlation analysis result of different locations and PM sizes

Since there are not many studies were found on $PM_{1.0}$ and $PM_{4.0}$ thus a linear modeling was performed to predict the trend of $PM_{1.0}$ and $PM_{4.0}$ using $PM_{2.5}$ and PM_{10} which are most commonly used PM parameters. To do that, $PM_{1.0}$ and $PM_{4.0}$ were considered as dependent variable and $PM_{2.5}$ and PM_{10} were considered as the predictor variable. Outcome of linear modeling would better define the characteristics of $PM_{1.0}$ and $PM_{4.0}$. Especially for $PM_{1.0}$ and $PM_{4.0}$ which are not commonly used for PM study, linear modeling would be a good way to predict their trend using $PM_{2.5}$ and PM_{10}. Also, it is another way to determine the correlation of different PM sizes. This model analyzes the accuracy of $PM_{2.5}$ and PM_{10} to predict the concentration level of $PM_{1.0}$ and $PM_{4.0}$. Figure 5.8 shows the outcome of the linear modeling for Location 3.

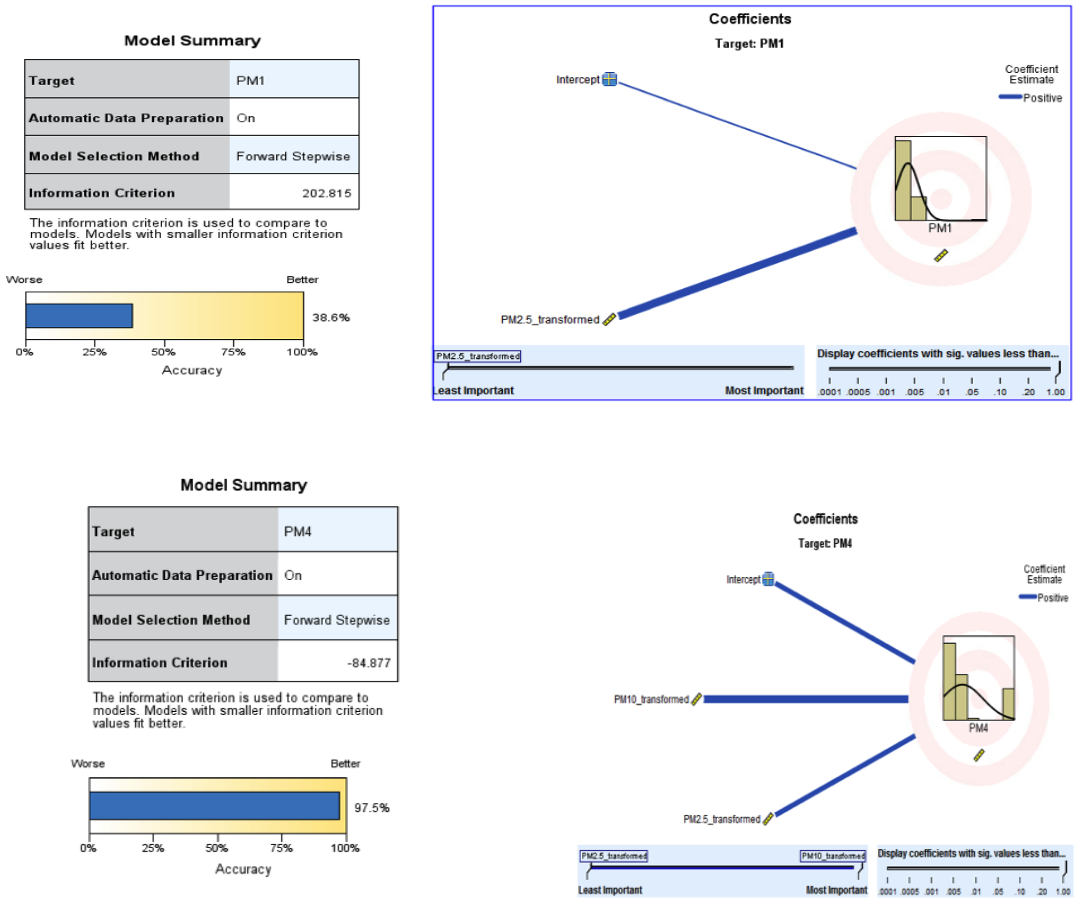


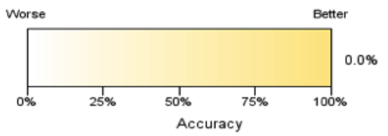
Figure 5. 8 Analysis of linear modeling for Location 3

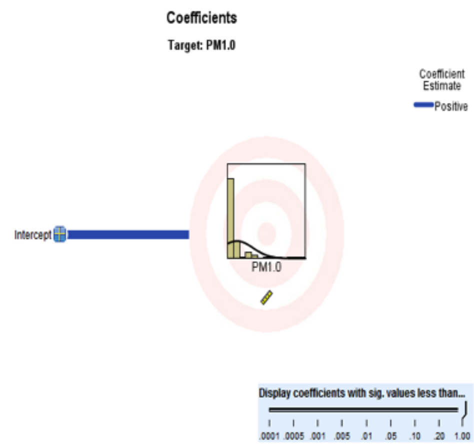
Figure 5.8 illustrated that $PM_{2.5}$ and PM_{10} predicted 38.6% of the dependent variable ($PM_{1.0}$) with a positive intercept. It also suggested that only $PM_{2.5}$ variable utilized to predict $PM_{1.0}$, PM_{10} did not transform into $PM_{1.0}$ variable. For $PM_{4.0}$, it was found that the predictor variables predicted 97.5% of the dependent variable. This time both predictors transformed into the dependent variable, however, the thickness of PM_{10} suggested that PM_{10} predictor was utilized more than $PM_{2.5}$ predictor for the linear modeling. Figure 5.9 shows the result of linear modeling analysis for Location 2.

Model Summary

Target	PM1.0
Automatic Data Preparation	On
Model Selection Method	Forward Stepwise
Information Criterion	592.917

The information criterion is used to compare to models. Models with smaller information criterion values fit better.
No effects were selected. The final model includes the intercept only.

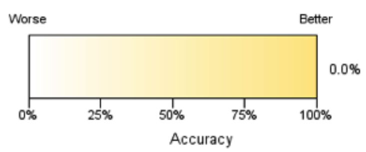




Model Summary

Target	PM4.0
Automatic Data Preparation	On
Model Selection Method	Forward Stepwise
Information Criterion	564.096

The information criterion is used to compare to models. Models with smaller information criterion values fit better.
No effects were selected. The final model includes the intercept only.



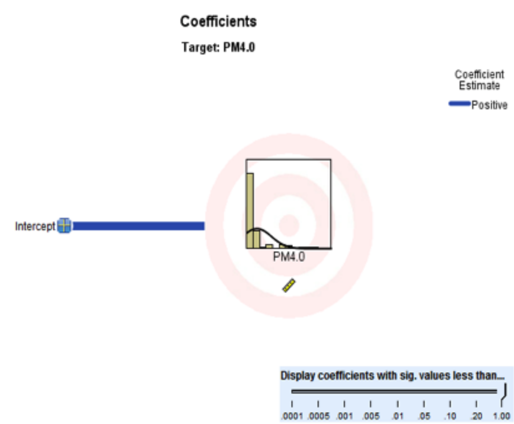


Figure 5. 9 Analysis of linear modeling for Location 2

For Location 2, both predictor variables failed to predict the dependent variables. The main reason behind that was the poor correlation among the different PM sizes measured on that location. Previous analysis on Location 2 showed a relatively high standard deviation value which also supports the result of linear modeling. Outcome of

Pearson's correlation test also supported the similar result on that location. Figure 5.10 illustrates the linear modeling analysis for Location 1.

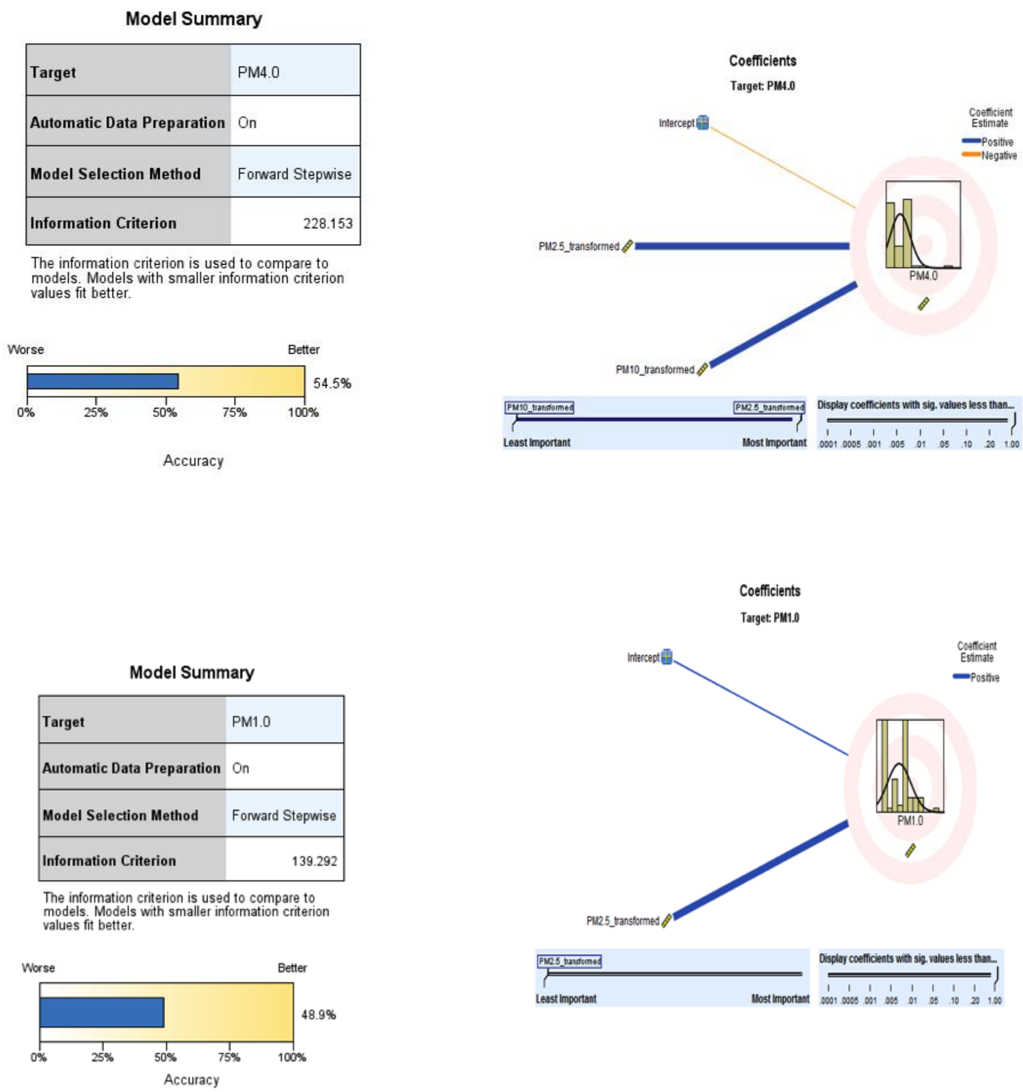


Figure 5. 10 Analysis of linear modeling for Location 1

Unlike Location 2, Location 1 exhibited a better linear modeling result. $PM_{2.5}$ and PM_{10} variables predicted $PM_{1.0}$ variable with an accuracy rate of 48.9% which was 54.6% for $PM_{4.0}$ variable. Outcome of this result also suggested a moderate correlation among the different PM sizes for this location. As expected before, $PM_{2.5}$ predictor was mostly utilized for dependent $PM_{1.0}$ prediction. For $PM_{4.0}$, both predictor variables utilized, however, the thickness of $PM_{2.5}$ was slightly better than PM_{10} which indicated that $PM_{2.5}$ was utilized relatively higher than PM_{10} variable.

5.5 CONCLUSION

This study was structured to determine the concentration of PM emitting from construction sites. In order to do that, particulate matter concentration was measured in two different construction sites, one was using CLT and another one was steel. A reference location was also used to measure the PM in order to compare the concentrations emitted from construction sites. The data collected from three different locations were analyzed extensively to statistically validate the result of the study.

The findings of the study indicated that construction sites are responsible for emitting high PM concentration in comparison to the other locations. Analyzing the data of two different construction sites indicated that CLT is a relatively safe construction material than steel regarding PM emission. Steel construction displays more hazardous activities than the CLT construction that can produce more PM. Activities such as welding, fabrication observed several times during the data collection believe to be responsible for the high concentration of emission. On the other hand, CLT construction does not require many welding works thus it is presumable that CLT produce relatively less PM during construction.

Statistical analysis indicated a difference of PM emission in construction sites and the reference location. Construction site which was using CLT displayed an increasing emission rate of 18.3%-55.1% in comparison to the reference location. The rate was much higher for steel construction site as it exhibited an increasing rate of 68.7%-83.1% in comparison to the reference site.

Although both construction sites emitted a higher concentration of particulate matters in comparison to reference site, the average concentration of both construction sites still remained below the EPA standard for PM. However, $PM_{2.5}$ concentration in steel construction project showed a higher average concentration level than the EPA national average database for the year of 2000-2016. Although EPA did not indicate their data collection locations, the higher concentration level still reveals that $PM_{2.5}$ emitted from the steel construction site is not compatible with the national average. Concentration level found in the CLT construction site was significantly lower than the EPA standard and national average data.

Majority of the studies on particulate matter air pollution focused on the emission of $PM_{2.5}$ and PM_{10}. All the standards are also based on those two sizes. However, this study was aimed to gather emission information of two other particulate matters having different sizes ($PM_{1.0}$ and $PM_{4.0}$). Since there were not many available data exist on $PM_{1.0}$ and $PM_{4.0}$, this study determined the correlation on different particulate matters and according to the study, particulate matters illustrated a moderate to poor correlation among each other. Especially in the steel construction project, the correlations were very poorly. Moderate correlations were found in other data collection locations. Linear modeling analysis suggested that $PM_{2.5}$ and PM_{10} can predict the concentration level of $PM_{1.0}$ and $PM_{4.0}$ with an accuracy rate of 38.6%-97.5%.

The findings of this study are compatible with the previous literature on PM production in construction sites and support the general concept of PM emission trends in the construction areas. Moraes et al. (2016) found PM_{10} concentration level of 46-214 µg/m^3 for the concrete construction site which is in the range of PM_{10} emission in the steel construction site obtained in this study (3-914 µg/m^3). However, the CLT construction site possessed a significantly less PM_{10} concentration level compared to both steel and concrete construction sites (2-32 µg/m^3). Haynes and Savage (2007) showed that because of the concrete construction of a rail transport hub in London, average concentration levels of PM_{10} and $PM_{2.5}$ increased up to 215 µg/m^3 and 172 µg/m^3 respectively. This study also concluded that the particulates were likely to be from construction activities rather than transport or continental secondary dust sources. Ketchman and Bilec (2013) found a total $PM_{2.5}$ production of 945 kg to excavate 32,000 m^3 of land. Chang et al. (2014) found a maximum PM_{10} concentration of 60 µg/m^3 for a concrete construction site. All of these studies indicated a similar trend of PM emissions during the construction activities.

The short sampling duration of the data collection process could be a limitation of the study. However, the research team believed that using the DustTrak allowed the research team to use a log interval of 59 seconds which means data was collected every 59 seconds. As a result, a very consistent set of data was measured in a 15 minutes time frame. A large log interval might create a high standard deviation in the data set which would disvalue the output of the sampling process. Another reason to adopt 15 minutes sampling time was to observe the activity cycle as in both sites it was found that 15 minutes was sufficient to measure all the activities under the same activity cycle. Also, different measurement time of the PM sizes might arise confusions regarding the value of the measurement. But the research team is concerned that the purpose of this study is comparing two different construction materials, an obvious focus was given to those distinct activities specifically related to two different materials. The research team was successfully able to include all the major activities performed in the construction sites during data collection. The research team tried to focus on specific activities and their emission potential. In that case, the data collection procedure was not compromised. Also, monitoring the weather data supported that there is no correlation of PM emission level with weather factors (e.g. temperature, humidity, and wind speed). Since no correlation was found between weather data and PM emissions, it is possible to say that the PM emission does not vary with the change of time rather it varies with specific activities.

Finally, this study reveals that although construction sites are accountable for emitting a high concentration of particulate matters, still the concentration level is satisfying the standards. The result of this study further discusses the impact of construction materials in particulate matter emissions. Future research should include the control measures of particulate matters during construction works.

CHAPTER 6: DEVELOPING A MULTI-CRITERIA DECISION-MAKING FRAMEWORK TO EVALUATE CONSTRUCTION FEASIBILITY OF MASS TIMBER MATERIALS

Modified from:

Ahmed, S., Arocho, I., (n.d). "Developing a Decision-Making Framework to Select the Most Preferred Building Materials in the U.S. Construction Industry" (Manuscript submitted for review in ASCE Journal of Management in Engineering).

Ahmed, S.; Arocho, I.; (2021). "Choosing by advantages method to select a preferred building material in the U.S. construction industry". Abstract accepted for Construction Research Congress 2022 (Manuscript under review).

6.1 INTRODUCTION

Construction is a highly resource-intensive industry where decisions are often made with minimal research and proper understanding regarding the subject matter (Fischer and Adams, 2011). In the project management operation process, unsuccessful decision-making can generate waste and create conflict. Participation of the stakeholders in the decision-making process and existing concerns regarding sustainability also generate complexities in decision-making (Oehlberg et al., 2010). The absence of information regarding multi-criteria decision-making is another driving element that controls the business experts from steady and congruent decision making (Arroyo et al., 2016). As a result, a scientific method is required to surpass the challenges associated with decision-making. Furthermore, a sound decision-making structure is a fundamental part to make transparency and shared rationale among the stakeholders.

Among many other multi-criteria decision-making tools, choosing by advantages (CBA) is a scientific method that compares value-added advantages of the alternatives (Nnaji et al. 2018). The concept of CBA was introduced by Jim Suhr for the US Department of Agriculture's Forest Service in 1999. The CBA framework is developed on a few predefined criteria and facts that decrease the subjectivities of decisions (Abraham et al., 2013). In order to avoid potential biases, only advantages are incorporated in the CBA framework that transforms personal opinions and judgments into relevant facts and quantifiable data (Suhr, 1999).

The research was aimed to develop a multi-criteria decision-making framework to select a preferred building material for the US construction industry. Three different building materials: concrete, steel, and mass timber were used as alternatives to identify the most preferred building material in terms of CBA analysis. Mass timber is a new form of building material that is gaining momentum in the US construction market (Ahmed and Arocho, 2021). Despite having several advantages including low carbon footprint, environmental sustainability, and natural product; mass timber products need extensive attention in terms of their industry perception and cost compatibility (Ahmed and Arocho, 2020). The research was developed by conducting a nationwide semi-structured questionnaire survey distributed among the industry practitioners in the US, which was predefined using the CBA framework. The outcomes of the survey were utilized to develop the CBA framework as well as to determine the existing industry exposure on mass timber building materials.

The study focused on two major objectives. The first objective of the study is to develop a scientific multi-criteria decision-making framework using the CBA method. The second objective of the study is to evaluate the current level of work exposure among the US construction industry practitioners regarding mass timber building construction projects. The research team has found two unique contributions to this study:

- Developing a sound multi-criteria decision-making tool to select the most preferred building material in the US context
- Determine the current exposure of mass timber as a building material in the US construction industry

6.2 LITERATURE REVIEW

This section discusses the context of mass timber building materials in the U.S. construction industry, including its existing advantages and challenges. Also, the background of a sound decision-making method is reviewed in an extensive manner.

6.2.1 Inception of Mass Timber in the US Construction Market

Despite having double-digit growth rates in the last two decades in Europe, mass timber material is still struggling to find acceptance from industry practitioners (Crespell and Gagnon, 2011). Since its inception in the North American market back in the mid-2000s, some pilot building projects have been accomplished using this new material (Pei et al., 2016). The biggest initial challenge was to develop a comprehensive building code that significantly hindered the progress of mass timber materials in the U.S. In 2011, the first performance-based standard of mass timber building material was developed through a collaborative endeavor of APA-The Engineered Wood Association and FPInnovations (Borjen et al. 2012). More timber manufacturing plants later started producing commercial timber panels. SmartLAM was the first U.S. manufacturers that started commercial timber production in 2012. Now, several leading timber manufacturing companies such as Structurlam, Nordic, and DR Johnson Lumber Company have received APA certification for timber production (Pei et al., 2016). To improve the design efficiency of mass timber buildings, FPInnovations have developed the first peer-reviewed handbook in 2013 (Karacabeyli and Lum, 2014). Pacific Northwestern states such as Oregon and Washington have played a vital role to establish the concept of mass timber materials by setting up more manufacturing plants and conducting more mass timber building projects. At present, multiple research projects are underway to determine the feasibility of mass timber products.

6.2.2 Innovativeness of Mass Timber Materials

Mass timber products have enormous potential to solve many global problems. Due to rapid urbanization and increasing demand for housing, building construction has become more frequent. However, the majority of building materials are known to be high energy-intensive. Crampton (2017) found that the building construction process consumes up to 40 percent of global energy use and produces one-third of the total greenhouse gas emission. Building materials such as concrete and steel have a high carbon footprint that contributes 5 percent of total global carbon emissions (Yale Environment360, 2019). Given this situation, it is imperative to use low energy-intensive building materials having a low impact on global warming and carbon emissions. Wood-based products are a good source of carbon sequestration, and they are known for having a low carbon footprint (NCSU, 2018). According to Ahmed and Arocho (2019), mass timber construction sites emit significantly fewer particulate matter in the air compared to the other construction sites.

The production process of timber panels is completely prefabricated in a built environment, which reduces on-site energy consumption and construction complexities. Besides, the timber construction process requires small labor and crew size that helps to reduce the labor demand in those areas where supply is low. The establishment of timber manufacturing plants contributes to economic growth by providing more employment to the local communities.

6.2.3 Challenges of Using Mass Timber Products

Despite being considered as an innovative and environmentally friendly material, mass timber has several drawbacks that substantially hindering its current growth in the U.S. market. Since there are fewer projects of mass timber materials, there is a lack of quantifiable data on the full-scale design model (Mohammadi and Ling, 2017). Ahmed and Arocho (2021) reported that US construction practitioners are still reluctant to accept mass timber as a mainstream building material. Ling (2014) found that a fire performance test has been performed on a very limited basis in timber joints. The lamination process of timber panels requires extensive use of chemical adhesives that emit volatile organic compounds (VOCs) in the surrounding air, which is hazardous to indoor air quality (Sun et al. 2020). Mallo and Espinoza (2015) reported that the installation inefficiency of mass timber causes considerable acoustic problems. Compared to a typical wood-frame building system, mass timber panels require three times more wood, increasing the cost of construction (Mallo and Espinoza, 2015). The presence of moisture can damage the quality of timber panels. Lack of awareness and work experience among the industry practitioners are obstructing this material from being adopted on a more frequent basis. At present, the majority of timber manufacturing facilities are located in the Pacific Northwest region of the country. As a result, it is difficult to transport timber panels to other parts of the country in terms of cost optimization. Considering these factors, it is crucial to evaluate the future of mass timber building products in the U.S. construction industry. A sound and scientific product comparison between mass timber and other traditional building materials such as concrete and steel could help to identify the actual feasibility of mass timber products.

6.2.4 Importance of Decision-Making in Construction

In the architecture, engineering, and construction industry (AEC), decisions are often made without understanding the technicality of a problem or doing minimal analysis (Fischer and Adams, 2011). Failure to make sound decisions generates conflicts and waste in the project management and operation process. Increasing participation of project stakeholders and growing concerns regarding the social and environmental impacts of a project brings complexities in decision-making (Oehlberg et al., 2010). Although practitioners look for better decision-making tools, the lack of literature does not provide ample reference for them to select the best method for a specific context (Arroyo et al., 2016). In this circumstance, a systematic and scientific multi-criteria decision-making method is necessary to overcome the challenges associated with decision-making. Besides, it creates transparency and a shared rationale for arguing in favor of a sustainable alternative (Arroyo et al., 2016).

6.2.5 Choosing-by-Advantages (CBA) Method of Decision-Making

The CBA is a sound multi-criteria decision-making tool that compares only the value-added advantages of several alternatives and initially developed by Jim Suhr for the U.S. Department of Agriculture's Forest Service in 1999 (Nnaji et al. 2018). The CBA decision-making process is based on mutually agreed-upon criteria and relevant facts that reduce the subjectivities of decisions (Abraham et al., 2013). This method involves identifying only the advantages of the alternatives, rather than both advantages and disadvantages, and anchored personal judgments to relevant facts and quantifiable data that minimizes the chance of potential bias and arbitrary decisions (Suhr, 1999). CBA framework is superior than other multi-criteria decision-making framework such as Linear Optimization, Analytic Hierarchy Process (AHP), and Weighting-Rating Calculation (WRC). The Linear Optimization framework works better for infinite number of alternatives. However, for a few alternatives, CBA has better output. AHP and WRC weigh the factors in terms of their relevant importance. However, since the factors does not represent a context-based judgment, it is not possible to weigh the factors. As a result, the framework creates unnecessary discussion and waste. By contrast, CBA method is based on understanding the advantages of a particular alternative over another. Later, the decision-makers evaluate the importance of those advantages. Therefore, CBA helps the decision-makers to solely focus on the decision context.

The CBA has five major components: alternatives, factor, criterion, attribute, and advantage. Alternatives are two or more materials from which one must be chosen. Factors are the elements for which alternatives are compared. Factors should represent social, economic, and environmental aspects (Arroyo et al., 2016). Criteria are the rules or guidelines that every alternative may satisfy. Attributes are the quality of each alternative. Advantages are the benefits of the attributes. Figure 6.1 shows the definition of CBA components.

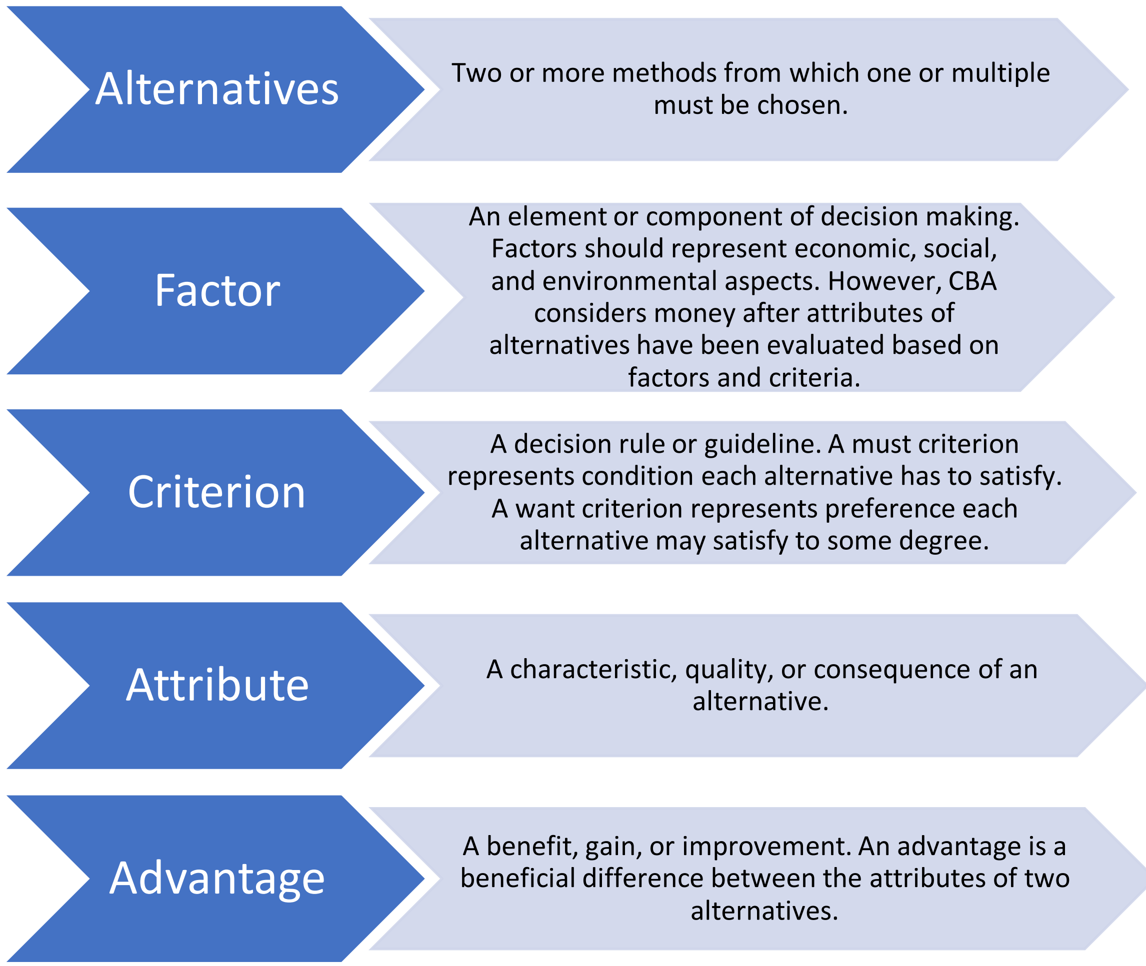


Figure 6. 1 Definition of CBA components (Arroyo et al. 2016)

According to (Arroyo et al. 2016), the decision-making process of CBA includes seven different steps. In the first step, alternatives are identified for comparison. In the second step, factors are developed to compare the alternatives. In the third step, the stakeholders define the must and want criteria for each factor. In the fourth step, attributes are described for each alternative. The fifth step decides the advantages of each alternative based on the subjective judgment of the participants. In sixth step, the stakeholders select the most advantageous factor amongst the other and assigned an importance of advantage (IofA) score of 100 to that advantage. In CBA framework, which is called paramount advantage. After deciding the paramount advantage, the stakeholders assigned IofA score to other advantages relative to the paramount advantage. Finally, in step seven, the stakeholders evaluate the cost data and select the best alternative. Figure 6.2 demonstrates the CBA analysis process.

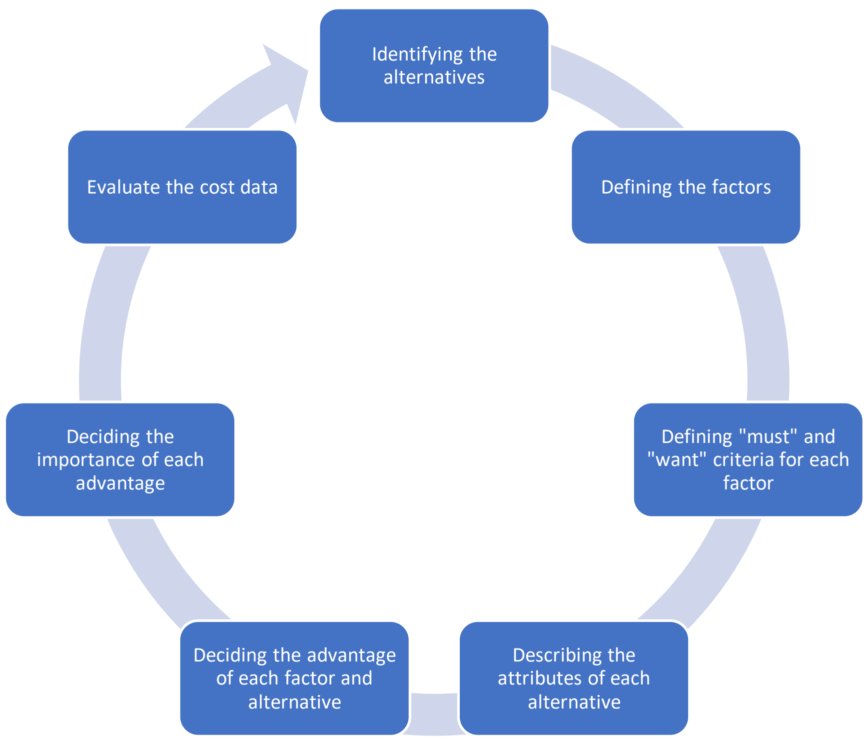


Figure 6. 2 CBA analysis process (Arroyo et al. 2016)

6.3 RESEARCH METHODOLOGY

The study used both qualitative and quantitative research methods. The qualitative method was used to design the CBA framework whereas the quantitative method was used for developing a nationwide questionnaire survey. To continue with the CBA process, a semi-structured questionnaire survey was developed and distributed among 1,050 construction companies and architectural firms in the U.S. The research team received 44 responses from the participants with a response rate of 4.2%. Although the response rate was low, it was sufficient to interpret with the CBA decision-making tool. Before distributing the survey, the Institutional Review Board (IRB) of Oregon State University reviewed and approved the study.

6.3.1 Step-by-Step CBA Process

This section summarizes all the required steps applied for the CBA analysis. The research team followed all seven steps discussed in the literature review section.

6.3.1.1 Developing Alternatives

The first step of the CBA process is to identify the alternatives. The overreaching goal of this study is to identify the most preferred building material for the U.S. construction industry. In addition to that. The research also focuses on evaluating the feasibility of mass timber building material in the US construction industry. To find the actual feasibility of this material, it is crucial to analyze its comparability with traditional building materials such as concrete and steel. Hence, the research team defined mass timber, concrete, and steel as the three alternatives for the study.

6.3.1.2 Defining Factors

In CBA, it is important to identify the factors to make a comparison among the alternatives. The process of identifying the factors is subjective and depends on the requirements of the stakeholders. In this study, the study team utilized previous research experience and existing construction trends in the US to develop the factors. Based on that, eight different factors were identified as key to a successful construction project and represent the views of all stakeholders involved in a construction project. The factors are schedule, safety, quality, environmental pollution, work experience, acceptance level, future, and structural and acoustic performance of the alternatives.

6.3.1.3 Define the 'Must' and 'Want' Criteria

For each factor, the study team established a criterion to evaluate the alternatives. Depending on the attribute, a criterion can be 'must' or 'want'. Some criteria are easily quantifiable (e.g., for environmental pollution, the criterion can be "the lower the pollution, the better") and considered as 'must' criteria. On the other hand, some criteria are not measurable, and the research team had to agree on what they want (e.g., for acceptance level, the criterion can be "higher the acceptance, the better"). These criteria are considered as 'want' criteria. Table 6.1 describes the criteria for all the factors.

Table 6.1 Criteria for the factors

Factor	**Criteria**
Schedule	Faster the construction, the better (Must)
Safety	Fewer accidents during construction, the better (Must)
Quality	More durable the material, the better (Must)
Environmental Pollution	Lower the pollution, the better (Must)
Work Experience	Higher the experience, the better (Must)
Acceptance Level	Higher the acceptance, the better (Want)
Future	Brighter the future, the better (Want)

Structural and Acoustic Performance	More rigid the material, the better (Must)

6.3.1.4 Summarizing the Attributes

In this step, an attribute is defined for each of the factors for all three alternatives. The attributes can be derived from multiple sources such as the manufacturer's technical documents, results from the pilot testing of the alternatives, and the previous studies (Nnaji et al. 2018). In this study, the study team used previous literature and research experience to define those attributes. Table 6.2 summarizes the attributes used for the study.

Table 6.2 Summary of attributes for each factor

Factor	Alternative 1: Mass Timber	Alternative 2: Concrete	Alternative 3: Steel
	Attribute	Attribute	Attribute
Schedule	Project completion time is very fast	Project completion time is somewhat fast	Project completion time is fast
Safety	Construction process is very safe	Construction process is safe	Construction process is somewhat safe
Quality	Durability is questionable	Very durable material	Durable material
Environmental Pollution	Very low pollution potential	High pollution potential	Very high pollution potential
Work Experience	Significantly low work experience	High work experience	High work experience
Acceptance Level	Acceptance level is low	Very high	High
Future	Future is somewhat promising	Future is very promising	Future is promising
Structural and Acoustic Performance	Materials is somewhat rigid	Material is very rigid	Material is rigid

6.3.1.5 Deciding the Advantages of the Alternatives

After summarizing the attributes, the criteria are applied to determine the advantage of the alternatives. This part of the study was performed by the survey respondents as they were asked to identify the best alternative based on predetermined factors and criteria. For each factor, the alternative that was found most advantageous compared to other alternatives, considered as the most preferred alternative for that specific factor. Subsequently, the alternative with no advantage was considered as the least preferred material.

6.3.1.6 Assigning Importance of Advantage (IofA) Score

A crucial part of the CBA process is to assign the importance of advantage (IofA) score to each factor for all the alternatives. Scores should be assigned based on experience and subjective judgment to facilitate the decision-making process. In this study, the survey participants were asked to assign an IofA score to each alternative for all previously determining factors based on their work experience and knowledge of working in mass timber building projects. Among all the respondents, the study team used responses only from those participants who were previously involved in mass timber construction projects. At first, the respondents were assigned a maximum score of 100 to the paramount advantage from all the factors. The paramount advantage was selected from the most preferred attributes and factors. In the next step, the participants were asked to assign the IofA score to all other advantages relative to the paramount advantage. IofA score for the least preferred attribute always gets a zero for all the factors. The study team, after receiving responses from the participants, summed up the total IofA score for each alternative, and determine which one gets the highest IofA score.

6.3.1.7 Evaluating the Cost Data

The final step of the CBA process is to evaluate the cost data of the alternatives and compare the cost with the IofA scores. In the CBA process, the cost is considered as a constraint instead of value because costs are often restricted in construction projects. Often time, the allowable cost of a construction project is limited and does not generate any value. Also, the cost is considered as an extrinsic characteristic of an alternative, which can be changed by negotiation and depends on the existing market condition. Thus, cost should not be analyzed in the same way as other factors. CBA does not imply selecting the least expensive alternative, but rather this process vitalizes selecting an alternative that possesses the best project outcomes within certain financial restrictions. The research team utilized a previous study that compared dollars per square feet construction cost of concrete, steel, and mass timber/light-frame wood buildings built in the US between 2013-2015 (McLain, R; 2015) to evaluate the cost-value performance of the alternatives. The study analyzed per square feet cost of 202 concrete buildings, 383 mass timber/ light-frame wood buildings, and 983 steel buildings built between 2013-2015.

6.3.2 Survey Development for the Study

The questionnaire survey developed for this study has three major parts. The first part of the survey covered demographic information of the participants including the type of company, number of employees, average annual budget, job position, and work experience. The second part of the survey comprised questions related to the CBA process. In this part, the respondents were asked to provide one advantage for all predetermined factors and attributes for all three alternatives. After that, they were asked to select the paramount advantage from all the factors and attributes based on their experience and knowledge. In the last part, the respondents assigned an IofA score of 100 to their selected paramount advantage and assigned an IofA score to all other advantages relative to the paramount advantage. A web-based tool named Qualtrics was used to develop the survey. This software allows the researchers to create their questionnaire surveys and distribute the surveys using a simple web link. The survey was semi-structured, meaning it has both quantitative as well as open-ended qualitative questions. The survey was developed in such a way so that the participants can demonstrate their opinions and experience in the most efficient manner.

6.3.3 Sample Selection

Once the survey was developed, the research team applied to the Institutional Review Board (IRB) of Oregon State University to review the survey study. IRB promotes ethical principles of respect for the human subjects participate in the research. It also protects the right and welfare of the study participants. After receiving the IRB approval, the study team selected samples used for the study. A total of 850 construction companies and 200 architectural firms were contacted to participate in the study. Oregon State University Department of Civil and Construction Engineering has a list of general contractors and specialty subcontractors, which was used for the study. The list of architects was developed from ArchDaily “Top 300 Architectural Firms in the U.S.” (Walsh 2019). Heavy civil contracting companies were excluded from the study since they do not use mass timber materials. Samples were selected regardless of company size and budget to allow consistency. Also, the samples were selected from all around the country to ensure a nationwide representation of the participants.

6.3.4 Survey Distribution

The research team used participants' publicly available emails to distribute the survey. The research team aimed to conduct a double-round of survey distribution method to ensure maximum participation of the industry practitioners. However, due to some logistic difficulties, the study team had to use a single-round of survey distribution. The survey window was open for 2 months to allow ample time for the participants to answer the surveys. The responses from the participants were stored anonymously in the Qualtrics for data analysis.

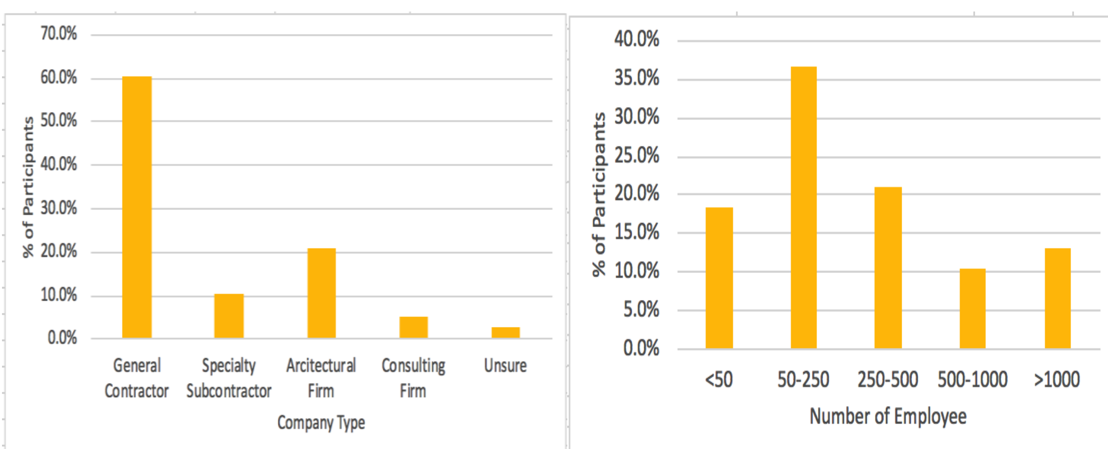
6.4 RESULT

The result section comprised of two parts: demographic information of the participants and analyzing the CBA outcomes. Findings of the CBA framework were tabulated and discussed comprehensively.

6.4.1 Demographic Information of the Participants

The research team specifically focused on the company demographic of the participants to ensure consistency of the study. Another crucial objective of the demographic analysis was to determine the diversity and current level of awareness among the industry practitioners regarding mass timber building materials. Thus, data analysis was performed on demographic information of the respondents' workplace focusing on the type of company, the number of employees, average annual budget, and years of experience in mass timber construction.

The findings of demographic information suggested that the participants came from very diverse backgrounds including small to very large companies, general contractors to consulting firms. Among all the participants, 60.5% came from general contracting companies followed by the architectural firm (21%). However, 2.6% of the participants were unsure about their company type. In regard to employee size, 36.7% of the respondents mentioned that their company's employee size is 50-250, representing small to mid-size companies. However, a significant percentage of participants (10.5% and 13.2%) indicated that their employee size is 500-1000 and >1000 respectively, which imitate participation of large companies as well. Information on the average annual budget of the companies also suggested the participation of large companies as 32.4% of participants responded that their average annual budget is >$400 million. While answering the question of work experience on mass timber, the majority of the participants said their experience level is between 0-1 year, which indicates that the concept of mass timber building is still not familiar among the industry practitioners. Figure 6.3 shows the demographic information of the participants.



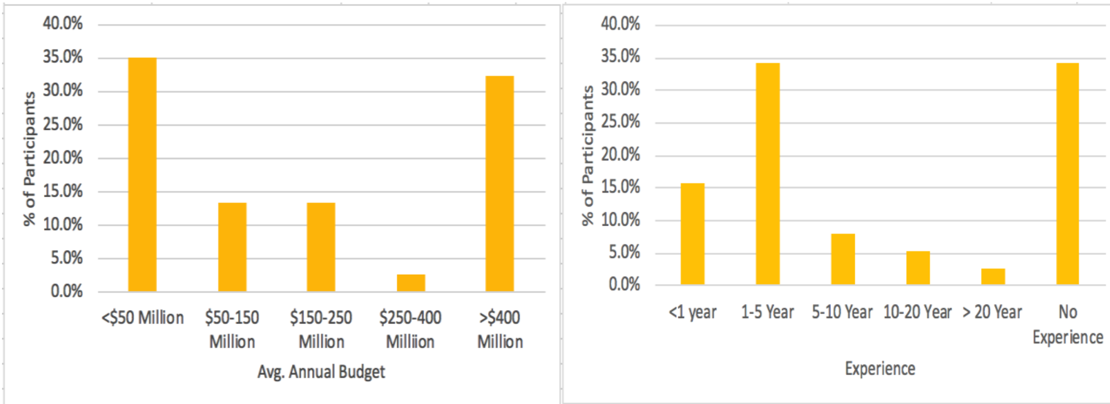


Figure 6. 3 Demographic information of the participants (n=44)

6.4.2 Evaluating the Alternatives Using CBA Framework

The most important part of the study is to evaluate the alternatives using the CBA multi-criteria decision-making method. Although the total number of participants of the study was 44, for the CBA analysis process, the research team only utilized the responses from those who have experience in mass timber building construction projects. Exclusion of respondents without having experience in mass timber construction helped the study to attain maximum accuracy. Also, the research team screened out some of the responses because the participants could not properly follow the instruction while answering the survey. As a result, their responses became erroneous and failed to align with the CBA methodology. Finally, the CBA framework was developed based on 26 accurate responses from the participants.

As mentioned before, the research team developed eight different factors for the study along with a criterion and attribute for each of the factors and alternative. The participants were asked to mention one advantage based on the criterion for that particular factor and alternative. The study team used qualitative content analysis to determine the most presiding advantage of each factor and alternative. Next, the participants were asked to select the most important advantage that they mentioned earlier, which is called paramount advantage in CBA terminology. Among all the advantages, the schedule advantage for the concrete option was selected as the paramount advantage as the highest number of participants concluded that the project completion time of concrete buildings is relatively faster than its steel and mass timber counterpart. The participants stated that due to a high degree of precision and increasing collaboration among the project parties, the majority of concrete construction projects are completed on time and ahead of the initial schedule. They further illustrated that the trades involved in concrete construction are highly experienced and familiar with the work type, which also helps concrete building projects to finish on time. The paramount advantage for this study was selected based on frequency as six participants selected concrete schedule as the most important advantage, which was highest among all other factors. After selecting the paramount advantage, the participants assigned a score of importance (IofA) to the advantages they indicated. First, they assigned an IofA score of 100 to their respected paramount advantage and then they assigned an IofA score to other advantages relative to the paramount advantage. The research team used the mean IofA score for the other advantages to determine the final IofA scores for each of the factors and alternative. For each factor, the alternative with the highest IofA score was considered as the most preferred alternative. Similarly, alternative with the lowest IofA score was considered as the least preferred alternative. The least preferred alternatives were later assigned with an IofA score of zero to simplify the calculation process. According to data analysis, the concrete option has been chosen as the most preferred alternative for schedule, work experience, acceptance level, and structural and acoustic performance factors. Besides selecting the schedule advantage of concrete as the paramount advantage, the participants also pointed that trades and subs are highly experienced with concrete construction that results in wide acceptance of concrete material among the industry practitioners and stakeholders. They further indicated that concrete exhibits better compression and acoustic performance compared to steel and mass timber. The participants selected mass timber as the most preferred alternative for safety, quality, environmental pollution, and future factors. They concluded that the mass timber construction operation process is safer compared to concrete and steel due to less on-site labor requirement. They further stated that prefabricated nature and low carbon emission of mass timber materials are two vital driving factors that can lead this material as the future of building construction. Surprisingly, steel was not selected as the most preferred alternative for any factors. Although the participants of the study mentioned that steel has certain advantages for schedule, work experience, and current acceptance level, it was insufficient to be selected as the most preferred alternative when comparing with concrete and mass timber.

Once assigning the mean IofA score to each alternative for eight predefined factors, the research team summed up the total IofA scores. Among all three alternative building materials, concrete was determined as the most preferred building material with a total IofA score of 612.7 followed by mass timber (367) and steel (236.2). Table 6.3 summarizes the outcomes of CBA analysis.

Table 6.3 Summary of CBA framework

Factor (Criterion)	Alternative 1: Concrete	Alternative 2: Mass Timber	Alternative 3: Steel
Schedule (Faster the construction, the better)	Attribute: Project completion time is somewhat fast Advantage: Fast Completion due to collaboration **IofA: 100 (Paramount advantage)**	Attribute: Project completion time is very fast Advantage: Quick to assemble **IofA: 0 (Least preferred)**	Attribute: Project completion time is fast; Advantage: Quick assembly and erection **IofA: 81.9**
Safety (Fewer accidents during construction, the better)	Attribute: Construction process is safe; Advantage: Less safety hazard, inherent fire protection; **IofA: 74.1**	Attribute: Construction process is very safe; Advantage: Less on-site labor; **IofA: 76.5 (Most preferred)**	Attribute: Construction process is somewhat safe; Advantage: Less onsite work, **IofA: 0 (least preferred)**
Quality (More durable the material, the better)	Attribute: Material durability is high; Advantage: Very durable material; **IofA: 74.8**	Attribute: Material durability is questionable; Advantage: Pre-fab material **IofA: 75.8 (most preferred)**	Attribute: Material durability is high; Advantage: Pre-fab with high tolerances; **IofA: 0 (Least preferred)**
Environmental Pollution (Lower the pollution, the better)	Attribute: High pollution potential; Advantage: Lower pollution than steel; **IofA: 56.3**	Attribute: Very low pollution potential, Advantage: Low carbon emission; **IofA: 71.7 (Most preferred)**	Attribute: Very high pollution potential; Advantage: Renewability; **IofA: 0 (Least preferred)**
Work Experience (Higher the experience, the better)	Attribute: High work experience; Advantage: Highly experience workforce; **IofA: 77.6 (Most preferred)**	Attribute: Significantly low work experience; Advantage: Simple labor training; **IoA: 0 (Least preferred)**	Attribute: High work experience; Advantage: Experienced workforce; **IofA: 75.2**
Acceptance Level (Higher the acceptance, the better)	Attribute: Acceptance level is very high; Advantage: Highly accepted by all trades; **IofA: 80.6 (Most preferred)**	Attribute: Acceptance level is low; Advantage: Becoming more acceptable; **IofA: 0 (Least preferred)**	Attribute: Acceptance level is high; Advantage: Widely accepted and cheapest; **IofA: 79.1**
Future (Brighter the future, the better)	Attribute: Future is very promising; Advantage: Widely accepted because of material availability; **IofA: 70.8**	Attribute: Future is somewhat promising; Advantage: Support green building movement **IofA: 74.7 (Most preferred)**	Attribute: Future is promising; Advantage: Readily available material; **IofA: 0 (Least preferred)**
Structural and Acoustic Performance (More rigid the material, the better)	Attribute: The material is very rigid; Advantage: Great in compression and acoustic; **IofA: 78.5 (Most preferred)**	Attribute: The material is somewhat rigid; Advantage: Structurally good, acoustic needs work; **IofA: 68.3**	Attribute: The material is rigid; Advantage: Great in tensile, acoustically better; **IofA: 0 (Least preferred))**
Total IofA Score	**612.7**	**367**	**236.2**

6.4.3 Value-Cost Analysis of the Alternatives

In the CBA process, a value-cost analysis has to be performed before selecting the most value-generating alternative. Typically, with the absence of cost factor, the alternative with the highest IofA score should be selected. However, the alternatives used for the study perform differently in terms of cost competitiveness. As a result, a metric-based value-cost analysis is required to determine the most value-generating alternative.

In this study, dollars per square foot construction cost of concrete, steel, and mass timber buildings built in the US between 2013-2015 are compared with the IofA scores obtained through the CBA framework. Based on the analysis, it was found that steel is the most expensive building material ($190/SF) compared to concrete and mass timber with the lowest IofA score of 236.2. Mass timber was found as the least expensive material ($115/SF). However, its IofA score (367) was lower than concrete (612.7). Concrete material was placed in a favorable position compared to mass timber and steel with the highest IofA score of 612.7 and a moderately expensive cost ($164/SF). The result indicated that although the material cost of concrete is 42.6% higher than the mass timber option, the IofA score of concrete is 40.1% higher than mass timber. Figure 6.4 depicts the outcome of the value-cost comparison.

Figure 6. 4 Value-cost analysis of the alternatives

6.4.4 Selection of the Best Alternative

Based on the circumstance detailed in the value-cost analysis, concrete generates the most value compared to steel and mass timber. It is the most impactful building material in terms of schedule, work experience, current acceptance level, and structural and acoustic performance. Although concrete is not the most cost-effective material, its functionality and industry-wide acceptance make this material dominant over its steel and mass timber counterpart. It also has a lower cost per square feet cost compared to steel. Since cost is a crucial project success parameter, it is important for the stakeholder to determine the best possible alternative with certain financial boundaries. Although the cost for concrete was higher than mass timber, but concrete adds the highest value in terms of importance score. That being said, concrete is the most preferred building material using the CBA framework in this study.

6.5 CONCLUSION AND RECOMMENDATION

A scientific decision-making process is essential for improving the overall construction project management. Particularly for the construction industry where decision-making is even more critical, a scientifically backed framework of decision-making could potentially enhance the project performance outcomes. Concerning building materials, increasing concerns are circulating among the stakeholders to ensure sustainability. As a highly resource-intensive industry, construction industry practitioners are becoming more lenient to achieve sustainable green development. To attain that goal, and improved collaboration among the stakeholders with a sound decision-making process is highly recommended.

The study centered on developing a sound multi-criteria decision-making framework to determine the most preferred building material in the US construction industry. Three different building materials: concrete, steel, and mass timber are used as the study alternatives. Although concrete and steel are already established as conventional building materials in the US construction industry, mass timber is a new and sustainable material, which is still gaining momentum. Hence, mass timber was included with concrete and steel to identify the existing industry perception regarding this material, which is another major objective of the study.

To develop the CBA framework, the research team used eight major parameters associated with building construction: schedule, safety, quality, work experience, environmental pollution, the current level of acceptance, future, and structural and acoustic performance. The alternatives were compared to each other with the scope of these eight predefined factors. To collect the data and develop the framework, a nationwide questionnaire survey was conducted. Since the CBA process only compares advantages among the alternatives, the participants were asked to define one advantage for each of the factors for all three alternatives, based on which the framework was developed, and the final decision was made.

In order to identify the diversity and consistency of the participants in terms of their company size, demographic information is also analyzed that includes the type of company, number of employees, average annual budget, and participants' experience in mass timber building construction projects. The research team wanted to ensure that the participants from different project parties with different company sizes participate in the study.

The outcomes of the study suggested that according to the CBA framework, concrete is the most preferred building material among the industry practitioners with a total IofA score of 612.7. The highest number of participants selected the schedule advantage of concrete material as the paramount advantage. The participants mentioned that project completion time for concrete building is faster than steel and mass timber due to the high level of collaboration among the project entities. Concrete was also selected as the most preferred material for work experience, current acceptance level, and structural and acoustic performance-related advantages. Mass timber alternative received the second-highest IofA score (367) with being selected as the most preferred building material for safety, quality, environmental pollution, and future advantages. The participants concluded that less on-site labor requirement, prefabricated nature of mass timber panels, and low carbon emission rate make this product a compelling alternative. Also, the participants mentioned that mass timber has the brightest future compared to concrete and steel because of its sustainability, environmental susceptibility, and natural availability. Finally, the steel option received the lowest IofA score (236.2) and was selected as the least preferred alternative for safety, quality, environmental pollution, future, and structural and acoustic related advantage. The participants indicated that steel building construction sites are less safe than concrete and mass timber. Also, its environmental pollution potential is higher than the other two alternatives.

An important part of the CBA framework is value-cost analysis. The CBA process does not consider cost as an advantage, rather it states cost as a constraint. Thus, a value-cost analysis of the alternatives is required to provide additional information to the stakeholders in terms of the financial aspects of the projects. The findings of value-cost analysis suggested that mass timber was the least expensive material compared to steel and concrete while steel was the most expensive option with the lowest value generation. Concrete on the other hand was moderately expensive with the highest value generation. Although concrete is more expensive than mass timber considering its numerous advantages and current industry-wide acceptance, concrete was selected over mass timber as the most preferred building material for this study.

The demographic information of the respondents demonstrated that they are representative of mid-level to large construction entities including general contractors, architectural firms, and specialty subcontractors. An important finding of the study suggested that construction industry practitioners have a low level of work experience in mass timber building construction projects. Around 35% of the respondents said that they have no work experience in mass timber while 15% of them said their experience level is less than a year.

The findings of the study have multiple contributions to mainstream construction research. The study developed a scientific multi-criteria decision-making framework that determines the most preferred building material in the US. The industry practitioners can utilize this study as a guideline before selecting their structural material. Since the method only assesses the advantages of the alternatives, the decision-makers can easily identify the most value-generating alternative for their projects. It will also allow them to evaluate their project performance within financial boundaries, which will eventually help them to make sound decisions. Finally, the outcome of the study will encourage the stakeholders to use the CBA framework for other alternatives and help them to eliminate conflicts and waste from the project management operation process.

The proposed decision-making framework of this study has several limitations. First, the survey return rate for the study is low. For future research, more participants from the industry should be included. Second, the study participants did not go through any specific training program for the CBA method. As a result, some of the participants failed to fill out the survey in the right way. It is recommended that future participants should go through proper training protocols on the CBA framework before joining the study. Third, the study only utilized eight factors to compare the alternatives. In reality, decision-makers may have more factors that they want to consider before concluding. Finally, the cost information used for the study was obtained from previous research performed between 2013-2015. In order to perform a value-cost analysis, more recent cost information of the alternatives is required.

CHAPTER 7: CONCLUDING REMARKS

7.1 SUMMARY OF RESEARCH

The research centers on determining the feasibility of mass timber building materials in the US construction market. To achieve this goal systematically, three different aspects of mass timber materials were analyzed in the dissertation. Since the concept of mass timber is still gaining momentum in the US market, the research performed an industry perception study on mass timber to identify the current awareness level among the industry practitioners regarding this material. It further determines existing construction-related advantages and challenges associated with mass timber and how to overcome those challenges by providing several recommendations. The study was developed by conducting industry-wide questionnaire surveys distributed among the general contractors, specialty subcontractors, architects, and mass timber manufacturers in the US.

The dissertation next focuses on evaluating the construction cost compatibility of mass timber building projects compared to the traditional building material. To perform this study, an 18-story mass timber student residence hall located in Canada was used as a case study. The initial cost estimate of the building utilized both mass timber and concrete. The building was finally made with mass timber and the final cost estimation was performed for mass timber as well. However, the project management team also utilized their previous experience to model a final cost estimation for concrete material as well. As a result, this study analyzed four different estimations for the study, budgeted cost of mass timber building, budgeted cost of a concrete building, actual cost of mass timber building, and modeled cost of the concrete building. The study considered 17 construction activities to compare the cost difference for both materials. It also analyzed the change orders that occurred during the construction and found a total of 205 change orders categorized in 10 root causes.

The next part of the dissertation is to assess the air pollution potential of mass timber materials. To accomplish that objective, a mass timber building construction site, a steel building construction site, and a regular location were used. The study focuses on particulate matter (PM) concentration in the air because of its importance and ubiquitous nature. PMs are also positively correlated with other air pollutants in the air, thus it was used in the study to determine the air pollution potential of the building materials. Four different sizes of PM were analyzed to ensure accuracy. A total of 900 data points of four different PM sizes were collected from three locations for five days to perform statistical analysis. Several statistical methods were used to validate the findings of the study.

The final part of the dissertation includes developing a multi-criteria decision-making framework to evaluate the construction feasibility of mass timber materials. A sound decision-making tool named choosing-by-advantages (CBA) was used for the evaluation process. CBA is a value-based method and focuses only on the advantages that make it superior to other decision-making methods. It also promotes collaboration and provides a transparent rationale for the decision-makers when choosing among two or more alternatives. The study is developed by conducting an industry-wide questionnaire survey to allow the practitioners to participate in the CBA framework. The study incorporated eight major factors used for building constructions to develop the CBA framework. The outcomes of the study determine if mass timber is a preferred building material for the US construction industry compared to concrete and steel.

7.2 MAJOR FINDINGS AND KEY CONTRIBUTIONS

Several major findings and key contributions are presented at different chapters of this dissertation. A summary of those are presented below:

7.2.1 Chapter 3 (Manuscript 1,2, and 3)

The awareness level among the US industry practitioners regarding mass timber is significantly low. The majority of the building contractors and architects who participated in the study were not involved in mass timber building construction projects. Those who have been involved in mass timber construction also exhibit a very low level of work experience (0-1 year).

Small labor requirements, prefabricated nature, renewability, and low carbon footprint of timber panels are some of the advantages of mass timber identified by the participants. Inexperience and unskilled labor, lack of coordination among the project parties, unawareness, high cost, design difficulty, material unavailability, and insufficient manufacturing plants are the major challenges of mass timber.

Several recommendations are provided that will augment the adoption of mass timber materials in the US. An increasing number of mass timber buildings and manufacturing facilities, collaboration among the project parties, awareness, code development, and support from local authorities are the major factors that could enhance the future of this material.

7.2.2 Chapter 4 (Manuscript 4 and 5)

The construction cost of mass timber building is relatively more expensive than the concrete option. Among all different activities, the cost of engineered wood was found as the main factor of higher cost. The installation cost of the timber structure was also found relatively high. Mass timber panels need extensive use of cranes to fly and install the panels, indicating that high installation cost is related to the high usage of cranes. Another notable cost source was the cost of project staffing, indicating that the operation cost of manpower specialists in mass timber construction is higher than the traditional workforce. Change orders are found as a significant source of construction cost increase. In this study, change orders were characterized in ten different categories, and analysis determined that change order request from the consultant is the primary source of a change order for this project in terms of frequency and dollar amount. Descriptive statistics of the change orders suggested that the cost associated with change orders is not frequency-dependent but rather it depends on the type of activity. An interesting observation regarding the change order is although the building was constructed by mass timber, its impact on change orders is insignificant.

Several recommendations are provided to reduce the cost of mass timber building construction. Since the cost of engineered wood is high mostly because of material unavailability, it is important to make timber products available all around the country. Increasing the number of timber manufacturing plants will certainly help to reduce the price of wood. Equipment operation needs to be optimized to reduce the installation cost, and a qualified workforce needs to develop to decrease the cost of project staffing.

The study also suggested some remedies to avoid change orders during the construction phase of the project. The findings of the study demonstrate that coordination between the project parties is highly important so that any type of error can be avoided during construction. Project pre-planning would be an effective action to detect design deficiencies in the early phase of the project. Hiring an experienced project management team can also play a crucial role to reduce change orders and increase the value of the project.

7.2.3 Chapter 5 (Manuscript 6 and 7)

Construction sites are responsible for emitting high PM concentrations compared to other locations. Mass timber is a relatively less hazardous construction material than steel regarding PM emission. Steel construction involves more hazardous activities than mass timber construction that can produce more PM. Activities such as welding, and fabrication were observed several times during data collection are believed to be responsible for a high concentration of emission. On the other hand, timber construction does not require any welding works thus it is presumable that mass timber produces relatively less PM during construction. Although both construction sites emitted a higher concentration of particulate matter than the reference location, in the majority of the cases, concentration levels are found below EPA standard for particulate matters. Timber is considered an environmentally friendly material and this study also indicated that the air pollution footprint of timber building construction is significantly less than a steel building construction.

7.2.4 Chapter 6 (Manuscript 8 and 9)

According to the CBA framework, concrete is the most preferred building material in the US construction industry followed by mass timber and steel. Concrete has advantages over mass timber and steel in schedule, work experience, current acceptance level, and structural and acoustic performance. Mass timber is found advantageous in terms of safety, quality, environmental pollution, and future. Steel did not get selected as the most preferred material for any factors. Although mass timber ranked second according to CBA methodology, it was found that less on-site labor requirement, prefabricated nature, and low carbon emission rate make mass timber product an alluring alternative for the future. In addition to that, because of its sustainable and environmentally friendly nature, mass timber has the potential to become the most preferred building material in the future.

7.3 LIMITATIONS AND FUTURE WORK

The research work performed in this dissertation have multiple limitations, which may be overcome in the future following the suggested work as below.

- A significant part of this dissertation is developed by using questionnaire surveys. It is crucial to involve the maximum number of participants to accurately project the findings. In this study, the rate of participants is relatively low. Although the rate is sufficient for statistical analysis and validation, it is recommended that future research will incorporate more participants for more accurate outcomes.

- The cost competitiveness study of this dissertation is based on only one project. As a result, it is difficult to generalize the findings of the study. Future research should include more construction projects to justify the results.
- In order to perform any multi-criteria decision-making analysis, it is important to teach the method to potential participants. In this study, the participants did not get any prior chance to familiarize themselves with the CBA tool. As a result, some of the participants failed to respond to the survey accordingly. Future research should undertake a prior training session to educate the participants about the method.

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APPENDIX A: QUESTIONANIRE SURVEY FOR GENERAL CONTRACTORS

Questionnaire Survey (Constructor)

Start of Block: Default Question Block

Q1 Type of company? (Select all that applies)

- ▢ General contractor (1)
- ▢ Specialty subcontractor (2)
- ▢ Engineering firm (3)
- ▢ Consultant (4)

Q2 Number of employees?

- ◯ <50 (1)
- ◯ 50-250 (2)
- ◯ 250-500 (3)
- ◯ 500-1000 (4)
- ◯ >1000 (5)

Q3 Average annual budget?

- <50 million (1)
- 50-150 million (2)
- 151-250 million (3)
- 250-400 million (4)
- >400 million (5)

Q4 What job title best describes you?

- Project Manager (1)
- Project Engineer (2)
- Foreman (3)
- Site Supervisor (4)
- Worker (5)

Q5 Have you heard about mass timber building?

- Yes (1)
- No (2)

Q6 Have you ever been involved in mass timber building construction?

- Yes (1)
- No (2)

Q7 Years of experience on mass timber building construction?

- <1 (1)
- 1-5 (2)
- 5-10 (3)
- 10-20 (4)
- >20 (5)

Q8 In your opinion, how available are mass timber materials in the U.S.?

- Very much (1)
- Somewhat (2)
- Not at all (3)

Q9 Do you believe that the geographic location of the construction site affects the overall quality of the project?

- Yes (1)
- No (2)

Q10 If your answer is yes in the previous question, describe how the geographic location of the construction site affects the overall quality of the project.

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Q11 From your experience, identify the type of building that is most suitable for mass timber construction. (Select all that apply)

- ▢ Family housing (1)
- ▢ Commercial buildings (2)
- ▢ Health care buildings (3)
- ▢ Industrial buildings (4)

Q12 Select the response that best characterizes how you feel about the statement: "The construction cost of mass timber building is higher than the traditional concrete and steel buildings".

- ◯ Strongly agree (1)
- ◯ Agree (2)
- ◯ Somewhat agree (3)
- ◯ Neither agree nor disagree (4)
- ◯ Somewhat disagree (5)
- ◯ Disagree (6)
- ◯ Strongly disagree (7)

Q13 Select the response that best characterizes how you feel about the statement: "The construction time of mass timber building is faster than the traditional concrete and steel buildings".

- ◯ Strongly agree (1)
- ◯ Agree (2)
- ◯ Somewhat agree (3)
- ◯ Neither agree nor disagree (4)
- ◯ Somewhat disagree (5)
- ◯ Disagree (6)
- ◯ Strongly disagree (7)

Q14 Identify how expensive is mass timber building construction in comparison to concrete and steel.

- Very Expensive (>10%) (1)
- Somewhat Expensive (>5%) (2)
- Neither expensive or inexpensive (3)
- Inexpensive ((4)
- Very Inexpensive ((5)

Q15 Identify the completion time of mass timber buildings in comparison to concrete and steel buildings.

- Extremely fast ((1)
- Moderately fast ((2)
- Slightly fast ((3)
- Neither fast or slow (4)
- Slightly slow (>5%) (5)
- Moderately slow (>10%) (6)
- Extremely slow (>20%) (7)

Q16 In your opinion, how safe is mass timber building construction operation in comparison to concrete and steel?

◯ Very safe (1)

◯ Safe (2)

◯ Not sure (3)

◯ Unsafe (4)

◯ Very unsafe (5)

Q17 List three reasons that support your opinion that mass timber construction operation process is safe in comparison to concrete and steel construction.

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Q18 List three reasons that support your opinion that mass timber construction operation process is not safe in comparison to concrete and steel construction.

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Q19 In your opinion, what is the efficiency level of the workers involved in mass timber construction?

- ○ Very efficient (1)
- ○ Somewhat efficient (2)
- ○ Neither efficient or inefficient (3)
- ○ Somewhat inefficient (4)
- ○ Very efficient (5)

Q20 List three specific construction related difficulties that you have experienced in mass timber building construction.

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Q21 Identify three major factors that would streamline the construction process operation of mass timber building.

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Q22 In your opinion, how complicated is the mass timber construction operation process in comparison to concrete and steel buildings?

- ◯ Very complicated (1)
- ◯ Somewhat complicated (2)
- ◯ Neither complicated or uncomplicated (3)
- ◯ Somewhat uncomplicated (4)
- ◯ Very uncomplicated (5)

Q23 Identify the top three reasons that result in complication of mass timber building construction.

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Q24 Have you ever experienced any health-related issues because of working in a mass timber construction project?

- ◯ Yes (1)
- ◯ No (2)

Q25 If your answer to the previous question is yes, describe what type of health-related issues you have experienced.

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End of Block: Default Question Block

APPENDIX B: QUESTIONANIRE SURVEY FOR ARCHITECTS

Questionnaire Survey (Architects and Designers)

Start of Block: Default Question Block

Q1 Have you heard about mass timber buildings?

- ○ Yes (1)
- ○ No (2)

Q2 Have you ever involved in mass timber building design?

- ○ Yes (1)
- ○ No (2)

Q3 Identify the existing level of awareness among the architect community regarding mass timber buildings (Select your response).

- ○ Architects and designers are completely aware (1)
- ○ Architects and designers are somewhat aware (2)
- ○ Architects and designers are neither aware or unaware (3)
- ○ Architects and designers are somewhat unaware (4)
- ○ Architects and designers are completely unaware (5)

Q4 List three current design-related difficulties of mass timber buildings.

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Q5 Identify the sufficiency of codes and specifications available for designing mass timber buildings (Select your response).

- ○ Codes and specifications are very much sufficient (1)
- ○ Codes and specifications are somewhat sufficient (2)
- ○ Codes and specifications are neither sufficient or insufficient (3)
- ○ Codes and specifications are somewhat insufficient (4)
- ○ Codes and specifications are very much insufficient (5)

Q6 Do you believe that the geographic location of the building affects the overall quality of the project?

- ○ Yes (1)
- ○ No (2)

Q7 If your previous answer is yes, describe how the geographic location of the building affects the overall quality of the project.

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Q8 From your experience, identify the type of building most suitable for mass timber material. (Select your response/s).

- ▢ Family housing (1)
- ▢ Commercial buildings (2)
- ▢ Health care buildings (3)
- ▢ Industrial buildings (4)

Q9 Identify the current social acceptance of mass timber building (Select your response).

- ○ Very high (1)
- ○ High (2)
- ○ Neither high or low (3)
- ○ Low (4)
- ○ Very low (5)

Q10 List three points to improve the existing design-related difficulties of mass timber buildings.

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Q11 List three positive factors affecting the mass timber building projects.

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Q12 List three negative factors affecting the mass timber building projects.

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Q13 In your opinion, what is the future of mass timber building in the North American construction industry? (Select your response).

- Very good (1)
- Good (2)
- Neither good or bad (3)
- Bad (4)
- Very bad (5)

Q14 How many years of experience you have designing mass timber buildings? (select your response)

- <1 year (1)
- 1-5 years (2)
- 5-10 years (3)
- 10-20 years (4)
- >20 years (5)

Q16 Number of employees in your company?

- ◯ <50 (1)
- ◯ 50-250 (2)
- ◯ 250-500 (3)
- ◯ 500-1000 (4)
- ◯ >1000 (5)

Q17 Average annual budget of your company?

- ◯ <50 Millions (1)
- ◯ 51-100 Millions (2)
- ◯ 151-250 Millions (3)
- ◯ 251-400 Millions (4)
- ◯ >400 Millions (5)

End of Block: Default Question Block

APPENDIX C: QUESTIONANIRE SURVEY FOR MANUFACTURER

Questionnaire Survey (Manufacturer)

Start of Block: Default Question Block

Q1 List three major advantages of current mass timber production technology.

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Q2 List three major challenges that current mass timber manufacturers are facing.

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Q3 In your opinion, what is the future of mass timber building in the North American construction industry?

- ◯ Very good (1)
- ◯ Good (2)
- ◯ Neither good or bad (3)
- ◯ Bad (4)
- ◯ Very bad (5)

Q4 Identify three major factors that would streamline the current production process of mass timber.

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Q5 Have you ever experienced any health-related issues because of working in mass timber manufacturing plant?

- ◯ Yes (1)
- ◯ No (2)

Q6 If your answer to the previous question is yes, describe what type of diseases you have experienced.

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Q7 How many years of experience you have in mass timber manufacturing?

○ <1 year (1)

○ 1-5 years (2)

○ 5-10 years (3)

○ 10-20 years (4)

○ >20 years (5)

Q8 Number of employees in your company?

○ <50 (1)

○ 50-250 (2)

○ 251-500 (3)

○ 501-1000 (4)

○ >1000 (5)

Q9 Average annual budget of your company?

○ <50 Millions (1)

○ 50-150 Millions (2)

○ 151-250 Millions (3)

○ 251-400 Millions (4)

○ >400 Millions (5)

End of Block: Default Question Block

APPENDIX D: QUESTIONANIRE SURVEY FOR CBA STUDY

CBA Study Survey

Start of Block: Default Question Block

Q1 Q#1. What type of company do you work for?

- General Contractor (1)
- Specialty Subcontractor (2)
- Architectural Firm (3)
- Consulting Firm (4)
- Unsure (5)

Q2 Q#2. How many employees work at your company?

- <50 (1)
- 50-250 (2)
- 250-500 (3)
- 500-1000 (4)
- >1000 (5)
- Unsure (6)

Q3 Q#3. What is your company's annual budget?

- (1)
- $50-150 million (2)
- $150-250 million (3)
- $250-400 million (4)
- >$400 million (5)
- Unsure (6)

Q4 Q#4. What job title best describes you?

- Project Engineer (1)
- Project Manager (2)
- Architect (3)
- Site Supervisor (4)
- Worker (5)
- Other (6)

Q5 Q#5. How many years of experience do you have on concrete building construction?

○ No Experience (1)

○ <1 Year (2)

○ 1-5 Year (3)

○ 5-10 Year (4)

○ 10-20 Year (5)

○ >20 Year (6)

Q6 Q#6. How many years of experience do you have on mass timber building construction?

○ No Experience (1)

○ <1 Year (2)

○ 1-5 Year (3)

○ 5-10 Year (4)

○ 10-20 Year (5)

○ >20 Year (6)

Q7 Q#7. How many years of experience do you have on steel building construction?

- ○ No Experience (1)
- ○ <1 Year (2)
- ○ 1-5 Year (3)
- ○ 5-10 Year (4)
- ○ 10-20 Year (5)
- ○ >20 Year (6)

Q8 Q#8. Based on your experience in the U.S. construction industry, rank mass timber, concrete, and steel building materials in terms of construction convenience with 1 being the most convenient and 3 the least convenient.

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Q9 Q#9. Based on your experience in the U.S. construction industry, which of the following is the most important factor for a construction project?

- ○ Schedule (1)
- ○ Quality (2)
- ○ Safety (3)
- ○ Work Experience (4)
- ○ Environmental Pollution Potential (5)
- ○ Current Acceptance Level of a Specific Building Material (6)
- ○ Future of a Specific Building Material (7)
- ○ Structural and Acoustic Performance (8)

Q10 Q#10. Based on your experience in the U.S. construction industry, write an advantage for each of the following factors for all three building materials.

	Schedule (1)	Quality (2)	Safety (3)	Work Exp. (4)	Env. Pollution Potential (5)	Acceptance Level (6)	Future (7)	Structural and Acoustic Performance (8)
Mass Timber (1)								
Concrete (2)								
Steel (3)								

Q11 Q#11. On a scale of 1-100, assign a score of importance to each of the following factors for **mass timber** building option (Please assign 100 only once to your most preferred building material in Q#8 and the most important factor you selected in Q#9. As an example, if you select concrete in Q#8 as your number one preferred building material and schedule as the most important factor in Q#9, assign 100 to schedule factor for concrete option and assign other importance scores relative to that score).

0 10 20 30 40 50 60 70 80 90 100

Schedule ()	
Quality ()	
Safety ()	
Work Experience ()	
Environmental Pollution Potential ()	
Acceptance Level of Mass Timber ()	
Future of Mass Timber ()	
Structural and Acoustic Performance ()	

Q12 Q#12. On a scale of 1-100, assign a score of importance to each of the following factors for concrete building option (Please assign 100 only once to your most preferred building material in Q#8 and the most important factor you selected in Q#9. As an example, if you select concrete in Q#8 as your number one preferred building material and schedule as the most important factor in Q#9, assign 100 to schedule factor for concrete option and assign other importance scores relative to that score).

0	10	20	30	40	50	60	70	80	90	100

Schedule ()	
Quality ()	
Safety ()	
Work Experience ()	
Environmental Pollution Potential ()	
Acceptance Level of Concrete Building ()	
Future of Concrete Building ()	
Structural and Acoustic Performance ()	

Q13 Q#13. On a scale of 1-100, assign a score of importance to each of the following factors for steel building option (Please assign 100 only once to your most preferred building material in Q#8 and the most important factor you selected in Q#9. As an example, if you select concrete in Q#8 as your number one preferred building material and schedule as the most important factor in Q#9, assign 100 to schedule factor for concrete option and assign other importance scores relative to that score).

0 10 20 30 40 50 60 70 80 90 100

Schedule ()	
Quality ()	
Safety ()	
Work Experience ()	
Environmental Pollution Potential ()	
Acceptance Level of Steel Building ()	
Future of Steel Building ()	
Structural and Acoustic Performance ()	

End of Block: Default Question Block

APPENDIX E: MASTER ESTIMATE FILE FOR COST STUDY

Project: Brock Commons Tallwood Student Residences
Owner / Client: UBC Properties Trust
Date: 9-Jan-18

	CONCRETE OCT. 2015	WOOD HYBRID OCT. 2015	CONCRETE DEC. 2017	WOOD HYBRID DEC. 2017
Date	October 22, 2015	October 22, 2015	December 8, 2017	December 8, 2017
Suites:	305	305	305	305
Beds:	404	404	404	404
GSF:	162,752	162,752	162,752	162,752
TOTAL $:	$36,211,985	$39,028,292	$36,883,935	$39,203,356
Duration (months):	18.00	16.00	23.00	21.00

CONCRETE OCT. 2015 / WOOD HYBRID OCT. 2015

CONSTRUCTION PHASE	Concrete Oct. 2015 – TOTAL BUDGET: BUDGET	COST PER GSF	COST PER BED	PERCENT BUILDING	Wood Hybrid Oct. 2015 – TOTAL BUDGET: BUDGET	COST PER GSF	COST PER BED	PERCENT BUILDING
01-General Conditions	$ 2,608,637	$ 16.03	$ 6,457	7.20%	$ 2,398,010	$ 14.73	$ 5,936	6.14%
02-Existing Conditions/Demolition	$ -	$ -	$ -	0.00%	$ -	$ -	$ -	0.00%
03-Concrete	$ 6,444,569	$ 39.60	$ 15,952	17.80%	$ 3,621,537	$ 22.25	$ 8,964	9.28%
04-Masonry	$ 105,671	$ 0.65	$ 262	0.29%	$ 105,671	$ 0.65	$ 262	0.27%
05-Metals	$ 388,918	$ 2.39	$ 963	1.07%	$ 503,920	$ 3.10	$ 1,247	1.29%
06-Wood & Plastics	$ 714,259	$ 4.39	$ 1,768	1.97%	$ 5,103,689	$ 31.36	$ 12,633	13.08%
07-Thermal & Moisture Protection	$ 5,030,933	$ 30.91	$ 12,453	13.89%	$ 5,056,139	$ 31.07	$ 12,515	12.96%
08-Doors & Windows	$ 1,995,590	$ 12.26	$ 4,940	5.51%	$ 1,824,190	$ 11.21	$ 4,515	4.67%
09-Finishes	$ 3,736,954	$ 22.96	$ 9,250	10.32%	$ 4,589,581	$ 28.20	$ 11,360	11.76%
10-Specialties	$ 260,053	$ 1.60	$ 644	0.72%	$ 260,053	$ 1.60	$ 644	0.67%
11-Equipment	$ 638,101	$ 3.92	$ 1,579	1.76%	$ 638,101	$ 3.92	$ 1,579	1.63%
12-Furnishings and Common Area Fit-Outs	$ 1,438,360	$ 8.84	$ 3,560	3.97%	$ 1,438,360	$ 8.84	$ 3,560	3.69%
13-Special Construction	$ -	$ -	$ -	0.00%	$ -	$ -	$ -	0.00%
14-Elevators	$ 815,000	$ 5.01	$ 2,017	2.25%	$ 815,000	$ 5.01	$ 2,017	2.09%
21,22,23-Mechanical	$ 5,878,880	$ 36.12	$ 14,552	16.23%	$ 6,316,780	$ 38.81	$ 15,636	16.19%
26,27, 28-Electrical	$ 3,035,000	$ 18.65	$ 7,512	8.38%	$ 3,325,000	$ 20.43	$ 8,230	8.52%
31-Earthwork	$ 636,675	$ 3.91	$ 1,576	1.76%	$ 547,875	$ 3.37	$ 1,356	1.40%
32-Exterior Improvements	$ 700,492	$ 4.30	$ 1,734	1.93%	$ 700,492	$ 4.30	$ 1,734	1.79%
33-Utilities and Road Work	$ 884,140	$ 5.43	$ 2,188	2.44%	$ 884,140	$ 5.43	$ 2,188	2.27%
Sub Total	**$ 35,312,231**	**$ 216.97**	**$ 87,407**	**97.52%**	**$ 38,128,537**	**$ 234.27**	**$ 94,378**	**97.69%**
UBCPT Deduction - Offsite Civil Work Within Base Budget	$ -	$ -	$ -	0.00%	$ -	$ -	$ -	0.00%
Suite Deficiencies	$ 168,693	$ 1.04	$ 418	0.47%	$ 168,693	$ 1.04	$ 418	0.43%
Warranty Management	$ 168,693	$ 1.04	$ 418	0.47%	$ 168,693	$ 1.04	$ 418	0.43%
Overhead and Fee	$ 554,000	$ 3.40	$ 1,371	1.53%	$ 554,000	$ 3.40	$ 1,371	1.42%
Sub-Total Concept Budget	**$ 36,203,617**	**$ 222.45**	**$ 89,613**	**99.98%**	**$ 39,019,923**	**$ 239.75**	**$ 96,584**	**99.98%**
Risk Allowance **NIC**	$ 8,368	$ 0.05	$ 21	0.02%	$ 8,368	$ 0.05	$ 21	0.02%
Escalation Allowance **NIC**	$ -	$ -	$ -	0.00%	$ -	$ -	$ -	0.00%
Total Concept Budget excl. GST	**$ 36,211,985**	**$ 222.50**	**$ 89,634**	**100.00%**	**$ 39,028,292**	**$ 239.80**	**$ 96,605**	**100.00%**

CONCRETE DEC. 2017 / WOOD HYBRID DEC. 2017 / VARIANCE TO CONCRETE

CONSTRUCTION PHASE	Concrete Dec. 2017 – MODELED COST INCLUDING SCOPE CHANGES: PROFORMA COST	COST PER GSF	COST PER BED	PERCENT BUILDING	Wood Hybrid Dec. 2017 – ACTUAL COST WITH SCOPE CHANGES: FINAL COST	COST PER GSF	COST PER BED	PERCENT BUILDING	VARIANCE TO CONCRETE: COST	%
01-General Conditions	$ 3,123,013	$ 19.19	$ 7,730	8.47%	$ 3,353,942	$ 20.61	$ 8,302	8.56%	$ 230,928	7.39%
02-Existing Conditions/Demolition	$ -	$ -	$ -	0.00%	$ -	$ -	$ -	0.00%	$ -	#DIV/0!
03-Concrete	$ 6,444,569	$ 39.60	$ 15,952	17.47%	$ 3,444,546	$ 21.16	$ 8,526	8.79%	$ (3,000,023)	-46.55%
04-Masonry	$ 105,671	$ 0.65	$ 262	0.29%	$ 84,400	$ 0.52	$ 209	0.22%	$ (21,271)	-20.13%
05-Metals	$ 388,918	$ 2.39	$ 963	1.05%	$ 868,214	$ 5.33	$ 2,149	2.21%	$ 479,296	123.24%
06-Wood & Plastics	$ 714,259	$ 4.39	$ 1,768	1.94%	$ 3,694,941	$ 22.70	$ 9,146	9.43%	$ 2,980,681	417.31%
07-Thermal & Moisture Protection	$ 5,030,933	$ 30.91	$ 12,453	13.64%	$ 5,070,685	$ 31.16	$ 12,551	12.93%	$ 39,752	0.79%
08-Doors & Windows	$ 1,995,590	$ 12.26	$ 4,940	5.41%	$ 1,974,931	$ 12.13	$ 4,888	5.04%	$ (20,659)	-1.04%
09-Finishes	$ 3,736,954	$ 22.96	$ 9,250	10.13%	$ 4,791,605	$ 29.44	$ 11,860	12.22%	$ 1,054,651	28.22%
10-Specialties	$ 260,053	$ 1.60	$ 644	0.71%	$ 100,436	$ 0.62	$ 249	0.26%	$ (159,617)	-61.38%
11-Equipment	$ 638,101	$ 3.92	$ 1,579	1.73%	$ 575,381	$ 3.54	$ 1,424	1.47%	$ (62,720)	-9.83%
12-Furnishings and Common Area Fit-Outs	$ 1,438,360	$ 8.84	$ 3,560	3.90%	$ 2,092,968	$ 12.86	$ 5,181	5.34%	$ 654,607	45.51%
13-Special Construction	$ -	$ -	$ -	0.00%	$ -	$ -	$ -	0.00%	$ -	#DIV/0!
14-Elevators	$ 815,000	$ 5.01	$ 2,017	2.21%	$ 800,000	$ 4.92	$ 1,980	2.04%	$ (15,000)	-1.84%
21,22,23-Mechanical	$ 5,878,880	$ 36.12	$ 14,552	15.94%	$ 6,189,580	$ 38.03	$ 15,321	15.79%	$ 310,700	5.29%
26,27, 28-Electrical	$ 3,035,000	$ 18.65	$ 7,512	8.23%	$ 3,326,166	$ 20.44	$ 8,233	8.48%	$ 291,166	9.59%
31-Earthwork	$ 636,675	$ 3.91	$ 1,576	1.73%	$ 607,715	$ 3.73	$ 1,504	1.55%	$ (28,960)	-4.55%
32-Exterior Improvements	$ 700,492	$ 4.30	$ 1,734	1.90%	$ 455,073	$ 2.80	$ 1,126	1.16%	$ (245,419)	-35.04%
33-Utilities and Road Work	$ 1,243,713	$ 7.64	$ 3,078	3.37%	$ 1,243,713	$ 7.64	$ 3,078	3.17%	$ -	0.00%
Sub Total	**$ 36,186,180**	**$ 222.34**	**$ 89,570**	**98.11%**	**$ 38,674,294**	**$ 237.63**	**$ 95,728**	**98.65%**	**$ 2,488,114**	**6.88%**
UBCPT Deduction - Offsite Civil Work Within Base Budget	$ (193,631)	-$ 1.19	$ (479)	-0.52%	$ (193,631)	-$ 1.19	$ (479)	-0.49%	$ -	0.00%
Suite Deficiencies	$ 168,693	$ 1.04	$ 418	0.46%	$ -	$ -	$ -	0.00%	$ (168,693)	-100.00%
Warranty Management	$ 168,693	$ 1.04	$ 418	0.46%	$ 168,693	$ 1.04	$ 418	0.43%	$ -	0.00%
Overhead and Fee	$ 554,000	$ 3.40	$ 1,371	1.50%	$ 554,000	$ 3.40	$ 1,371	1.41%	$ -	0.00%
Sub-Total Concept Budget	**$ 36,883,935**	**$ 226.63**	**$ 91,297**	**100.00%**	**$ 39,203,356**	**$ 240.88**	**$ 97,038**	**100.00%**	**$ 2,319,421**	**6.29%**
Risk Allowance **NIC**	$ -	$ -	$ -	0.00%	$ -	$ -	$ -	0.00%	$ -	0.00%
Escalation Allowance **NIC**	$ -	$ -	$ -	0.00%	$ -	$ -	$ -	0.00%	$ -	0.00%
Total Concept Budget excl. GST	**$ 36,883,935**	**$ 226.63**	**$ 91,297**	**100.00%**	**$ 39,203,356**	**$ 240.88**	**$ 97,038**	**100.00%**	**$ 2,319,421**	**6.29%**

ORIGINAL EXPECTED HYBRID TIMBER PREMIUM COSTS VS. CONCRETE BUILDING

	Incremental Costs of BSSB Site-Specific Regulation		
1	Concrete Works Associated with NBCC 2015 due to SSR	310,000	1.90
2	Acoustic Concrete Topping	275,393	1.69
3	Temporary Riser for Fire-Protection during Construction	40,688	0.25
4	10,000 Gallon Emergency Water Tank	73,159	0.45
5	GWB Ceiling Fire Rated & Acoustical Assembly	1,395,732	8.58
6	Fire Protection - Fire Pump, Sprinkler heads, flex connectors	115,300	0.71
7	Plumbing - Floor drains suites, flex connectors, expansion/contraction loops, copper piping to en-suites	285,300	1.75
8	HVAC - Stair pressurization, expansion/contraction segments, flex connectors	37,300	0.23
	SUB-TOTAL SSR EXPECTED INCREMENTALS:	**2,532,872**	**15.56**
	Other Cost Differences of Hybrid Timber Vs. Concrete		
9	Concrete Works (Non SSR Balance)	(3,314,842)	(20.37)
10	Saving by not doing slab prep for spraytex	(93,582)	(0.58)
11	Steel Roof Structure (Metal Deck)	381,514	2.34
12	S&I Wood Structure (material, prep, install)	3,626,604	22.28
13	Temporary Water Protection	325,503	2.00
14	Temporary Heating Premium	56,963	0.35
15	Beauty Cap to Ceiling Inside Façade Panels	(171,400)	(1.05)
16	Floor prep for hard surfaces	(262,360)	(1.61)
17	Spraytex to Concrete Ceilings	(280,745)	(1.72)
18	General Conditions (Schedule savings)	(210,627)	(1.29)
19	Additional Soil Anchors (Concrete Option)	(88,800)	(0.55)
20	Saving for Inverted Roof in lieu of Built-up System for Wood Option	25,205	0.15
21	Electrical - Conduit not in Concrete Slabs	290,000	1.78
	SUB-TOTAL OTHER EXPECTED INCREMENTALS:	**283,434**	**1.74**
	TOTAL ALL EXPECTED INCREMENTALS:	**$ 2,816,307**	**$ 17.30**
	Wood Hybrid Concept Budget, October 2015:	$ 39,028,292	$ 239.80

TOTAL ALL ACTUAL INCREMENTALS:	**$ 2,319,421**	**$ 14.25**
Wood Hybrid Completed Project, December 2017:	$ 39,203,356	240.88