Comparing the Environmental Impacts of Using Mass Timber and Structural Steel

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Mass timber has seen a gradual rise in demand in the past decade, but it has yet to out-pace steel as the construction industry's primary material. Due to the lack of overall mass timber developments, there has been a lack of extensive research on the construction material, primarily the environmental impacts of using mass timber as a primary structural framing material. This dissertation is about comparing structural steel, and mass timber's total embodied carbon emissions. A critical review of previous literature was conducted and used as precedents for the research. Using construction documents for three separate projects retrieved from semi-structured interviews, accurate estimates were conducted. The data from each estimate was input through the Embedded Carbon in Construction Calculator (EC3 Calculator) to provide extensive total carbon emissions measurements regarding each construction material. The data indicated that using structural steel as the primary framing option would increase the project's overall environmental impact by roughly 84% compared to using mass timber. A unique find from the research was that concrete foundations produced carbon emissions equal to or greater than the total carbon emitted by structural steel. The results provide sufficient evidence supporting the use of mass timber as a structural framing material.

Key Words: Mass Timber, Structural Steel, Embedded Carbon Emissions, EC3 Calculator, Framing

Introduction

The construction industry has maintained a so-called "status quo" regarding construction materials. Since the early 20th century, structural steel and concrete have increased the job site and have created skyscrapers that have continuously shaped modern skylines. The rapid urban development and growth have had a considerable environmental cost that does not seem to slow down soon. As written (Architecture 2030) in the "New Buildings: Embodied Carbon" article, the construction industry has produced an average of 3.729 trillion metric tons of carbon dioxide per year and equates to roughly 11% of the total global carbon dioxide emissions. With the growing trend of reinvigorating wood construction, new construction methods involving mass timber have gained traction in Europe and Japan, with North America following suit (Kavanagh, P.). Although there has been extensive research regarding the structural aspects of mass timber, there is not much research regarding the environmental cost of using mass timber. This research explores the environmental cost of using mass timber compared to steel on the job site– specifically the embodied carbon from cradle-to-grave. These findings will then aid the industry by showing that mass timber construction is not a trend and the future of sustainability in the built environment.

Literature Review

Cross-laminated timber (CLT) and other mass timber construction materials are a relatively forgotten building material that has gradually picked up momentum in recent years. With sustainability coming to the forefront of discussions in recent decades and the increasing demand for more mid-rise and high-rise wooden buildings, the manufactured material's environmental impacts have come into question.

The purpose of the review is to provide further background for the case study. This report follows the relevant previous research of Kavanagh and Nakano (2020).

Kavanagh, Roche, Brady, and Lauder performed a case study that extensively analyzed the life cycle of Stadhaus at Murray Groce in London, United Kingdom– a bamboo veneer building. The case study utilizes eco-cost (€/kg) and global warming potential, measured in $kgCO_2$. The authors presented the immense sustainable prospect for the use of CLT and other mass timber products. The construction speed and the energy costs were of note in the research, both of which were significantly reduced using timber rather than conventional concrete (Kavanagh, p. 97). The paper also noted that a complete life cycle assessment (LCA) had become internationally recognized as a method for assessing certain building materials' potential environmental impacts from cradle-to-grave (Kavanagh, p.95). The researchers developed a standardized panel system to compete with the building's CLT panels and analyzed the complete cradle-to-grave cycle of both design options. The assessment took into account 1) the material extraction, 2) transportation, 3) manufacturing maintenance, and 4) end-of-life with notable exclusions such as material and energy requirements. The data used to perform the analysis were the 1) types of construction materials, 2) their quantities, 3) volumes, 4) areas, and 5) weight. Kavanagh and their team concluded that bamboo has a lower environmental impact than CLT. The study found that bamboo grows faster than traditional timber while maintaining the same or better structural elements as timber.

Nakano, Karude, and Hattori (2020) approached the topic differently. The team performed an extensive case study highlighting the environmental impacts of a CLT building in Kumamoto City in the Kyushu Region. Their study investigated the materials and energy used to build the CLT building and relate it to its total environmental impact from the material's manufacturing to the end of construction. (Nakano, K., Karube, M., & Hattori, N., 2020, p. 1). Although mass timber is widely viewed as reliable and abundant, its sustainability has varied from regular lumber to engineered wood due to the intricacies of the manufacturing processes. Nakano, Karude, and Hattori (2020) surveyed the building and created a hyper-detailed estimate of all materials used. Additionally, the team incorporated an extensive inventory of transportation and installation methods used during the building's construction, close to accurate measurements. Their research concluded that concrete, cement-based stabilizers, and rebar accounted for most greenhouse gas emissions throughout the cradle-to-cradle process (Nakano, K., Karube, M., & Hattori, N., 2020, p. 12). The paper suggests using biomass-based energy and extensive recycling protocols to reduce environmental impacts, especially at the end-of-life stage.

Sahoo, Bergman, Rosenbaum, Gu, and Liang (2019) all came together to research the most abundant renewable resource on the planet and its environmental performance. They noticed that throughout the mass timber material's life cycle, the manufacturing stage tends to produce the most prominent environmental impact. Key challenges that they came across during their research of the life cycle assessment of manufactured wood included handling uncertainties in the supply chain and complex interactions of environment, material conversion, resource use for product production, and quantifying the emissions released. As the green building movement grew over the last couple of decades, emerging wood building products were developed along with other forest-based products which used LCA in their product development (Sahoo, Bergman, Rosenbaum, Gu, and Liang, 2019, p.8). Additionally, the team noticed that residential and commercial buildings consumed about 40% of all energy used in the United States. Although most energy is used during the building occupation (i.e., after construction), there is increased awareness of decreasing the embodied energy, the amount of energy used in the production of building material, and the overall aim of lowering the environmental footprint of the building. (Sahoo, Bergman, Rosenbaum, Gu, Liang, 2019, p. 9) The team's results showed that the CLT buildings exhibited better environmental performance, such as lower GW compared with their corresponding building alternatives.

Appraisal

This chapter sets out to establish a factual background on available research regarding the environmental impacts of mass timber structures. There is a lack of research regarding the ecological impact of mass timber buildings and their life cycle, especially in North America. All three papers' life cycle assessments lead to more significant implications regarding climate change, ozone depletion, and environmental conditions existing in predominantly urban settings, along with detailed breakdowns of the greenhouse gas emissions of certain materials. A bamboo alternative appears to have a lower environmental impact than standard mass timber; however, this paper will strictly analyze the embodied carbon emissions of mass timber due to supply constraints. Although Nakano and their team included the building's foundations in their calculations and assessments, there weren't further comparisons between various framing materials.

Limitation of Study

One limitation of the project was the accessibility of the tool used for this research. Due to the public access to the instrument, fewer options for building materials and manufacturers were provided when inputting the data. This paper's primary tool was also in its beta phase, which meant it is not fully developed yet. Additionally, some documents lacked sufficient data to analyze due to the nature of their confidentiality thoroughly. As a result, some of the input data might have been slightly skewed, but all outcomes are as accurate as possible and suitable to the information provided.

Methodology

This chapter will discuss the primary tools used to perform this research. A mixed-method approach was implemented to perform comparative, analytical case studies of three projects.

Project Aim

The purpose of this document is to perform an extensive comparative analysis of various buildings, either have been built or will be built soon. The study will compare the environmental cost of using mass timber and structural steel on the job site as primary framing materials– specifically the carbon emissions from cradle-to-grave. The research will provide crucial, detailed insight into the carbon footprint mass timber produces compared to its steel counterpart. The study will allow us to determine which construction material is ideal for its environmental impact. This document, and subsequent future papers on the subject matter, will aid contractors in making more environmentally conscious decisions regarding which building materials they want on the job site. Additionally, the tools used in this research can be advocated for widespread usage due to their simplicity and detail-oriented nature.

Procedure of Data Collection

Semi-structured interviews were conducted with industry professionals– precisely professional contacts– regarding the use of mass timber as a primary structural material for future job sites and to obtain construction documents of either finished projects and projects in the preconstruction phase (see Table 1). Each interview was administered to industry professionals from three different companies: 1) Gilbane Building Company, 2) XL Construction, and 3) a confidential contact. The questions are intended to collect personal opinions and gauge to what extent industry leaders know about mass timber and sustainability as a whole. Regarding sustainability, some questions were meant to obtain what various professionals considered sustainable building practices.

From the construction documents, detailed estimates were made with the given information. A detailed inventory was curated with a focus primarily on the structural framing and foundations of each building. A few assumptions were made based on industry-standard practices regarding the foundation and assumptions made based on available specifications. Once final estimates have been completed, all data is inputted into the Embedded Carbon in Construction Calculator (EC3 Tool) to calculate each project's total carbon footprint from cradle-to-grave. The final calculations used $kgCO_2$ as the unit of measurement. The software produced Environmental Product Declarations (EPD) and mass diagrams to illustrate each project's materials' flow. The reports were more accessible and visible, allowing for more accurate embodied carbon evaluations.

Table 1

Interview questions for professional contacts

1	What is your stance on sustainability?
2	What is your opinion on mass timber? What about steel framing?
3	Have you worked on projects involving mass timber, or will you in the future?
4	What sustainability challenges and advantages have you faced regarding the projects you've worked on?
5	What advantages have you noticed with [said material] compared to others?
6	Have you heard of or worked with the EC3 Calculator before?
7	What's your educated guess on the difference in carbon emissions between steel framing and mass timber?
8	Do you think they are roughly the same? If so, why?

9	Will you be willing to provide construction documents on a project that you've been working on?

The responses provided were given by an industry professional with multiple Mass Timber projects under his belt. In this paragraph, we will only be touching on some of these questions and responses, and we will be referring to our contact as Jake. When asked about his sustainability stance, Jake mentions that the environment is the most important thing to him when he is on the job site. The industry should work towards lowering its carbon footprint and overall keep trending towards green construction practices. Jake also explained the pros and cons of mass timber framing, stating that the pros by far outweigh the cons. The pros included it being a much more lean way of doing construction, especially from a constructability standpoint; more coordination involved less labor needed. The one con was transporting the material to the job site. This itself is difficult due to the locations of the mass timber manufacturers. When asked about the EC3 calculator, our industry contact had not previously heard of it but did want to learn more and asked exactly what went in the calculator to give us our data. I believe this shows that the calculator is still in its early beta phase but has excellent potential to merge sustainable building tools for the future.

Data Analysis & Results

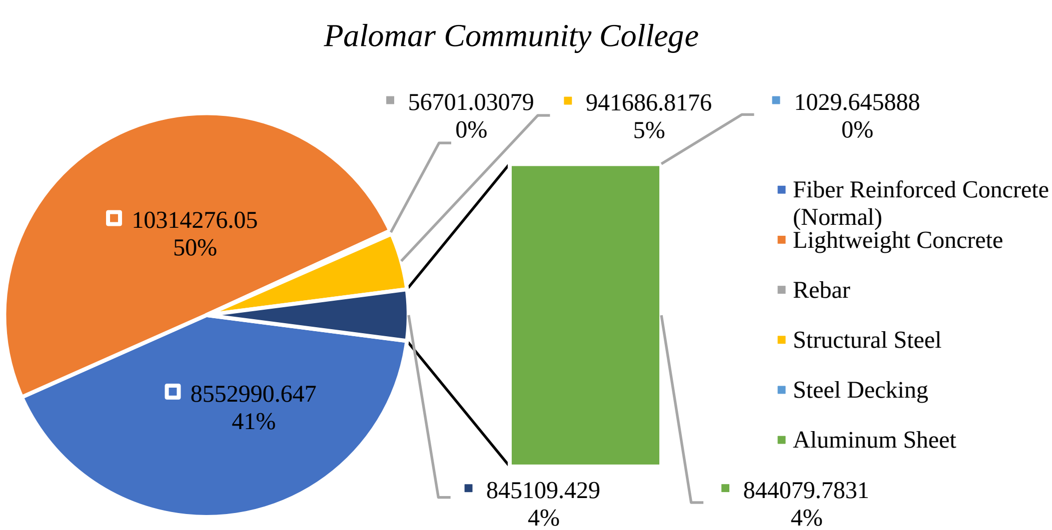

Figure 1. Conservative/realized embodied carbon of Palomar Community College Library

Palomar Community College, located in San Marcos, CA, commissioned Gilbane Building Company to construct a new 4-story library building. The structure is a complete steel frame building utilizing structural steel, aluminum, and steel decking. All estimates for the building's framing elements were inputted into the calculator to produce the final results. The total conservative embodied carbon emissions estimate for the project equated to 20.71×10^6 $kgCO_2$. The concrete foundation's conservative and realistic estimates are the same since they are the most accurate calculations with the available information. The concrete foundation's entirety accounted for 91.1% of total emissions, equivalent to roughly 18.87×10^6 $kgCO_2$ (see figure 1). The entire structural steel frame's realistic embodied carbon emissions, including the aluminum exterior shell, was 13%, equating to roughly 1.79×10^6 $kgCO_2$ (see figure 1). The rebar used for the foundations and the steel decking present on each floor produced an estimated 57,731 $kgCO_2$, which is a small enough amount to deem it as insignificant.

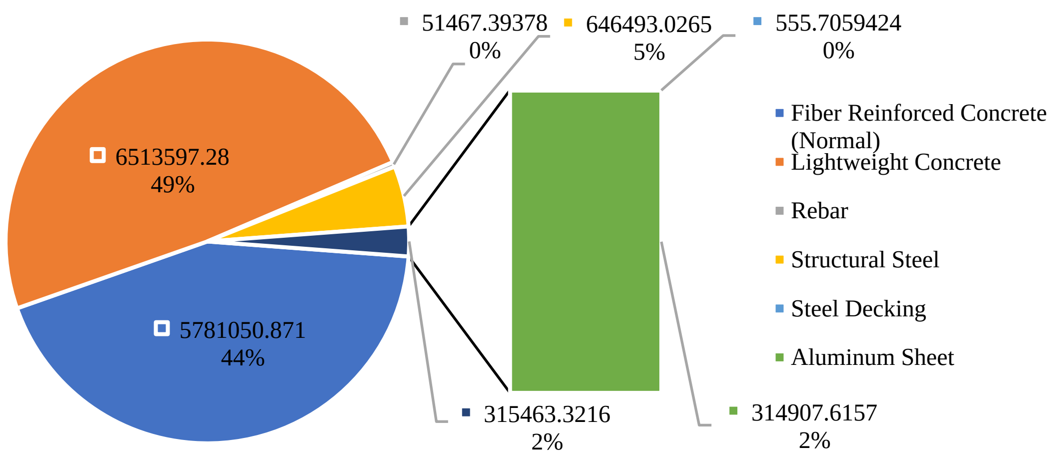

Figure 2. Achievable embodied carbon of Palomar Community College Library

With extensive recycling measures and increased productivity on the job site, the achievable embodied carbon emissions are significantly lower than the baseline estimates, which equates to 13.31×10^6 $kgCO_2$ (see figure 2). Lightweight and normal reinforced concrete comprise 93% of the total carbon emissions, which equate to roughly 12.29×10^6 $kgCO_2$ (see figure 2). The complete structural steel shell totaled 9% of the total carbon emissions equivalent to 9.61×10^5 $kgCO_2$ (see figure 2). The rebar used for the foundations and the steel decking present on each floor produced an estimated 52,023 $kgCO_2$, which is a small enough amount to deem it neglectable. There is a noticeable reduction in embodied carbon emissions once proper recycling practices are in place and sourcing construction materials are produced with more environmentally conscious manufacturing practices. Notably, the structural steel shell saw a 46% reduction in carbon emissions with an estimated difference of 8.24×10^5 $kgCO_2$ reduction. To break down the reduction of the building's shell's carbon emissions, the aluminum exterior had the most drastic decrease in emissions. Strict implementation of sustainability procedures on the job site and sound material source reduced the building's total emissions by 63% or 5.29×10^5 $kgCO_2$.

For further comparisons and calculations, please refer to Appendix A.

Confidential Project

Steel Framing Option

From an interview with a professional contact, construction documents were provided for a confidential project. The professional contact provided an opportunity to compare the embodied carbon emissions between structural steel framing and mass timber framing with the same building. All columns, beams, and girders were made of steel-wide flanges, particularly $W16 \times 31$ and $W24 \times 62$ galvanized steel members. The height of each story is assumed to be the standard 10 feet in height. The concrete foundation is thought to be a traditional foundation with a 6-inch footing, and each floor has 3-inch concrete flooring on steel decking per specifications.

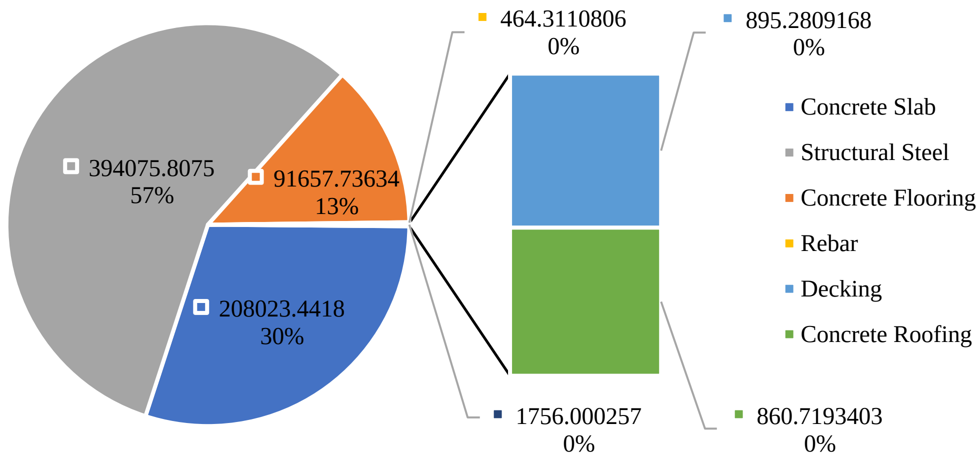

Figure 3. Conservative/realized embodied carbon of a confidential project using steel framing

The total conservative embodied carbon emissions estimate for the project equated to 6.96×10^5 $kgCO_2$. As previously stated, the concrete foundation's conservative and realistic estimates are the same since they are the most accurate calculations with the provided information. The concrete foundation's entirety accounted for 30% of total emissions, equivalent to roughly 2.08×10^5 $kgCO_2$ (see figure 3). The project's structural steel frame accounted for 57% of the total embodied carbon emissions, equating to roughly 3.94×10^5 $kgCO_2$ (see figure 3). The rebar used for the foundations and the steel decking present on each floor produced an estimated 1,360 $kgCO_2$, which is a neglectable amount compared to other building elements. However, the 3-inch concrete flooring composed 13% of total carbon emissions, approximately 91,658 $kgCO_2$ (see figure 3).

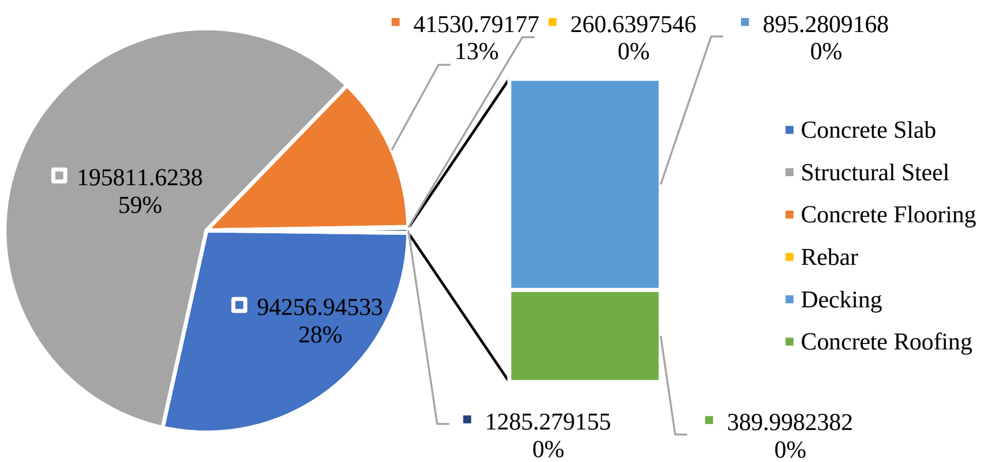

Figure 4. Achievable embodied carbon of a confidential project using steel framing

With proper recycling procedures and proper material sourcing, the total achievable embodied carbon emissions estimate for the project equated to 3.33×10^5 $kgCO_2$. The assumption is that the concrete foundation will remain consistent through all estimates for the project. Therefore, the concrete foundation's entirety accounted for 28% of total emissions, equivalent to roughly $94{,}256$ $kgCO_2$ (see figure 4). Additionally, the project's structural steel frame accounted for 59% of the total embodied carbon emissions, equating to roughly 1.96×10^5 $kgCO_2$ (see figure 4). The rebar used for the foundations and the steel decking present on each floor produced an estimated 1,156 $kgCO_2$, which is a neglectable amount compared to other building elements. The 3-inch concrete flooring composed 13% of total carbon emissions, which is approximately 41,531 $kgCO_2$ (see figure 4). Although the embodied carbon percentage of structural steel for the achievable estimates is greater than the conservative estimates, there is a drastic difference of 1.98×10^5 $kgCO_2$ between the conservative and achievable estimates. In addition to the difference between the structural steel, the concrete slab's embodied carbon emissions can be significantly reduced by 1.14×10^5 $kgCO_2$ if there are extensive sustainability measures taken before, during, and after the project's construction.

All other calculations and extensive graphical comparisons are found in Appendix B.

Mass Timber Framing Option

Using the same construction documents, the mass timber option was thoroughly analyzed. All estimates were as accurate as possible per the original plans and specifications. All columns, beams, and girders were glulam laminated timber ranging in size from dimensions as small as $6\frac{3}{4} \times 12$ to as large as $10\frac{3}{4} \times 22\frac{1}{2}$. As previously stated, each story's height is assumed to be the standard 10 feet in height. The concrete foundation is believed to be a traditional foundation with a 6-inch footing. Additionally, the first floor will use 5-ply CLT panels, while the second floor will use 3-ply CLT panels.

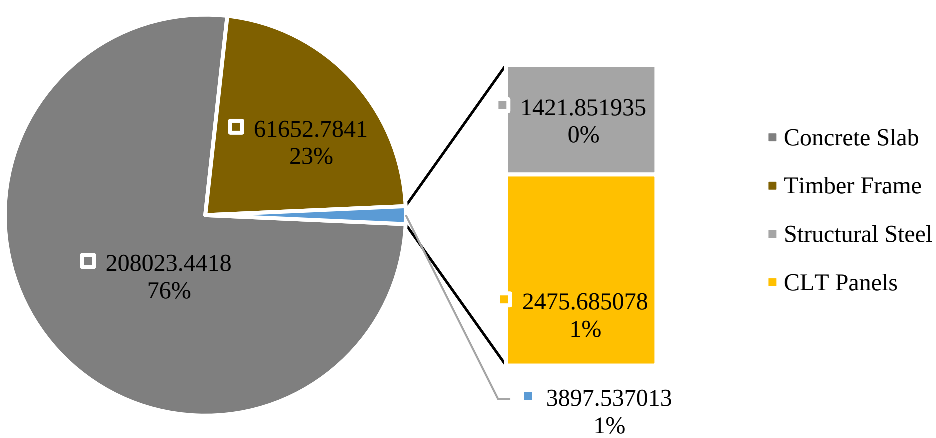

Figure 5. Conservative/realized embodied carbon of a confidential project using mass timber framing

The total conservative embodied carbon emissions estimate for the project with the mass timber framing option equated to 2.74×10^5 $kgCO_2$. As previously stated, the concrete foundation's conservative and realistic estimates are the same since they are the most accurate calculations with the provided information. The prevailing assumption will be that the concrete foundation will remain the same throughout the project's analysis. The concrete foundation's entirety accounted for 76% of total emissions, equivalent to roughly 2.08×10^5 $kgCO_2$ (see figure 3). The project's mas timber frame accounted for 23% of the total embodied carbon emissions, equating to roughly 61,653 $kgCO_2$ (see figure 5). The building's structural steel component produced an estimated 1,422 $kgCO_2$, which is a neglectable amount compared to other building elements. However, the CLT panels composed 1% of total carbon emissions, approximately 2,476 $kgCO_2$ (see figure 5). The rebar estimates for the structural steel option were used as precedence for the rebar estimates for the mass timber option. As a result, the rebar for the concrete slab was a negligible amount that accounted for approximately 0% of the project's total embodied carbon emissions (see figure 3).

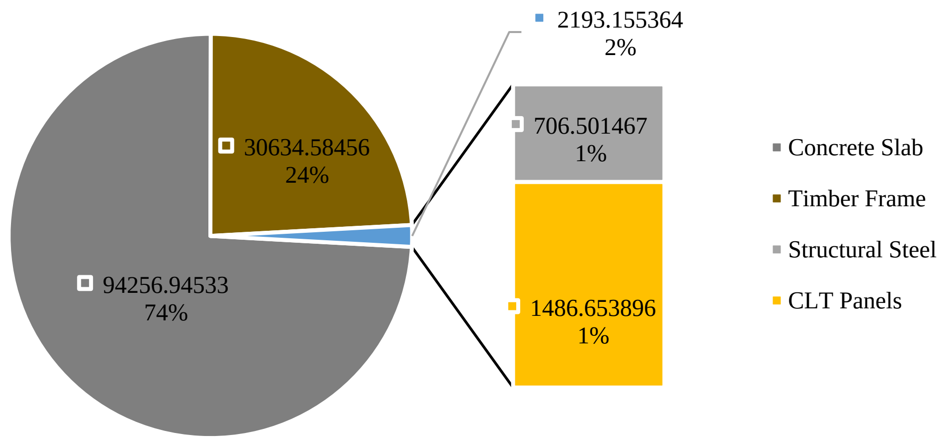

Figure 6. Conservative/realized embodied carbon of a confidential project using mass timber framing

With extensive sustainability measures and proper material sourcing, the total achievable embodied carbon emissions estimate for the project equated to 1.27×10^5 $kgCO_2$. The concrete foundation for 74% of total emissions, equivalent to roughly 94,257 $kgCO_2$ (see figure 6). The project's mas timber frame accounted for 24% of the total embodied carbon emissions, equating to approximately 30,636 $kgCO_2$ (see figure 6). The building's structural steel component produced an estimated 707 $kgCO_2$, equating to roughly 1% of the building's total embodied carbon. Additionally, the CLT panels composed 1% of total carbon emissions, approximately 2,476 $kgCO_2$ (see figure 6). As previously stated, the rebar estimates for the structural steel option were used as precedence for the rebar estimates for the mass timber option. As a result, the rebar for the concrete slab was a negligible amount that accounted for approximately 0% of the project's total embodied carbon emissions (see figure 3). The carbon emissions for the concrete foundation saw a reduction of roughly 1.14×10^5 $kgCO_2$. The most substantial reduction would be the mass timber framing and CLT panel building components, seeing an almost 50% or 31,018 $kgCO_2$ and 989 $kgCO_2$, respectively. Another building element that saw a dramatic decrease was the structural steel component, reducing more than 50% or 715 $kgCO_2$.

All further calculations and extensive graphical comparisons are found in Appendix C.

Comparing Structural Steel and Mass Timber Framing Options

The confidential project offered a variety of statistics regarding the building's total embodied carbon. The only constant building element throughout the analysis is the concrete foundation. The realistic and achievable estimates of both framing options were 2.08×10^5 $kgCO_2$ and 94,257 $kgCO_2$ respectively. The only difference between the foundation's framing options was its embodied carbon emission percentage compared to the project's total emissions. For the steel framing option, structural steel comprises most of the building's total emissions with the conservative and achievable containing 3.94×10^5 $kgCO_2$ and 1.96×10^5 $kgCO_2$ respectively. However, the difference between using structural steel and mass timber is more drastic, with a conservative decrease of 3.32×10^5 $kgCO_2$ and an achievable decrease of 1.65×10^5 $kgCO_2$ when using mass timber framing rather than structural steel framing. This translates to an 84% reduction of conservative and achievable carbon emissions estimates. Aside from the rough framing differences, the flooring systems also indicate a drastic difference in total carbon emissions. The steel decking and the concrete flooring will be considered one flooring system, equating to 92,553 $kgCO_2$ and 42,426 $kgCO_2$ for the conservative and achievable estimates, respectively. Using CLT panels instead of the steel flooring system, there is a conservative decrease of 90,077 $kgCO_2$ and an achievable decrease of 40,939 $kgCO_2$. Additionally, there would be a total decrease of 39% and 38% for the realistic and achievable embodied carbon emissions.

All further calculations and extensive graphical comparisons between the steel framing and mass timber option are found in Appendix B and Appendix C.

XL Construction Mass Timber Amenities Project

From an interview with another professional contact, construction documents were provided for a confidential project located in South San Francisco. This project's scope included constructing a new single-story office building with commercial uses adjacent to an existing building. The building's structural components had a concrete slab and footings, glulam beams, glulam timber posts, CLT panels, and structural steel components such as buckling-resistant brace frames and steel beams.

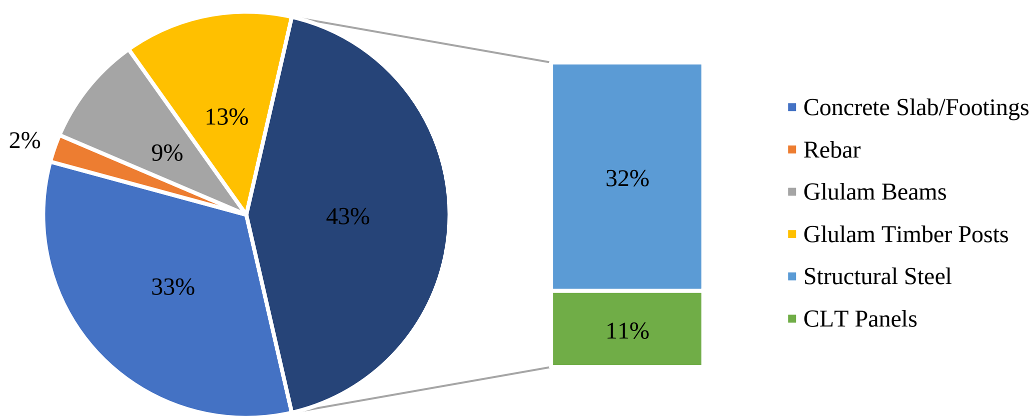

Figure 6. Conservative/realized embodied carbon of a confidential project using mass timber framing

The total conservative embodied carbon emissions estimate for this project equated to 6.99×10^5 $kgCO_2$. Compared to the other mass timber projects above, we continue to see much of the embodied carbon is coming from the concrete and structural steel components. The concrete foundation's entirety accounted for 33% of total emissions, equivalent to roughly 3.19×10^5 $kgCO_2$ (see figure 6). The structural steel components were not far behind as they accounted for 32% of the total embodied carbon emissions, equating to roughly $2.47x10^5$ $kgCO_2$. The building's mass timber component only accounted for 32% of the building's total emissions, including the glulam beams, glulam timber posts, and CLT panels. The rebar estimates for the concrete slab were a negligible amount that accounted for approximately 2% of the total embodied carbon emissions put off. As stated in figure 6 above, this chart takes on the conservative amount of embodied carbon from our estimate. This is also known as the burden of the doubt methodology. This means that the EC3 tool assesses EPD comparability and assigns your element default variability factors when no EPD is provided. This helps the EC3 calculator manage any uncertainty in the data. Then it takes the "burden of the doubt' and assumes the highest level based on estimated variability.

Conclusion

The construction industry is continuously changing, and it must continue to trend towards greener construction practices such as mass timber framing. The purpose of this research was to perform multiple extensive comparative analyses of various buildings from three different professional contacts. The study compared the embodied carbon emissions of using mass timber and structural steel on the job site as primary framing materials. Through the multiple project comparisons of steel framing and mass timber, it is evident that mass timber produces significantly fewer carbon emissions than its steel counterpart. A point of contention from the research was the number of carbon emissions produced using concrete foundations equal to or greater than the total carbon emitted by structural steel. Although substituting structural steel with mass timber as a primary framing material is more feasible, one of the main implications the study found was how the environmental impact of concrete could be reduced by implementing stricter Stormwater Pollution Prevention Plans to find a more sustainable substitute for concrete.

Mass timber is a trend within the construction industry and the future of the green and sustainable building. CLT and other mass timber products transform the built environment among European countries and Canada as we speak. The United States is beginning to rediscover the uses of mass timber and is now reaping the benefits of mass timber. However, due to its overly prescriptive building codes and limited manufacturers, more extensive research continues to be hampered in the states. As discussed above, carbon emissions are just one of the benefits of mass timber. More to be explored on how mass timber could impact the construction industry and the built environment.

Future Research

The study's environmental analysis of each project provided strong evidence for substituting steel for mass timber. Additionally, California recently adopted the entire series of building codes from the International Code Council (ICC), joining four other states as early adopters of the 2021 codes (Softwood Lumber Board, 2020). The regulations provided specifications for constructing mass timber buildings ranging from 9 stories tall to 18 stories tall. Codifying building codes for mass timber has indicated California's and the country's transition to a more environmentally conscious built environment. Once mass timber gains more momentum in the United States, the 3.729 trillion metric tons of carbon dioxide the construction industry produced could be significantly reduced. With the United States joining the international push for greener building practices, this would curb the damaging effects humanity has had on the planet and create a more habitable planet for future generations.

The research done for this project was done to compare the carbon emissions put off by mass timber and steel framing construction practices by utilizing a new construction tool, the EC3 calculator. Although this research proved successful in providing evidence that mass timber is the ideal construction material for sustainable projects, additional research is required for the construction material. When performing the investigation, a significant point to note was that the EC3 Calculator did not provide extensive mass timber manufacturers in the United States. Structurlam was one of the few mass timber producers in the country. That might contribute to the lack of extensive mass timber research present in the United States. This research should be used as an excellent addition to other papers that have analyzed the life cycle of mass timber. Also, this paper can be a starting point for further research on the topic of carbon analysis of the construction material. With that being said, there is a multitude of unknowns regarding mass timber and its benefits. Possible other issues and additional areas of research include:

- Cost Impact of Mass Timber vs. Steel Framing
- Strength Comparisons of Mass Timber and Steel Framing
- Seismic Strength of Mass Timber
- More Extensive Life-Cycle Assessment of Mass Timber
- Factors Influencing the United States Lack of Mass Timber Manufacturing
- Fire Resistance of Mass Timber
- Analysis of Building Codes Hindering Mass Timber Usage in the United States

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Appendix A

Table 2

Palomar Community College Library embodied carbon emissions calculations

Element	Baseline (kgCO2e)	Conservative (kgCO2e)	Achievable (kgCO2e)
Fiber Reinforced Concrete (Normal)	10652266.86	8552990.647	5781050.871
Lightweight Concrete	10652252.31	10314276.05	6513597.28
Rebar	103870.5299	56701.03079	51467.39378
Structural Steel	723880.6924	941686.8176	646493.0265
Steel Decking	1490.935441	1029.645888	555.7059424
Aluminum Sheet	1357709.965	844079.7831	314907.6157

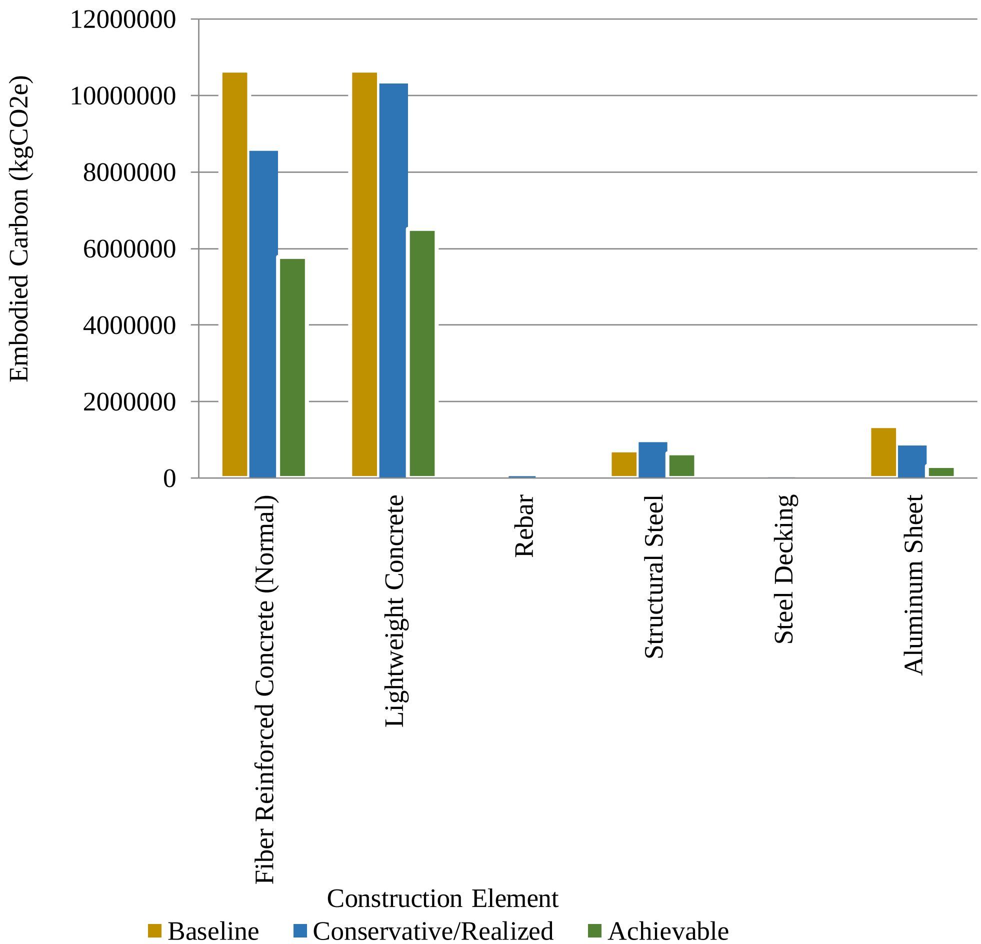

Figure 7. Complete embodied carbon calculations of Palomar Community College Library

Appendix B

Table 3

Embodied carbon emissions calculations of a confidential project with a steel framing option

Element	Baseline (kgCO2e)	Conservative (kgCO2e)	Achievable (kgCO2e)
Concrete Slab	186407.955	208023.442	94256.9453
Structural Steel	468882.028	394075.808	195811.624
Concrete Flooring	82133.6818	91657.7363	41530.7918
Rebar	754.360399	464.311081	260.639755
Decking	995.99359	895.280917	895.280917
Concrete Roofing	771.282941	860.71934	389.998238

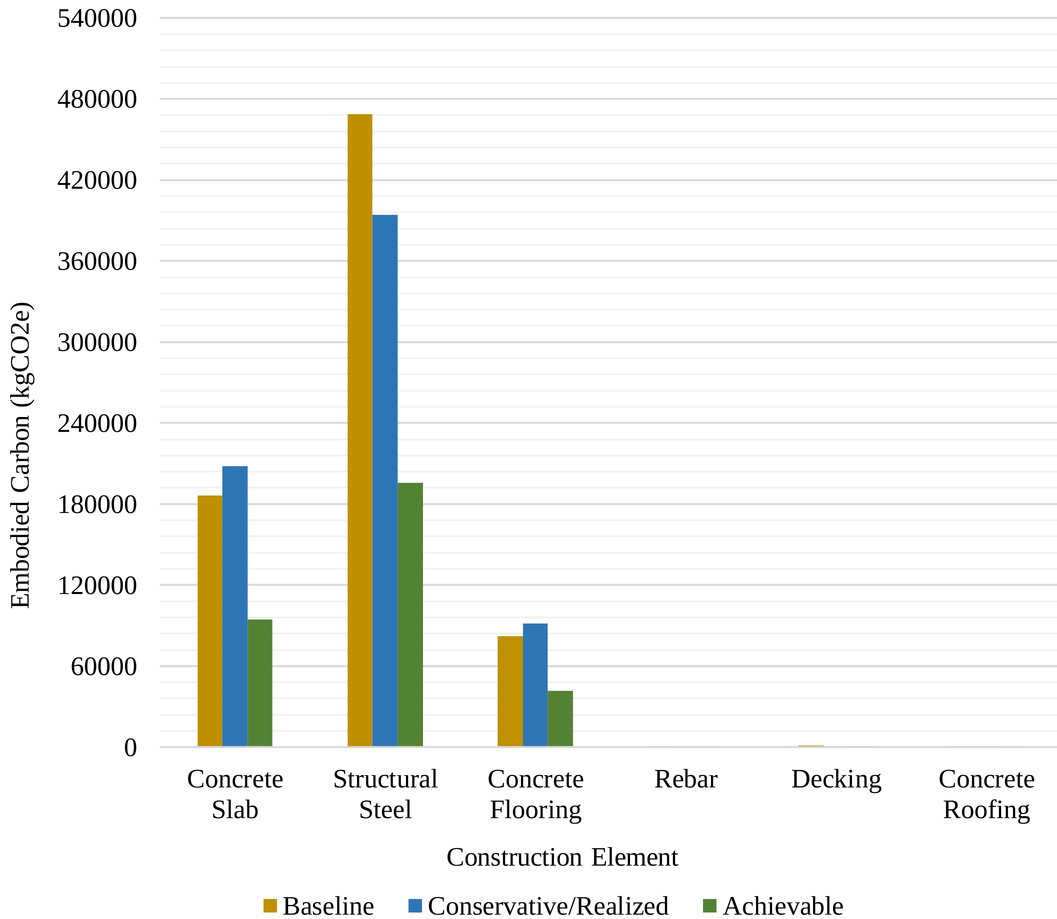

Figure 8. Complete bar graph of embodied carbon calculations of a confidential project with steel framing

Appendix C

Table 4

Embodied carbon emissions calculations of a confidential project with a mass timber framing option

Element	Baseline (kgCO2e)	Conservative (kgCO2e)	Achievable (kgCO2e)
Concrete Slab	186407.955	208023.442	94256.9453
Timber Frame	126793.778	61652.7841	30634.5846
Structural Steel	1691.75779	1421.85194	706.501467
CLT Panels	6642.45261	2475.68508	1486.6539

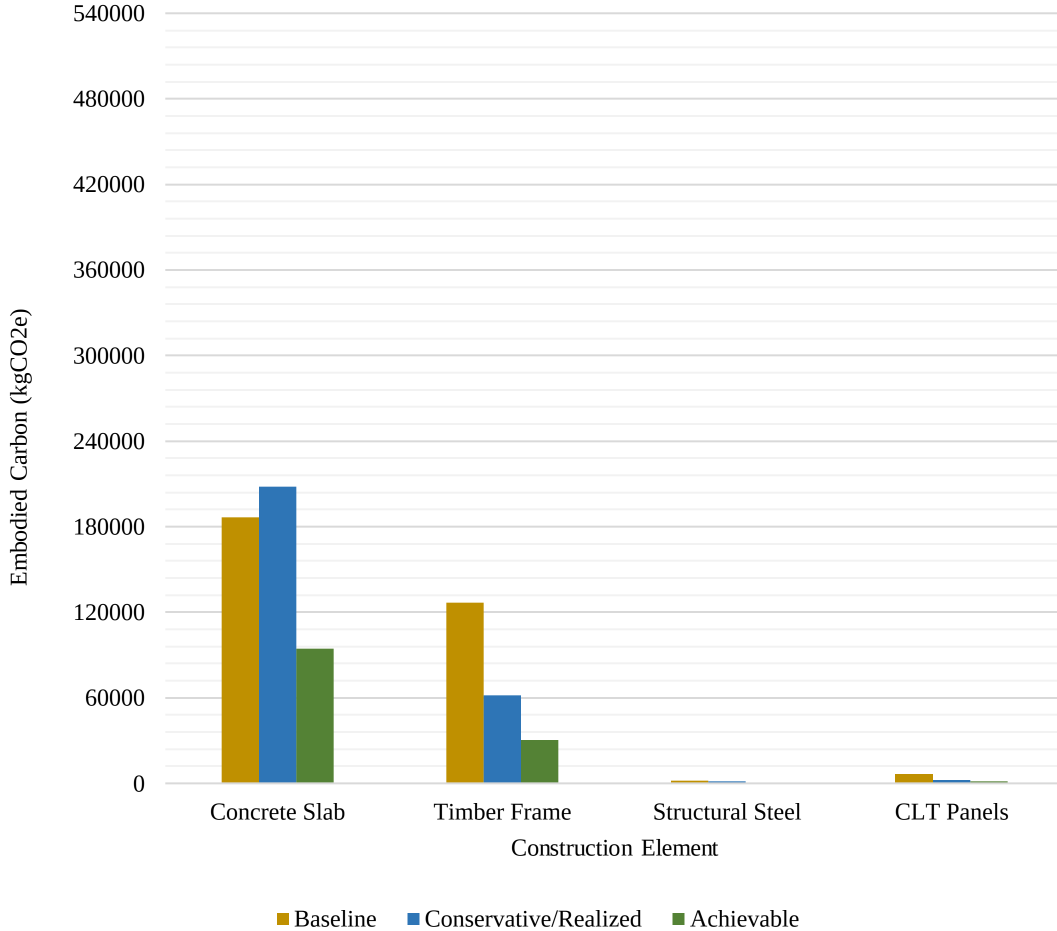

Figure 9. Complete bar graph of embodied carbon calculations of a confidential project with mass timber framing

Appendix D

Table 4

Embodied carbon emissions calculations of a confidential project with a steel framing option

Element	Baseline (kgCO2e)	Conservative (kgCO2e)	Achievable (kgCO2e)
Concrete Slab/Footings	281,000	317000	157000
Rebar	18900	13200	6860
Glulam Beams	74900	35400	18900
Glulam Timber Posts	115000	44700	36500
Structural Steel	275,000	247000	107000
CLT Panels	91700	42000	24300

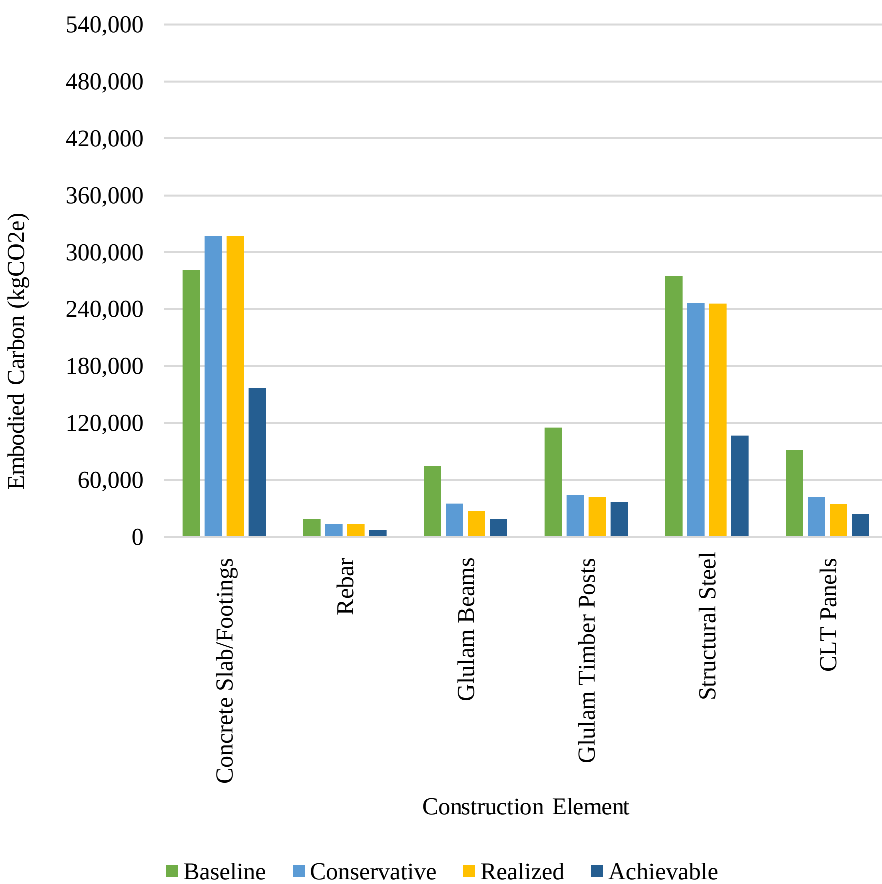

Figure 10. Complete bar graph of embodied carbon calculations of an XL Construction Project