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Comparative Life Cycle Assessment of Mass Timber and Concrete Residential Buildings: A Case Study in China

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Abstract: As the population continues to grow in China's urban settings, the building sector contributes to increasing levels of greenhouse gas (GHG) emissions. Concrete and steel are the two most common construction materials used in China and account for 60% of the carbon emissions among all building components. Mass timber is recognized as an alternative building material to concrete and steel, characterized by better environmental performance and unique structural features. Nonetheless, research associated with mass timber buildings is still lacking in China. Quantifying the emission mitigation potentials of using mass timber in new buildings can help accelerate associated policy development and provide valuable references for developing more sustainable constructions in China. This study used a life cycle assessment (LCA) approach to compare the environmental impacts of a baseline concrete building and a functionally equivalent timber building that uses cross-laminated timber as the primary material. A cradle-to-gate LCA model was developed based on onsite interviews and surveys collected in China, existing publications, and geography-specific life cycle inventory data. The results show that the timber building achieved a 25% reduction in global warming potential compared to its concrete counterpart. The environmental performance of timber buildings can be further improved through local sourcing, enhanced logistics, and manufacturing optimizations.

Keywords: mass timber; embodied carbon; climate change; carbon reduction; building footprint; built environment; forest products; life cycle analysis

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1. Introduction

The building and construction industry is one of the largest contributors of greenhouse gas emissions and is responsible for 36% of the global energy consumption [1]. It has become increasingly crucial to reduce the environmental impact associated with the building sector, including using alternative construction materials to reduce the carbon footprint of buildings. The use of wood in buildings as alternative materials can help mitigate climate change since wood-based structural materials have a lower carbon footprint than their non-wood counterparts, such as steel and concrete. Moreover, trees sequester carbon from the atmosphere, and wood products can keep that carbon stored away from the atmosphere for their lifetimes [2,3]. In recent years, the environmental performances of mass timber have been evaluated extensively in the U.S. [4–6], which calls for further examination of the potential of wider application of mass timber in buildings in other countries.

As the most populated country globally, China has experienced rapid urbanization for decades, and the building sector contributed a significant amount of greenhouse gas emissions [7,8]. Most of the buildings in China use traditional building materials that are usually energy-intensive. For instance, concrete and steel account for over 60% of the total

carbon emission among all building components [9], but regardless of their contribution to the carbon footprint of buildings, they remain the two most commonly used materials in China.

The Population Division (UNPD) of the Department of Economic and Social Affairs at the United Nations (UN DESA) has predicted that 80% of China's population will be living in urban areas by 2050, an increase from ~36% in 2000 [10]. Guo et al. [7] suggested that under the current urbanization plan in China, it is likely that the building sector will continue to contribute a significant amount of energy consumption and CO_2 release. A recent study suggested that China's new building constructions may likely turn to a slower rate after 2020 and the focus of the construction industry will be the maintenance and renovation of existing buildings, as well as the end-of-life (EoL) management of demolished old buildings [11]. Nonetheless, as China expressed determination to reduce carbon emission in the near future, it has become increasingly important for emission-intensive industries to adopt changes and seek options that can help reduce their carbon footprint.

In 2015, China submitted a document to the United Nations Framework Convention on Climate Change (UNFCCC) specifically expressing the intent to control emissions from the building and transportation sectors through various measures, including plans to accelerate the share of low-carbon communities and green buildings in new constructions [12]. For the building sector, all possible mitigation measures throughout a building's life cycle need to be considered to achieve emission reduction, including substituting concrete and steel with wood products.

Cross-laminated timber (CLT), along with many other mass timber products, is being recognized as an environmentally sustainable alternative to concrete and steel. Recent works in the U.S. have shown that buildings that incorporate mass timber, particularly CLT, achieve lower environmental impacts compared to their functionally equivalent concrete or steel counterparts [13–16]. Studies outside of the U.S. also suggested the benefits of using mass timber materials from an environmental perspective [17–19]. It is important to note that one of the advantages of using mass timber over other timber products in construction is that mass timber can be used as a structural component in tall buildings. This characteristic can be particularly important for urban areas that have a demand for tall buildings due to higher population density. In China, studies have also suggested that using wood products to replace concrete and steel in the construction industry can significantly reduce carbon emissions [20]. However, research that primarily focuses on CLT or mass timber materials is required for these products to gain public acceptance and market shares on a wider scale.

In recent years, CLT has started to gain some recognition in China. The National Forestry and Grassland Bureau has released a design and technical standard for the use of CLT in mid- to high-rise buildings. The CLT standard, known as LY/T3039-2018, was officially implemented in 2019 and provides a foundation for applying CLT in new constructions. Nonetheless, issues such as regulation, marketing, public acceptance, assembly, and production cost remain great challenges for the use of prefabricated materials such as CLT in the construction industry [21,22]. Furthermore, studies that investigate the role of alternative materials in reducing the carbon footprint of building constructions often lack data specifically appropriate for China cases [23]. At the current stage, the few existing CLT buildings in China are predominately used for demonstration purposes [24], and although some studies associated with the environmental aspects of CLT and CLT buildings have been conducted in China in the last several years [7,25,26], research on the production process and application of CLT, as well as a comparative analysis of whole-building performance, is still at an early stage.

Although 10 million residential multi-family buildings are built in China each year, only a negligible number of buildings use wood as the primary material. Most of these houses use imported materials and are often built due to special demands [27]. Promoting the wider use of CLT in China's construction industry requires tremendous support from

the government and policy makers, but the implementation of such policy and regulations are relatively slow [20].

This case study used current data appropriate to China's manufacturing and building processes to conduct a comparative life cycle assessment for a timber building and a concrete building in China. The purpose of this study was to investigate the environmental impacts of CLT as a building material and provide a comprehensive comparison between timber building and concrete building. Quantifying the emission mitigation potentials of using CLT in new buildings can help accelerate associated policy development and provide valuable references for developing more sustainable constructions at the regional and national levels.

2. Materials and Methods

This study used a life cycle assessment (LCA) approach based on the ISO 14040 and ISO 14044 standards [28,29]. The standards provide guidelines for LCA and include specifications for phases such as goal and scope definition, system boundary, inventory analysis, impact assessment, interpretation, and limitations of LCA.

2.1. Goal and Scope

The primary goal of this study was, using a cradle-to-gate LCA model, to evaluate the environmental impacts of a timber building and a functionally equivalent conventional concrete building in China. Both buildings are 8-story residential buildings with an 80-year service life. Each building has a total area of 3524 m^2. The functional unit in this study was 1 m^2 of floor area.

2.2. System Boundary

The system boundary defines which life cycle activities were included in the analysis. Figure 1 illustrates the system boundary based on a building life cycle. Processes that occur at each life cycle phase of a building are classified and structured in a modular format as shown in Figure 1.

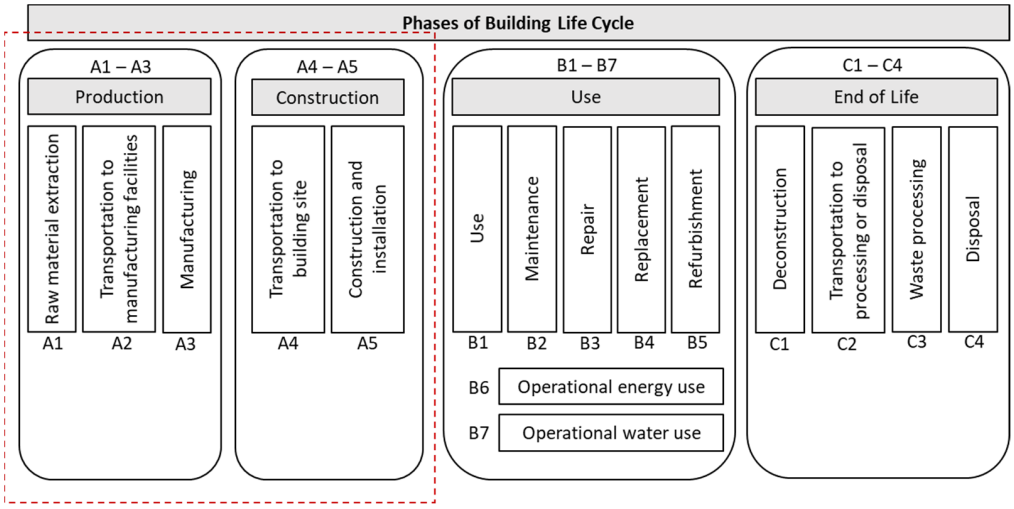

Figure 1. System boundary of a building's life cycle stages. This study focused on A1–A5.

The system boundary for this assessment was cradle to gate and included several modules: A1, resource extraction; A2, transportation of materials to product manufacturing; A3, product manufacturing; A4, transportation of materials to construction site; and A5, construction energy consumption. The building use phase and the end-of-life phase were not included in this study.

2.3. Building Design

Two functionally equivalent 8-story residential buildings were assessed in this study. A Chinese architectural design firm, JAZ Build Co. Ltd., provided a full set of CAD drawings for an 8-story concrete residential building in Chongqing, China, which was used as the basis for developing a functionally equivalent mass timber building. A design team from atelierjones designed the mass timber building using Revit based on the CAD drawing provided. The baseline building is a conventional building using concrete and steel as its primary material (i.e., concrete building), whereas the timber building used CLT as the primary material (i.e., timber building). According to EN 15978 [30], a functional equivalent approach quantifies a set of design criteria that both buildings have in common (e.g., walls, floors, foundation). In this study, only the floors, foundation, and walls were modeled for both buildings. Studies have shown that buildings in China have much shorter lifespan than those in North America, likely due to rapid urbanization and high demands for newer constructions over the past few decades [31,32]. However, in an effort to mitigate climate change while expecting potentially slower new construction rate [11,12], buildings will potentially achieve longer service life in the future. Specific approach and assumptions are described in the following sections.

2.3.1. Functional Equivalent Approach

A functionally equivalent approach was taken for the building modeling from the beginning so that building components that were the same for either building would not be modeled to be part of the LCA analysis. This included large functionally equivalent elements such as exterior façade materials, as it was assumed that these would not be materially affected by the mass timber structural material. Other areas, such as bathroom fixtures, furniture, kitchen appliances, countertops, mechanical soffits, and interior floor coverings, such as hardwood floors or carpets, were not modeled, as these areas would be the same for both the mass timber and concrete baseline buildings.

However, wall and floor assemblies that were materially impacted, such as the acoustical ratings (both sound and impact) between floors and common walls, were modeled. Additional consideration was given to the fire and life safety performance of the mass timber construction and all mass timber assemblies following the requisite code performances as required under the new International Code Council (ICC) provisions for mass timber buildings. Gypsum wallboard (GWB) was assumed as the requisite non-combustible protection, as designed to the hourly ratings of the required wall/floor assemblies per the new ICC codes. As this GWB protection was required only for the mass timber assemblies, they were modeled accordingly but not modeled for the equivalent non-combustible concrete assemblies.

2.3.2. Building Site

The building models used location-specific data as it is a built design provided by a Chinese firm. Therefore, when analyzing the LCA data provided by the model, it should be acknowledged that the model was designed for the City of Chongqing in the Southwestern region of China and that alternate designs could be required for seismic structural concerns or varying soil types and pressure. Additional refinement could be made for varying urban demographic zones or city block sizes as well. Any further need for sun shading, solar panel orientations, or other site-specific concerns were not considered as part of the analysis as they would be considered functionally equivalent requirements for both building types.

2.3.3. Building Size and Shape

The mass timber building design follows the exact same shape and size as the original concrete baseline building. Both buildings are standard regularly shaped buildings. The total area of the buildings is 3524 m^2.

2.3.4. Building Program

The scope, program, and layout of the model follow a typical modern Chinese market design. The residential units were large, likely market-rate, with two to three bedrooms, two per floor, around a symmetrical entry core and exit stairs, stacked vertically for 8 stories, with no commerce or retail on the ground floor. The building program matches the existing design provided by the Chinese firm. No changes were made to the program. China's residential program differs from North American design in a few key ways; namely, the floorplates were not designed for a multitude of apartments around a double-loaded corridor but rather two multi-bedroom condos sharing a joint elevator/stair access per floor. While the kitchens, bathrooms, and bedrooms were all laid out according to the provided design, only their demising walls, both between the units and between the functional areas, were modeled so as to capture the greatest number of differences between the two buildings.

2.3.5. Thermal Performances

Two key areas were looked at by the architectural team that could contribute to regional and construction differences in the models. The first were the different wall assemblies, given the mass timber vs. concrete material for the opaque wall sections. While the team did not have the expertise to analyze how Chinese Energy code might differ among regions, it is assumed that, in a larger study, this is one area where large differences might exist in material takeoffs based on varying regional needs.

As mass timber has a small but key contribution to the thermal and energy performance of the building, we considered the insulation of the buildings in our modeling. Typically, a mass timber panel has an R-value of 1.25/inch, or approximately R = 5 for a 4-inch-thick wall panel. While this only impacts the building where solid/opaque walls are considered, it was significant enough to be included. As the exterior wall assembly is largely the same between models due to large expanses of glass windows and doors, these areas were considered functionally equivalent for both the mass timber and concrete buildings; hence the exterior walls were not modeled.

2.3.6. Building Code Assumptions

As the model used in the LCA study is an existing building, no extensive code analysis was studied, although the transposition from the existing concrete design to the mass timber does fit within the new codes as developed by the ICC Tall Wood Building Committee measures, as passed by the Online Governmental Voting process in January 2019. The goal was to adhere as closely as possible to the requirements for structural/seismic requirements, as well as life safety requirements, as the conceptual level modeling allowed for. This included, particularly, the non-combustible protection required on the exterior face of the mass timber, as well as around the building cores, where mass timber was allowed.

2.4. Cross-Laminated Timber Production

Data associated with the production of CLT, including lumber sourcing, wood species mix, waste treatment, resin types, transportation mode, and production capacity, were gathered through surveys collected during an onsite visit to a CLT manufacturing facility in Southeast China. Energy consumption during the CLT manufacturing phase was based on existing studies for CLT production in the U.S. [5] and adjusted for the appropriate geographic location. The primary wood species used in CLT production was *Picea abies*, commonly known as European spruce or Norway spruce, and the lumber requirement for 1 m^3 of CLT was approximately 1.25 m^3. The density of the species mix is assumed to be 420 kg/m^3 with 12% moisture content. CLT was the primary material used in the floor and wall structures in the timber building. PUR resin is used in CLT production and applied in the finger joint and layup phases. A total of 4.52 kg of resin, including adhesive and primer, is used for 1 m^3 of CLT. An estimate of 2.63 m^3 of natural gas is used to dry 1.25 m^3 of lumber from 19% moisture content to 12%.

2.5. Transportation

Material transportation associated with module A4 used actual manufacturing facility locations in China. Local manufacturing facilities closer to the building site were selected when possible. Lumber used for CLT manufacturing was assumed to be imported from Europe based on interviews and surveys conducted in China. Transportation distances for the primary materials used in the buildings are shown in Table 1.

Table 1. Transportation assumptions of building materials to building site.

Material Name	Truck (km)	Rail (km)
Concrete	157	-
CLT	100	1993
Rebar	100	1300
Gypsum Concrete	157	-
Fiberglass Batt	65	1321
Gypsum Wallboard	47	-
Galvanized Steel Sheet, 25 ga	100	742

2.6. Construction and Installation

In this study, module A5 considered the diesel fuel consumption for lifting the building materials by crane as a way to quantify the energy consumption associated with construction and installation. As shown in function (1), estimated fuel use in liters (L) was calculated under the assumption that materials were lifted by crane to $\frac{1}{2}$ the height of the building [33]:

$$\text{Fuel (L)} = 0.000037\ \text{Mh} + \text{M}/500 + 0.83 \quad (1)$$

where: M = mass of the material being lifted in kg. h = height at which the material is being lifted. Half of the building height was assumed.

2.7. Assumptions

1. The timber building design was based on design data provided by a Chinese architecture firm for a functionally equivalent concrete building.
2. Lumber was assumed to be dried from 19% moisture content to 12% moisture content in a natural-gas-powered kiln. Natural gas has been increasingly popular as a coal alternative in China as new industrial energy efficiency requirement took place [34,35].
3. Electricity used during CLT manufacturing was based on the U.S. case study as the manufacturing process remains similar, despite the manufacturing facility location.

2.8. Life Cycle Impact Assessment

Life cycle impacts defined in the ISO 21930 [36], as well as freshwater consumption and hazardous/non-hazardous waste, were quantified using the TRACI 2.1 mid-point characterization methodology [37] in SimaPro v.9 [38]. Primary energy consumption was calculated using the cumulative energy demand (CED) method. Several databases incorporated in SimaPro were used in addition to survey data, including the USEI [39] and ecoinvent databases [40]. Impact categories reported in this study are shown in Table 2.

2.8.1. Data Collection

Data associated with the CLT production process in China were collected through surveys, onsite interviews, and published works. The research team visited a CLT manufacturing facility in Eastern China to investigate the types of production equipment and the source of raw materials used in production. The production process of CLT in China is relatively similar to that of other countries, and therefore, the U.S. CLT production process described in [5] was applied in this study. Information on the type and source of resin used in CLT panels was obtained through surveys and interviews collected during the visit to the manufacturing facility.

Table 2. Life cycle assessment impact categories included in this study as per ISO 21930.

Indicator	Abbreviation	Unit
Global warming potential, fossil	GWP	kg CO_{2e}
Depletion potential of the stratospheric ozone layer	ODP	kg $CFC11_e$
Acidification potential of soil and water sources	AP	kg SO_{2e}
Eutrophication potential	EP	kg PO_{4e}
Formation potential of tropospheric ozone	SFP	kg O_{3e}
Abiotic depletion potential (ADP fossil) for fossil resources	ADPf	MJ, NCV
Abiotic depletion potential (ADP element) for fossil resources	ADPe	kg, Sb_e
Fossil fuel depletion	FFD	MJ Surplus
Renewable primary energy carrier used as energy	RPRE	MJ, NCV
Non-renewable primary energy carrier used as energy	NRPRE	MJ, NCV
Consumption of freshwater resources	FW	m^3
Hazardous waste disposed	HWD	kg
Non-hazardous waste disposed	NHWD	kg

2.8.2. Life Cycle Inventory

Impacts of materials used in the buildings were modeled based on existing life cycle databases. Electricity and fuel consumption data available in the ecoinvent 3 and USEI 2.2 databases were applied in the LCA model. Data for China were used whenever possible. If specific data for China were not available, global-level data were used. Table 3 lists the data sources and life cycle inventory (LCI) process used for this study.

Table 3. Data sources used for material, energy, and fuel consumption in both the mass timber and concrete buildings.

Indicator	Abbreviation	Unit
CLT	CLT	Chen et al. 2019 [5], survey, and interview
Concrete, Reinforced	Concrete, sole plate, and foundation {RoW}| concrete production, for civil engineering, with cement CEM I	ecoinvent 3
Concrete, Non-reinforced/Gypsum Concrete	Concrete, normal {RoW}| unreinforced concrete production, with cement CEM II/	ecoinvent 3
Rectangular Mullion: 3–5/8″ C Stud	Steel, low-alloyed, hot rolled {RoW}| production | APOS, U	ecoinvent 3
Fiberglass Batt Insulation	Glass wool mat {RoW}| production | APOS, U	ecoinvent 3
Gypsum Wallboard	Gypsum fiberboard {RoW}| production | APOS, U	ecoinvent 3
Rebar	Reinforcing steel {RoW}| production | APOS, U	ecoinvent 3
Road Transport	Transport, freight, lorry 7.5-16 metric ton, EURO5 {RoW}| transport, freight, lorry 7.5-16 metric ton, EURO5 | APOS, U	ecoinvent 3
Rail Transport	Transport, freight train {CN}| diesel | APOS, U	ecoinvent 3
Sea Transport	Transport, freight, sea, transoceanic ship {GLO} | processing | APOS, U	ecoinvent 3
Construction Energy	Diesel, burned in building machine/GLO US-EI U	USEI 2.2

3. Results

This section provides an overview of the building material comparison between the two buildings, as well as a detailed life cycle impact analysis.

3.1. Comparison of Building Materials

A comparison of the building materials used in the timber and the concrete building is shown in Table 4. The floor component in the timber building is mainly assembled with CLT panels but requires additional gypsum concrete on top of the slab. Both buildings use fiberglass batt insulation as part of the wall assembly for added thermal performance and soundproofing. The requirement of metal stud and rebar is significantly higher in the concrete building than that of the timber building; for instance, 25,700 kg of rebar is required in the concrete building's foundation, while only 5197 kg of rebar is required in the timber building. While both buildings require fiberglass insulation and gypsum boards in the walls, the amount required is lower in the timber building.

Table 4. Comparison of building assemblies and material quantities in the timber and concrete buildings.

Assembly	Material Name	Unit	Timber	Concrete
Floors	CLT	m^3	959	-
	Concrete	m^3	30	835
	Gypsum Concrete	m^3	201	-
Foundation	Concrete	m^3	72	98
	Rebar	kg	5197	25,700
Walls	CLT	m^3	487	-
	Concrete	m^3	12	458
	Fiberglass Batt	m^2	1778	6751
	Gypsum Wallboard	m^2	1919	5688
	Metal Stud	kg	27,924	108,108

3.2. Impact Analysis

Tables 5 and 6 present the actual impacts of the buildings and the differences between the timber and concrete buildings for each impact category. The concrete building was used as the baseline for comparison. Figure 2 illustrates the differences in percentage between the timber and concrete buildings using the concrete building as the baseline (i.e., 100%).

While the timber building showed a reduction in total GWP and many impact categories, the concrete building demonstrated lower impacts in categories such as ozone depletion, acidification, smog, and fossil fuel depletion. It should be noted that the acidification and smog potential of the timber building were particularly high, which may be attributed to the longer transportation distances of raw materials. For example, the CLT manufacturing process in China showed higher impacts compared to the U.S. CLT manufacturing due to the fact that lumber was imported from Europe and the required transportation was an important driver of higher impacts in these categories.

Most of the impacts were associated with modules A1–A3, which included resource extraction, transportation, and material production. The overall performance in module A4 mainly depended on the transportation distances of building materials and the mode of transportation. Concrete is usually produced locally and is generally more accessible to buyers. This gives concrete some advantages in terms of transportation impacts. In contrast, because there are very few CLT manufacturers in China, CLT needs to be transported further away from the building site. In this study, CLT was assumed to be purchased from a manufacturer in the Southeastern region in China, over 2000 km from the building site. Nonetheless, because the overall mass of the materials used in the timber building is lighter than that of the concrete building, the timber building performed better in terms of GWP regardless of the further transportation distance.

Table 5. Life cycle impacts per m^2 floor area in the timber building.

Timber Building						
LCIA Indicator	**Abbreviation**	**Unit**	**A1–A3**	**A4**	**A5**	**Total**
Global warming potential, fossil	GWP	kg CO_2e	191.73	26.10	3.47	221.3
Depletion potential of the stratospheric ozone layer	ODP	kg CFC11e	2.11×10^{-5}	5.33×10^{6}	5.59×10^{-7}	2.70×10^{-5}
Acidification potential of soil and water sources	AP	kg SO_2e	1.78	0.174	0.034	2.0
Eutrophication potential	EP	kg Ne	0.53	0.05	0.004	0.6
Formation potential of tropospheric ozone	SFP	kg O_3e	28.87	4.54	1.00	34.4
Abiotic depletion potential (ADP fossil) for fossil resources	ADPf	MJ, NCV	2107.84	353.99	47.91	2509.7
Abiotic depletion potential (elements)	ADPe	kg Sbe	8.18×10^{-3}	7.44×10^{-5}	5.57×10^{-7}	8.26×10^{-3}
Fossil fuel depletion	FFD	MJ Surplus	210.59	48.18	7.13	265.9
Renewable primary energy carrier used as energy	RPRE	MJ, NCV	6782.44	8.78	0.14	6791.4
Non-renewable primary energy carrier used as energy	NRPRE	MJ, NCV	3560.11	364.29	48.68	3973.1
Consumption of freshwater resources	FW	m^3	2.94	0.09	4.55×10^{-3}	3.0
Hazardous waste disposed	HWD	kg	0.04	1.64×10^{-2}	2.02×10^{-2}	0.1
Non-hazardous waste disposed	NHWD	kg	63.30	14.49	0.43	78.2

Table 6. Life cycle impacts per m^2 floor area in the concrete building.

Concrete Building						
LCIA Indicator	**Abbreviation**	**Unit**	**A1–A3**	**A4**	**A5**	**Total**
Global warming potential, fossil	GWP	kg CO_2e	252.57	34.32	8.66	295.6
Depletion potential of the stratospheric ozone layer	ODP	kg CFC11e	1.56×10^{-5}	8.02×10^{-6}	1.39×10^{-6}	0.0
Acidification potential of soil and water sources	AP	kg SO_2e	1.00	0.127	0.08	1.2
Eutrophication potential	EP	kg Ne	0.89	0.0405	0.010	0.9
Formation potential of tropospheric ozone	SFP	kg O_3e	14.95	2.69	2.50	20.1
Abiotic depletion potential (ADP fossil) for fossil resources	ADPf	MJ, NCV	1811.36	502.76	119.64	2433.8
Abiotic depletion potential (elements)	ADPe	kg Sbe	2.41×10^{-2}	1.24×10^{-4}	1.39×10^{-6}	2.42×10^{-2}
Fossil fuel depletion	FFD	MJ Surplus	162.06	72.40	17.81	252.3
Renewable primary energy carrier used as energy	RPRE	MJ, NCV	540.65	6.31	0.36	547.3
Non-renewable primary energy carrier used as energy	NRPRE	MJ, NCV	5877.94	511.22	121.55	6510.7
Consumption of freshwater resources	FW	m^3	8.32	0.09	1.14×10^{-2}	8.4
Hazardous waste disposed	HWD	kg	0.04	7.32×10^{-3}	5.04×10^{-2}	0.1
Non-hazardous waste disposed	NHWD	kg	213.53	21.87	1.08	236.5

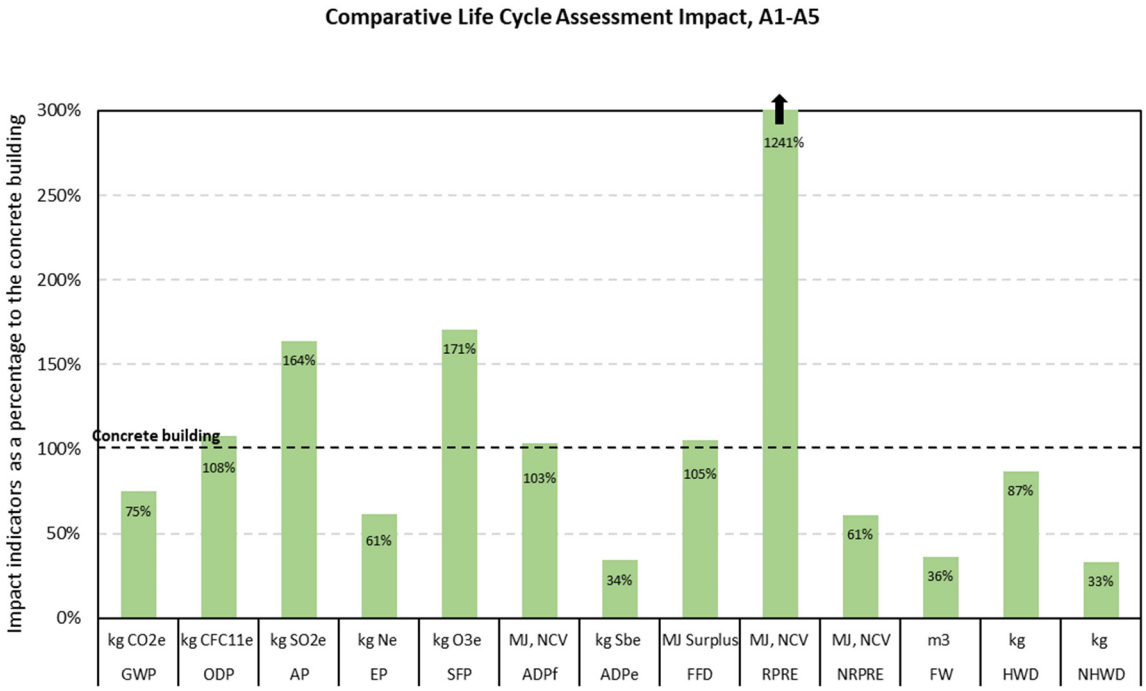

Figure 2. Comparison of LCA impacts in the timber and concrete buildings.

3.3. Contribution Analysis

A contribution analysis was performed to investigate the impacts associated with each building material and assembly. Knowing the impacts posted by individual materials or assemblies can help optimize the production process of construction materials.

3.3.1. Building Assemblies

A contribution analysis was conducted using the GWP (kg CO_2 eq.) to examine the impact of each building assembly and material. Overall, the GWP of the timber building was 25% lower than that of the concrete building (Table 7). In modules A1–A3, the floor component of the timber building had a 26% higher global warming impact than the concrete building, but its foundation and wall components had significantly lower GWP. This might be attributed to the lower requirement of materials in the timber building. For instance, the concrete and rebar requirements for the foundation were also lower for the timber building. The floor component was more material-intensive than other components in the timber building, which made it account for a higher percentage of impacts. Despite the longer transportation distance for CLT, the overall GWP in module A4 was 24% lower in the timber building because of a lower total material mass. All assemblies in the timber building showed lower GWP in module A5, which can be attributed to its lower mass that helped to reduce the fuel consumption in heavy machinery. Figure 3 provides the contribution to the total GWP of each building assembly (A1–A5). While the floor assembly was the largest GWP contributor in the timber building (i.e., 42%), the wall assembly contributed the highest global warming impact in the concrete building.

3.3.2. Building Materials

Table 8 shows the global warming impacts of the buildings by materials. In modules A1-A3, all materials used in the timber building showed a reduction in GWP compared to the same materials used in the concrete building. The largest reduction in GWP was shown by concrete, with a 91% lower impact in the timber building. This was expected since the timber building replaced most of the concrete with CLT. It is important to note that the GWP of CLT in modules A1–A3 was slightly higher than that of concrete, which

may be associated with the higher impacts of raw material transportation from overseas. Nonetheless, the overall GWP of the timber building was 24% lower.

Table 7. GWP contribution of the timber and concrete buildings by assembly.

Assembly	Timber	Concrete	Difference
A1–A3 (kg CO_2 eq./m^2 floor)			
Floor	105.64	84.11	26%
Foundation	10.66	26.51	−60%
Wall	75.44	141.95	−47%
Total	191.73	252.57	−24%
A4 (kg CO_2 eq./m^2 floor)			
Floor	17.38	19.16	−9%
Foundation	1.77	2.80	−37%
Wall	6.95	12.36	−44%
Total	26.10	34.32	−24%
A5 (kg CO_2 eq./m^2 floor)			
Floor	2.32	4.88	−52%
Foundation	0.44	0.64	−31%
Wall	0.71	3.14	−77%
Total	3.47	8.66	−60%
Total A1–A5 (kg CO_2 eq./m^2 floor)			
Floor	125.34	108.15	16%
Foundation	12.87	29.95	−57%
Wall	83.09	157.45	−47%
Total	221.30	295.55	−25%

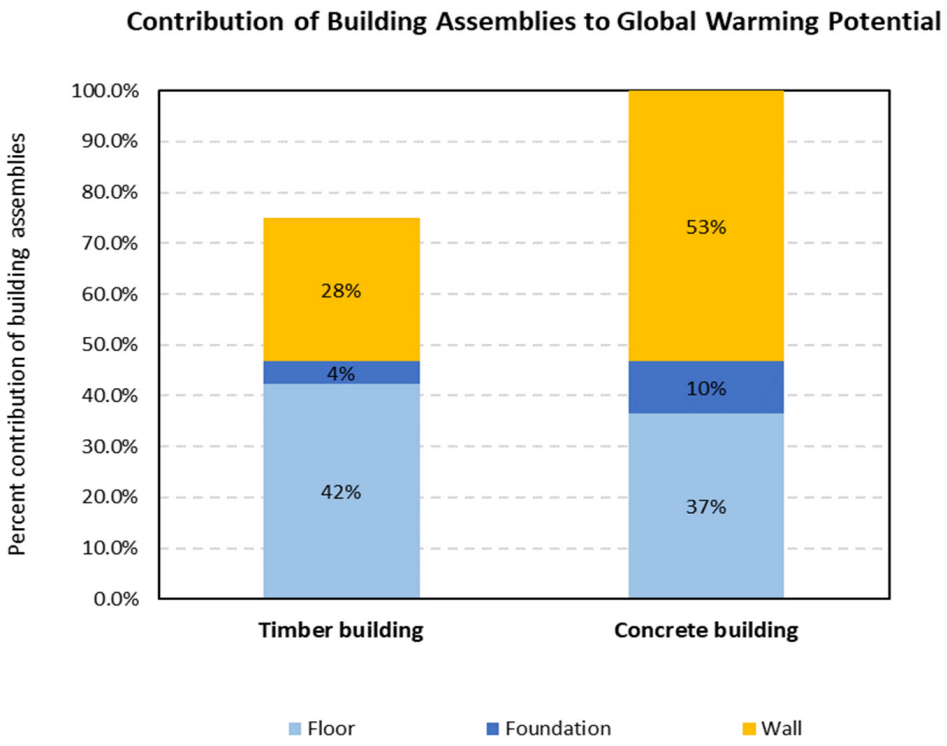

Figure 3. Contribution of building assemblies to total GWP.

Table 8. GWP contribution of the timber and concrete buildings by building material.

Assembly	Timber	Concrete	Difference
A1–A3 (kg CO_2 eq./m^2 floor)			
CLT	137.50	-	-
Concrete	11.57	135.16	−91%
Gypsum board	7.63	22.63	−66%
Gypsum concrete	11.41	-	-
Insulation	3.78	14.36	−74%
Metal stud	16.47	63.77	−74%
Rebar	3.37	16.67	−80%
Total	191.73	252.57	−24%
A4 (kg CO_2 eq./m^2 floor)			
CLT	18.29	-	-
Concrete	2.634	31.867	−92%
Gypsum board	0.07	0.20	−66%
Gypsum concrete	4.56	-	-
Insulation	0.02	0.07	−74%
Metal stud	0.42	1.63	−74%
Rebar	0.11	0.56	−80%
Total	26.10	34.32	−24%
A5 (kg CO_2 eq./m^2 floor)			
CLT	1.48	-	-
Concrete	0.67	8.11	−92%
Gypsum board	0.06	0.17	−66%
Gypsum concrete	1.16	-	-
Insulation	0.01	0.05	−72%
Metal stud	0.07	0.26	−74%
Rebar	0.02	0.07	−77%
Total	3.47	8.66	−60%
Total A1–A5 (kg CO_2 eq./m^2 floor)			
CLT	157.27	-	-
Concrete	14.87	175.13	−92%
Gypsum board	7.76	22.99	−66%
Gypsum concrete	17.13	-	-
Insulation	3.81	14.48	−74%
Metal stud	16.96	65.65	−74%
Rebar	3.50	17.29	−80%
Total	221.30	295.55	−25%

Figure 4 illustrates the contribution of each material relative to the total building. CLT was the primary material used in the timber building, accounting for 53% of the total GWP contribution. Gypsum concrete and metal stud each accounted for 6% of the total GWP contribution. Since the building assessed in this case study is an eight-story, mid-rise building, extensive gypsum boards were not required for the walls, therefore reducing the overall GWP of the timber building. For the concrete building, although concrete was the primary material, gypsum boards and metal studs contributed a combined 30% of GWP.

3.4. Carbon Storage

The carbon storage in wood products was calculated assuming the carbon content equals half of the mass of wood [41]. Although the end-of-life stages were not within the system boundary for this study, this information can be used in end-of-life scenarios. Table 9 lists the amounts of carbon stored, fossil emission, biogenic carbon associated with the timber building, and the amount of CO_2 that is sequestered if the same quantity of biomass used for CLT production is regenerated in the forest. Biogenic carbon emission was calculated based on several key sources, including unallocated lumber which was not

used in the final CLT panels, carbon contents in the co-products, and emission generated from biofuel combustion. As shown in Table 9, more carbon is stored in the building than is released (fossil based) during production (embodied carbon). Biogenic carbon emission was not counted toward global warming contribution under the carbon neutrality assumption, which assumes that biogenic carbon emission from wood products is balanced by plant regeneration in sustainably managed forests. Under a sustainable forest management scenario, trees harvested to produce CLT are assumed to be replanted. If the amount of CO_2 sequestered by the newly generated trees (i.e., 1243 t CO_2 eq.) is added to the CO_2 stored in the CLT in the timber building, the total level of CO_2 can compensate for the emissions released during material production.

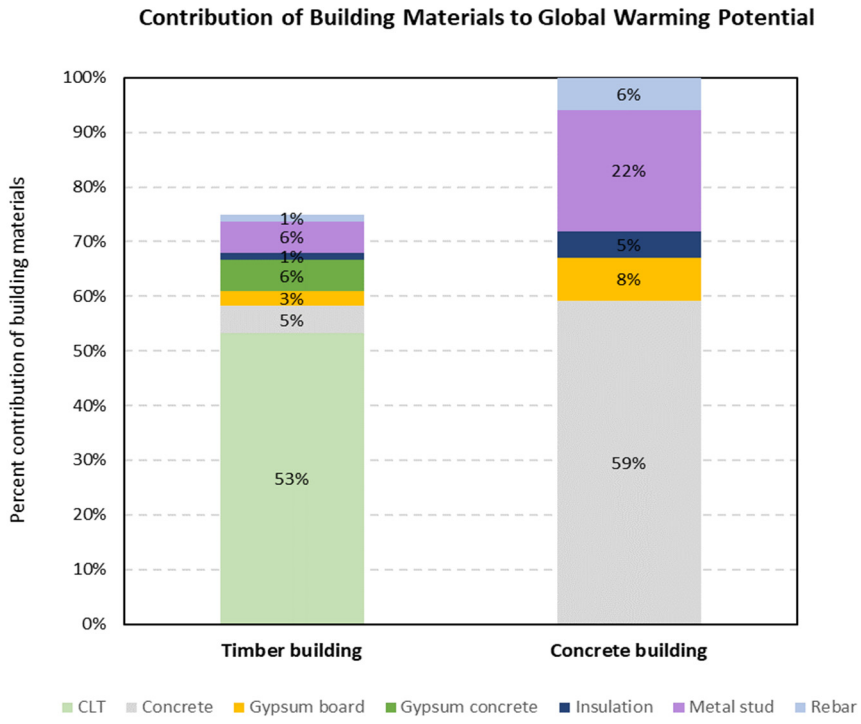

Figure 4. Contribution of building materials to total GWP.

Table 9. Total CO_2 eq. stored in CLT installed in the timber building and GWP from fossil fuel sources and from biogenic sources in the timber building.

CO_2 in Wood Product (t CO_2 eq.)	GWP Fossil (t CO_2 eq.)	CO_2 Biogenic (t CO_2 eq.)	CO_2 Sequestered in Biomass Regeneration (t CO_2 eq.)
1114	780	437	1243

4. Discussion

The results of this study suggest that the mass timber building has a lower global warming impact than the concrete building in all life cycle stages evaluated in this study (modules A1–A5), despite the longer traveling distance required for the raw materials used to produce CLT. This is the result of the lower amount of materials required in the timber building for each m^2 of floor area to achieve the same functionality. However, the actual materials required can vary significantly depending on the purpose, location, and design of the buildings.

CLT contributed the highest global warming impact among all materials used in the timber building in module A4. This could be attributed to the longer traveling distance

required to transport CLT to the building site, given that there are very few CLT manufacturing facilities in China. As part of the effort to restore forest coverage and ecological balance, China has launched a series of forest management programs since 1998 that led to a significant decrease in commercial harvesting [42]. Because of these strict restrictions, many Chinese manufacturers have relied on imported lumber and China has become a significant consumer in the global wood product trade market. The transportation distances of lumber and CLT considered in several U.S. case studies are a lot shorter than those presented in this study. On average, the evaluated transportation distance of lumber from sawmills to the CLT manufacturing facility is approximately 250 km by truck in the U.S. [5,43], whereas the distance evaluated in this study was over 20,000 km and involved multiple modes of transport (e.g., truck, train, and ship) because the lumber was sourced from Europe.

Longer transportation distances of the raw material can post significant environmental and economic burdens and undermine the potential of using wood products. However, using locally sourced wood would require changes in forest management policies. In recent years, China's forest coverage has increased due to afforestation and logging regulation efforts. Forest lands accounted for 22.2% of the total land area in 2015, compared to 20.4% in 2008 [7]. An increase in secondary forest lands may motivate policy makers to implement new forest management strategies that allow more commercial logging activities. With changes in forest management policies, along with the promotion of low-carbon alternative building materials, mass timber may play a role in reducing the environmental impact of the construction sector in China.

As a wood product, mass timber has the ability to store carbon and delay emissions to the atmosphere. As shown in Table 9, CLT in the timber building can store 1114 t CO_2 eq., which is more than the amount of CO_2 eq. released during its production stage (i.e., 780 t CO_2 eq.). Around 437 t CO_2 eq. was considered biogenic, which was assumed to not contribute to global warming since emission released from wood products is assumed to be balanced by carbon sequestration from new generations of trees. This logic is based on the assumption that the woods are harvested from sustainable sources. Under sustainable forest management scenarios, this carbon storage can help offset the greenhouse gas emitted during the building's life cycle stages [3]. In this case, 1243 t CO_2 eq. can be sequestered in the trees planted to replace the ones harvested for producing the CLT panels used in the timber building.

The U.S. recently adopted the latest 2021 International Building Code (IBC) and allowed mass timber to be used in buildings up to 18 stories high, which created more opportunities for tall wood buildings in the construction sector. Due to higher population density in urban settings, high-rise residential buildings are very common in China, and allowing the use of mass timber in taller buildings will help make mass timber a more competitive option as an alternative building material. However, given that research on mass timber buildings is still at a relatively early stage in China, more extensive work may be required before the changes in the building code can be adopted in China.

It should be noted that although all data used for the LCA model were considered appropriate for China, region-specific data within the country may be required to improve the accuracy of the model. For instance, road conditions and access to building materials can vary significantly depending on the region. Furthermore, the use phase and end-of-life phase of buildings were not included in this study. The inclusion of these life cycle phases would provide a more complete picture of the potential impacts of using mass timber in the building sector.

5. Conclusions

The timber building achieved better environmental performance in several impact categories. A 25% reduction in GWP was achieved in the timber building compared to the baseline concrete building. The timber building did not perform as well in some impact categories, such as AP and SFP, which could be associated with the longer transportation distance required for CLT. This study applied data appropriate for Chinese buildings

and identified key aspects associated with using mass timber as a building material. The environmental performance of timber buildings can be further improved by local sourcing, enhanced logistics, and manufacturing optimizations. The use of mass timber will require public awareness and policies that encourage the adoption of alternative building materials.

The two buildings evaluated in this case study are both eight-story residential buildings, and thus future research should be conducted under different geographical regions and with various building types. Nonetheless, the components described in this study (e.g., CLT manufacturing, building design, and energy consumption) are applicable for other types of buildings. Data and outcomes associated with this study can be applied in future studies for investigating the impacts of using mass timber in various building types appropriate for China.

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