## ID 103

# Utilizing the EC3 Calculator to Compare the Environmental Impacts of Mass Timber and Structural Steel

Khang Nguyen, [1] Steelee Morgan, [2] and Scott Kelting [3]*

[1] California Polytechnic State University, 93402 CA, USA
[2] California Polytechnic State University, 93402 CA, USA
[3] California Polytechnic State University, 93402 CA, USA
khangn8@gmail.com

## Abstract
Due to the popularity of lean construction and sustainability, utilizing carbon analysis to form educated, well-informed decisions for a more sustainable built environment can provide a strong case for mass timber construction. This dissertation uses extensive embodied carbon analysis of structural steel and mass timber during the preconstruction phase of a project using data from incomplete construction documents of a confidential project. A critical review of previous literature was conducted and used as precedents for the research. The data from the project estimates were input through the Embedded Carbon in Construction Calculator (EC3 Calculator) to provide extensive total carbon emissions measurements with emphasis on structural steel and mass timber. The data indicated that using structural steel as the primary framing option would decrease the project's overall environmental impact by roughly 84% compared to using mass timber. Additionally, implementing strict sustainability plans on the job site and responsible sourcing of materials can lead to a potential 54% reduction in the project's overall carbon output. From the results, detailed, data-driven decisions can be made regarding the project's more sustainable framing option. The results provide additional evidence supporting mass timber as a sustainable framing substitute for structural steel.

## Keywords
Mass Timber, Structural Steel, Preconstruction, EC3 Calculator, Carbon Analysis.

## 1. Introduction

The construction industry has maintained a so-called "status quo" regarding construction materials. Since the early 20th century, structural steel and concrete's usage has increased on the job site and have created skyscrapers that continuously shape modern skylines. The rapid urban development and growth have had a considerable environmental cost that does not show prominent signs of halting. Different materials used in the construction process have varying amounts of embodied carbon. With the reinvigorating wood construction on the rise, new construction methods involving mass timber have gained traction in Europe and Japan, with North America following suit. Although there has been extensive research regarding the structural aspects of mass timber, there is not much analysis regarding the environmental cost of using mass timber. This paper explores the environmental cost of using mass timber compared to steel on the job site– specifically the embodied carbon from cradle-to-grave and how that carbon analysis can potentially impact the trajectory of a project. These findings may provide a stronger case for using extensive carbon analysis during all stages of the preconstruction phase of a given project to discover the most sustainable material.

## 2. Background and Methods

Cross-laminated timber (CLT) and other mass timber construction materials are a relatively slower to embrace building material; however, it 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 this literature review is to provide further background for the case study. This report follows the relevant previous research of Kavanagh and Nakano (2016, 2020).

Kavanagh (2016) 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. 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, 2016). 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 considered the material extraction, transportation, manufacturing maintenance, and end-of-life with notable exclusions such as material and energy requirements. The data used to perform the analysis were the types of construction materials, their quantities, volumes, areas, and 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. 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 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. The paper suggests using biomass-based energy and extensive recycling protocols to reduce environmental impacts, especially at the end-of-life stage.

There is a lack of research regarding the ecological impact of mass timber buildings and their life cycle, especially in North America. Both 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. This paper sets out to add to the body of knowledge by comparing the environmental impacts of mass timber and structural steel of two similar projects using the EC3 tool. One project used mass timber and the other structural steel. The research question for this paper was: Is the EC3 calculator an effective tool to compare structural steel and mass timber in the preconstruction phase?

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## 3. Results

The EC3 Calculator draws its information from multiple databases to aid manufactures gain a greater transparency on their products. The EPDs utilize a range of total embodied carbon emissions for each construction element; therefore, the results are divided into three primary categories: Baseline, Conservative, and Achievable. The baseline estimates are the standard results the calculator produces based on data from each estimate. Traditionally, the baseline estimates are considered the most conservative or largest emitted carbon of a given product. The conservative results are most realistic estimates given current construction practices and manufacturing standards. The achievable estimates are based on currently available active sustainability practices on the job site and during the manufacturing process. For example, active sourcing and recycling practices are accounted into the achievable results. From the interview with the 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× 31 and W24× 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.

**Table 1.** Embodied carbon emissions calculations of a confidential project with a steel framing option

| Element | Baseline (kgCO2e) | Conservative (kgCO2e) | Achievable (kgCO2e) |
|---|---|---|---|
| Concrete Slab | 186407.96 | 208023.44 | 94256.95 |
| Structural Steel | 468882.03 | 394075.81 | 195811.62 |
| Concrete Flooring | 82133.68 | 91657.72 | 41530.79 |
| Decking | 995.99 | 895.28 | 895.28 |
| Concrete Roofing | 771.28 | 860.72 | 390.00 |

The total conservative embodied carbon emissions estimate for the project equated to $6.96 \times 10^5$ $kgCO_2$ . 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 $2.08 \times 10^5$ $kgCO_2$. The project's structural steel frame accounted for 57% of the total embodied carbon emissions, equating to roughly $3.94 \times 10^5$ $kgCO_2$. The rebar used for the foundations and thesteel 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 $kgCO_2$.

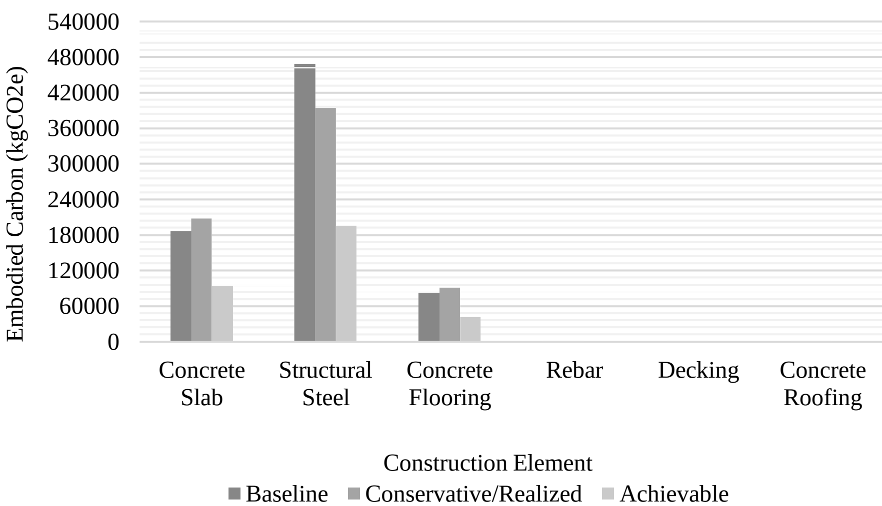


**Figure 1.** Complete bar graph of embodied carbon calculations of a confidential project with steel framing

The total conservative embodied carbon emissions estimate for the project equated to $6.96 \times 10^5$ $kgCO_2$ . 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 $2.08 \times 10^5$ $kgCO_2$. The project's structural steel frame accounted for 57% of the total embodied carbon emissions, equating to roughly $3.94 \times 10^5$ $kgCO_2$ as shown in Figure 1. The rebar used for the foundations and the steel decking present on each floor produced an estimated 1,360 $kgCO_2$, which is a neglectableamount compared to other building elements. However, the 3-inch concrete flooring composed 13% of total carbon emissions, approximately 91,658 $kgCO_2$.

Implementing proper recycling procedures and proper material sourcing would reduce the total achievable embodied carbon emissions estimate for the project to $3.33 \times 10^5$ $kgCO_2$. The prevailing 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 $kgCO_2$ as shown in Figure 1. Additionally, the project's structural steel frame accounted for 59% of the total embodied carbon emissions, equating to roughly

$1.96 \times 10^5$ $kgCO_2$ as shown in Figure 1. 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 $kgCO_2$ as shown inFigure 1. Although the embodied carbon percentage of structural steel for the achievable estimates is greater than the conservative estimates, there is a drastic difference of $1.98 \times 10^5$ $kgCO_2$ 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 $1.14 \times 10^5$ $kgCO_2$ if there are extensive sustainability measures taken before, during, and after the project's construction.

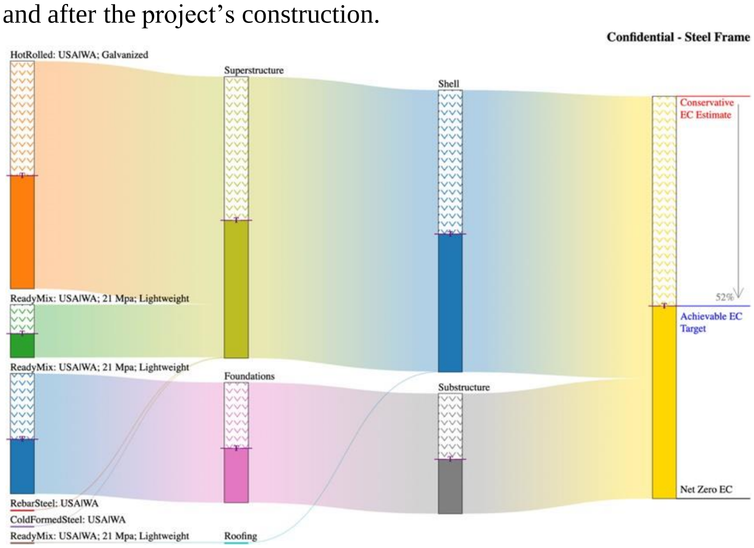


**Figure 2.** Mass diagram of confidential project using structural steel framing option produced from the EC3 Calculator

The mass diagram was produced from EC3 Tool using data from the estimates. The diagram breaks down each construction material related to the project and showcases its carbon output in relation to the material's total mass. The entirety of the material is displayed a single bar with a hatched pattern and a solid pattern. The material's total estimated carbon emissions are the sum of the hatched and solid pattern while the material's estimated achievable carbon output is solely the solid pattern at the bottom of each bar.

From that, the building's EPD indicated that the structural steel members produced the greatest amount of carbon emissions; however, the building's mass is primarily comprised of the concrete foundation and flooring system. As previously stated, the structural plans indicated that each floor of the building would include 3-inch concrete flooring, which contributed the third highest total embodied carbon emissions while having the second highest contribution to the building's overall mass as shown in Figure 2. Although the project's structural steel frame produced the greatest amount of carbon emissions, it had the third highest contribution to the structure's mass. The three construction elements whose mass contribution and carbon emissions draw a direct correlation are the rebar, stee decking, and concrete roofing and shown in Figures 1 and 2. All three materials had almost negligible contributions to the overall structure's total carbon emissions and mass.

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.

**Table 2.** Embodied carbon emissions calculations of a confidential project with a mass timber framing option

| Element | Baseline (kgCO2e) | Conservative (kgCO2e) | Achievable (kgCO2e) |
|---|---|---|---|
| Concrete Slab | 186407.96 | 208023.44 | 94256.95 |
| Timber Frame | 126793.78 | 61652.78 | 30634.58 |
| Structural Steel | 1691.76 | 1421.85 | 706.50 |
| CLT Panels | 6642.45 | 2475.69 | 1486.65 |

The total conservative embodied carbon emissions estimate for the project with the mass timber framing option equated to $2.74 \times 10^5$ $kgCO_2$. 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 $2.08 \times 10^5$ $kgCO_2$ as shown in Table 2. The project's mas timber frame accounted for 23% of the total embodied carbon emissions, equating to roughly 61,653 $kgCO_2$. 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 $kgCO_2$ as shown in Figure 3. 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 as shown in Figure 3.

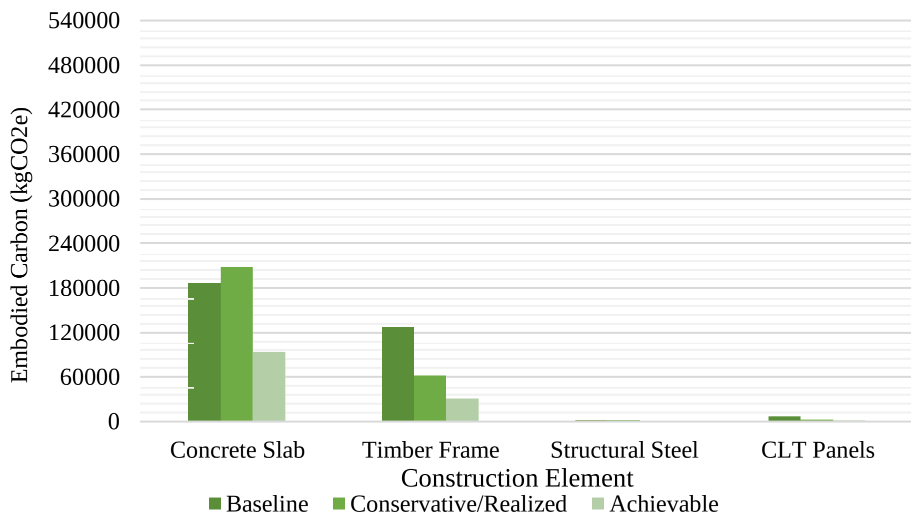


**Figure 3.** Complete bar graph of embodied carbon calculations of a confidential project with mass timber framing

The total achievable embodied carbon emissions target for the project equated to $1.27 \times 10^5$ $kgCO_2$. The concrete foundation's total contribution remained the same at roughly 94,257 $kgCO_2$ or 74% of the project's total emissions. The project's mas timber frame accounted for 24% of the total embodied carbon emissions, equating to approximately 30,636 $kgCO_2$. 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 $kgCO_2$ as shown in Figure 3. 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 as shown in Figure 3. The carbon emissions for the concrete foundation saw a reduction of roughly $1.14 \times 10^5$ $kgCO_2$. The most substantial reduction would be the mass timber framing and CLT panel building components, seeingan almost 50% or 31,018 $kgCO_2$ and 989 $kgCO_2$, respectively. Another building element that saw a dramatic decreasewas the structural steel component with a reduction of more than 50% or 715 $kgCO_2$.

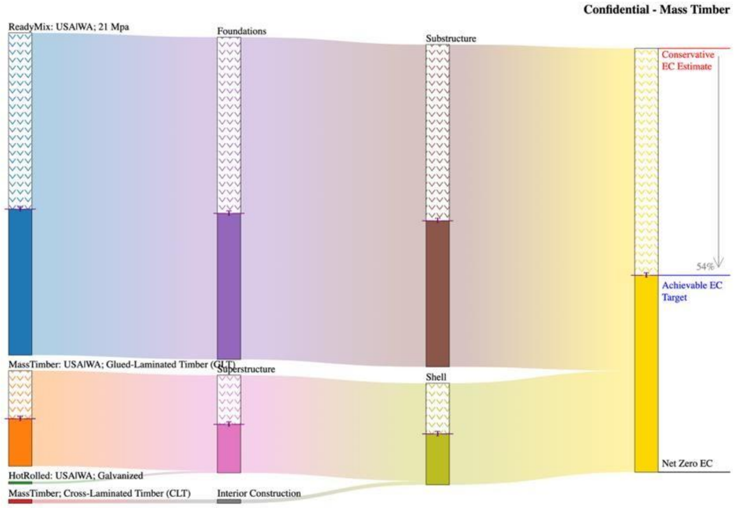


**Figure 4.** Mass diagram of confidential project using the mass timber framing option produced from the EC3 Calculator

The mass diagram for the mass timber framing option follows the typical patterns regarding mass and total embodied carbon emissions. The concrete foundation had the highest contribution in terms of mass and the carbon emissions of the building while the mass timber frame accounted for the second highest embodied carbon emissions and the building's overall mass as shown in Figures 2 and 4. Even though the project utilizes the same floor plan with different framing options, the concrete foundation has prominent contribution to the project's overall carbon footprint is as noticeable as its reduction in emission. The construction elements that had almost negligible impact to the building were the CLT panels and structural steel.

4.2.3. 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 $2.08 \times 10^5$ $kgCO_2$ 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 $3.94\times 10^5$ $kgCO_2$ and $1.96 \times 10^5$ $kgCO_2$ respectively as shown in Figure 5. However, the difference between using structural steel and mass timber is more drastic, with a conservative decrease of $3.32 \times 10^5$ $kgCO_2$ and an achievable decrease of $1.65 \times 10^5$ $kgCO_2$ when using mass timber framing rather than structural steel framing as shown in Figure 5. 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.

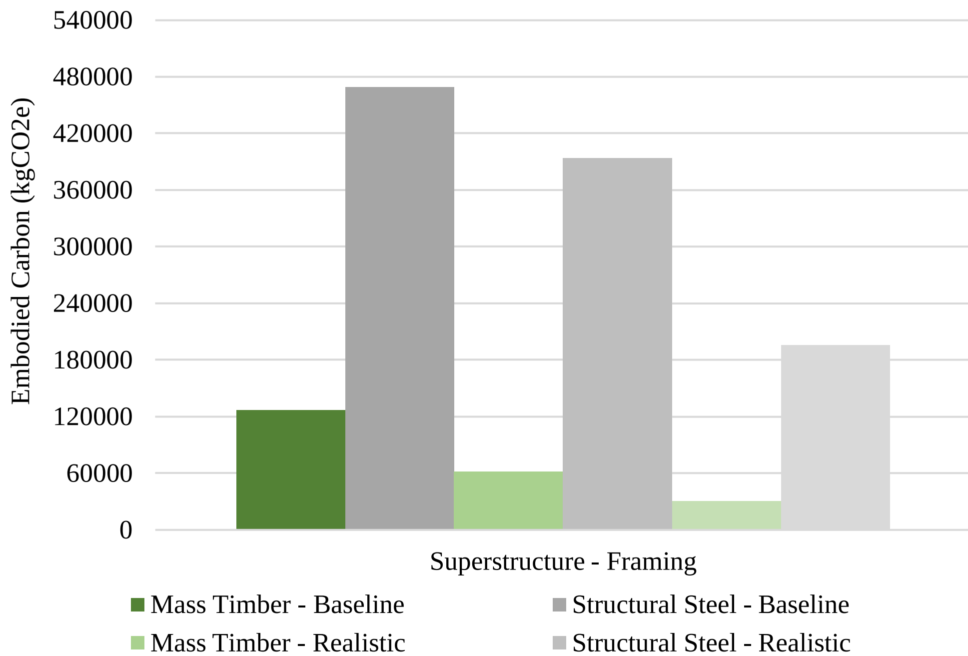


**Figure 5.** Complete bar graph of embodied carbon comparisons of a confidential project with structural steel and mass timber framing

From the mass diagrams of both framing options and the data presented, there is a greater reduction in carbon emissions from the mass timber framing option than the steel framing option. The overall project's achievable carbon footprint can be 54% lower than the conservative estimates, which is 2% lower than the steel option, but significant nonetheless as shown in Figure 4. A probable explanation would be the amount of construction elements involved in the building's framing. The steel option has roughly 67% more building components than the mass timber option thus making the mass timber framing option less involved than its steel counterpart as shown in Figures 1 and 3. As a result, its carbon emission contribution is less significant than the steel framing option.

## 4. Discussion

The designs of the confidential project were in their preliminary stages when it was analyzed for the paper. The industry professional discussed that the project is still in its preconstruction phase and had a vague idea of which framing material was more suited for their client's goal for a sustainable building. The data produced from the EC3 Tool visibly provided evidence that supported mass timber as a more sustainable alternative for structural steel; however, a notable point of contention from the research was the limited access to manufacturers, as previously stated. Nevertheless, the data and the direct comparisons provided a clear contrast between the two materials' carbon output. It was fortunate that the confidential project was in the early stages of development because questions concerning its sustainable output could be answered upfront before it breaks ground. Thus, the EC3 Tool and the data it produced could be used to make well-informed decisions driven by empirical data. The decisions made from the data could potentially range from selectively sourcing the materials, significant alterations to the design of the building, and the development of more stringent stormwater pollution prevention plans. The data could impact every aspect of the project to reduce its environmental impact.

A notable flaw in the tool was most likely due to it still being in its beta phase, and limited access is granted to the public and students. As a result, it was challenging to produce more precise data. Additionally, the project was in its infancy; therefore, the provided plans were incomplete, and the vendors were not providing more accurate data collection. Although the tool–at the time it was used for this paper–was still in its beta phase and there were limited resources regarding the project, it produced incredible data that proved invaluable to the report. Additionally, with the EC3 Calculator slated to be integrated into Revit and Tally, carbon analysis of a given project is gradually incorporated into the preconstruction phase (EC3 Tool, 2021). California recently adopted the series of building codes from the International Code Council (ICC) to accelerate the transition, 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. The move towards sustainability will force every industry to adapt, especially the construction industry. With the tool's future integration into design software, designers, contractors, and owners can perform in-depth analysis on their project regarding all aspects of its construction, including the most sustainable building materials.

**5. Conclusions**

The construction industry is continuously changing, and it must continue to trend towards sustainable construction practices such as mass timber framing. Mass timber is growing in popularity within the construction industry and marks 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 its benefits. 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.

The study's environmental analysis of structural steel and mass timber provided evidence that the EC3 Toolcan prove to be a crucial tool in the move towards a more sustainable built environment. Investing time upfront to solve potential issues is the cornerstone of preconstruction, and with the rapid demand for more sustainable projects, carbon analysis of the building will be part of that equation. The research performed for this project was done to support the integration of carbon analysis into the preconstruction phase by comparing two different framing options of a project that's still in its preliminary design stage. Although the EC3 Calculator was developed a few years ago, it is still in its beta stages of development, which indicates greater opportunities for the tool to produce more accurate data and other useful information. While there is room for improvement, the authors' found the EC3 Calculator to be and effective tool. The authors plan to conduct similar studies as the EC3 Calculator continues to improve.

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