

Optimizing Mass Timber Bay Size in terms of Costs and EC Emission

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Abstract

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The built environment accounts for the largest portion of global carbon emissions. In particular, carbon emissions known as embodied carbon (EC) emitted from traditional building structures such as concrete and steel frames accounts for one-third of the total emissions. In the future, the proportion of EC is expected to increase further and in response to this, a significant amount of studies suggest the use of mass timber structure as a low carbon solution. However, the cost of mass timber is still relatively high compared to traditional material, which is a primary reason that mass timber is still under-utilized. In addition, studies on optimization of mass timber bay size, which can be an effective method to lower costs and EC emission, are limited. That makes it difficult to identify the optimal alternatives in terms of cost and EC emission under current mass timber design processes. To fill this knowledge gap, this study aims to develop a new approach—named the timber bay cost and carbon optimization approach (TBCCOA)—which can support effective comparison

between various mass timber alternatives in terms of volume, cost and EC emission in the initial design stage. To demonstrate the validity and usability of the TBCCOA, I developed two scenarios, and valuable findings on optimization of mass timber bay size were discovered by comparing the cost and EC emission of diverse virtual structure alternatives. The key findings of the scenarios include that (1) 6 m × 6 m is the optimal bay size for mass timber structure in terms of volume, cost and EC emission in general and (2) the application of square bay is more efficient than the rectangular bay. These results of the present study can support project stakeholders, when adopting mass timber as building structure, to reduce construction costs and EC emission of buildings at the initial design stage, as a way to mitigate global climate change. In addition, future researchers can utilize the information derived from this study as a stepping stone for bay size standardization of mass timber buildings.

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TABLE OF CONTENTS

LIST OF FIGURES.....	8
LIST OF TABLES.....	10
LIST OF EQUATIONS.....	11
CHAPTER 1. INTRODUCTION.....	12
CHAPTER 2. LITERATURE REVIEW.....	15
Mass Timber Structure.....	15
Types of Carbon Emission and Significance of EC Emission.....	16
Timber Bay Design Tool.....	17
Life Cycle Assessment and Environmental Product Declaration.....	18
Definition of Bay.....	20
Point of Departure.....	20
CHAPTER 3. RESEARCH METHODOLOGY.....	22
Overall Research Process.....	22
Quantifying the Costs of Mass Timber Components.....	24
Quantifying the EC Emissions of Mass Timber Components.....	25
CHAPTER 4. TIMBER BAY COST AND CARBON OPTIMIZATION APPROACH (TBCCOA).....	26
Advantages of the Initial Stages of Timber Bay Design.....	26
Preliminary Testing for Scenario.....	28
Steps in TBCCOA.....	30
Comparison of Results.....	35
CHAPTER 5. SCENARIO 1.....	36
Project Description.....	36
Data Collection.....	39
Scenario Results.....	40
CHAPTER 6. SCENARIO 2.....	48
Project Description.....	48
Data Collection.....	49
Scenario Results.....	50

CHAPTER 7. CONCLUSION.....	57
Findings and Recommendations	57
Limitations	59
Future Study	61
REFERENCES.....	62
APPENDIX.....	66

LIST OF FIGURES

Figure 1. Global energy-related CO2 emissions by sector (2015).....	12
Figure 2. Cross-Laminated Timber (CLT) (right) and glulam (left)	15
Figure 3. Life cycle stages from BS EN 15978:2011	19
Figure 4. Research Methodology Diagram	22
Figure 5. Research Process Framework.....	23
Figure 6. EPD range of glulam sourced from EC3.....	25
Figure 7-1. Existing mass timber design process.....	27
Figure 7-2. Mass timber design process using the TBCCOA.....	27
Figure 8. Optimization Graph of Timber Volume Per Area for a Square Bay Steps in TBCCOA.....	29
Figure 9-1. The default value of the Timber Bay Design Tool	30
Figure 9-2. The adjusted value of the Timber Bay Design Tool	30
Figure 10. 3D model of Timber Bay.....	31
Figure 11. EPD data sourced from EC3.....	34
Figure 12. Typical Floor Assembly of Brock Commons Tallwood House	37
Figure 13. Plans of alternatives for Scenario 1	38
Figure 14. 3D models of 6 m × 6 m alternatives for Scenario 1	39
Figure 15-1. CLT volume per area of all alternatives.....	41
Figure 15-2. Glulam volume per area of all alternatives	41
Figure 15-3. Mass Timber total volume per area of all alternatives.....	42
Figure 16-1. CLT ratio of mass timber volume, cost and EC emissions (3-story building)....	44
Figure 16-2. Glulam ratio of mass timber volume, cost and EC emissions (3-story building).....	44
Figure 17. Plans of alternatives (Number of purlins=1) for Scenario 2.....	49
Figure 18. 3D models of alternatives (Number of purlins=1) for Scenario 2.....	49

Figure 19-1. CLT volume per area of all alternatives.....	51
Figure 19-2. Glulam volume per area of all alternatives	51
Figure 19-3. Mass Timber total volume per area of all alternatives.....	51
Figure 20. Mass Timber Design Process Framework.....	59

LIST OF TABLES

Table 1. Types of mass timber for structure components	16
Table 2. Variables and Constants of the Study	28
Table 3. Results of the preliminary testing	29
Table 4. CLT panel costs	33
Table 5. Cost and EPD data per volume	35
Table 6. Bay size and area of Scenario 1 alternatives.....	38
Table 7. Mass timber volume information of 3-story building alternatives	40
Table 8. Mass timber volume, cost, EC emission information of 3-story building alternatives	43
Table 9. Quantity ratio comparison between square vs square bays and square vs rectangular bays....	46
Table 10. Bay size and area of Scenario 2 alternatives.....	48
Table 11. Mass timber volume information of building which has 1-purlin	50
Table 12-1. Mass timber volume, cost, EC emission information of 1-purlin building alternative.....	53
Table 12-2. Mass timber volume, cost, EC emission information of 2-purlin building alternative.....	53
Table 12-3. Mass timber volume, cost, EC emission information of 3-purlin building alternative.....	54
Table 13-1. Volume per Area value of all alternatives of Scenario 2.....	54
Table 13-2. Cost per Area value of all alternatives of Scenario 2.....	54
Table 13-3. Embodied Carbon Emission per Area value of all alternatives of Scenario 2.....	55

LIST OF EQUATIONS

(1) Length of Girder-1	32
(2) Length of Girder-2	32
(3) Length of Purlin	32
(4) Length of Column	32
(5) Length of Panel	32
(6) Width of Panel.....	32
(7) Number of panels	32
(8) Number of purlins	32
(9) Total volume of each component	32
(10) Total volume of overall mass timber.....	32

CHAPTER 1. INTRODUCTION

There is no doubt that the recent extreme climate events and change around the world is deeply affecting our lives. Especially, millions of people from all over the world are suffering from rising temperatures in the summer. The critical cause of such global warming over several decades is anthropogenic gas emissions which trap the heat in the earth (Barcelo et al., 2013). The United Nations Environment Program highlighted global energy-related CO₂ emissions by sector and the buildings and construction industry account for the biggest portion (39%) among sectors as shown in Figure 1 (Global Status Report 2017, 2022). Specifically, buildings which emit operational carbon (OC) account for 28% and the construction industry which emits embodied carbon (EC) accounts for 11% of global CO₂ emissions (Abel, 2020). Given the trend, the present study focuses on EC emissions and detailed explanation about OC and EC with significance of embodied carbon will be dealt in Chapter 2.

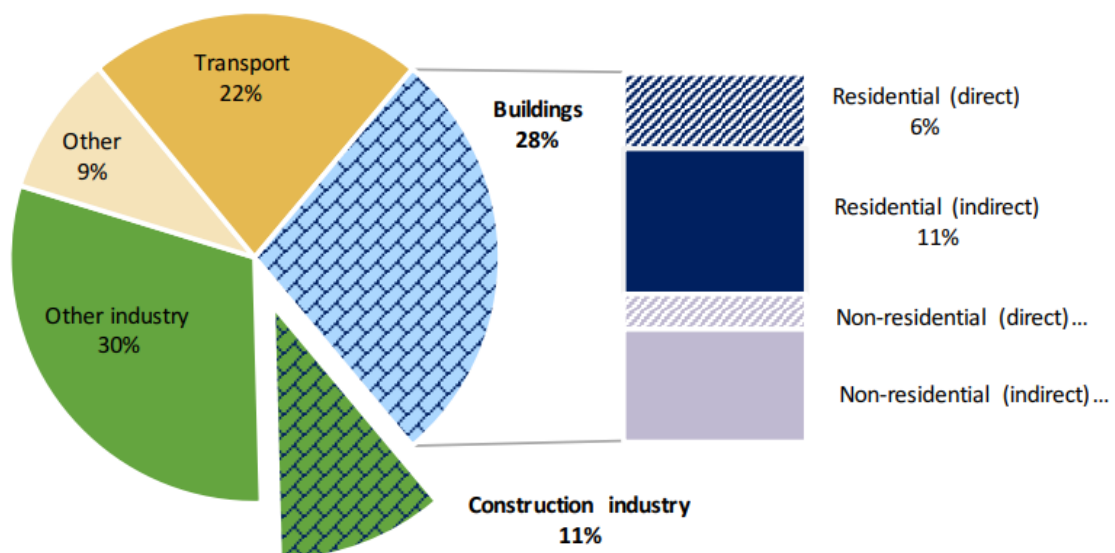


Figure 1. Global energy-related CO₂ emissions by sector (2015)

(Image source: https://worldgbc.org/wp-content/uploads/2022/03/UNEP-188_GABC_en-web.pdf)

To reduce EC from construction, low-carbon building material such as mass timber can be an ideal solution. Previous studies have shown that mass-timber-structured buildings are superior to traditional structures such as concrete and steel in terms of sustainability (Chen et al., 2021; Liang et al., 2020). Despite these environmental advantages, studies have also shown that mass timber is inferior to traditional material in terms of cost. For example, Harte (2017) reported that the construction cost of a mass timber building is around 8% higher than the reinforced concrete structure of a building in similar conditions and size. More seriously, the higher cost of timber structures is one of the significant factors that disrupt achieving sustainable aims and “Optimizing cost is an urgent prerequisite to embodied carbon reduction” (Chaggaris, 2021). This is a significant reason why more buildings are still being built with traditional structure types even though the use of mass timber has been increasing recently. To minimize the cost of mass timber and strengthen its sustainable characteristics, it is necessary to find the optimal bay size of the mass timber structure in terms of volume. This is because the volume of the structure is proportional to the cost and EC emission. However, it should be noted that the ratio of volume to cost and volume to EC emission is not necessarily 1:1 (the relationship between them will be discussed in Chapter 5 Scenario 1 in greater details).

Under the current design process of mass timber structure, it is difficult to identify the optimal alternatives in terms of volume, cost and EC emission in an efficient method. It is because the process of designing wood structure alternatives and the process of estimating cost and EC emission is complicated and separated. To integrate these processes and suggest straightforward methods to find the optimal alternatives, the objective of the present study is to develop a new approach titled the timber bay cost and carbon optimization approach (TBCCOA). The TBCCOA aims to improve the efficiency of mass timber initial design process to save time and expense invested.

Additionally, I developed two scenarios with virtual mass timber structure to demonstrate the validity and usability of TBCCOA. The results of the scenarios show that TBCCOA can be used effectively as a guideline of mass timber structure design. Furthermore, several results were found that have many implications for mass timber optimization. The detailed contents of findings are described in Chapter 7 Conclusion.

With the application of TBCCOA, project stakeholders can simplify the process of identifying the optimal mass timber alternative in terms of cost and EC emissions, by applying the findings of this study to the initial mass timber structure design process. Through this, this study will support project stakeholders to reduce the volume of mass timber by applying the optimal mass timber bay size for future projects. This, in turn, should help increase the value of mass timber as a substitute of traditional structures by reducing the cost and EC emission as well. The results of the study indicate that using optimized alternatives of mass timber structure not only has a positive effect on the global climate environment but also brings financial benefits to the project stakeholders concurrently.

CHAPTER 2. LITERATURE REVIEW

This Chapter provides a summary of literature review that was conducted at the onset of the study. It starts from knowledge about mass timber and contains the basic information necessary for this study to be conducted. And it ends with a description of starting point and knowledge gap of this study.

Mass Timber Structure

As a feasible alternative for traditional structures, mass timber comprises a group of engineered wood products that function as structural components (Harte, 2017; SkyCiv, 2021). Representative types of mass timber are as follows: Cross-Laminated Timber (CLT), Glue-Laminated Timber (Glulam), Laminated Veneer Lumber (LVL), Dowel-Laminated Timber (DLT) and Mass Plywood Panel (MPP) (Ayanleye et al., 2022).

The most commonly used types are CLT, glulam and LVL (Wang et al., 2018) and this study deals with CLT and glulam only, to simplify the research process and results. In specific, CLT is fabricated by the adhesion of transverse and longitudinal layers of timber with adhesives for structure (Kremer & Symmons, 2015). Glulam is manufactured with the composition of wood laminations that are attached with long-lasting adhesives (APA, 2022).



Figure 2. Cross-Laminated Timber (CLT) (right) and glulam (left)

(Image source: <https://kallesoemachinery.com/>)

The structure of a mass timber building is composed of a combination of vertical, horizontal, and floor structural members. They are called columns, beams and panels, respectively, and the two components of the beams are girders and purlins. Girders are supported by the columns and the purlins are frames located between the girders. Based on the comparable strength and properties of stiffness with a reinforced concrete slab (Kremer & Symmons, 2015), the CLT is normally utilized as a panel. The rest of the structural members, such as columns and beams, are usually engineered by glulam. This study will use this fundamental knowledge as a precondition of research, as shown in Table 1, to estimate the volume of mass timber separately for the scenarios.

Table 1. Types of mass timber for structure components

Structure components		Type
Panel		CLT
Column		Glulam
Beam	Girder	
	Purlin	

Types of Carbon Emission and Significance of EC emission

The environmental features of building are largely related to the two types of carbon emission, namely, operational carbon and embodied carbon. The quantity of OC emissions is measured from the operation of the buildings that burn fossil fuels (Jankovic & Christophers, 2022) such as heating, cooling and lighting. Therefore, on the assumption that the insulation and mechanical/electrical performance of buildings is similar, there is no significant correlation between the type of structure and OC emissions. In contrary, the EC of buildings refers to carbon emissions which are emitted during the whole life cycle of the buildings from the production of material to demolition stages and it includes not only the emissions from the

structure itself but also by-products of the process of manufacturing and transportation (Anderson & Moncaster, 2020). Therefore, building structure selection type is directly related to the emission of EC.

Comparing the two types of global energy-related CO₂ emissions, ratio of OC is higher than EC as described in Chapter 1. However, the ratio of OC emitted from buildings has decreased recently due to progress in energy efficiency technology and strengthened building codes addressing energy efficiency (Liu & Leng, 2022). This means as the proportion of OC emissions is reduced by higher energy efficiency of building systems, the proportion of EC emissions rises (Jensen et al., 2020). Therefore, as a countermeasure to the emerging issue of EC emitted from future buildings, sustainable construction such as mass timber can be considered as a feasible solution.

Timber Bay Design Tool

As a supportive mean of structural calculation, this study used the Timber Bay Design Tool. The Timber Bay Design Tool was developed by Fast + Epp, an international structural engineering firm headquartered in Canada. Various parameters—such as bay dimension, the number of purlins and the number of building floors—can be adjusted within a certain range. As a result of the combination of chosen parameters, the sizes of a unitary girder, purlin, column and panel are provided with timber volume/area (m³ / m²) information. To quantify the timber volume of the entire building structure, a timber bay cost and carbon optimization approach (TBCCOA) has been developed and will be presented in Chapter 4 with the support of the tool.

By utilizing the tool, it is possible to explore the optimized timber bay size for specific situations of projects and this will be helpful to suggest an optimized way to

minimize the volume of mass timber. Ultimately, finding a minimized timber volume alternative will contribute to the reduction of EC emissions and costs. Below are the notes mentioned with the tool, providing the structural rationale for this tool and its limitations (Fast + Epp, 2022).

- “Outputs should be considered preliminary and are intended for concept purposes only. The structural engineer of record is responsible for the final design.”
- “Calculations performed based on CSA O86-14 & BCBC 2018.”
- “Vibration calculations are preliminary and should be investigated on a case-by-case basis.”
- “Panels and glulam members have fabrication and shipping constraints that vary between suppliers. Layouts should be reviewed with your selected suppliers.”
- “Floor panels are assumed to be two-span continuous, equally loaded interior panels.”
- “Calculations are performed using Douglas Fir species for columns, girders, purlins and GLT panels; spruce–pine–fir species are used for CLT/NLT/DLT panels.”
- “Volume take-offs are preliminary and assume a rectangular building layout; final volumes will vary depending on building shape.”

Life Cycle Assessment and Environmental Product Declaration

To achieve a significant reduction of GHG emissions which mostly consist of carbon dioxide, accurate calculations of gas emissions should come first and the emission of any material can be measured by life cycle assessment (LCA) (Mohebbi et al., 2021). LCA was devised at the Midwest Research Institute in the USA in the 1970s (Klöpffer, 1997) and has developed rapidly over the last few decades (Guinée et al., 2010). Based on the definition by the International Organization for Standardization (ISO), LCA is a means of evaluating the life cycle of a product system which consumes and emits any sources affecting the environment

(Finnveden et al., 2009; ISO, 2006a). Specifically, a product’s life cycle includes the extraction of raw materials, processing, manufacturing, distribution (or transportation), use and final disposal. (Guine et al., 2002). Besides, by extending the perspective to the entire building, the stages and impact of the building life cycle can be described, as in Figure 3. Through this diagram defined by European standard EN 15978, one can simply understand the prominent impact of EC emitted from all the stages of the building life cycle.

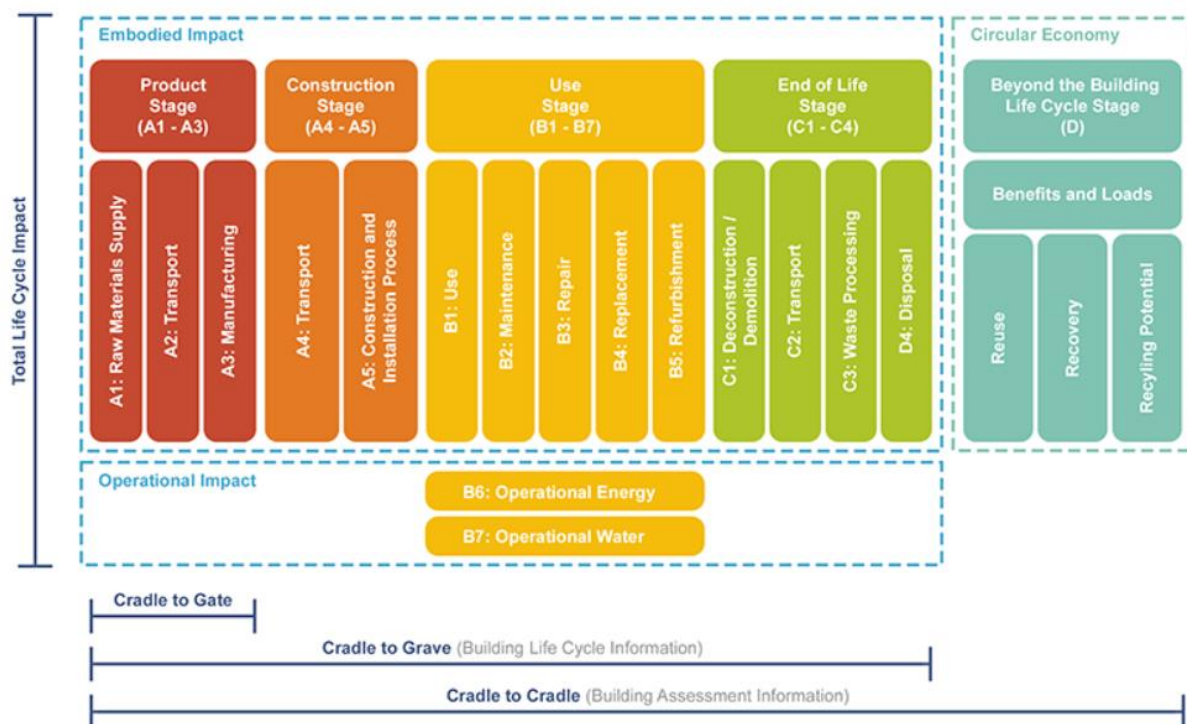


Figure 3. Life cycle stages from BS EN 15978:2011
(Overbey, 2021, <https://www.buildingenclosureonline.com/>)

However, measuring the EC emissions of individual buildings through LCA is extremely cumbersome and expensive to conduct (Miran, 2020). Therefore, to simplify the process of calculating the EC emissions of buildings or bays, this study will use the consolidated data or standardized output of LCA, which is called the Environmental Product Declaration (EPD). As a tool used increasingly for environmental communication (Ibáñez-

Forés et al., 2016), EPDs are standardized reports that contain environmental data dependent on LCA and are independently verified by a third party (Layne Evans, 2013). They comply with ISO standards which are applicable worldwide and they are utilized for products, materials and services as well (Layne Evans, 2013). The pros and cons with characteristics of EPDs will be discussed in Chapter 3 Research Methodology to explain the way for the use of EPD's in this study.

Definition of Bay

For consistent use of terminology, the mass timber structure in one grid of the architectural drawing is named 'bay'. The dictionary meaning of bay related to architecture is "a unit of form in architecture" and the unit is defined as "the zone between the outer edges of an engaged column, pilaster, or post" in detail (Dictionaries and Translators on dictionary.sensagent.com, n.d.). Although the term can be replaced with words such as module or grid, I decided to use the term 'bay' to avoid confusion with the word modular and to imply the concept of design to the term.

Point of Departure

The point of departure for this study was a previous study conducted about costs and EC emissions of mass timber building in the 'conceptual' stage of projects (Wiggins, 2021). Through a self-developed model, the researcher efficiently identified the cost and EC of a structure compared to existing methods and provided value for project stakeholders who aim to reduce EC by using a mass timber structure. While Wiggins' study was focused on conceptual estimating, the present study aims to provide the volume of mass timber easily by use of a systematic approach, which will be introduced in Chapter 4. In addition, this study

focuses more on the mass timber structure itself, presenting the cost and EC as a result of the study and suggesting optimized structure size alternatives.

Numerous studies compare traditional structural systems such as concrete or steel with mass timber in terms of the effectiveness of cost and EC emission by LCA. However, there is a scarcity of research on optimized bay size of mass timber structures, which focuses on the cost and EC emissions. Furthermore, no studies were conducted about the relationship between cost and EC emission per volume of mass timber following changes in various conditions. In response, the present study aims to fill the knowledge gap by developing research approach and scenarios in the succeeding chapters.

CHAPTER 3. RESEARCH METHODOLOGY

This study applied a quantitative research methodology to derive relevant data such as volumes, costs and embodied carbon emissions of mass timber structures (see Figure 4). Quantitative research is defined as one of the methods that are related to the collection and analysis of data that are structured with numeric values (Goertzen, 2017). The objectives of this quantitative research are to quantify the numerical results and find optimal alternatives for mass timber bay designs. Moreover, the quantitative research methodology was introduced to the scenarios to verify the feasibility of the TBCCOA developed in this study.

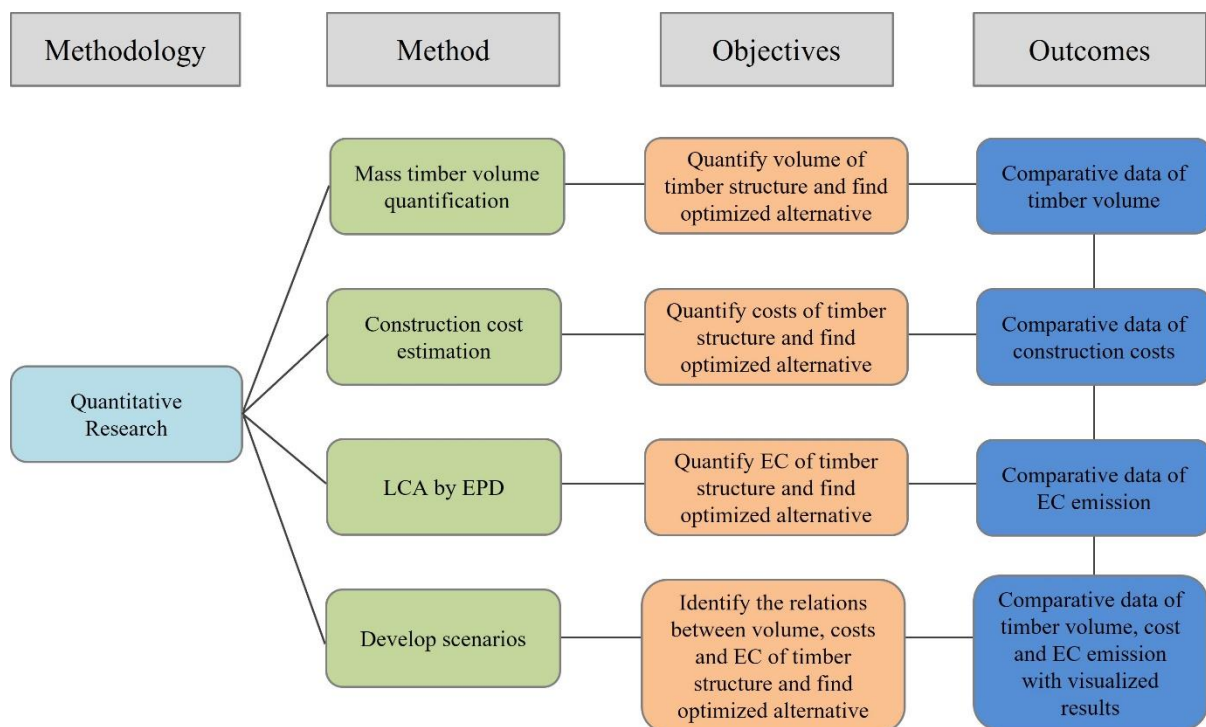


Figure 4. Research Methodology Diagram

Overall Research Process

The research began with inputting some simple information into the Timber Bay Design Tool. To get data from the tool, the information such as bay size, building stories, the number of

purlins, the width of purlin and girder and type of building has to be entered into the tool. This study will progress by utilizing bay size, building stories and number of purlins as variables and the rest of the input values will be fixed to control the results. The size of each structural component—panel, girder, purlin and column—will be determined effectually as output data from the tool with the feeding of information. Then, the volume of each component could be calculated easily. By identifying the number of each type of member that makes up the entire structure of the building, the researcher can obtain total volume of the mass timber structure. Consecutively, by multiplying the total volume with the unit cost and EPD data, the total cost and quantity of the EC emissions of mass timber will be computed. Finally, the optimal alternative can be selected according to the purpose of the project. Figure 5 briefly shows the process of this study and more detailed explanation will be covered in Chapter 4.

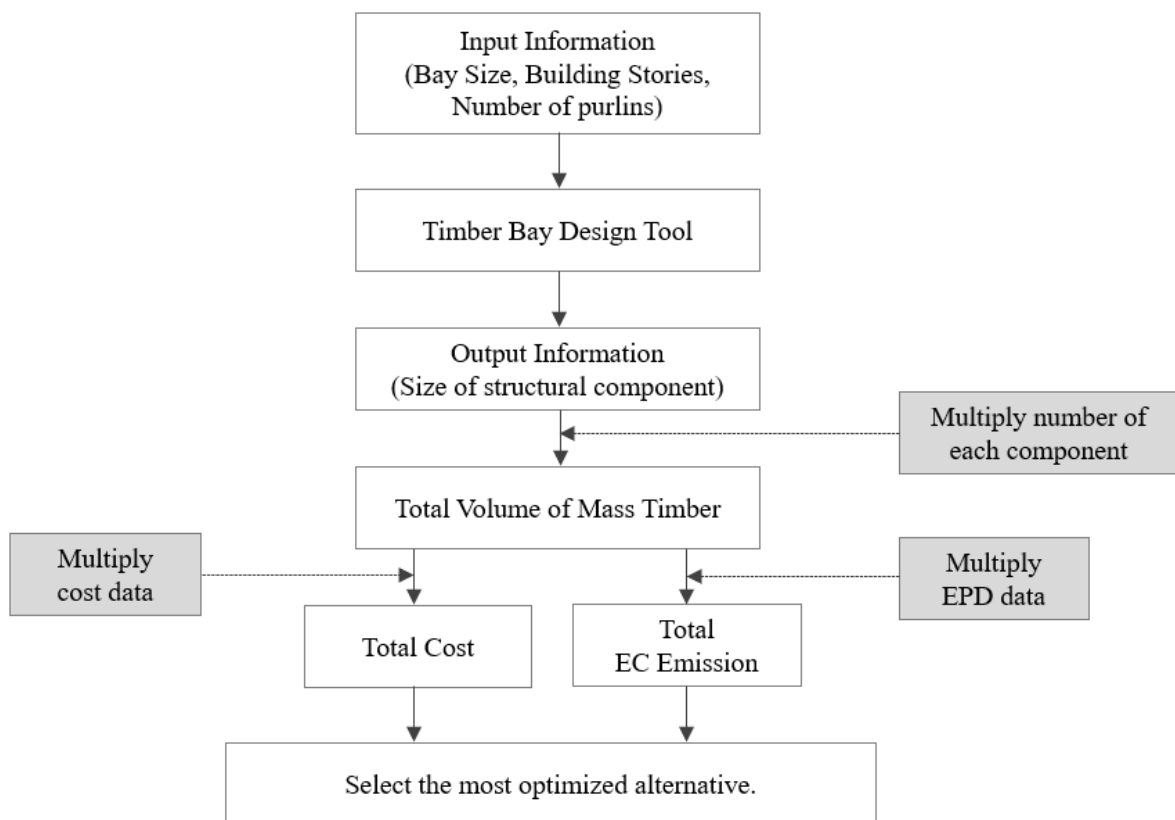


Figure 5. Research Process Framework

Quantifying the Costs of Mass Timber Components

Since the volume will be calculated through the Timber Bay Design Tool as described above, the total cost of a mass timber structure would be easily obtained by applying the unit cost estimation of mass timber. For the cost estimating, the data from a private company, named Roen Associates located in Seattle, which specializes in early-stage construction cost consulting were adopted. Even though the published estimating information such as RS Means as a representative of average costs in the US is available, there were two main reasons that the region-specific data were selected. First, the Timber Bay Design Tool and its calculations are based on provincial building code (BCBC 2018) in British Columbia, Canada as mentioned in literature review. Second, the EPD data utilized to measure the quantity of EC emissions in this study is based in Washington State, US. Therefore, it will be reasonable to use localized cost data in this study, which uses data generated in the Pacific Northwest region of North America. Using the data based on the same region for the cost and EC makes an accurate and meaningful comparison between alternatives to find the optimal option possible.

According to the interview with the cost data provider, the offered unit cost includes the overall cost from mass timber production to on-site installation but excludes the general contractor's markups and management fee. The unit cost is consistently updated by research with various general contractors every six months to reflect fluctuations in market prices.

As the exactness of an estimate is evaluated by the degree to which the estimated value is consistent with the real cost (Garold, 2001b), a cost estimate method using +/- accuracy of percentage range is frequently used. However, this research did not apply the concept of accuracy range because the objective of this study is to find optimal alternatives among various bay size alternatives rather than calculate an accurate cost.

Quantifying the EC Emissions of Mass Timber Components

Like the process of quantifying costs of mass timber, standardized data are necessary to assay the total quantity of EC emissions from a mass timber structure and EPDs offer a suitable solution. As a growing source of environmental performance in the field of construction materials (Waldman et al., 2020), EPDs are independently verified reports presented in a concise and standardized way (Layne Evans, 2013). However, one of the disadvantages of EPDs is that they vary widely about output (Rasmussen et al., 2021). These kinds of features of EPDs can cause inaccurate comparisons between the results of reports (Waldman et al., 2020) and EPDs have the range of accuracy to make up for variations, such as cost data. For the same reason with cost estimating for mass timber, this study only adopted a single value of EPDs by using a typical range of 60% of known products, as shown in Figure 6.

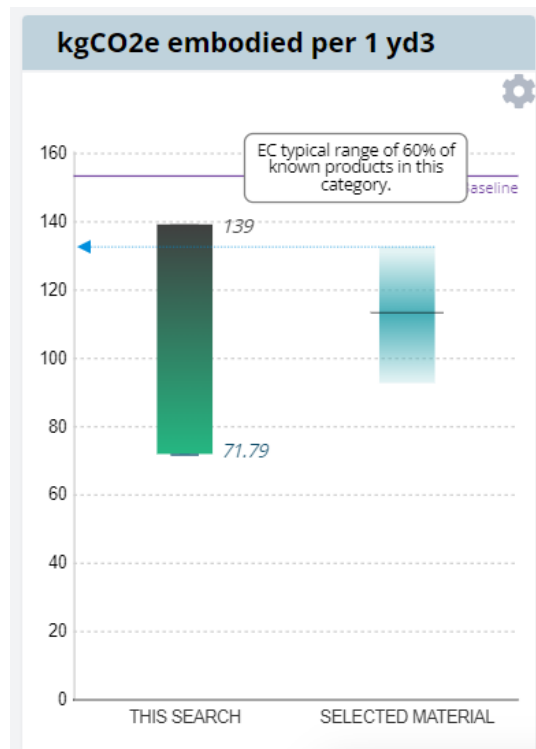


Figure 6. EPD range of glulam sourced from EC3

(<https://www.buildingtransparency.org/>)

CHAPTER 4. TIMBER BAY COST AND CARBON OPTIMIZATION APPROACH (TBCCOA)

Advantages of the Initial Stages of Timber Bay Design

This study involved developing a systematic approach, termed the timber bay cost and carbon optimization approach (TBCCOA). TBCCOA can help streamline the process to find optimized timber bay size alternatives in terms of volume, cost and EC emissions on the conceptual, pre-design and schematic design phases. In addition, the applicability of the TBCCOA was tested and validated through two scenarios. The TBCCOA can improve the efficiency of timber bay design for various stakeholders, including the client, architect, structural engineer and general contractor in the initial stages of a project in terms of time and cost commitment.

In current practices, experts in each field must be involved in designing a mass timber structure and determining its volume, cost and EC emission. For example, designing a structure and estimating its volume requires collaboration between an architect and a structural expert in wood structure. An estimator is needed to obtain costs and LCA professionals with specialized software must participate in quantifying EC emissions. In addition, a collaboration between stakeholders would be required to consolidate the data and reach a conclusion. In other words, designing a wood structure alternative and ascertaining its cost and the extent of EC emissions is a complicated process that requires a great deal of time and cost. In addition, the process of finding the optimized alternatives would be iterative, as shown in Figure 7-1. Therefore, complexity in current practices can hamper the effective and expedited comparison between miscellaneous alternatives of mass timber structures based on different bay sizes. As a result, it can increase the possibility that the owner of the building

fails to select the optimal bay of a mass timber structure with regard to both cost and sustainability.

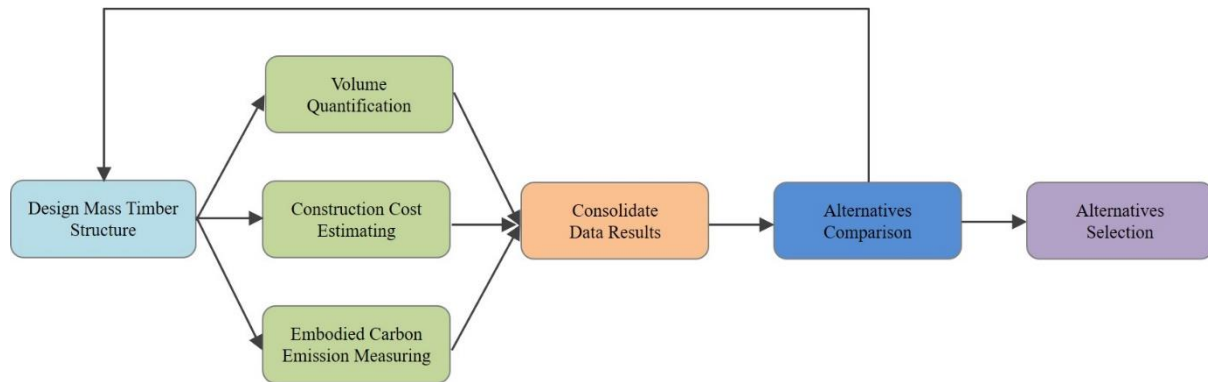


Figure 7-1. Existing mass timber design process

However, the TBCCOA can improve the mass timber design process, as shown in Figure 7-2. By applying the TBCCOA, the initial process to compare various alternatives can be done in a short time before starting to design the mass timber structure.

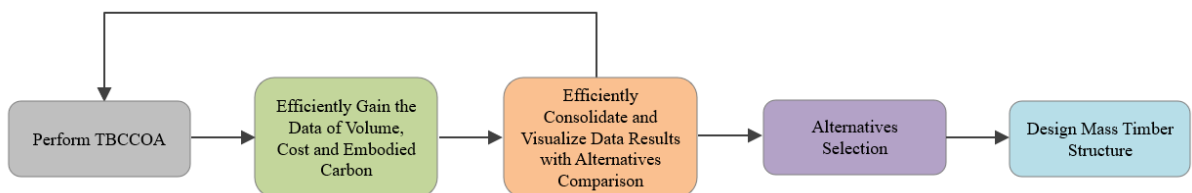


Figure 7-2. Mass timber design process using the TBCCOA

The TBCCOA supports easy generation of various timber bay size alternatives by using the Timber Bay Design Tool, for those who have basic knowledge of design without involving respective experts and a specialized software. By utilizing the output of the tool, the TBCCOA aids in acquiring the data of volume, cost, and EC emission of mass timber simultaneously. By comparison of alternatives, a user can decide optimal one expeditiously.

Preliminary Testing for Scenario

The Timber Bay Design Tool is based on reliable structural information to calculate the size of each component under various conditions. However, the tool has several limitations. As noted in Chapter 2, outputs are intended only for the preliminary stage and must be confirmed by a structural expert and supplier for the final design on a case-by-case basis. An email interview with a Fast + Epp staff member who has technical knowledge of the tool, indicated that the height of the bay is fixed at 6 m. That means the study analysis is limited in terms of exploring other heights. Also, architectural factors such as ceiling height were not considered. As stated in Chapter 3, only the bay dimension, number of purlins and building stories were used as variables and the rest of the elements such as applied panel type, loading, fire resistance and beam (purlin and girder) width were fixed as default values of the tool to control the results. The ranges of each variable and fixed values of the constants adopted in this study are shown in Table 2.

Table 2. Variables and Constants of the Study

Variables	Range
Bay Dimension	3 – 14 m
Number of Purlins	1 – 3
Building Stories	1 – 18
Constants	Fixed Value
Bay Height	6 m
Panel Type	CLT
Loading Type	Residential
Fire Resistance	0 min
Purlin Width	215 mm
Girder Width	265 mm

The Timber Bay Design Tool is used only as a means of generating data in this study, but it can provide clues about how the scenario should be designed by analyzing the output data. Therefore, a preliminary testing was conducted under the environment of Table 2 and the results are shown in Table 3.

Table 3. Results of the preliminary testing

Factor	Optimized Condition
Bay Dimensions	6 m × 6 m
Shape of Bay	Square-shaped
Number of Purlins	Less Number
Building Stories	Lower Story

In terms of bay dimensions, the optimal alternative among square bays is 6 m × 6 m, which is the result obtained by comparing the total timber volume per area of each bay from 3 m to 14 m in length as shown in Figure 8 (The data in this graph was earned under the number of purlins as three and the stories of buildings as six). The graph also shows the most inefficient alternative as 3 m × 3 m with total timber volume of 0.178 m³ / m². The results of the preliminary testing provided valuable lessons in designing the scenarios in Chapter 5 and 6.

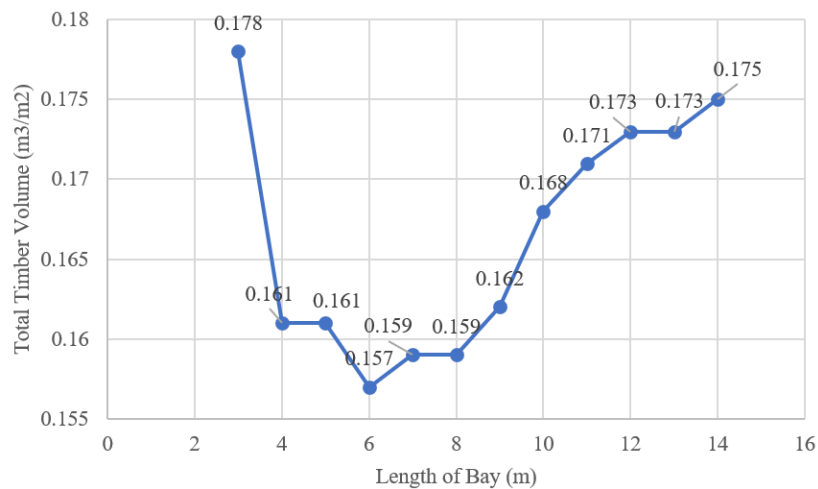


Figure 8. Optimization Graph of Timber Volume Per Area for a Square Bay

Steps in TBCCOA

As briefly described in Figure 5 above, there are a few steps for performing the TBCCOA. Steps are not only the process of the study but also the methodology and approach to find an optimized timber bay in terms of costs and EC emissions. The step-by-step use of the TBCCOA with a detailed explanation and visualized information is provided hereinafter.

(1) Input mass timber bay information in the Timber Bay Design Tool

The TBCCOA starts from using the Timber Bay Design Tool. Figure 9-1 shows the default value of the tool. Bay dimensions are 9 m and the story of the building is six. To get necessary information from the tool, a researcher has to enter intended information in the tool. For example, I changed the bay dimensions to 6 m and the building story as one (See Figure 9-2). The given value is used for the rest of the variables such as the number of purlins and panel type.

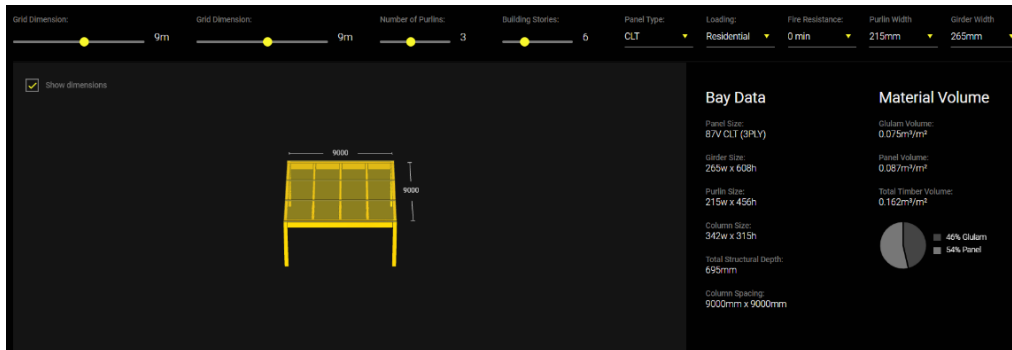


Figure 9-1. The default value of the Timber Bay Design Tool
(<https://www.fastapp.com/concept-lab/apps/timber-bay-design>)

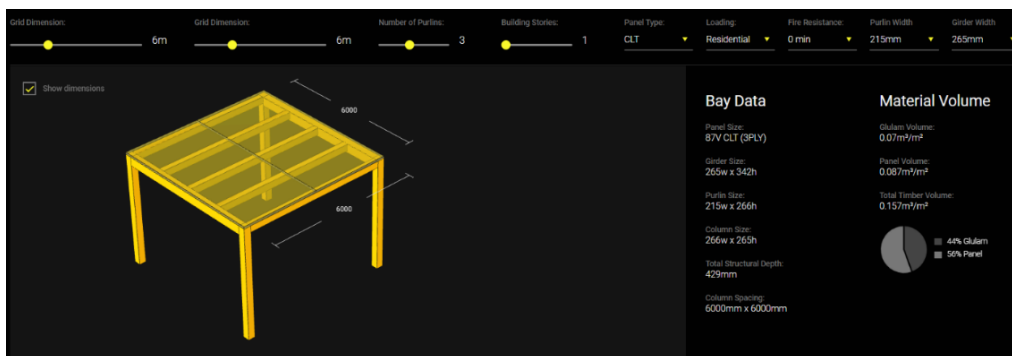


Figure 9-2. The adjusted value of the Timber Bay Design Tool

(2) Identify the output information of the tool

After feeding in information regarding the bay and building, “Bay Data” and “Material Volume” on the screen of the tool will be updated based on the value of the input data. For instance, the size (height) of the girder changed from 608 mm to 342 mm with a comparison of Figure 9-1 and Figure 9-2. Also, the rest of the data have been revised except for the panel size. It is an essential process to identify the output information of the tool as elements for calculating the volume of CLT and glulam. For reference, the unit of “Bay Data” is millimeters (mm) and the “Material Volume” is calculated as volume per area (m^3 / m^2).

(3) Check the size and number of each structural component

Even though the output information of the tool gives the width and height of the beam (girder and purlin) and column, their length has to be determined manually to calculate the volume of each component. The length or width of each component could be obtained by a simple equation that looks like Eq. (1) to (6) and the use of a 3D model makes it more understandable, as shown in Figure 10. By assumption, the center lines of every bay pass by the center of the columns.

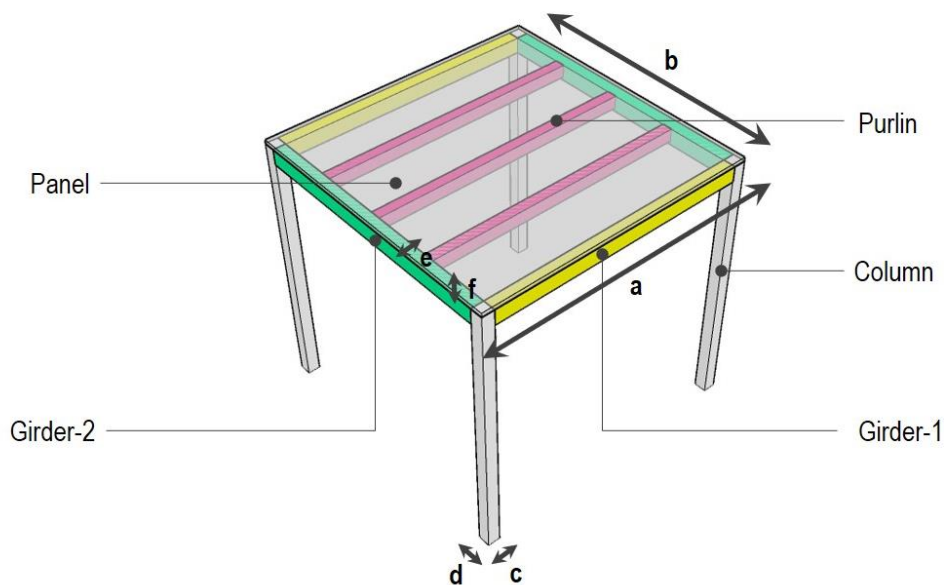


Figure 10. 3D model of Timber Bay

$$L1 \text{ (Length of Girder-1)} = a - c \quad (1)$$

$$L2 \text{ (Length of Girder-2)} = b - d \quad (2)$$

$$L3 \text{ (Length of Purlin)} = a - e \quad (3)$$

$$L4 \text{ (Length of Column)} = 6 \text{ m} - f \quad (4)$$

$$L5 \text{ (Length of Panel)} = a + c \quad (5)$$

$$W1 \text{ (Width of Panel)} = b + d \quad (6)$$

Where a = Length of Bay, b = Width of Bay, c = Width of Column, d = Height of Column, e = Width of Girder-2, f = Thickness of Panel, $a \geq b$, $c \geq d$

When calculating the number of each structural component required, it is possible to clearly apply equations for panel and purlin such as Eq. (7) and (8).

$$N1 \text{ (Number of panels)} = \text{Number of bays on one floor} \times \text{Number of Floors} \quad (7)$$

$$N2 \text{ (Number of purlins)} = \text{Number of purlins applied to one bay} \times (7) \quad (8)$$

However, the number of girders and columns fluctuates irregularly based on the shape of a building. Therefore, counting the number of girders and columns requires manual effort, particularly if the shape of the plan is atypical.

(4) Calculate the total volume of mass timber

Based on the preparation in previous steps, the user can calculate the total volume of mass timber through Eq.(9) and (10).

Total volume of each component

$$= \text{Volume of each component} \times \text{Number of component on one floor} \times \text{Number of Floors} \quad (9)$$

$$\text{Total volume of overall mass timber} = \text{Sum of (9)} \quad (10)$$

One of the crucial steps to be added between Eq.(9) and (10) and it is the segregation of CLT and glulam. As I mentioned on Chapter2 Literature Review, panel is produced by CLT and both beam and column are engineered by glulam. The reason why types of mass timber have to be distinguished is that the unit cost and EPD value of the two are different. And it affects the research results in the aspect of ratio of Volume : Cost and Volume to Embodied Carbon Emission.

(5) Find out the cost data

To determine the cost of a mass timber structure, specific cost data per type of mass timber must first be obtained. In this study, as mentioned in Chapter 3, a construction consulting firm’s database, as shown in Table 4, was used. The data provided are the cost per area by the thickness of the CLT panel and the cost on the rightmost side of the table is converted into the cost per volume. The thicker the CLT panel, the lower the cost per volume and it was identified through interviews with data providers that it was the result of labor savings. Unlike CLT panels, the cost of glulam was offered as a single cost and per volume. However, since it is provided in board feet units (\$ 9 / bf), I converted it to a cubic meter (m³) unit to align with the CLT cost. It is \$ 3,829.79 / m³, which is higher than the unit cost of all CLT panels.

Table 4. CLT panel costs

Description	Cost / Area (\$ / SF)	Volume (m³ / SF)	Cost / Volume (\$ / m³)
CLT Panel, 87 mm (3.43’')	\$ 27.00	0.008	\$ 3,340.53
CLT Panel, 105 mm (4.13’')	\$ 30.30	0.010	\$ 3,106.16
CLT Panel, 139 mm (5.47’')	\$ 34.70	0.013	\$ 2,687.11
CLT Panel, 175 mm (6.89’')	\$ 40.20	0.016	\$ 2,472.63
CLT Panel, 191 mm (7.52’')	\$ 44.60	0.018	\$ 2,513.46
CLT Panel, 245 mm (9.65’')	\$ 51.20	0.023	\$ 2,249.44
CLT Panel, 315 mm (12.4’')	\$ 60.00	0.029	\$ 2,050.27

(6) Find out EPD data

Like the process to find cost data, EPD data of CLT and glulam is required respectively to get EC emissions from mass timber structure. There are a lot of EPD sources; however, data derived from EC3 tool was adopted for this study as it was developed as a construction calculator particularly for EC (Building Transparency, 2022). Figure 11 shows both EPD of CLT and glulam extracted by a specific manufacturer in a particular place, Colville, WA. It was identified that glulam emits around 10% more EC per volume than CLT and they use yd^3 unit. However, conversion of the volume unit is required to make the comparison between the cost and EC emission compatible. In results, CLT emits $159.57 \text{ kgCO}_2\text{e}$ per 1 m^3 and glulam emits $172.65 \text{ kgCO}_2\text{e}$ per 1 m^3 as 1 yd^3 can be converted to 0.76455 m^3 .

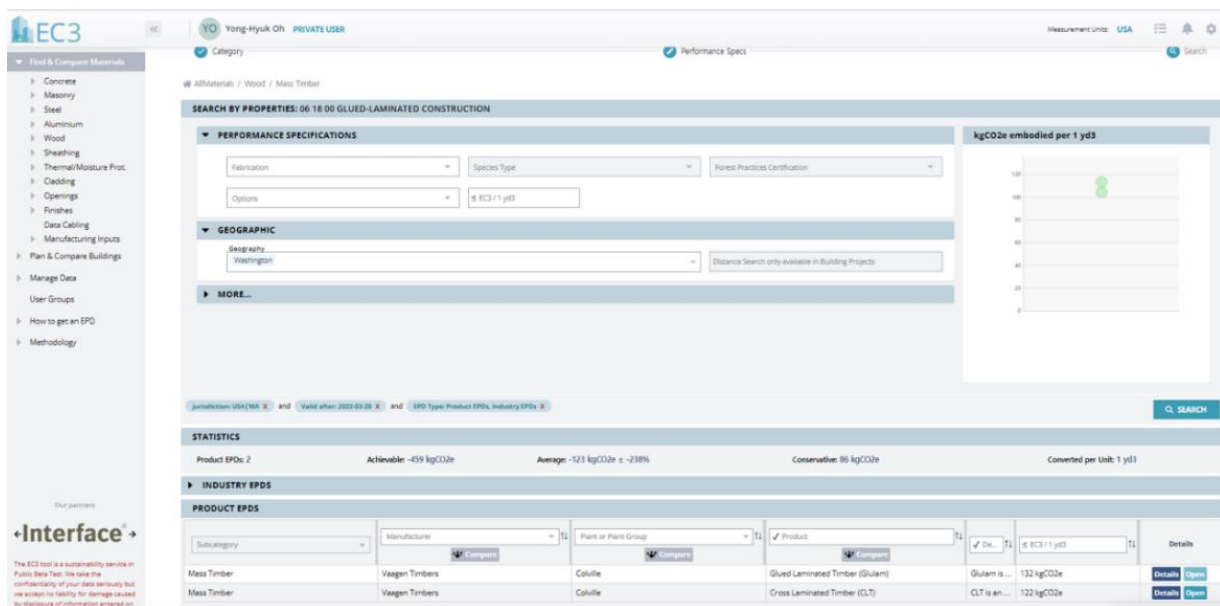


Figure 11. EPD data sourced from EC3
(<https://www.buildingtransparency.org/>)

(7) Calculate total cost and EC emissions

Based on steps (5) and (6), the data of cost and EPD are simply arranged as shown in Table 5.

The total cost and EC emissions are computed by multiplication of the mass timber volume and the value in Table 5.

Table 5. Cost and EPD data per volume

Description	CLT		Glulam
Cost / Volume (\$ / m ³)	CLT Panel, 87 mm (3.43")	\$ 3,340.53	\$ 3,829.79
	CLT Panel, 105 mm (4.13")	\$ 3,106.16	
	CLT Panel, 139 mm (5.47")	\$ 2,687.11	
	CLT Panel, 175 mm (6.89")	\$ 2,472.63	
	CLT Panel, 191 mm (7.52")	\$ 2,513.46	
	CLT Panel, 245 mm (9.65")	\$ 2,249.44	
	CLT Panel, 315 mm (12.4")	\$ 2,050.27	
Embodied Carbon Emission / Volume (kgCo2e / m ³)	159.57		172.65

Comparison of Results

In the case of generating various alternatives, the results of the study need to be compared after performing the TBCCOA to select the optimal alternative in terms of cost and EC emissions. The process of comparison will be presented in Chapter 5 and 6 as scenarios.

CHAPTER 5. SCENARIO 1

Two scenarios were developed targeting an entire virtual building structure by extending the preliminary testing that was limited to a bay. As mentioned in Chapter 4, the goal is to apply the results of the preliminary testing using the Timber Bay Design Tool to the scenarios. For both scenarios, I assumed the type of virtual buildings as residential and this information was set out in the Timber Bay Design Tool.

Scenario 1 was to validate whether the 6 m × 6 m bay is the optimal size and whether a square bay is more efficient in terms of cost and embodied carbon emissions than a rectangular bay.

Project Description

Based on the results of the preliminary testing, it was necessary to compare various sizes of square bays to validate that the 6 m × 6 m bay is the optimal size. Also, the process of selecting between a square and a rectangular bay with the same unit area must be performed prior to comparing the efficiency according to the bay shape. To develop a scenario while satisfying these two conditions required deciding a proper building footprint which accommodates various bay sizes. Additionally, to increase the reliability of the study, an actual hybrid mass-timber-structured building, namely, the Brock Commons Tallwood House built in Vancouver, Canada in 2017 (Brock Commons Phase 1–Tallwood House, n.d.) was referenced for scenario 1. As an 18-story (54 m) student residence of the University of British Columbia, its footprint is 56 m × 15 m with a 4 m × 3 m bay size as shown in Figure 12.

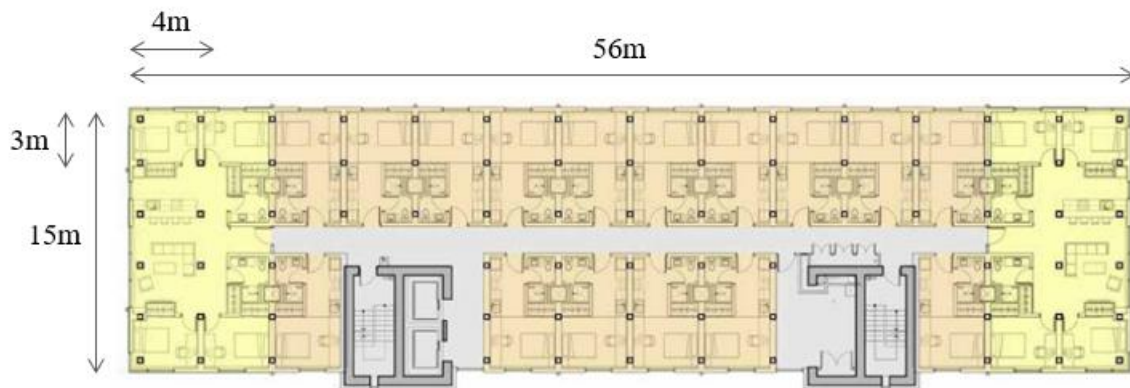


Figure 12. Typical Floor Assembly of Brock Commons Tallwood House
 (https://www.naturallywood.com/wp-content/uploads/brock-commons-design-preconstruction-overview_case-study_naturallywood.pdf)

To create various alternatives for square bays within the given building footprint, it is advantageous to have multiple common divisors for the length and width of the building. However, the building footprint of size 56 m × 15 m does not have common divisors. Therefore, the building footprint size was adjusted for scenario 1 based on the following prerequisites:

1. Similar to the building footprint size of the referenced project.
2. Be able to make square bays of various sizes (The length and width of the building have many common divisors).
3. Be able to create square and rectangular bays with the same area.
4. Bay size must be within the bay dimension range (3 m to 14 m) of the Timber Bay Design Tool (Available up to one decimal place).

The building footprint, adjusted by reflecting the prerequisites, is 54 m × 18 m and the selected bay size and area are shown in Table 6. The information gained from alternatives 1 to 4 was used for comparison of the square bays and a comparison between alternatives 4 and 5 was used for the square bay versus the rectangular bay in terms of optimization.

Table 6. Bay size and area of scenario 1 alternatives

Alternatives	Width (m)	Length (m)	Area (m ²)
1	3.0	3.0	9.00
2	4.5	4.5	20.25
3	6.0	6.0	36.00
4	9.0	9.0	81.00
5	13.5	6.0	81.00

In addition to the bay size, the stories of the building were used as a variable to identify the optimal alternatives of mass timber volume. The number of stories of the building used in this scenario is 3, 6, 9 and 12. To control the scenario results, the number of purlins was fixed at 3 and the remaining fixed values such as bay height and panel type were set as shown in Table 2. The plans of each alternative and 3D model for 6 m × 6 m alternatives are shown in Figure 13 and Figure 14 respectively.

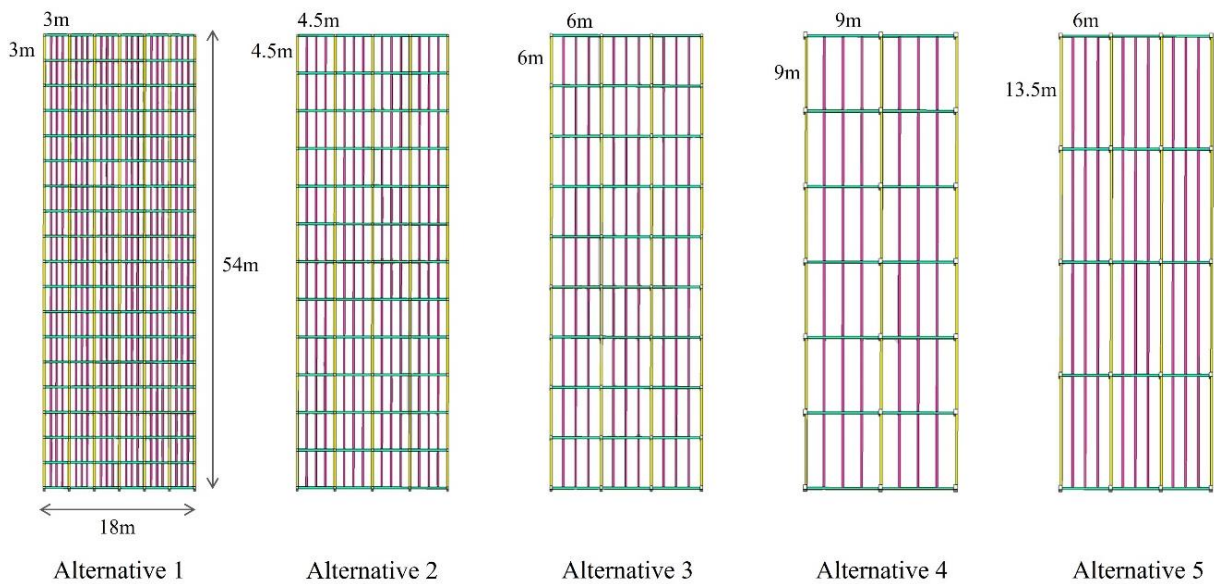


Figure 13. Plans of alternatives for scenario 1

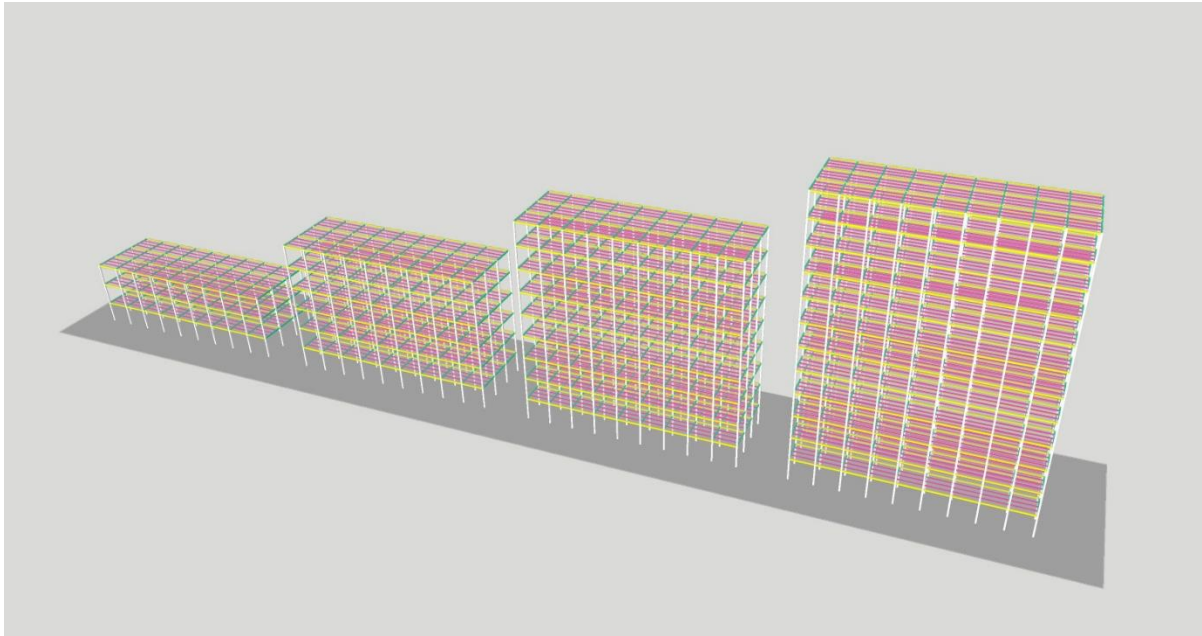


Figure 14. 3D models of 6 m × 6 m alternatives for scenario 1

Data Collection

Based on the information in the project description, I developed mass timber volume data of all alternatives by performing steps (1) to (4) of the TBCCOA introduced in Chapter 4.

Representatively, Table 7 shows the result of calculating the size, volume and number of each component with the total mass timber volume of each bay in a three-story building. The results for other floors—6, 9 and 12—are to be found in Appendix 1. In addition, the cost and EC results for each alternative can be obtained by performing step (7) of the TBCCOA and the optimal alternative in terms of cost and EC emission can be found by using these results. Furthermore, the relationship between volume, cost and EC emission may be inferred.

Table 7. Mass timber volume information of 3-story building alternatives

Building Story = 3

Gross Floor Area (GFA) = 2,916m²

Bay Size (m)	Components	Components Size (m)	Components Volume (m ³)	Number of Components in one floor	Total Volume (m ³)	CLT Volume / Area (m ³ /m ²)	Glulam Volume / Area (m ³ /m ²)	Total Volume / Area (m ³ /m ²)
3.0 x 3.0	Panel	3.000 x 3.000 x 0.087	0.783	108	253.692	0.087	0.100	0.187
	Girder	0.265 x 0.114 x 2.734	0.083	126	31.221			
		0.265 x 0.114 x 2.735	0.083	114	28.258			
	Purlin	0.215 x 0.114 x 2.735	0.067	324	65.158			
	Column	0.266 x 0.265 x 5.913	0.417	133	166.306			
Sum					544.634			
4.5 x 4.5	Panel	4.500 x 4.500 x 0.087	1.762	48	253.692	0.087	0.083	0.170
	Girder	0.265 x 0.228 x 4.234	0.256	60	46.047			
		0.265 x 0.228 x 4.235	0.256	52	39.917			
	Purlin	0.215 x 0.190 x 4.235	0.173	144	74.736			
	Column	0.266 x 0.265 x 5.913	0.417	65	81.277			
Sum					495.670			
6.0 x 6.0	Panel	6.000 x 6.000 x 0.087	3.132	27	253.692	0.087	0.080	0.167
	Girder	0.265 x 0.342 x 5.734	0.520	36	56.125			
		0.265 x 0.342 x 5.735	0.520	30	46.779			
	Purlin	0.215 x 0.266 x 5.735	0.328	81	79.700			
	Column	0.266 x 0.265 x 5.913	0.417	40	50.017			
Sum					486.312			
9.0 x 9.0	Panel	9.000 x 9.000 x 0.087	7.047	12	253.692	0.087	0.087	0.174
	Girder	0.265 x 0.608 x 8.734	1.407	18	75.990			
		0.265 x 0.608 x 8.735	1.407	14	59.110			
	Purlin	0.215 x 0.456 x 8.735	0.856	36	92.489			
	Column	0.266 x 0.265 x 5.913	0.417	21	26.259			
Sum					507.540			
13.5 x 6.0	Panel	13.500 x 6.000 x 0.087	7.047	12	253.692	0.087	0.122	0.209
	Girder	0.265 x 0.608 x 13.234	2.132	16	102.349			
		0.265 x 0.608 x 5.735	0.924	15	41.581			
	Purlin	0.215 x 0.608 x 13.235	1.730	36	186.849			
	Column	0.266 x 0.265 x 5.913	0.417	20	25.008			
Sum					609.479			

Scenario Results

The scenario revealed a number of meaningful findings, which can support project stakeholders when building a mass-timber-structured building. The results will be reviewed in two parts. The first part pertains to a perspective in terms of mass timber volume only and the second part is about volume, cost, EC emissions and their relationships.

(1) Results in terms of mass timber volume

To identify the change in the volume of mass timber according to the alternatives, Volume/Area (m^3 / m^2) data in the right column of table 7 and Appendix 1 were used. The data were visualized as shown in Figures 15-1, 2 and 3 for better understanding. Also, to determine the relationship between CLT and glulam which constitutes mass timber, the volume changes of CLT and glulam were observed.

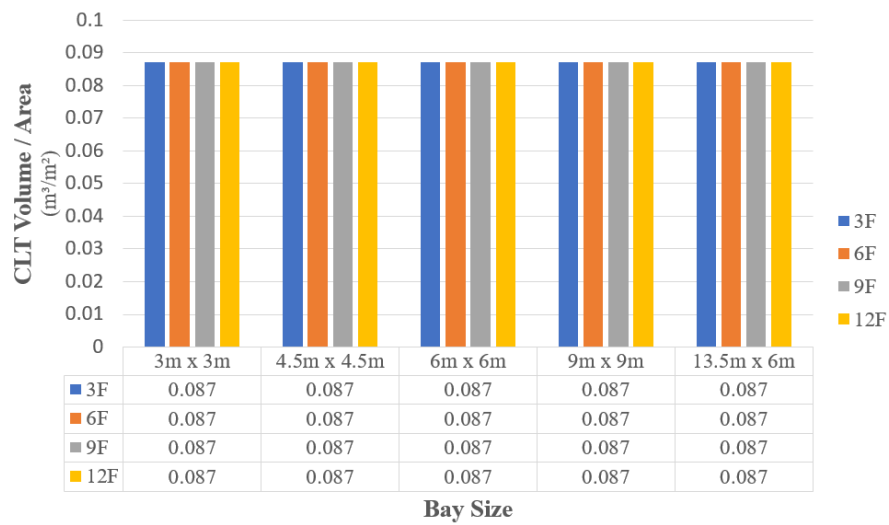


Figure 15-1. CLT volume per area of all alternatives

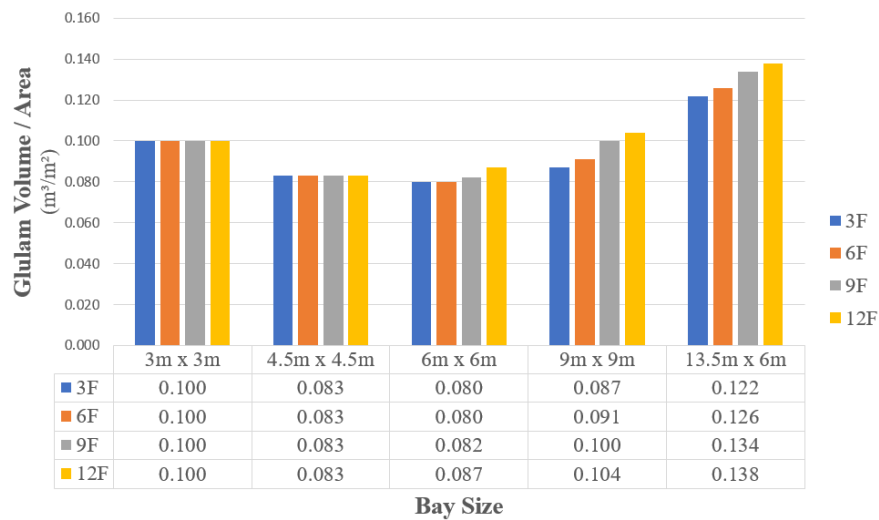


Figure 15-2. Glulam volume per area of all alternatives

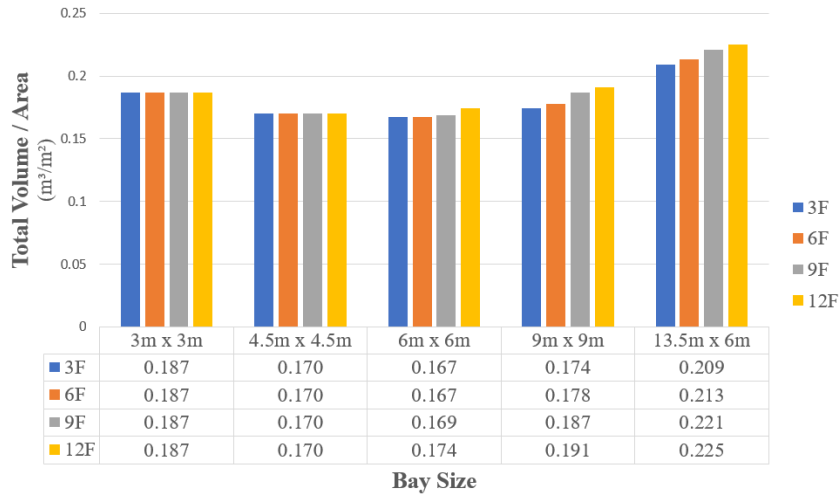


Figure 15-3. Mass Timber total volume per area of all alternatives

First, glulam governs the optimization of mass timber volume. Figure 15-1 shows that the results of CLT volume per area are constant at $0.087 \text{ m}^3 / \text{m}^2$ for all alternatives. The reason for this is that the thickness of the panels is fixed at 87 mm even though the variable varied. Meanwhile, Figure 15-2 presents the results of glulam volume per area which are changing based on the bay size variation and shows which one is the optimal alternative floor by floor. Figure 15-3, which is the result of the sum of Figure 15-1 and Figure 15-2, shows the same graph shape as Figure 15-2. This result implies that the volume variation of glulam governs the optimization of mass timber volume.

Second, the optimal alternatives can be changed based on the stories of building. Figure 15-3 indicates that the 6 m × 6 m bay is the optimal size from 3 stories to 9 stories of the building in terms of mass timber volume. However, I found that the optimal alternative for a 12-story building is 4.5 m × 4.5 m. This shows that although a 6 m × 6 m bay is an optimal alternative for a mid to low-rise building, smaller bays can be an optimal alternative for higher floors. This phenomenon is caused by size changes in a structure’s component (column). In detail, the column width of the 9-story building for the 6 m × 6 m bay is 304

mm and the same portion of the 12-story building is 380 mm as shown in Appendix 1. The drastic increase in the size of the component hinders the optimization of volume. However, the 4.5 m × 4.5 m bay has the same component size for 9- and 12-story buildings. In other words, for structural engineering reasons, the size of components of a structure can be increased as the story of a building rises and thus the optimal alternative may be reversed.

Lastly, a square bay is more optimal than a rectangular bay. In the perspective of comparing the square bay and rectangular bay, Figure 15-3 shows obvious but important results. Two objects with the same area, 9 m × 9 m and 13.5 m × 6 m, indicate square bays are optimal in all circumstance of the building’s stories. The volume data from Table 7 and Appendix 1 support these results as the lengths of girders and purlins are longer in rectangular bays.

(2) Results in terms of mass timber volume, cost and EC emissions

To identify the quantities of volume, cost and EC emission of the mass-timber-structured building, the total volume from Table 7 was multiplied by the cost and EPD data shown in Table 5. Table 8 shows their results and each alternative is divided into CLT and glulam with their ratios. The rest of the data from 6 to 12-story buildings are listed on Appendix 2.

Table 8. Mass timber volume, cost, EC emission information of 3-story building alternatives

Building Story = 3
Gross Floor Area (GFA) = 2,916m²

Bay Size (m)	Volume (m ³)					Cost					EC emission (kgCo2e / m ³)				
	CLT		Glulam		Total	CLT		Glulam		Total	CLT		Glulam		Total
3.0m x 3.0m	253.692	47%	290.942	53%	544.634	\$847,466	43%	\$1,114,247	57%	\$1,961,713	40,482	45%	50,231	55%	90,713
4.5m x 4.5m	253.692	51%	241.978	49%	495.670	\$847,466	48%	\$926,724	52%	\$1,774,189	40,482	49%	41,777	51%	82,259
6.0m x 6.0m	253.692	52%	232.620	48%	486.312	\$847,466	49%	\$890,887	51%	\$1,738,353	40,482	50%	40,162	50%	80,644
9.0m x 9.0m	253.692	50%	253.848	50%	507.540	\$847,466	47%	\$972,184	53%	\$1,819,650	40,482	48%	43,827	52%	84,308
13.5m x 6.0m	253.692	42%	355.787	58%	609.479	\$847,466	38%	\$1,362,588	62%	\$2,210,054	40,482	40%	61,427	60%	101,908

The trends of the ratio of CLT in terms of volume, cost, and EC emission of each alternative is shown in Figure 16-1 and the ratio of glulam is shown in Figure 16-2. The findings listed below are all derived from Table 8, Figures 16-1, 2 and Appendix 2.

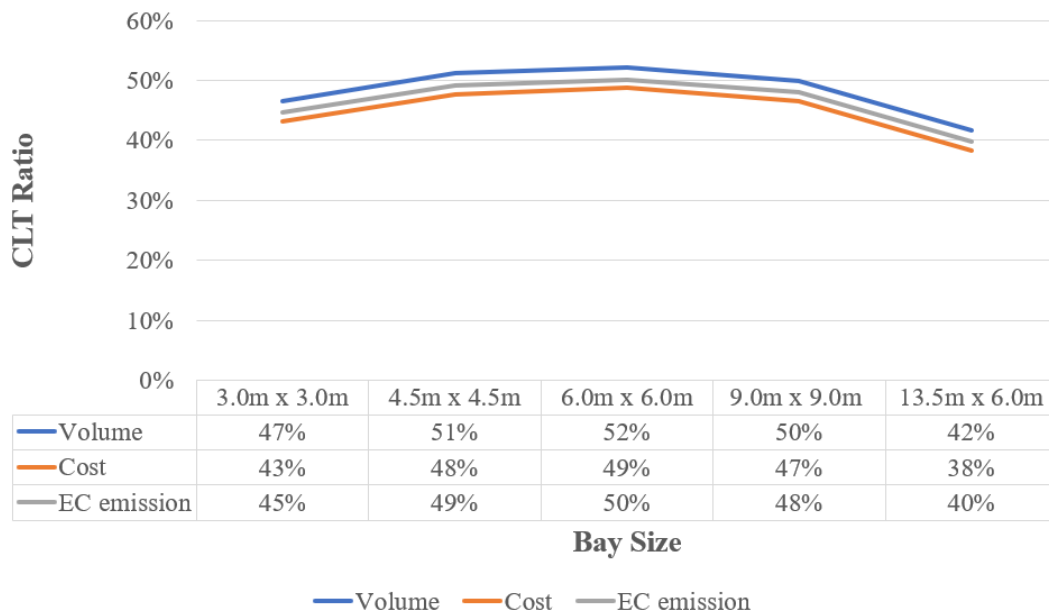


Figure 16-1. CLT ratio of mass timber volume, cost and EC emissions (3-story building)

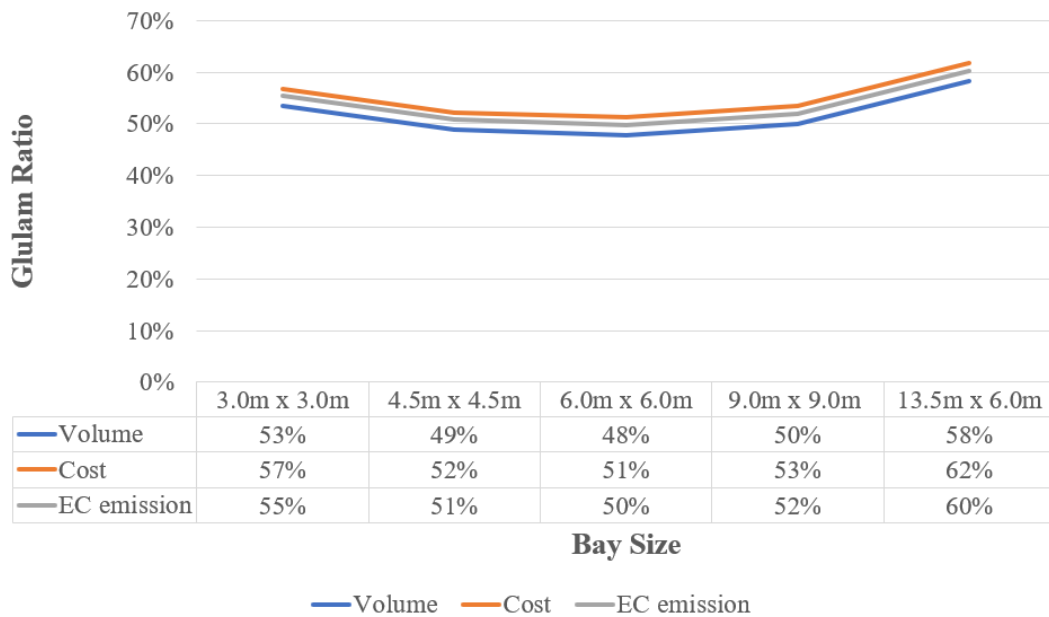


Figure 16-2. Glulam ratio of mass timber volume, cost and EC emissions (3-story building)

First, ratio of volume: cost: EC emission of mass timber structures is not 1: 1: 1.

Figure 16-1 and Figure 16-2 show that the ratios of CLT and glulam volume change according to the bay size. This is because the mass timber structure composed of components, namely, CLT and glulam varies according to the bay size and the floors of the building. Plus, the ratios of cost and EC emissions are different for each alternative and this result came from the different cost and EPD data of CLT and glulam. Therefore, these graphs show that the ratio of volume: cost: EC emission of mass timber structures is not 1: 1: 1 and it means that the optimal alternative in terms of volume, cost and EC emission can be different.

Second, optimization trends of volume, cost and EC emissions are similar. Even though the ratios of volume: cost: EC emission are not 1: 1: 1, all of the optimal alternatives in terms of volume are optimized in terms of cost and EC emissions in scenario 1 (the optimal alternatives by volume, cost and EC emissions are marked in yellow in Table 8 and Appendix 2). This shows that the optimization trends of the three factors—volume, cost and EC emissions—are similar in a broad framework and it can be identified through the shapes of graphs in Figures 16-1 and 16-2.

Third, glulam governs the optimization of mass timber volume, cost and EC emissions. Figure 16-1 and Figure 16-2 show that CLT and Glulam have opposite directions of optimization and the glulam optimized at 6 m × 6 m governs the overall optimization trend. This is the same result as was identified earlier in terms of mass timber volume. Additionally, the cost and EC emission ratio lines are always located below the volume in the CLT ratio graph and the opposite phenomenon appears in the glulam ratio graph. This is because the cost and EPD value of CLT are smaller than those of glulam, as identified in Table 5.

Lastly, based on the quantity data of mass timber volume, cost and EC emission, the result that a square bay is more optimal than a rectangular bay can be identified again in more

depth. Using the data obtained from Table 8, I compared the quantity ratio between the square versus square alternatives and square versus rectangular alternatives as shown in Table 9.

Table 9. Quantity ratio comparison between square vs square bays and square vs rectangular bays

Building Story = 3

Gross Floor Area (GFA) = 2,916m²

Comparison	Bay Size (m)	Volume (m ³)		Cost		EC emission (kgCo2e / m ³)	
		Total	Increase Ratio	Total	Increase Ratio	Total	Increase Ratio
Square vs Square Bays	3.0m x 3.0m	544.634	11.99%	\$1,961,713	12.85%	90,713	12.49%
	4.5m x 4.5m	495.670	1.92%	\$1,774,189	2.06%	82,259	2.00%
	6.0m x 6.0m	486.312	-	\$1,738,353	-	80,644	-
	9.0m x 9.0m	507.540	4.36%	\$1,819,650	4.68%	84,308	4.54%
Square vs Rectangular Bays	9.0m x 9.0m	507.540	-	\$1,819,650	-	84,308	-
	13.5m x 6.0m	609.479	20.08%	\$2,210,054	21.45%	101,908	20.88%

The criterion for comparing four square bays is the most optimized size, 6 m × 6 m.

According to Table 9, 4.5 m × 4.5 m bay increased by 1.92% and 9.0 m × 9.0 m bay increased by 4.36% compared to 6.0 m × 6.0 m bay in terms of volume. 3.0 m × 3.0 m bay increased by 11.99% as the largest increase between alternatives. Even though the increase rate in terms of cost and EC emission differs from the volume increase rate due to the difference in cost and EPD value of CLT and glulam, it is not remarkable. However, in the comparison between square bay and rectangular bay, 13.5 m × 6.0 m bay increased by 20.08% compared to 9.0 m × 9.0 m bay in terms of volume and increased by 21.45% in terms of cost as marked in yellow. The outstanding difference in results between square and rectangular bays suggests an important lesson for us. Converting from the most optimized square bay size to a different size of square bay does not significantly affect the optimization unless the size is changed largely. However, when designing

the overall structural plans, replacing square bays with rectangular bays has a considerable impact on optimization and should be avoided unless there are specific reasons.

CHAPTER 6. SCENARIO 2

Scenario 2 was to demonstrate the effect of the number of purlins on optimization.

Project Description

One of the important findings during the preliminary testing of the Timber Bay Design Tool is the variation in CLT panel thickness. If the number of purlins was set to 2 or more, the panel thickness was fixed at 87 mm in most scenarios. However, when the number of purlins was fixed to 1 targeting the various sizes of square bays, it was identified that the panel thickness gradually increased as the bay size increased. To determine the optimization trend according to the variation of panel thickness, scenario 2 adopted the number of purlins as a variable and the numbers of purlins were fixed as 1, 2 and 3. In addition, to develop a scenario with various square bays, a building footprint of 36 m × 36 m was adopted (36 is a number with various common divisors). The selected bay sizes and areas are shown in Table 9.

Table 10. Bay size and area of scenario 2 alternatives

Alternatives	Width (m)	Length (m)	Area (m ²)
1	3.0	3.0	9.00
2	4.5	4.5	20.25
3	6.0	6.0	36.00
4	9.0	9.0	81.00
5	12.0	12.0	144.00

To control the scenario results, the number of building stories was fixed at 6 and the remaining fixed values such as bay height and panel type were set as shown in Table 2. The plans of each alternative and 3D models for 1-purlin alternatives are shown in Figure 17 and Figure 18, respectively.

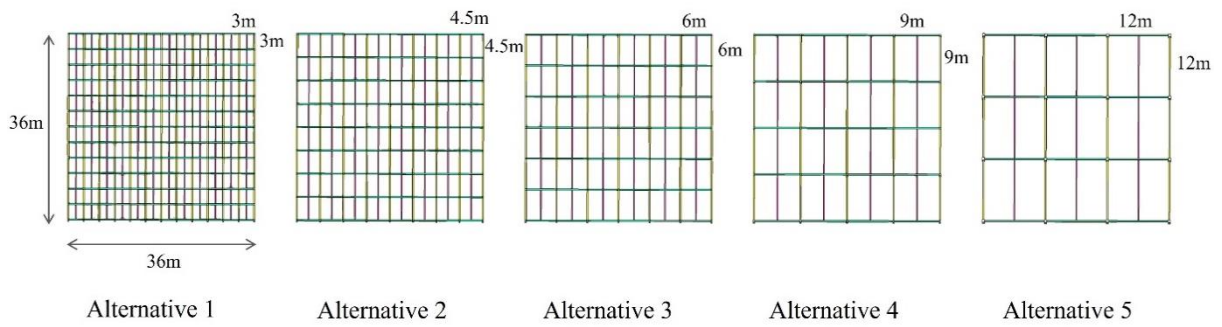


Figure 17. Plans of alternatives (Number of purlins=1) for scenario 2

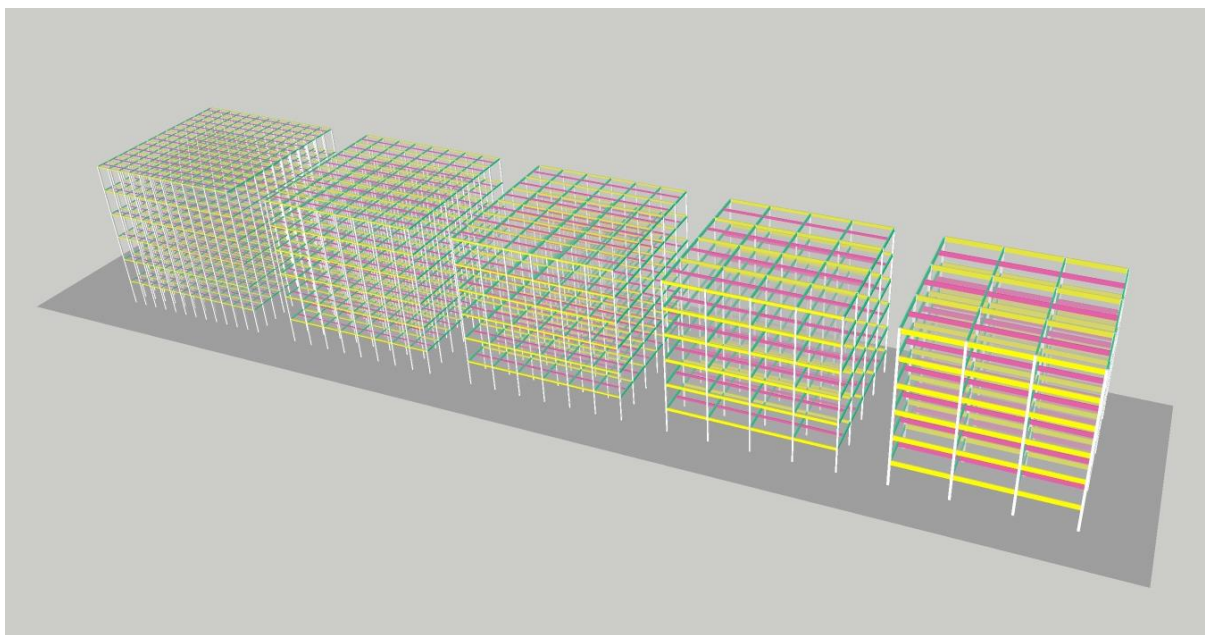


Figure 18. 3D models of alternatives (Number of purlins=1) for scenario 2

Data Collection

The process of data collection is same as that used in scenario 1. Table 10 presents the size and volume of mass timber structure for 1-purlin alternatives. The results of other structures which have two and three purlins are indicated in Appendix 3.

Table 11. Mass timber volume information of building which has 1-purlin

Building Story = 6

Purlin = 1

Gross Floor Area (GFA) = 7,776m²

Bay Size (m)	Components	Components Size (m)	Components Volume (m ³)	Number of Components in one floor	Total Volume (m ³)	CLT Volume / Area (m ³ /m ²)	Glulam Volume / Area (m ³ /m ²)	Total Volume / Area (m ³ /m ²)
3.0 x 3.0	Panel	3.000 x 3.000 x 0.087	0.783	144	676.512	0.087	0.091	0.178
	Girder	0.265 x 0.152 x 2.734	0.110	156	103.077			
		0.265 x 0.152 x 2.735	0.110	156	103.115			
	Purlin	0.215 x 0.152 x 2.735	0.089	144	77.224			
	Column	0.266 x 0.265 x 5.913	0.417	169	422.643			
Sum					1382.571			
4.5 x 4.5	Panel	4.500 x 4.500 x 0.087	1.762	64	676.512	0.087	0.065	0.152
	Girder	0.265 x 0.228 x 4.234	0.256	72	110.513			
		0.265 x 0.228 x 4.235	0.256	72	110.540			
	Purlin	0.215 x 0.228 x 4.235	0.208	64	79.718			
	Column	0.266 x 0.265 x 5.913	0.417	81	202.568			
Sum					1179.852			
6.0 x 6.0	Panel	6.000 x 6.000 x 0.087	3.132	36	676.512	0.087	0.061	0.148
	Girder	0.265 x 0.342 x 5.734	0.520	42	130.957			
		0.265 x 0.342 x 5.735	0.520	42	130.980			
	Purlin	0.215 x 0.342 x 5.735	0.422	36	91.086			
	Column	0.266 x 0.265 x 5.913	0.417	49	122.541			
Sum					1152.077			
9.0 x 9.0	Panel	9.000 x 9.000 x 0.105	8.505	16	816.480	0.105	0.071	0.176
	Girder	0.265 x 0.646 x 8.658	1.482	20	177.860			
		0.265 x 0.646 x 8.685	1.487	20	178.414			
	Purlin	0.215 x 0.570 x 8.735	1.070	16	102.766			
	Column	0.342 x 0.315 x 5.895	0.635	25	95.260			
Sum					1370.780			
12.0 x 12.0	Panel	12.000 x 12.000 x 0.243	34.992	9	1889.568	0.243	0.100	0.343
	Girder	0.265 x 1.102 x 11.468	3.349	12	241.128			
		0.265 x 1.102 x 11.520	3.364	12	242.221			
	Purlin	0.215 x 1.102 x 11.735	2.780	9	150.140			
	Column	0.532 x 0.480 x 5.757	1.470	16	141.130			
Sum					2664.188			

Scenario Results

(1) Results in terms of mass timber volume

As in scenario 1, the volume per area data of Table 10 and Appendix 3 were used to create graphs as shown in Figures 19-1, 2 and 3 and the findings listed below were deduced from them.

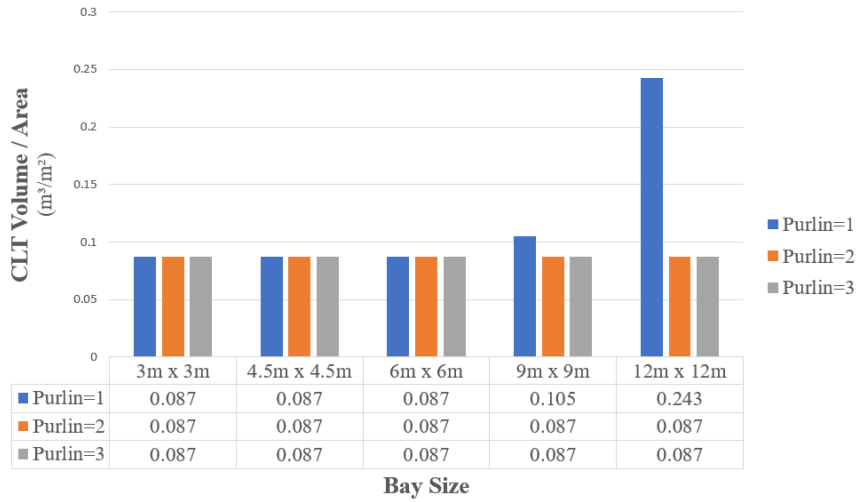


Figure 19-1. CLT volume per area of all alternatives

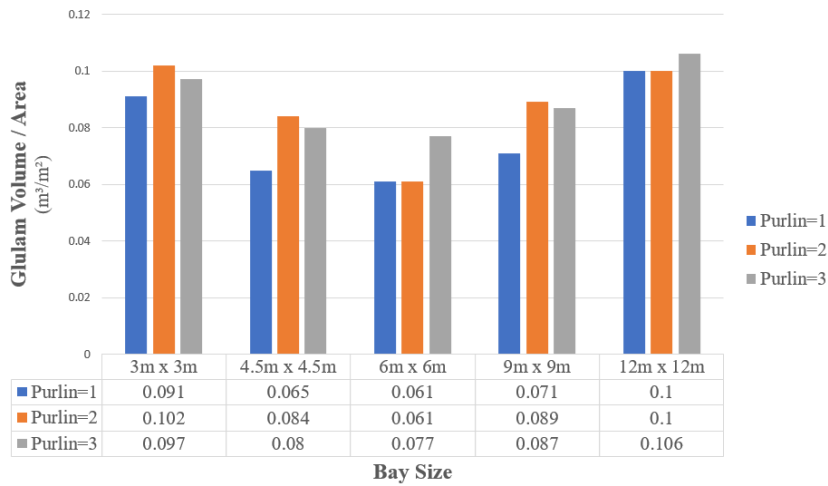


Figure 19-2. Glulam volume per area of all alternatives

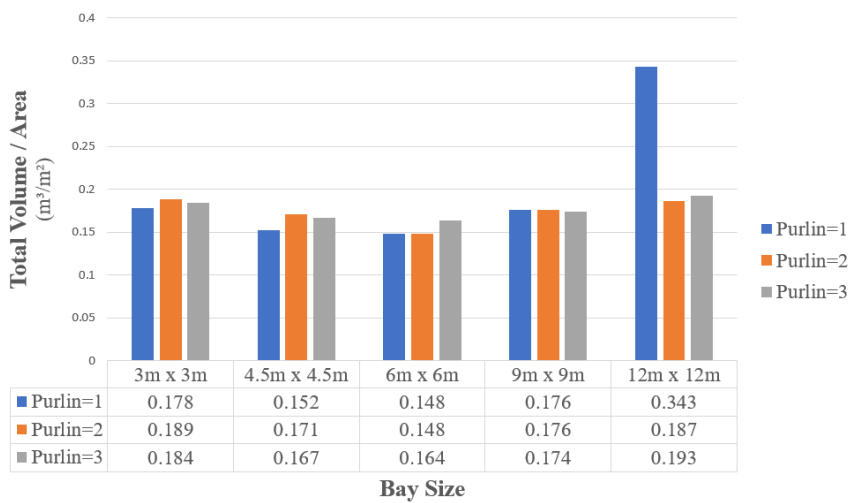


Figure 19-3. Mass Timber total volume per area of all alternatives

First, both CLT and glulam can govern the optimization of mass timber volume. Compared to the results of scenario 1 in terms of CLT volume per area, scenario 2 distinctively revealed that the quantity of CLT volume/area increased in the scenario of 9 m × 9 m and 12 m × 12 m bays and this is only the scenario with 1-purlin (See Figure 19-1). This phenomenon occurs because the CLT panel gradually becomes thicker as the bay size increases beyond a certain size (9 m × 9 m for this scenario) in the scenario of 1-purlin alternative. Specifically, unlike all other alternatives, the thickness of the 9 m × 9 m CLT panel is 105 mm and 243 mm for the 12 m × 12 m bay and these results can be identified easily by the conversion of Figure 19-1. By comparison of Figures 19-1, 2 and 3, scenario 2 identified that both CLT and glulam can govern the optimization of mass timber volume in contrast to scenario 1.

Second, the number of optimized purlins is different depending on the bay sizes. Figure 19-3 indicates that the optimized number of purlins varies depending on the bay sizes. In detail, the 1-purlin alternative is more optimal than the 2- or 3-purlin alternatives for 3 m × 3 m and 4.5 m × 4.5 m alternatives. The 6 m × 6 m bay size shows both 1- and 2-purlin alternatives are more optimal than the 3-purlin alternative. However, the 3-purlin is the optimal alternative for the 9 m × 9 m bay size and the 2-purlin is the most effective alternative for the 12 m × 12 m bay size. Even though the results may look as if there is no consistency, the data suggest mass timber optimization can be done in terms of volume. For the small to mid-sized bay under 6 m in length, a 1-purlin structure can be effective, but for bigger size alternatives over 9 m in length, it is recommended to adopt more than the 1-purlin alternative for optimization of mass timber volume.

Lastly, a 6 m × 6 m bay size is the optimal alternative under conditions of the same number of purlins and Figure 19-3 shows this. For instance, among the 1-purlin alternatives, the 6 m × 6 m is the optimal alternative as $0.148 \text{ m}^3 / \text{m}^2$ total volume per area. Likewise, the

6 m × 6 m bay size is more efficient than other sizes in the scenario of 2-purlin and 3-purlin structure alternatives. This means that the 6 m × 6 m is the optimal alternative under the conditions of scenario 2 unless a bay of a specific size must be selected.

(2) Results in terms of mass timber volume, cost and EC emissions

By the same process as with scenario 1, Table 10 and Appendix 3 were multiplied by the data shown in Table 5 and the results are shown in Tables 11-1, 2 and 3.

Table 12-1. Mass timber volume, cost, EC emission information of 1-purlin building alternative

Building Story = 6
Purlin = 1
Gross Floor Area (GFA) = 7,776m²

Bay Size (m)	Volume (m ³)					Cost					EC emission (kgCo2e)				
	CLT		Glulam		Total	CLT		Glulam		Total	CLT		Glulam		Total
3.0 x 3.0	676.512	49%	706.059	51%	1382.571	\$2,259,909	46%	\$2,704,060	54%	\$4,963,968	107,951	47%	121,901	53%	229,852
4.5 x 4.5	676.512	57%	503.340	43%	1179.852	\$2,259,909	54%	\$1,927,686	46%	\$4,187,594	107,951	55%	86,902	45%	194,853
6.0 x 6.0	676.512	59%	475.565	41%	1152.077	\$2,259,909	55%	\$1,821,315	45%	\$4,081,223	107,951	57%	82,106	43%	190,057
9.0 x 9.0	816.480	60%	554.300	40%	1370.780	\$2,536,118	54%	\$2,122,851	46%	\$4,658,968	130,286	58%	95,700	42%	225,986
12.0 x 12.0	1889.568	71%	774.620	29%	2664.188	\$4,250,470	59%	\$2,966,631	41%	\$7,217,101	301,518	69%	133,738	31%	435,256

Table 12-2. Mass timber volume, cost, EC emission information of 2-purlin building alternative

Building Story = 6
Purlin = 2
Gross Floor Area (GFA) = 7,776m²

Bay Size (m)	Volume (m ³)					Cost					EC emission (kgCo2e)				
	CLT		Glulam		Total	CLT		Glulam		Total	CLT		Glulam		Total
3.0 x 3.0	676.512	46%	796.220	54%	1472.732	\$2,259,909	43%	\$3,049,354	57%	\$5,309,263	107,951	44%	137,467	56%	245,418
4.5 x 4.5	676.512	51%	656.742	49%	1333.254	\$2,259,909	47%	\$2,515,186	53%	\$4,775,094	107,951	49%	113,387	51%	221,338
6.0 x 6.0	676.512	59%	476.823	41%	1153.335	\$2,259,909	55%	\$1,826,132	45%	\$4,086,040	107,951	57%	82,323	43%	190,275
9.0 x 9.0	676.512	49%	692.824	51%	1369.336	\$2,259,909	46%	\$2,653,369	54%	\$4,913,278	107,951	47%	119,616	53%	227,567
12.0 x 12.0	676.512	47%	777.280	53%	1453.792	\$2,259,909	43%	\$2,976,819	57%	\$5,236,727	107,951	45%	134,197	55%	242,148

Table 12-3. Mass timber volume, cost, EC emission information of 3-purlin building alternative

Building Story = 6

Purlin = 3

Gross Floor Area (GFA) = 7,776m²

Bay Size (m)	Volume (m ³)			Cost			EC emission (kgCo2e)								
	CLT		Glulam	Total	CLT		Glulam	Total	CLT		Glulam	Total			
3.0 x 3.0	676.512	47%	751.042	53%	1427.554	\$2,259,909	44%	\$2,876,331	56%	\$5,136,240	107,951	45%	129,667	55%	237,618
4.5 x 4.5	676.512	52%	622.917	48%	1299.429	\$2,259,909	49%	\$2,385,642	51%	\$4,645,551	107,951	50%	107,547	50%	215,498
6.0 x 6.0	676.512	53%	597.013	47%	1273.525	\$2,259,909	50%	\$2,286,435	50%	\$4,546,344	107,951	51%	103,074	49%	211,025
9.0 x 9.0	676.512	50%	677.505	50%	1354.017	\$2,259,909	47%	\$2,594,701	53%	\$4,854,610	107,951	48%	116,971	52%	224,922
12.0 x 12.0	676.512	45%	826.599	55%	1503.111	\$2,259,909	42%	\$3,165,699	58%	\$5,425,608	107,951	43%	142,712	57%	250,663

The data of volume, cost and EC emissions per area are shown in Tables 12-1, 2 and 3 and this can be helpful to identify the optimal alternative by bay sizes. The finding listed below is derived from Tables 11-1, 2 and 3 and Tables 12-1, 2 and 3.

Table 13-1. Volume per Area value of all alternatives of scenario 2

Bay Size (m)	Volume / Area (m ³ / m ²)		
	Number of purlins		
	1	2	3
3 x 3	0.178	0.189	0.184
4.5 x 4.5	0.152	0.171	0.167
6 x 6	0.1482	0.1483	0.164
9 x 9	0.176	0.176	0.174
12 x 12	0.343	0.187	0.193

Table 13-2. Cost per Area value of all alternatives of scenario 2

Bay Size (m)	Cost / Area (\$ / m ²)		
	Number of purlins		
	1	2	3
3 x 3	\$ 638.37	\$ 682.78	\$ 660.52
4.5 x 4.5	\$ 538.53	\$ 614.08	\$ 597.42
6 x 6	\$ 524.85	\$ 525.47	\$ 584.66
9 x 9	\$ 599.15	\$ 631.85	\$ 624.31
12 x 12	\$ 928.13	\$ 673.45	\$ 697.74

Table 13-3. Embodied Carbon Emission per Area value of all alternatives of scenario 2

Embodied Carbon Emission / Area (kgCo2e / m ²)			
Bay Size (m)	Number of purlins		
	1	2	3
3 x 3	29.559	31.561	30.558
4.5 x 4.5	25.058	28.464	27.713
6 x 6	24.442	24.469	27.138
9 x 9	29.062	29.265	28.925
12 x 12	55.974	31.140	32.236

The finding is that the proportional relationship between volume and cost can be reversed. Overall results from scenario 2 indicate similar findings as scenario 1. The ratio of volume: cost: EC emission of the mass timber structure is not 1: 1: 1 and optimization trends of volume, cost and EC emissions are similar from the perspective of the number of purlins as a standard. For instance, the optimal alternative in terms of volume, cost and EC emissions is 6 m × 6 m when the number of purlins is one (See yellow marks in Table 11-1). Other conditions with 2- or 3-purlin alternatives as presented in Tables 11-2 and 3 also show the same results. However, Tables 12-1, 2 and 3 show that the proportional relationship between volume and cost does not exist when the perspective has been changed from the number of purlins to the size of the bay. Tables 12-1, 2 and 3 show the volume, cost and EC emissions per area, respectively, for all of the alternatives in scenario 2 to identify the optimal solution. For example, the optimal alternative in terms of volume is a 1-purlin structure for 3 m × 3 m, 4.5 m × 4.5 m and 6 m × 6 m and this is the same with cost and EC emissions. For the 9 m × 9 m bay size alternative, the optimal number of purlins is three in terms of volume and EC emission; however, the optimal number of purlins is one in terms of cost. This means that the consistent relationship between volume and cost can be reversed in certain situations and it was attributed to two main reasons.

First, the variation of the ratio of CLT and glulam can be a significant factor as their cost per volume is different. Referring to Tables 11-1 and 3, the total volume of the 1-purlin structure (1,370.780 m³) for a 9 m × 9 m bay size is slightly larger than the 3-purlin structure (1,354.017 m³). However, the ratio of glulam for the 1-purlin structure is 40% and for the 3-purlin structure is 50%. This means that, as identified in Table 5, since the cost of glulam is higher than that of CLT, the 3-purlin structure with a higher glulam ratio is more affected by the cost increase than the 1-purlin structure.

Second, the change in cost per volume of CLT according to the change in the thickness of the CLT panel can be another factor. As shown in Table 10, the panel thickness of the 9 m × 9 m bay of the 1-purlin structure is 105 mm and 87 mm for the 3-purlin structure (See Appendix 3). As identified in Table 5, a thicker CLT panel has a lower cost per volume, which may have influenced the cost optimization of the 1-purlin structure. Moreover, according to Table 11-1, the high ratio (60%) of CLT for the 1-purlin alternative may have a big impact on lowering the overall cost of mass timber.

CHAPTER 7. CONCLUSION

Findings and Recommendations

Mass timber structure is in the limelight as a sustainable substitute for traditional structural materials; however, there is a scarcity of research on how to optimize the bay size of mass timber structures. In response, this study suggested a method for finding the optimal bay size of mass timber in terms of volume, cost and embodied carbon emission and two scenarios proved its validity. In this process, the results of the scenarios present several findings that could be used as guidelines in the design stage of mass timber structure.

First of all, optimization of glulam governs overall optimization of mass timber structure. Except for the CLT panel, other components such as column, girder and purlin consist of glulam and the ratio of glulam over 50% on average. As the thickness of the CLT panel is fixed in almost all alternatives, optimized design of glulam becomes more crucial.

Secondly, the optimal bay size for mass timber structure is generally $6\text{ m} \times 6\text{ m}$ under various circumstances. However, the optimal size may change to other sizes depending on the change of variables. The meaningful finding through the scenarios is that the commonly optimized size is $6\text{ m} \times 6\text{ m}$ and the optimized size in a wide variety of scenarios will not deviate much from this.

Thirdly, the square bay is more optimized than the rectangular bay. Even though this finding cannot be identified for numerous scenarios, the results from scenario 1 clearly indicates this finding. In addition, the fact that the surface area of a cube building is always smaller when compared to the surface area of a cuboid building (when two buildings have the same building footprint and height) empirically supports this finding.

Fourthly, the number of optimized purlins varies depending on the bay sizes. According to what was identified in scenario 2, 1-purlin structure is effective for small to

mid-sized bays under 6 m length. For the big-sized bay over 9 m length, it is recommended to adopt 2- or 3-purlin structures and the optimized number of purlins will be different based on the specific conditions of the projects.

Lastly, the optimal alternative for volume is most likely to be the most effective alternative in terms of cost and embodied carbon emissions; however, the proportional relationship between volume and cost can be reversed in specific conditions. In detail, if one alternative's ratio of CLT is high and the CLT panel is thicker than the other alternatives, the possibility of reversed optimization between volume and cost will increase. However, the reversed scenario between the mass timber volume and EC emission was not discovered in this study and it is attributed to the ratio difference of EPD between CLT and glulam is less than the ratio difference of cost.

In conclusion, the present study suggests a mass timber design process framework (see Figure 20) which contains useful findings for real-world projects. Above all, starting with a 6 m × 6 m bay is recommended at the initial design stage of mass timber design for optimization of cost and embodied carbon emission. If the bay size needs to be varied to meet other design requirements, I propose to keep the bays as square as possible and not to deviate too much from the 6 m × 6 m size. Checking the optimized number of purlins and inducing glulam optimization for specific alternatives are also key for adjusting bay size. Then, project stakeholders will select some potential alternatives and analyze them to compare cost and EC emission. Finally, the optimal alternative for the project will be confirmed through decision-making process and there are two kinds of way to select the optimal alternative. If the optimal alternative in terms of cost is the most effective alternative in terms of EC emission as well, this alternative will be chosen without any doubt. However, the project stakeholders will consider and select the best alternative based on their own priority if the low-priced alternative is not the optimal alternative in terms of EC emission.

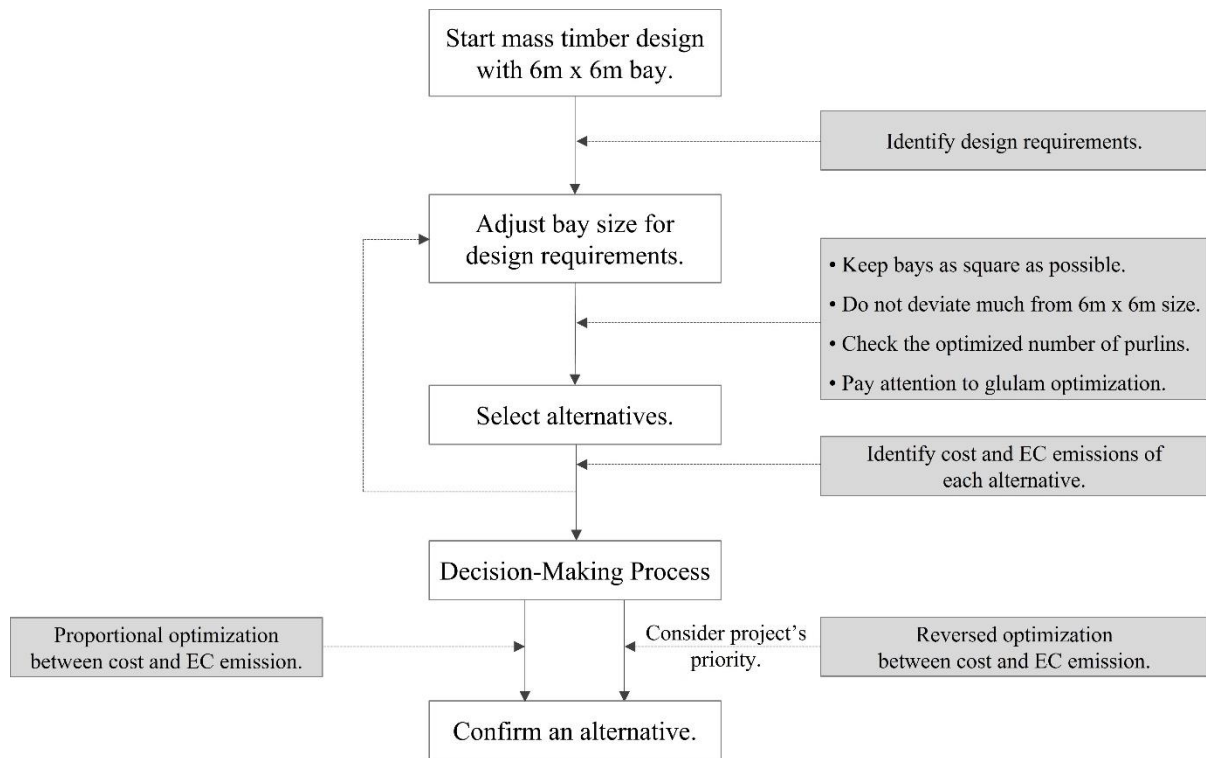


Figure 20. Mass Timber Design Process Framework

Limitations

Although this study can suggest a method to find an optimized mass timber bay size in terms of cost and EC emission, the following limitations are acknowledged:

1. As mentioned in Chapter 4, the height of one story is fixed at 6 m in the Timber Bay Design Tool. Since the height of a typical residential building is 3 m, there are many limitations to using the Timber Bay Design Tool for real buildings. However, according to the email interview with a Fast + Epp staff member, they're in the process of updating the Timber Bay Design Tool to apply various heights. Additionally, there is no architectural consideration such as ceiling height as mentioned in Chapter 4. Even though various heights of beams (girder, purlin) were created in the scenarios, they didn't impact the results of this study.

2. This study used various localized data. Structural logic of the Timber Bay Design Tool, cost and EPD data are based on the Pacific Northwest region of North America. To use the TBCCOA in other regions, it is necessary to apply provincial regulations or codes to calculate the size of mass timber components. Plus, specific cost and EPD should be used by region.
3. As mentioned in Chapter 2, the Timber Bay Design Tool is intended to be used in the preliminary design phase. Comparing the various alternatives through TBCCOA is only meaningful at the initial mass timber design stage and it is up to the estimators and LCA experts to quantify the final result of costs and embodied carbon emissions.
4. This study deals with only mass timber components to identify the optimal bay size, however, mass timber components are normally assembled by lots of steel connectors. Also, a hybrid mass timber system which combines concrete slab and mass timber columns with beams is commonly used for residential buildings.
5. To validate the TBCCOA, only two scenarios were performed. However, there will be a myriad of scenarios in real situations in which combinations of various timber bay sizes, shapes and number of bays. It means findings and recommendations mentioned in this study may not be an absolute solution for every project.
6. The cost data in Table 5 and EPD in Figure 11 may not be valid continuously in the future. The expiration of the cost in Table 5 is end of June 2023 as confirmed by cost data provider, Roen Associates. The EPD data in Figure 11 issued on 4/15/2021 and valid until 4/15/2026.
7. As mentioned in Chapter 3, this study did not apply the concept of accuracy range and it means the results value of cost and EC emissions may not be accurate. However, this study put more significance on comparisons to find the optimal alternatives in terms of cost and EC emission.

Future Study

Since the construction sector makes up a large percentage of the global carbon emissions, continuous efforts are required to mitigate global climate change from the construction sector. There are various methods that lead to positive changes, yet the importance of endeavors to reduce EC emission by substituting conventional building material to sustainable one should be highlighted. However, the use of mass timber for building structure still has a high-cost barrier and the starting point of this study is to propose an optimal bay size to overcome the barrier.

To identify the optimal alternatives in terms of volume, cost and EC emission, the TBCCOA was devised and various findings useful in the initial design stage were obtained through scenarios. The novelty of the study lies in that it dealt with optimization of mass timber bay size and the relationship between volume, cost and EC emission. Additionally, this study accomplished the prime objective of relatively comparing cost and EC emission between alternatives, rather than calculating exact figures. To promote the use of mass timber as a building structure, I recommend for future researchers to minimize study limitations and propose more practical guidelines in the mass timber design stage.

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APPENDIX

(1) Mass timber volume information of 6, 9 ,12-story building alternatives (Scenario 1)

Building Story = 6

Gross Floor Area (GFA) = 5,832m²

Bay Size (m)	Components	Components Size (m)	Components Volume (m ³)	Number of Components in one floor	Total Volume (m ³)	CLT Volume / Area (m ³ /m ²)	Glulam Volume / Area (m ³ /m ²)	Total Volume / Area (m ³ /m ²)
3.0 x 3.0	Panel	3.000 x 3.000 x 0.087	0.783	108	507.384	0.087	0.100	0.187
	Girder	0.265 x 0.114 x 2.734	0.0826	126	62.441			
		0.265 x 0.114 x 2.735	0.0826	114	56.515			
	Purlin	0.215 x 0.114 x 2.735	0.0670	324	130.316			
	Column	0.266 x 0.265 x 5.913	0.417	133	332.612			
Sum					1089.268			
4.5 x 4.5	Panel	4.500 x 4.500 x 0.087	1.762	48	507.384	0.087	0.083	0.170
	Girder	0.265 x 0.228 x 4.234	0.2558	60	92.095			
		0.265 x 0.228 x 4.235	0.2559	52	79.834			
	Purlin	0.215 x 0.190 x 4.235	0.1730	144	149.472			
	Column	0.266 x 0.265 x 5.913	0.417	65	162.555			
Sum					991.339			
6.0 x 6.0	Panel	6.000 x 6.000 x 0.087	3.132	27	507.384	0.087	0.080	0.167
	Girder	0.265 x 0.342 x 5.734	0.520	36	112.269			
		0.265 x 0.342 x 5.735	0.520	30	93.541			
	Purlin	0.215 x 0.266 x 5.735	0.328	81	159.401			
	Column	0.266 x 0.265 x 5.913	0.417	40	100.034			
Sum					972.628			
9.0 x 9.0	Panel	9.000 x 9.000 x 0.087	7.047	12	507.384	0.087	0.091	0.178
	Girder	0.265 x 0.608 x 8.658	1.395	18	150.658			
		0.265 x 0.608 x 8.685	1.399	14	117.543			
	Purlin	0.215 x 0.456 x 8.735	0.856	36	184.978			
	Column	0.342 x 0.315 x 5.913	0.637	21	80.263			
Sum					1040.826			
13.5 x 6.0	Panel	13.500 x 6.000 x 0.087	7.047	12	507.384	0.087	0.126	0.213
	Girder	0.265 x 0.608 x 13.158	2.120	16	203.522			
		0.265 x 0.608 x 5.685	0.916	15	82.437			
	Purlin	0.215 x 0.608 x 13.235	1.730	36	373.697			
	Column	0.342 x 0.315 x 5.913	0.637	20	76.441			
Sum					1243.481			

Building Story = 9

Gross Floor Area (GFA) = 8,748m²

Bay Size (m)	Components	Components Size (m)	Components Volume (m ³)	Number of Components in one floor	Total Volume (m ³)	CLT Volume / Area (m ³ /m ²)	Glulam Volume / Area (m ³ /m ²)	Total Volume / Area (m ³ /m ²)
3.0 x 3.0	Panel	3.000 x 3.000 x 0.087	0.783	108	761.076	0.087	0.100	0.187
	Girder	0.265 x 0.114 x 2.734	0.0826	126	93.662			
		0.265 x 0.114 x 2.735	0.0826	114	84.773			
	Purlin	0.215 x 0.114 x 2.735	0.0670	324	195.474			
	Column	0.266 x 0.265 x 5.913	0.4168	133	498.918			
Sum					1633.902			
4.5 x 4.5	Panel	4.500 x 4.500 x 0.087	1.762	48	761.076	0.087	0.083	0.170
	Girder	0.265 x 0.228 x 4.234	0.2558	60	138.142			
		0.265 x 0.228 x 4.235	0.2559	52	119.751			
	Purlin	0.215 x 0.190 x 4.235	0.1730	144	224.208			
	Column	0.266 x 0.265 x 5.913	0.4168	65	243.832			
Sum					1487.009			
6.0 x 6.0	Panel	6.000 x 6.000 x 0.087	3.132	27	761.076	0.087	0.082	0.169
	Girder	0.265 x 0.342 x 5.696	0.516	36	167.258			
		0.265 x 0.342 x 5.735	0.520	30	140.336			
	Purlin	0.215 x 0.266 x 5.735	0.328	81	239.101			
	Column	0.304 x 0.265 x 5.913	0.476	40	171.486			
Sum					1479.257			
9.0 x 9.0	Panel	9.000 x 9.000 x 0.087	7.047	12	761.076	0.087	0.100	0.187
	Girder	0.265 x 0.608 x 8.544	1.377	18	223.011			
		0.265 x 0.608 x 8.610	1.387	14	174.793			
	Purlin	0.215 x 0.456 x 8.735	0.856	36	277.467			
	Column	0.456 x 0.390 x 5.913	1.052	21	198.746			
Sum					1635.093			
13.5 x 6.0	Panel	13.500 x 6.000 x 0.087	7.047	12	761.076	0.087	0.134	0.221
	Girder	0.265 x 0.608 x 13.044	2.102	16	302.637			
		0.265 x 0.608 x 5.610	0.904	15	122.024			
	Purlin	0.215 x 0.608 x 13.235	1.730	36	560.546			
	Column	0.456 x 0.390 x 5.913	1.052	20	189.282			
Sum					1935.566			

Building Story = 12

Gross Floor Area (GFA) = 11,664m²

Bay Size (m)	Components	Components Size (m)	Components Volume (m ³)	Number of Components in one floor	Total Volume (m ³)	CLT Volume / Area (m ³ /m ²)	Glulam Volume / Area (m ³ /m ²)	Total Volume / Area (m ³ /m ²)
3.0 x 3.0	Panel	3.000 x 3.000 x 0.087	0.783	108	1014.768	0.087	0.100	0.187
	Girder	0.265 x 0.114 x 2.734	0.0826	126	124.882			
		0.265 x 0.114 x 2.735	0.0826	114	113.030			
	Purlin	0.215 x 0.114 x 2.735	0.0670	324	260.631			
	Column	0.266 x 0.265 x 5.913	0.4168	133	665.225			
Sum					2178.537			
4.5 x 4.5	Panel	4.500 x 4.500 x 0.087	1.762	48	1014.768	0.087	0.083	0.170
	Girder	0.265 x 0.228 x 4.234	0.2558	60	184.189			
		0.265 x 0.228 x 4.235	0.2559	52	159.668			
	Purlin	0.215 x 0.190 x 4.235	0.1730	144	298.944			
	Column	0.266 x 0.265 x 5.913	0.4168	65	325.110			
Sum					1982.679			
6.0 x 6.0	Panel	6.000 x 6.000 x 0.087	3.132	27	1014.768	0.087	0.087	0.174
	Girder	0.265 x 0.342 x 5.735	0.520	36	224.538			
		0.265 x 0.342 x 5.620	0.509	30	183.363			
	Purlin	0.215 x 0.266 x 5.735	0.328	81	318.801			
	Column	0.380 x 0.265 x 5.913	0.595	40	285.811			
Sum					2027.280			
9.0 x 9.0	Panel	9.000 x 9.000 x 0.087	7.047	12	1014.768	0.087	0.104	0.191
	Girder	0.265 x 0.608 x 8.570	1.381	18	298.252			
		0.265 x 0.608 x 8.507	1.371	14	230.269			
	Purlin	0.215 x 0.456 x 8.735	0.856	36	369.956			
	Column	0.494 x 0.430 x 5.913	1.256	21	316.522			
Sum					2229.767			
13.5 x 6.0	Panel	13.500 x 6.000 x 0.087	7.047	12	1014.768	0.087	0.138	0.225
	Girder	0.265 x 0.608 x 13.006	2.096	16	402.341			
		0.265 x 0.608 x 5.570	0.897	15	161.539			
	Purlin	0.215 x 0.608 x 13.235	1.730	36	747.394			
	Column	0.494 x 0.430 x 5.913	1.256	20	301.449			
Sum					2627.492			

(2) Mass timber volume, cost, EC emission information of 6, 9, 12-story building alternatives (Scenario 1)

Building Story = 6

Gross Floor Area (GFA) = 5,832m²

Bay Size (m)	Volume (m3)				Cost						EC emission (kgCo2e / m ³)				
	CLT		Glulam		Total	CLT		Glulam		Total	CLT		Glulam		Total
3.0 x 3.0	507.384	47%	581.884	53%	1089.268	\$1,694,931	43%	\$2,228,495	57%	\$3,923,426	80,963	45%	100,462	55%	181,426
4.5 x 4.5	507.384	51%	483.955	49%	991.339	\$1,694,931	48%	\$1,853,448	52%	\$3,548,379	80,963	49%	83,555	51%	164,518
6.0 x 6.0	507.384	52%	465.244	48%	972.628	\$1,694,931	49%	\$1,781,787	51%	\$3,476,719	80,963	50%	80,324	50%	161,288
9.0 x 9.0	507.384	49%	533.442	51%	1040.826	\$1,694,931	45%	\$2,042,970	55%	\$3,737,902	80,963	47%	92,099	53%	173,062
13.5 x 6.0	507.384	41%	736.097	59%	1243.481	\$1,694,931	38%	\$2,819,096	62%	\$4,514,027	80,963	39%	127,087	61%	208,050

Building Story = 9

Gross Floor Area (GFA) = 8,748m²

Bay Size (m)	Volume (m3)				Cost						EC emission (kgCo2e / m ³)				
	CLT		Glulam		Total	CLT		Glulam		Total	CLT		Glulam		Total
3.0 x 3.0	761.076	47%	872.826	53%	1633.902	\$2,542,397	43%	\$3,342,742	57%	\$5,885,139	121,445	45%	150,693	55%	272,138
4.5 x 4.5	761.076	51%	725.933	49%	1487.009	\$2,542,397	48%	\$2,780,171	52%	\$5,322,568	121,445	49%	125,332	51%	246,777
6.0 x 6.0	761.076	51%	718.181	49%	1479.257	\$2,542,397	48%	\$2,750,484	52%	\$5,292,881	121,445	49%	123,994	51%	245,439
9.0 x 9.0	761.076	47%	874.017	53%	1635.093	\$2,542,397	43%	\$3,347,300	57%	\$5,889,697	121,445	45%	150,899	55%	272,344
13.5 x 6.0	761.076	39%	1174.490	61%	1935.566	\$2,542,397	36%	\$4,498,049	64%	\$7,040,446	121,445	37%	202,776	63%	324,221

Building Story = 12

Gross Floor Area (GFA) = 11,664m²

Bay Size (m)	Volume (m3)				Cost						EC emission (kgCo2e / m ³)				
	CLT		Glulam		Total	CLT		Glulam		Total	CLT		Glulam		Total
3.0 x 3.0	1014.768	47%	1163.769	53%	2178.537	\$3,389,863	43%	\$4,456,989	57%	\$7,846,852	161,927	45%	200,925	55%	362,851
4.5 x 4.5	1014.768	51%	967.911	49%	1982.679	\$3,389,863	48%	\$3,706,895	52%	\$7,096,758	161,927	49%	167,110	51%	329,036
6.0 x 6.0	1014.768	50%	1012.512	50%	2027.280	\$3,389,863	47%	\$3,877,709	53%	\$7,267,572	161,927	48%	174,810	52%	336,737
9.0 x 9.0	1014.768	46%	1214.999	54%	2229.767	\$3,389,863	42%	\$4,653,192	58%	\$8,043,054	161,927	44%	209,770	56%	371,696
13.5 x 6.0	1014.768	39%	1612.724	61%	2627.492	\$3,389,863	35%	\$6,176,393	65%	\$9,566,256	161,927	37%	278,437	63%	440,363

(3) Mass timber volume information of buildings which have 2, 3-purlin (Scenario 2)

Building Story = 6

Purlin = 2

Gross Floor Area (GFA) = 7,776m²

Bay Size (m)	Components	Components Size (m)	Components Volume (m ³)	Number of Components in one floor	Total Volume (m ³)	CLT Volume / Area (m ³ /m ²)	Glulam Volume / Area (m ³ /m ²)	Total Volume / Area (m ³ /m ²)
3.0 x 3.0	Panel	3.000 x 3.000 x 0.087	0.783	144	676.512	0.087	0.102	0.189
	Girder	0.265 x 0.190 x 2.734	0.138	156	128.847			
		0.265 x 0.190 x 2.735	0.138	156	128.894			
	Purlin	0.215 x 0.114 x 2.735	0.067	288	115.836			
	Column	0.266 x 0.265 x 5.913	0.417	169	422.643			
Sum					1472.732			
4.5 x 4.5	Panel	4.500 x 4.500 x 0.087	1.76175	64	676.512	0.087	0.084	0.171
	Girder	0.265 x 0.304 x 4.234	0.341	72	147.351			
		0.265 x 0.304 x 4.235	0.341	72	147.386			
	Purlin	0.215 x 0.228 x 4.235	0.208	128	159.437			
	Column	0.266 x 0.265 x 5.913	0.417	81	202.568			
Sum					1333.254			
6.0 x 6.0	Panel	6.000 x 6.000 x 0.087	3.132	36	676.512	0.087	0.061	0.148
	Girder	0.265 x 0.304 x 5.734	0.462	42	116.407			
		0.265 x 0.304 x 5.735	0.462	42	116.427			
	Purlin	0.215 x 0.228 x 5.735	0.281	72	121.448			
	Column	0.266 x 0.265 x 5.913	0.417	49	122.541			
Sum					1153.335			
9.0 x 9.0	Panel	9.000 x 9.000 x 0.087	7.047	16	676.512	0.087	0.089	0.176
	Girder	0.265 x 0.760 x 8.658	1.744	20	209.247			
		0.265 x 0.760 x 8.685	1.749	20	209.899			
	Purlin	0.215 x 0.494 x 8.735	0.928	32	178.127			
	Column	0.342 x 0.315 x 5.913	0.637	25	95.551			
Sum					1369.336			
12.0 x 12.0	Panel	12.000 x 12.000 x 0.087	12.528	9	676.512	0.087	0.100	0.187
	Girder	0.265 x 1.064 x 11.544	3.2549	12	234.356			
		0.265 x 1.064 x 11.570	3.2623	12	234.884			
	Purlin	0.215 x 0.722 x 11.735	1.8216	18	196.735			
	Column	0.456 x 0.430 x 5.913	1.1594	16	111.304			
Sum					1453.792			

Building Story = 6

Purlin = 3

Gross Floor Area (GFA) = 7,776m²

Bay Size (m)	Components	Components Size (m)	Components Volume (m ³)	Number of Components in one floor	Total Volume (m ³)	CLT Volume / Area (m ³ /m ²)	Glulam Volume / Area (m ³ /m ²)	Total Volume / Area (m ³ /m ²)
3.0 x 3.0	Panel	3.000 x 3.000 x 0.087	0.783	144	676.512	0.087	0.097	0.184
	Girder	0.265 x 0.114 x 2.734	0.083	156	77.308			
		0.265 x 0.114 x 2.735	0.083	156	77.336			
	Purlin	0.215 x 0.114 x 2.735	0.067	432	173.754			
	Column	0.266 x 0.265 x 5.913	0.417	169	422.643			
Sum					1427.554			
4.5 x 4.5	Panel	4.500 x 4.500 x 0.087	1.76175	64	676.512	0.087	0.080	0.167
	Girder	0.265 x 0.228 x 4.234	0.256	72	110.513			
		0.265 x 0.228 x 4.235	0.256	72	110.540			
	Purlin	0.215 x 0.190 x 4.235	0.173	192	199.296			
	Column	0.266 x 0.265 x 5.913	0.417	81	202.568			
Sum					1299.429			
6.0 x 6.0	Panel	6.000 x 6.000 x 0.087	3.132	36	676.512	0.087	0.077	0.164
	Girder	0.265 x 0.342 x 5.734	0.520	42	130.957			
		0.265 x 0.342 x 5.735	0.520	42	130.980			
	Purlin	0.215 x 0.266 x 5.735	0.328	108	212.534			
	Column	0.266 x 0.265 x 5.913	0.417	49	122.541			
Sum					1273.525			
9.0 x 9.0	Panel	9.000 x 9.000 x 0.087	7.047	16	676.512	0.087	0.087	0.174
	Girder	0.265 x 0.608 x 8.658	1.395	20	167.397			
		0.265 x 0.608 x 8.685	1.399	20	167.919			
	Purlin	0.215 x 0.456 x 8.735	0.856	48	246.637			
	Column	0.342 x 0.315 x 5.913	0.637	25	95.551			
Sum					1354.017			
12.0 x 12.0	Panel	12 x 12 x 0.087	12.528	9	676.512	0.087	0.106	0.193
	Girder	0.265 x 0.988 x 11.544	3.022	12	217.616			
		0.265 x 0.988 x 11.570	3.029	12	218.107			
	Purlin	0.215 x 0.684 x 11.735	1.726	27	279.571			
	Column	0.456 x 0.430 x 5.913	1.159	16	111.304			
Sum					1503.111			