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Comparison of Embodied Carbon Footprint of a Mass Timber Building Structure with a Steel Equivalent

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Abstract: The main purpose of this study is to quantify and compare the embodied carbon (EC) from the materials used or designed to build the Adohi Hall, a residence building located on the University of Arkansas campus in Fayetteville, AR. It has been constructed as a mass timber structure. It is compared to the same building design with a steel frame for this study. Based on the defined goal and scope of the project, all materials used in the building structure are compared for their global warming potential (GWP) impact by applying a life cycle assessment (LCA) using a cradle-to-construction site system boundary. This comparative building LCA comprises the product stage (including raw material extraction, processing, transporting, and manufacturing) plus transportation to the construction site (nodule A1–A4, according to standard EN 15804 definitions). In this study, GWP is primarily assessed with the exclusion of other environmental factors. Tally®, as one of the most popular LCA tools for buildings, is used in this comparative LCA analysis. In this study, the substitution of mass timber for a steel structure with a corrugated steel deck and concrete topping offers a promising opportunity to understand the GWP impact of each structure. Mass timber structures exhibit superior environmental attributes considering the carbon dioxide equivalent (CO_2 eq). Emissions per square meter of gross floor area for mass timber stand at 198 kg, in stark contrast to the 243 kg CO_2 eq recorded for steel structures. This means the mass timber building achieved a 19% reduction in carbon emissions compared to the functional equivalent steel structure within the building modules A1 to A4 studied. When considering carbon storage, about 2757 tonnes of CO_2 eq are stored in the mass timber building, presenting further benefits of carbon emission delays for the life span of the structure. The substitution benefit from this construction case was studied through the displacement factor (DF) quantification following the standard process. A 0.28 DF was obtained when using mass timber over steel in the structure. This study provides insights into making more environmentally efficient decisions in buildings and helps in the move forward to reduce greenhouse gas (GHG) emissions and address GWP mitigation.

Keywords: whole-building LCA; global warming potential; displacement factor; substitution benefit

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1. Introduction

The construction industry is a significant contributor to greenhouse gas (GHG) emissions, responsible for almost 40% of total carbon emissions, as stated in the global status report released by the UN Environment and International Energy Agency [1]. Additionally, it is anticipated that North America will experience a rise in residential properties and infrastructure in the coming decade [2]. This highlights the considerable need for the building sector to reduce emissions and address the challenge of global climate change.

In terms of environmental impact, building materials and energy use during the service life of a building are the two major sources of concern [3]. The operational phase of a building, which covers its entire lifetime usage, is the most significant [4–6]. Therefore, most of the existing literature is focused on optimizing building energy use over its lifetime. Improving the efficiency of building operations has led to a reduction in operational carbon (OC). Efforts in research aimed at enhancing energy efficiency and adopting cleaner energy sources have resulted in decreased OC for buildings. Consequently, this has scaled up GHG emissions associated with embodied carbon (EC), emissions generated during the manufacturing, transportation, and construction phases, as well as the eventual demolition or repurposing of the building materials at the end of its life cycle [6–8]. However, there is still insufficient research focused on mitigating EC emissions in buildings [9]. To address the mentioned gap, the objective of this study is to explore the EC reduction potentials of a mass timber structure in comparison with an equivalent steel structure, especially focusing on institutional use in the United States.

2. Literature Review

Engineered wood products, such as glue-laminated (glulam) and cross-laminated timber (CLT), have gained increasing popularity for both residential and commercial constructions due to their environmentally sustainable performance [4,10]. Other qualities like the ease and speed of construction due to the high level of prefabrication and superior strength and thermal performance position mass timber products as a feasible substitute for traditional building materials such as reinforced concrete and steel [10,11]. These new materials have expanded the growth of the wood industry as a means of combating global warming.

Ref. [12] reviewed 62 peer-reviewed articles focused on the mass timber construction environmental life cycle. The study shows that, on average, almost 43% of GHG emissions are avoided if reinforced concrete structures are substituted with mass timber alternatives.

A comparative life cycle assessment (LCA) of mass timber, concrete, and steel structures conducted by Hegeir et al. [13] endeavored to evaluate the environmental impact of timber in Norwegian industrial buildings. In this study, the cradle-to-gate system boundary was established, which included transportation to the construction site. The study indicated that the best environmental performance was associated with mass timber structures. The steel or concrete structures had higher negative environmental impacts. Felmer and colleagues [14] compared the carbon emission associated with a mid-rise mass timber residential building in central Chile with an equivalent reinforced concrete building. The mass timber building had 42% lower EC compared to the equivalent concrete building.

Rinne et al. [15] compared the environmental performance of mass timber buildings with hybrid (mix of timber and concrete) and concrete ones in Finland. The study indicates that for modules A1–A3 of the building product stage (raw material extraction from nature, hauling to the factory, and manufacturing to final products) and module A4 (transportation of final products to the construction site), the mass timber building had the least emissions. The results of another study by Chen et al. [16] in China showed a 25% lower global warming potential (GWP) in a mass timber building compared to its equivalent concrete structure. The environmental performance of buildings, therefore, improves if the concrete is replaced by mass timber products.

The empirical evidence gathered from a systematic review conducted by Younis et al. [17] suggested that employing CLT as a substitute for traditional construction materials such as steel and concrete in multi-story buildings results in an average reduction of approximately 40% in carbon emission.

A study by Oh et al. [18] compared the environmental impact of reinforced concrete, CLT, and timber–concrete composite (TCC) slabs with equivalent structural performance in Korea, using Korean concrete and steel EPDs and Western countries' published glulam EPD as emission factors. According to the findings of the study, the emission of carbon dioxide was 75% and 65% lower in the case of CLT and TCC slabs, respectively, as compared to reinforced concrete slabs.

Puettmann and colleagues [19] focused on the comparison between mass timber buildings and their concrete equivalents, with interesting results. It was observed that although the total embodied energy involved in the production, transportation, and construction (module A1–A5 building LCA) was greater for all mass timber structures compared to their concrete equivalents, the EC of the mass timber structures resulted in a note-worthy reduction ranging from 22% to 50%. Milaj et al. [20] examined the carbon emissions avoided due to the substitution of steel and concrete materials with traditional wood building products, e.g., I-joints, OSB, and plywood, in six different buildings in Oregon, United States, using a cradle-to-grave life cycle analysis. The result of the study showed an average of 60% emission reduction.

The literature review shows that the studies listed above have been primarily conducted in Europe and Asia. Regardless, the quantity of conducted LCA studies pertaining to mass timber buildings in the United States is increasing [4]; however, it remains apparent that the current volume of research conducted in this area is yet to reach a level deemed comprehensive or sufficient [4]. In response to the mentioned gap, the US Forest Products Laboratory (FPL) is promoting the development of an enhanced population of real-building case studies across the United States. Once collected, the large database will be analyzed and processed to draw design and construction guidelines critical to the decarbonization of the environment. The study is part of that effort to increase the database and evaluate the environmental impacts of mass timber buildings in the United States context.

This article presents a comparative LCA of a newly constructed mass timber building on the university campus in Fayetteville, AR, that comprises CLT and glulam as the main structural materials, as compared to a functionally equivalent steel structure system. The primary objective of the study is to examine the GHG emissions resulting from EC for both structures throughout their life cycle, from the cradle to the construction site. The methodology employed for the current study is illustrated in Figure 1.

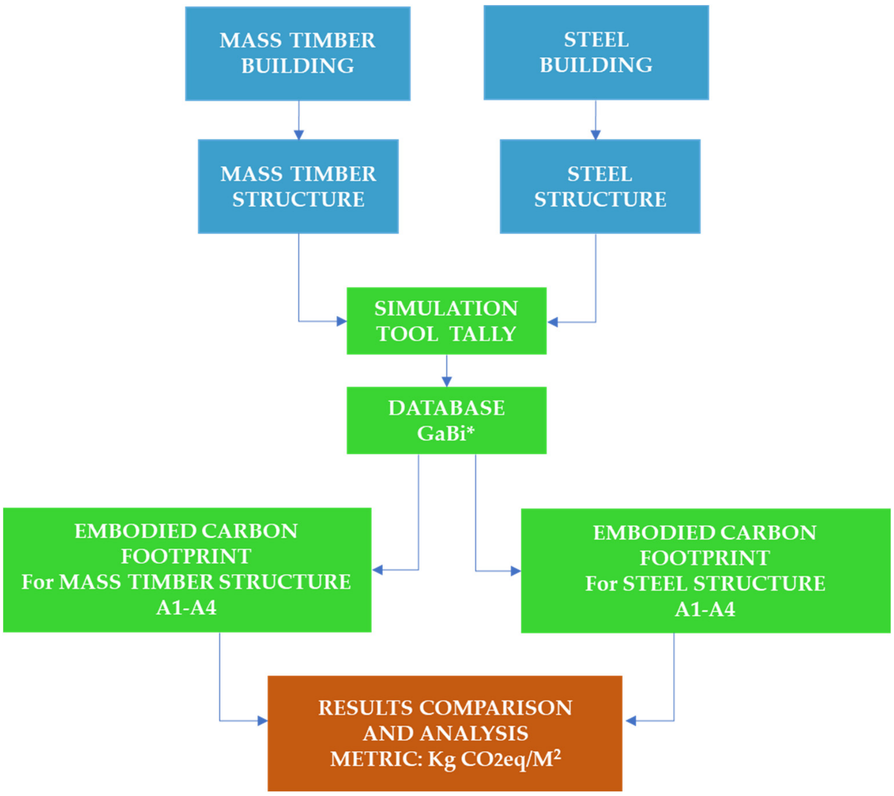

Figure 1. Flowchart showing modeling, analysis, and comparison steps. * "GaBi" stands for "Ganzheitliche Bilanzierung", which is German for "holistic accounting".

3. Materials and Methods

The environmental impacts of the two buildings are compared using the Tally® building LCA tool. Tally® is a commercially available LCA tool that has been developed inside the Autodesk Revit program. Its purpose is to facilitate building LCAs and to quantify the GWP, acidification, ozone depletion, etc.

3.1. Quantitative Method: Whole-Building LCA

A quantitative method is utilized to assess the complete environmental impact of a building structure from cradle to gate or cradle to grave. LCA as a quantitative tool has been chosen to examine the environmental impact of a building throughout the building lifespan. This approach is based on the material quantities extracted from the building's Revit model provided by the design team and the contractor after the building was completed. Due to the significant impact of the building sector on global warming specifically, the GWP and carbon emission are the variables under consideration in this study. In addition, the inventory of equipment and the materials' quantifications are also included.

3.2. Tools and Databases

Tools and software for conducting LCA projects, such as SimaPro, Tally®, OpenLCA, LCA Indicator, and others, have recently gained popularity [21,22]. As opposed to other software applications, Tally® is specifically targeted for conducting the whole-building LCA, and it is also designed to run on a BIM platform called Revit. As a result of this unique functionality, Tally® stands out from other LCA tools in the building sector.

Tally® can effortlessly extract building material inventory data from the Revit 3D model and perform a whole-building LCA using its equipped material database with life cycle inventory (LCI) and Environmental Product Declaration (EPD) data. Tally® is especially useful for architects during the early design phase when they make smart material choices. In this study, the noncommercial version of Tally® 2020.02.28.01 is chosen for quick analysis.

Tally®, the building LCA tool developed collaboratively by KT Innovations, Thinkstep, and Autodesk, incorporates a custom LCI database, which automatically integrates material characteristics and architectural specifications from the Revit model with the corresponding material's environmental impact data. Tally® employs the GaBi database, version 8.5 [23], to conduct the whole-building LCA modeling. The various environmental impacts are calculated in Tally® using the TRACI (Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts) method [24]. The TRACI method was developed by the US Environmental Protection Agency (EPA) in 1995 to be used in LCAs for impact assessment evaluations in North America.

3.3. The Case Study

The newly built mass timber structure building Adohi Hall is a remarkable addition to the University of Arkansas campus, boasting a modern and sustainable design (Figure 2). The building has a multifunctional layout, consisting primarily of student residential units, along with some business use and other supporting spaces that cover 200,000 square feet with six wings and five floors (source, MODUS Studio (Fayetteville, AR, USA) & Nabholz Construction Corp. (Conway, AR, USA)).

Adohi Hall's structure predominantly comprises CLT slabs, supported by glulam columns and beams. The basement and ground floor areas are, however, constructed with reinforced concrete slabs, as well as a combination of steel and concrete columns and beams. This innovative design was brought to life through the collaboration of Leers Weinzapfl Architects (LWA) and Modus Studio, who were in charge of the design, and Nabholz Construction Corp., the construction contractor. Adohi Hall's blend of natural materials and modern technology has set a new standard for sustainable construction, providing a comfortable and eco-friendly living space for students at the University of Arkansas (source, MODUS Studio & Nabholz Construction Corp).

Figure 2. Adohi Hall, University of Arkansas campus, Fayetteville, AR (MODUS Studio).

As mentioned above, Adohi Hall presents the ideal opportunity to examine the level of efficiency of this new material compared to steel when hypothetically constructed. As noted, Adohi Hall was initially designed with a steel frame edifice (Figure 3). To conduct the building LCA of Adohi Hall, material inputs were extracted from the building's Revit model provided by MODUS Studio and LWA. For consistent comparison, the research team relied on the expertise of engineers from Engineering Consultants Inc. to elaborate a Revit model of the steel structure building that was functionally equivalent to that of the building being evaluated. Driven by these considerations, the engineers sized the foundations for the steel structure to be 35% more than that of mass timber. Using the same spans, they also dimensioned the W-section beams and columns as well as the floors and roof, which comprised a corrugated steel deck with a concrete topping.

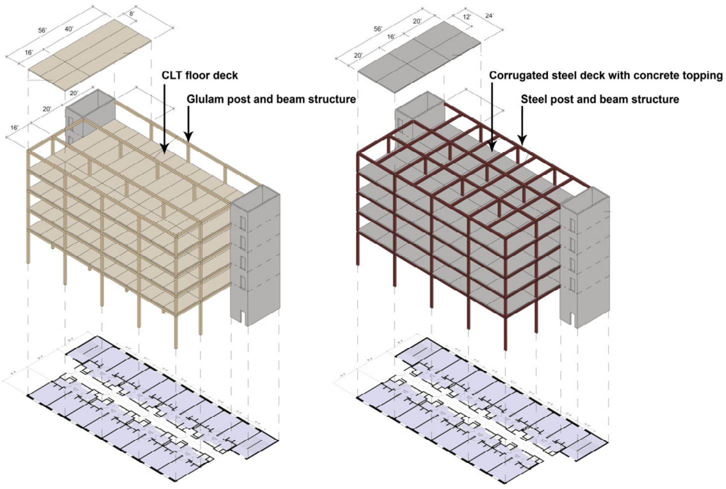

Figure 3. Schematic design of 3D model of Adohi Hall: mass timber versus equivalent steel structure (LWA and MODUS Studio).

The mass timber applied in Adohi Hall was sourced from the Binderholz factory in Graz, Styria, Austria, and transported by vessel from overseas to the port of Houston, Texas. Then, the containers were dispatched partially by train and truck to the construction site on the University of Arkansas campus, Fayetteville, Arkansas.

3.4. Goals, Scope, and System Boundaries

Given the building industry's significant impact on global warming, this study is exclusively focused on GWP impacts. The main goals of this study are (1) to determine the GWP impact from the mass timber structure (excluding enclosure) of the Adohi Hall (CLT floors and glulam columns and beams) using a cradle-to-construction site system boundary; (2) to compare the GWP of the mass timber structure to the steel equivalent design. The functional unit adopted for this building LCA study is chosen as 1 m^2 of gross floor area as the metric for comparison.

The EN 15978 standard [25] outlines the life cycle stages of a building for LCA analysis [25]. Figure 4 illustrates the life cycle stages of the building. For this study, the system boundary covers the product stage and transportation of building materials to the construction site, as highlighted in Figure 4 for modules A1 to A4.

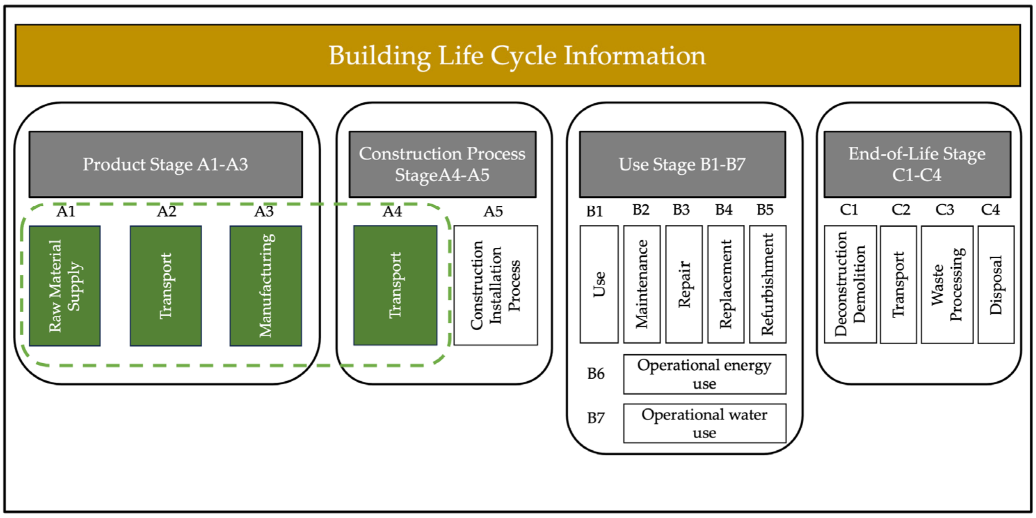

Figure 4. Building life cycle stages (adapted from [26]).

Modules A1–A3 of the standard [25] cover the stages of raw material supply, the transport of raw materials to factories, and then the manufacturing processes. Meanwhile, Module A4 is for assessing the environmental impacts related to materials and construction equipment transported to and from the building construction site, according to the EN standard [25]. It is important to mention that this study excludes equipment transportation. The materials of the building structure are, however, transported to the site to construct components such as columns, beams, shear walls, and slabs for roofs and floors inside the building. It must be noted that only the mass timber structure and its foundations are the subject of this study.

The hypothetical construction of a steel-equivalent building remains a theoretical construct yet to manifest in physical form. The absence of empirical on-site consumption data about the hypothetical steel equivalent building presents a substantial impediment, precluding the research team from conducting a comparative analysis of the construction-related impacts (A5 stage) between Adohi Hall and the hypothetical counterpart. Consequently, the research team has opted to omit the construction phase from their analytical framework, acknowledging the limitations imposed by the lack of pertinent data.

3.5. Assumptions

In accordance with the engineers' professional judgment, the foundation size of the steel structure was postulated to be 35% more than that of the mass timber building, as a premise for the study of this comparative analysis.

4. Analysis of the Results

4.1. Material Resource Environmental Efficiency

According to the findings, the Adohi Hall structure, which is primarily constructed from mass timber, has a total mass of 10,306 tons (including foundations). The comparable structure of steel has an estimated weight of approximately 15,694 tons. This comparison clearly demonstrates that the mass timber structure is significantly lighter than its steel counterpart, resulting in a weight reduction of approximately 35%. Figure 5 conveys a visual representation of the weight distribution of the various materials used in each structure. It shows a significant decrease in the amount of concrete used in the mass timber structure compared to the steel structure. This reduction is achieved by replacing concrete slabs with CLT panels and by reducing the size of the foundations, which is made possible by the lightweight nature of the mass timber structure.

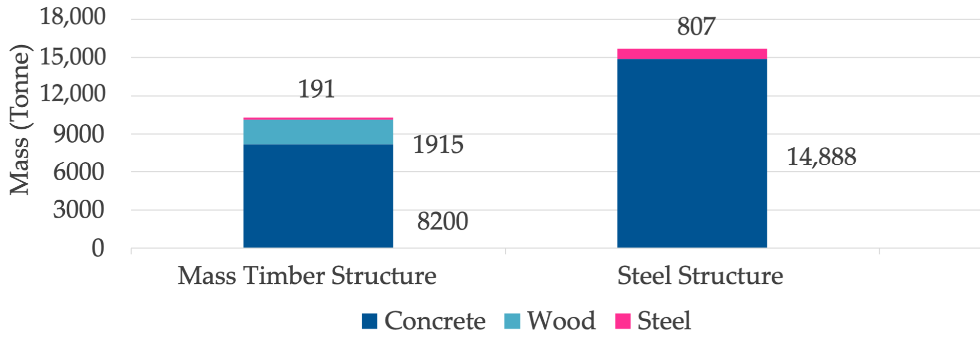

Figure 5. Total mass per building structure.

4.2. Product Stage (A1–A3) Assessment

Product stages A1 to A3 span the analysis of the different processes involved in producing a product, including raw material extraction, transportation to manufacturers, and the actual manufacturing process. The LCA quantified GHG emissions of the mass timber structure in the product stage as approximately 2853 tons of CO_2 eq. In contrast, the steel structure generated much higher GHG emissions, specifically around 4478 tons of CO_2 eq. Comparing the two functional equivalent designs for Adohi Hall, the findings demonstrate a significant reduction in GHG emissions for the mass timber structure of about 36% just in the product stage when compared to the steel model.

This substantial decrease in carbon emissions can be attributed to the inherent properties of mass timber as a sustainable building material. The production of steel involves energy-intensive processes like mining and smelting, which contribute to higher fossil-based carbon emissions. Conversely, mass timber utilizes less fossil energy for its manufacturing, in addition to being a renewable and carbon-neutral resource due to responsibly managed forests. The decision to use mass timber in constructing Adohi Hall has led to a notable reduction in the overall carbon emissions associated with the project.

According to the results presented in Figure 6, the production of concrete generates the most GHG emissions in both structures, approximately 70% of the total GWP impact for both structures. Of the total carbon footprint of the Adohi Hall (mass timber structure), 1892 tons of CO_2 eq is associated with the concrete material. However, there would be 3026 tons of CO_2 eq emission if the mass timber structure were to be replaced with an equivalent steel structure containing concrete floors (Figure 6).

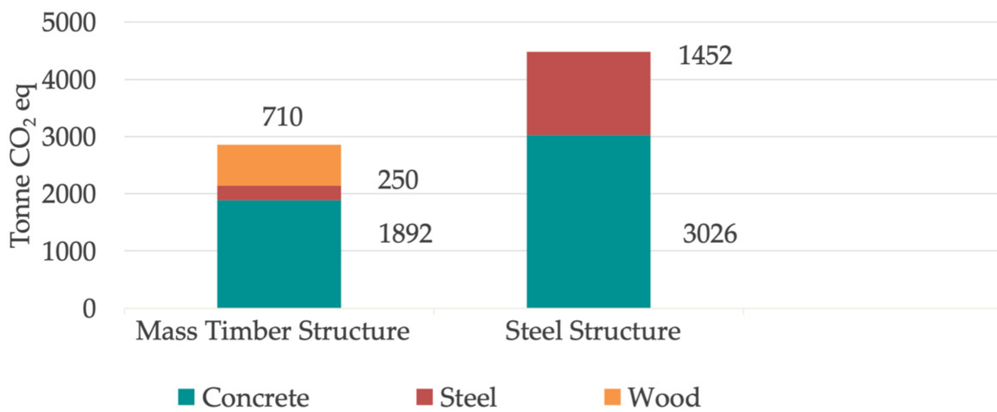

Figure 6. GWP contribution of each material (A1–A3) in the two structure types.

4.3. Transportation Stage (A4) Assessment

The results suggest that mass timber production is associated with lower carbon emissions compared to steel production, as evidenced in Figure 6. In this study, however, the transportation phase of mass timber structures generates a higher carbon footprint due to the overseas sourcing of the materials. In Figure 7, it is evident that the transportation of mass timber from abroad is linked to a substantial carbon footprint, amounting to 825 tons of CO_2 eq emissions. This is attributed to the greater geographical distance between the manufacturer of mass timber and the construction site, particularly in the case of Adohi Hall, where mass timber is sourced from Austria in Europe. The limited number of mass timber manufacturers in the United States contributes to increased transportation distances and, consequently, an amplified environmental impact for mass timber constructions.

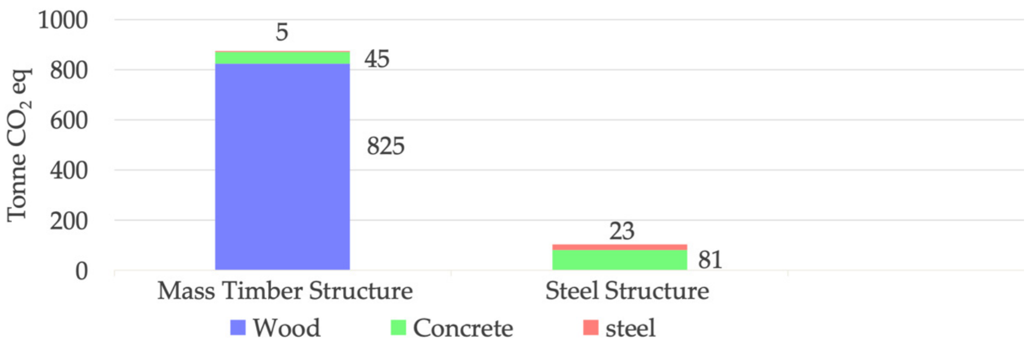

Figure 7. The GWP contribution of each material's transport (stage A4) with mass timber supplied from a factory in Austria.

This figure stands out when contrasted with the considerably lower emissions associated with locally supplied materials like steel and concrete with short transportation distances. The comparison result is depicted in Figure 7. Specifically, in the case of a steel structure alternative, the transportation of steel components and concrete results in emissions of, respectively, 23 and 81 tons of CO_2 equivalent, which is remarkably lower than the mass timber structure.

In the next step, the study assumes that mass timber was supplied from a hypothetic factory in Seattle, Washington, instead of being imported from Europe. Figure 8 indicates the GWP contribution of each material during the transport stage, assuming mass timber was supplied from a factory in Seattle, Washington, instead of being imported from Europe (adopted from [6]). Comparing the graphs in Figures 7 and 8, there is a huge reduction in emissions associated with mass timber transport.

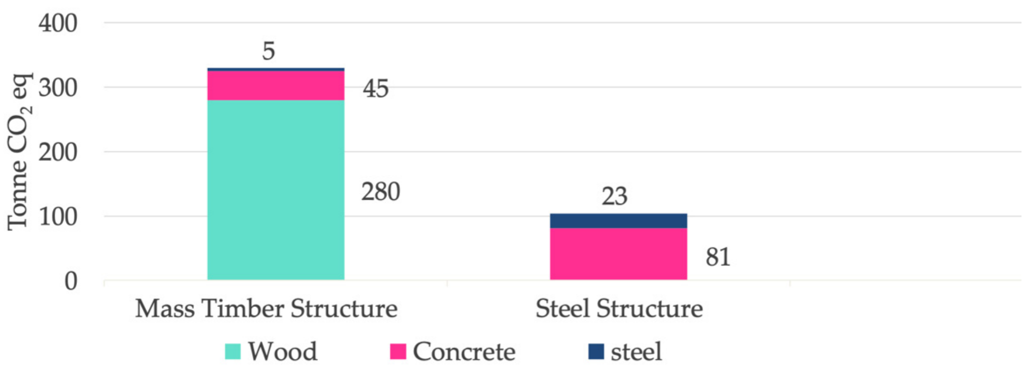

Figure 8. The GWP contribution of each material transport (stage A4) assuming mass timber was supplied from a factory in Seattle.

5. Discussion

By opting for a mass timber structure instead of steel, Adohi Hall has not only achieved a remarkable weight reduction but has also significantly minimized its environmental impact by lowering the total GHG emissions. These findings highlight the advantages of using mass timber in construction projects. This substantial reduction in weight, compared to a steel structure, causes a significant decrease in the amount of concrete required in the foundations. Concrete is a huge source of carbon emissions, as cement is the primary element of concrete. Throughout the cement production process, materials undergo high-temperature heating, demanding substantial energy input. The most carbon-intensive part of cement production is associated with the energy, primarily sourced from fossil fuels, used in the firing process of the material, as well as from the chemical reaction generated within the mixture upon exposure to heat [27]. Such a reduction in foundation size, therefore, significantly decreases the carbon footprint of the building.

Also, the higher carbon footprint associated with steel structures versus mass timber ones is mostly due to the high energy consumption of the steel Bessemer manufacturing process, which is mainly dependent on coal as its main fuel source [28]. In contrast, cleaner energy sources like gas and electricity are used for the manufacturing process of mass timber products. In addition, it is worth noting that the utilization of CO as a corrosion-reducing agent in steel production leads to high CO_2 emissions [28]. Figure 9 provides a comparison of the carbon footprint of the mass timber structure versus the equivalent steel structure. According to the results, Adohi Hall with its mass timber structure design has a carbon footprint of 2853 tons of CO_2 eq in the material production stages, while the steel structure design would have a carbon footprint of 4478 tons of CO_2 eq for the same life stage. In terms of the transportation stage, Adohi Hall, the mass timber structure, has a carbon footprint of 837 tons of CO_2 eq, while the steel structure has a lower carbon footprint of 104 tons of CO_2 eq. The limited number of mass timber manufacturers in the United States leads to increased transportation distances and, consequently, a higher environmental impact for mass timber products if sourced from overseas. In Figure 10, the carbon footprint per square meter of floor area is presented for both structures. The results illustrate that the mass timber structure produces 19% less carbon emissions than the steel structure within the boundary studied (Figure 9). This aligns with the growing global emphasis on sustainable construction practices and demonstrates the positive contribution of mass timber use to reducing the carbon footprint of the whole building sector.

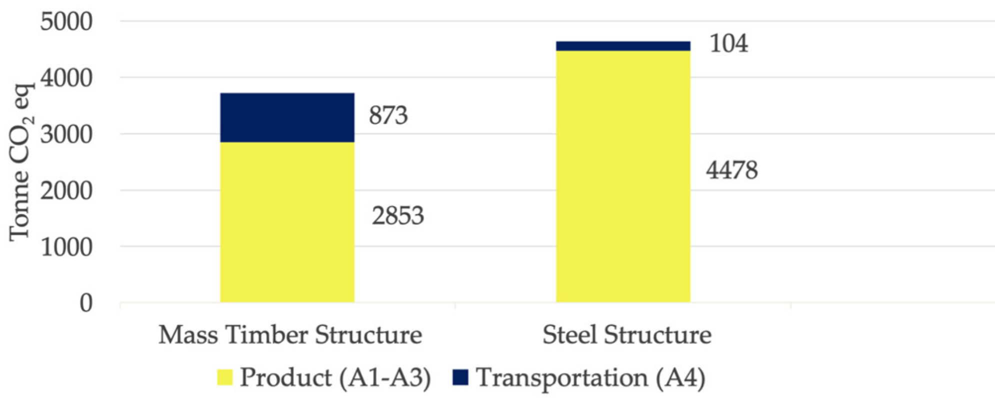

Figure 9. The contribution of carbon emissions from the product stage (A1–A3) and transportation stage (A4).

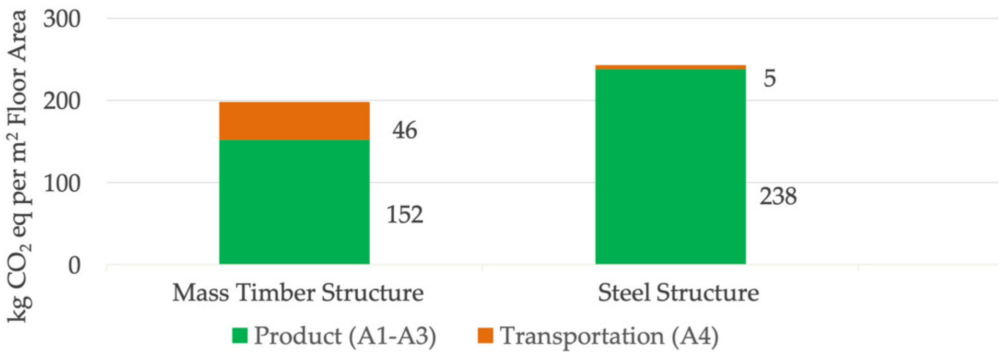

Figure 10. The contribution of carbon emissions due to product stage (A1–A3) and transportation stage (A4) per m^2 gross floor area.

When including biogenic carbon stored in the mass timber products of Adohi Hall, Figure 11 demonstrates a further reduction in the total carbon footprint for the mass timber structure as compared to the steel structure. This demonstrates that when the carbon stored in mass timber products is considered, the mass timber structure proves to be significantly more efficient than the steel structure in the stages that were studied here. Remarkably, the negative values in the graph associated with CO_2 eq emissions from wood products indicate that mass timber structures possess the ability to capture and retain more carbon dioxide than they released during the manufacturing and transportation processes. This can be ascribed to the process of carbon capture inherent to tree growth. As trees grow, they naturally absorb CO_2 from the atmosphere through their biological functions. Consequently, when wood products derived from responsibly managed forests are utilized in the construction of mass timber structures, they serve as carbon sinks by effectively storing carbon within the structural components. One advantage of mass timber is the ability to sequester carbon dioxide (biogenic carbon) throughout the life of the building. This is a capability that neither steel nor concrete has. Obviously, at the end of the building's life, such carbon will be discharged into the atmosphere if no additional steps of recycling or reusing are taken. This delay is, however, a critical advantage and must be seriously considered in the construction of buildings. This suggests that the use of mass timber in buildings could potentially offer a more sustainable alternative to traditional steel construction methods.

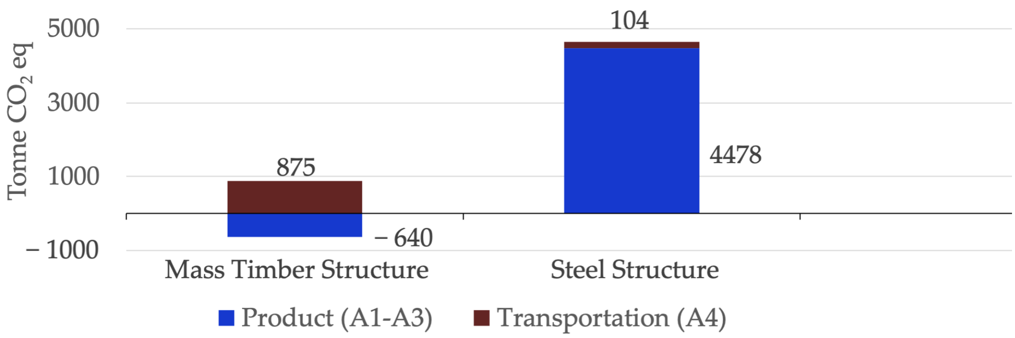

Figure 11. The GWP contribution from the product stage (A1–A3) and transportation stage (A4) includes biogenic carbon storage in mass timber products.

5.1. Displacement Benefits

It is imperative to establish a method for the quantitative assessment of the variance in GHG emissions arising from the utilization of wood versus a predominantly non-wood alternative. The metric employed for this evaluative process is denoted as the displacement factor (DF) [29]. According to soon-to-be-published US guidelines for quantifying harvested wood products' carbon inventory and emissions [30], the DF describes the amount of carbon emissions avoided when wood and wood-based products are substituted for non-wood, fossil-intensive products to achieve an equivalent function [30–32]. The DF gauges the level of emission reduction achieved for each unit of wood utilized. A higher DF signifies a higher reduction in GHG emissions [30,32] resulting from the substitution of wood in place of non-wood products.

The DF can be calculated using the following equation [30]:

$$DF = (GHG_{non\text{-}wood} - GHG_{wood})/(\text{Biogenic Carbon}_{wood} - \text{Biogenic Carbon}_{non\text{-}wood}),$$

where

$GHG_{non\text{-}wood}$ = GHG emissions for non-wood products or structure, obtained from LCA studies (kg CO_2 eq);

GHG_{wood} = GHG emissions for wood-based products or structures, obtained from LCA studies (kg CO_2 eq);

Biogenic Carbon_{wood} = Amount of carbon contained in the wood material (kg CO_2 eq);

Biogenic $\text{Carbon}_{non\text{-}wood}$ = 0, unless the non-wood contains biogenic carbon (kg CO_2 eq).

The following equation is used to calculate biogenic carbon in wood products [30]:

$$\text{Biogenic Carbon}_{wood} = \text{Weight of oven-dried wood} \times 50\% \times (44/12),$$

where

Weight of oven-dried wood = Weight of wet wood/(1 + MC%);

MC = Moisture content.

In the above equation [30], 50% of carbon is normally assumed in wood materials. Multiplying 50% by the weight of oven-dried wood obtains the carbon (C) content stored in the wood [30]. The carbon weight, divided by one mole of carbon, is then multiplied by the combined moles of carbon and oxygen to obtain the equivalent mass content of CO_2 released into the atmosphere.

In this study, the substitution in Adohi Hall of combined steel and concrete with mass timber gives a DF of 0.28, which is determined based on the above-described equation.

5.2. Limitations

The transportation stage includes material delivery from the factory to the construction site and equipment transportation. This study is only focused on material transporting; equipment hauling is not in the scope of the study. The reason for this is that the steel frame is only simulated and not actually constructed, which means that the energy consumption data associated with on-site equipment transportation during practical construction is not available to be accounted for. Moreover, in Tally®, you can only input distances for each material, and the calculations rely on the default LCI of the transportation means. There is no provision for incorporating additional detailed information to update the inventory datasets through a leverage option.

6. Conclusions and Future Research

Traditionally, efforts to reduce emissions in the building sector have focused on improving the efficiency of operational energy use. This has included measures such as improving insulation, using energy-efficient lighting and HVAC systems, and optimizing building layouts to minimize energy consumption. While these measures have been effective in reducing the OC, the focus of research has shifted in recent years towards the use of low-carbon-footprint materials in construction to reduce the EC.

This study on mass timber construction revealed that the mass timber building weighed approximately 35% less than its steel structure equivalent, highlighting a significant advantage for mass timber building designs in terms of material resource efficiency.

Replacing concrete with CLT slabs and reducing foundation size to support the lighter mass timber structure in Adohi Hall has led to 6688 tons less concrete being used than in the equivalent steel structure. This would transform to about 1134 tons of CO_2 eq (almost 40%) emission reductions. It is worth noting that the proximity of concrete and steel providers to building sites typically leads to reduced fossil fuel consumption during transportation. Conversely, the limited number of mass timber plants in the US resulted in longer transportation distances through overseas suppliers, thus resulting in greater environmental impacts for mass timber constructions. Nevertheless, despite this, there was still a significant reduction in the carbon footprint when replacing steel structures and concrete floors with mass timber in the building. In 2021, roughly 10% of the total global CO_2 emissions were associated with steel manufacturing [28,33]. Also, cement, the main element in concrete, is responsible for about 8% of the world's GHG emissions [27]. In fact, the study showed that by making such substitutions, a mass timber building could achieve a 19% reduction in carbon emissions from stages A1 to A4. These findings underscore the substantial potential of mass timber construction in mitigating climate change, as evidenced by a DF of 0.28, favoring the utilization of mass timber over steel structures.

In conclusion, this comparative study provides valuable insights into the environmental benefits of using mass timber in construction and underscores the significance of incorporating LCAs into architectural design decisions. Using this information, architects and engineers can make informed choices that prioritize sustainability and minimize the environmental impact of building materials and designs.

Future studies will extend the scope to include the operational stage (module B6–B7) of Adohi Hall, in accordance with Standard EN 15978 [25], following this assessment of GWP during the production phase and transportation. Moreover, forthcoming studies will investigate the environmental impact of mass timber products and whether they can be repurposed into recycled materials to provide a second life to engineered wood products or can be utilized as biofuels to replace fossil-based energy products at the end of the current building's life cycle. The findings of such a study will be the subject of the next phase of work. Furthermore, cost, performance, and regulatory considerations, while important, can be deterministic in the choice of materials to apply in a building; these will also be investigated in the scope of future research.

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