CARBON FOOTPRINT LIFE CYCLE ASSESSMENT OF MODULAR WOODEN CONSTRUCTION

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ABSTRACT

Due to the crisis of global warming, the urban development strategy of low-carbon cities has been consistently proposed. The strategy of energy conservation and carbon reduction has become a significant international effort to quantify environmental issues. The construction industries in many countries are predominantly reliant on conventional construction methods and processes characterized by high energy consumption and carbon emissions. This heavy reliance on steel and concrete has resulted in the depletion of land resources and incalculable environmental costs. Among these methods, reinforced concrete (RC) structures constitute the highest proportion. To mitigate the environment impacts caused by RC structures, the adoption of modular timber building systems as a design solution for lightweight buildings proves to be an effective and prudent strategy. The modules building unit created using timber construction offer benefits such as low embodied energy, carbon storage, shorter erection periods, low waste generation, and improved labour productivity. Consequently, modular timber building systems have the potential to be developed as affordable and high-quality building systems. This study uses the life cycle assessment tool to monitor the environmental impacts of modular timber construction systems during the raw material production and construction stages. The main research objectives are as follows: (1) Conduct a carbon inventory analysis of modular timber construction; (2) Estimate the carbon footprint of the production process for modular timber construction; and (3) Estimate the carbon footprint during the construction stage of modular timber construction. The results will be concluded in different stages as follows: (1) material production stage; (2) construction stage; and (3) net carbon emissions of modular wooden building, and will be compared to the existing related cases as well. The findings of this study will contribute to the sustainable development of construction industry in the future.
Keywords: modular building, timber structure, life cycle assessment, carbon footprint.

1 INTRODUCTION

A large percentage of domestic construction industry tends to adopt traditional methods and processes that are highly energy-intensive and have high carbon emissions. This has resulted in slow labour force improvement and a long-term reliance on steel and concrete, which underestimate the environmental costs. These practices lead to the depletion of land resources and the generation of difficult-to-estimate external costs. Moreover, high-quality construction is often tied to land development, resulting in high housing prices in emerging urban areas and difficulties in renovating buildings in older city areas, exacerbating disparities in construction quality. This is not only the case in Taiwan but also a challenge faced by ASEAN countries undergoing rapid economic development.

Since the 921 Earthquake in 1999, Taiwan has actively pursued green building practices suitable for sustainable development. Currently, lightweight steel structures and timber structures are the two main building materials promoted. Therefore, this study will use lightweight steel structures and timber structures as examples to explore the environmental impacts of building materials throughout their life cycle using life cycle assessment (LCA) techniques. The findings aim to provide references for future development of ‘green building materials’ in Taiwan.

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2 RESEARCH OBJECTIVES

The objective of this study is to develop a modular timber structural system framework through case analysis and comparison, based on the research findings of the Master's programme entitled 'Research on Modular System Construction for Open Timber Residential Buildings' by Guo Chengjing in 2019. Building upon the literature review results, the study aims to establish the architectural functionality and create a standardized spatial layout. By incorporating the design and structural analysis results of the modular timber structural system, the study calculates the carbon footprint of the entire life cycle of the system, including the carbon footprint of the manufacturing process and the construction process. The ultimate goal is to achieve a zero-energy residential system. The primary research objectives of this study on the life cycle carbon footprint assessment are as follows: (1) carbon inventory analysis of the modular timber structure; (2) calculation of the carbon footprint of the manufacturing process of the modular timber structure; and (3) calculation of the carbon footprint of the construction process of the modular timber structure.

In Taiwan, the promoted green building label system mainly focus on energy efficiency during the operational phase of the building life cycle, but there is still reliance primarily on high-energy and high-carbon-emitting materials such as steel and concrete, without considering the overall life cycle processes or embodied energy. Most existing research mainly focuses on carbon reduction design after the completion of buildings, with relatively little assessment conducted during the pre-completion stage. Therefore, this study aims to assess the carbon footprint of the production and construction stages of building materials.

3 RESEARCH METHODOLOGY

This study employs a literature review approach to explore relevant literature on life cycle, carbon footprint, and modular construction. Building upon the research findings of Guo Chengjing's Master's research mentioned above, the study utilizes SimaPro9.0, an LCA software, to calculate the life cycle carbon footprint of the modular timber structural system. The literature review method is utilized to examine existing literature related to life cycle, carbon footprint, and modular construction.

4 LITERATURE REVIEW

This study comprehensively reviews and summarizes relevant research on LCA conducted both domestically and internationally. The types, structures, and results of each study are integrated and presented in Tables 1 and 2. These tables provide reference data for the conclusions of this study.

After consolidating the data results of the same research stages from Table 1 and Table 2, it can be observed that the carbon dioxide emissions ranges from approximately 100 to 210 kg/m^2. This value can be compared with the carbon dioxide emissions obtained in this study to further examine the reasons for the differences between the two.

5 COMPOSITION OF MODULAR WOOD CONSTRUCTION SYSTEM

5.1 Primary structural system

The primary structural system is a frame-type structure system, and domestically produced cedar wood is used to construct the column and beam components. The column components have a cross-sectional dimension of 6×6 inches, which are assembled by bonding three pieces of wood with dimensions of 2×6 inches, 3×6 inches, and 2×6 inches. Metal connectors are then attached to friction-fit the metal connectors with the wooden columns (Fig. 1). The beam

Table 1: Domestic LCA research.

Researcher	Building type	Construction method	Research findings
[1]	High-rise	Steel frame structure, reinforced concrete (RC)	Based on a 50 year building lifespan, the highest energy consumption in steel frame structures occurs during the materials production stage, while the highest energy consumption in RC structures occurs during the construction phase. The least energy-intensive stage in the building lifecycle is the disposal of waste materials.
[2]	Frame structure (Span: 20 m, height: 6 m)	Wood Steel RC	Among the different construction materials, RC structures have the highest CO_2 emissions, followed by steel structures, and the lowest emissions are associated with wood structures. In terms of energy consumption, RC structures have the highest energy demand, followed by steel structures, and the lowest energy consumption is observed in wood structures.
[2]	Framed structure	(Span 20 m, height 6 m)	Comparing a frame structure built in wood, steel and RC respectively. The result shows RC structures have the highest CO_2 emissions, followed by steel structures, and wood structures the least. In terms of energy consumption, RC structures have the highest energy consumption, followed by steel structures, and wood structures have the lowest.
[3]	Residential	Cross-laminated timber (CLT)	In the production stage of building materials, the energy consumption of RC is 30,357 MJ, and the carbon dioxide emission is 61891.34 kg; the energy consumption of CLT is 27,609 MJ, and the carbon dioxide emission is −4354.02 kg, and the carbon emission difference between them is 66,245.36 kg. During the construction phase, the construction energy consumption per square meter of floor area of CLT wood structure buildings is approximately 40.9 kWh/m^2 less than that of RC buildings.
[4]	Residential	Wood, steel, RC	In the material production stage, the energy consumption for RC is 859,444 MJ, while for RC mixed with wood structures, it is 163,296 MJ. The corresponding CO_2 emissions are 93,890 kg for RC and 41,673 kg for RC mixed with wood structures.
[5]	Residential complex	Wood, RC	Due to the carbon sequestration property of wood, compared to RC structures with the same design parameters, wood structures have reduced material production stage emissions by approximately 608 kgCO_2-eq/m^2. Over the life cycle, wood structures can reduce emissions by 305 kgCO_2-eq/m^2 and have an energy surplus of approximately 75 MJ/m^2, leading to a total energy surplus of approximately 177 MJ/m^2 over the life cycle.
[6]	Residential	Wood, steel, RC	Wood structures, compared to RC structures, are the optimal choice in terms of low pollution and low carbon emissions in both material manufacturing and construction phases. Light steel structures fall between RC and wood structures in terms of pollution and carbon emissions.

Table 2: International LCA studies.

Researcher	Building type	Building structure	Research findings
[7]	(Residential)	(Wood)	Wood structures exhibit lower energy consumption compared to steel and concrete structures. In the LCA system boundary category of 'excluding energy recovery utilization, excluding wood material energy', the difference in global warming potential (GWP) in terms of carbon dioxide equivalent (CO_2e) ranges from 50 to 200 kg/m^2. In the boundary category of 'including energy recovery utilization, excluding wood material energy', the GWP difference ranges from 200 to 300 kg/m^2.
[8]	(Residential)	(RC)	The embodied energy of building materials is 187.2 MJ/m^2/yr. Assuming a building lifespan of 50 years, the operational energy is 47.44 MJ/m^2/year, accounting for only 25.3% of the former.
[9]	(Residential)	CLT	CLT buildings have an estimated energy consumption and carbon emissions that are 9.9% and 13.2% lower, respectively than RC buildings. This indicates that CLT has better energy-saving potential compared to RC in cold regions of China. Although the material cost of high-rise buildings is higher, both RC and CLT high-rise residential buildings demonstrate better energy efficiency than low-rise and mid-rise residential buildings in cold regions of China.
[10]	(Residential)	(Wood)	The adoption of prefabricated wood construction in Quebec resulted in a reduction of carbon dioxide emissions by up to 25% per square meter of building area compared to traditional RC buildings.
[11]	(Sports arena)	(Wood + steel)	The carbon footprint of mixed structure (steel + wood) is 1,081 kgCO_2-eq/m^2, while that of full steel structure is 1,828 kgCO_2-eq/m^2. The carbon footprint is lowest for full wood structure, at approximately 527 kgCO_2-eq/m^2.
[12]	(Residential)	–	The relative importance of energy use with respect to embodied energy is increasing, with energy use in a standard household accounting for approximately 10%–12% of the total energy use, while energy-efficient homes account for 36%–46%.
[13]	(Residential)	(Wood)	The two LCA tools show significant differences in estimation across different impact categories, with one of the factors contributing to the differences being the reference country. This is particularly associated with the reference country's power generation structure.

components have two cross-sectional dimensions. One is the 6×10 inch floor beam, which is formed by bonding three pieces of wood with dimensions of 2×10 inches, 3×10 inches, and 2×10 inches. The other is the 6×6 inch ceiling beam, which is formed by bonding three pieces of wood with dimensions of 2×6 inches, 3×6 inches, and 2×6 inches. Metal connectors are attached to all beam components and friction-fitted with the wooden columns. Additionally, wooden tendons are bonded to both sides of all beams to act as support beams. Finally, the column and beam components are connected using T-shaped (Fig. 2) and L-shaped (Fig. 3) metal fittings, which are secured with bolts to form a complete frame structure.

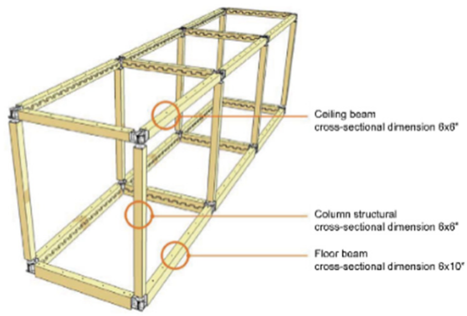

Figure 1: Wooden structural frame.

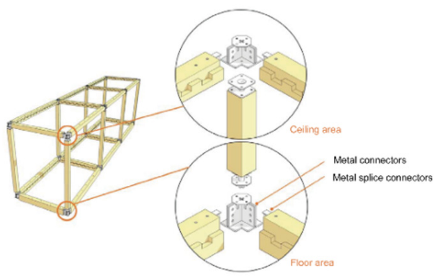

Figure 2: L-type connection.

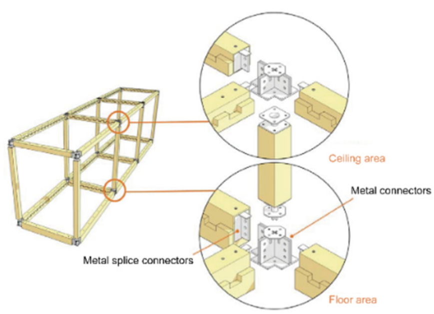

Figure 3: T-type connection.

The foundation consists of precast concrete footings and foundation columns. The connection method involves aligning pre-drilled holes in the concrete blocks with embedded steel bars on the other end. Once positioned, concrete is poured into the openings to solidify the connection (Fig. 4).

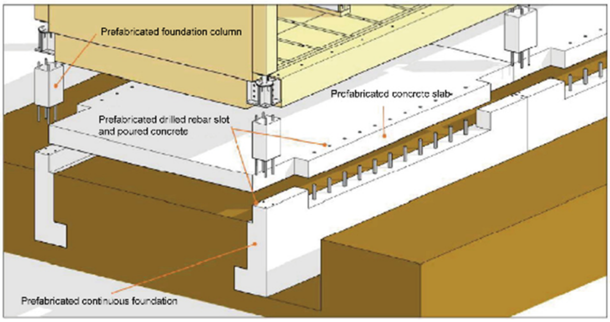

Figure 4: Precast concrete foundation.

5.2 Substructure system: ceilings, floors, partition walls, exterior walls

The substructure system also utilizes domestically sourced spruce timber as the material for its components. The ceilings, floors, and partition walls employ a framed construction method. The partition walls consist of 2×6 inch framed standard partition walls and 2×8 inch framed column-to-column partition walls. The exterior walls are constructed using CLT panels with a thickness of 140 mm to resist lateral forces. At the junctions, the ‘partition walls to exterior walls’ interface adopts a ‘metal-to-metal’ connection, while the ‘ceilings to floors’ interface adopts a ‘wood-to-wood’ connection. Embedded connections are employed to reduce the use of connecting metal elements. The floor elements are constructed using the 2×10 inch stud framed method. These floor elements are securely fixed onto the beams of the main structural system using a tongue-and-groove joint. All floor panels are designed to be removable, allowing easy access for maintenance of pipelines and utilities. A waterproofing layer is installed on top of the floor panels (Fig. 5).

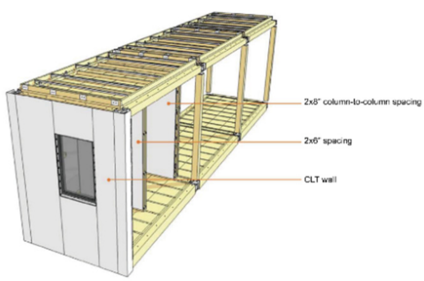

Figure 5: Modular structure’s skin and partitions.

The ceiling elements are constructed using the 2×6 inch stud framed method. Similar to the floor elements, the ceiling elements are fixed onto the beams of the main structural system

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using a tongue-and-groove joint. All ceiling panels are also designed to be removable, facilitating convenient access for maintenance of pipelines and utilities.

The roof adopts a single-slope roof design. The cross-section dimensions of the wooden truss module are 2×4 inches, with a thickness of 14 mm. There are two types of wooden truss lengths: 10.5 m for the trusses located at the centre service core (total of three trusses) and 9.2 m for the trusses on the left and right sides of the centre service core (total of ten trusses, five on each side). Therefore, there are a total of thirteen wooden trusses, with each truss spanning approximately 2.3 m and positioned at the intersection axis of the space modules. The wooden trusses are covered with a 12 mm waterproof layer and topped with a 2 mm gypsum board as the outermost layer. The roof overhangs by 160 cm (Fig. 6).

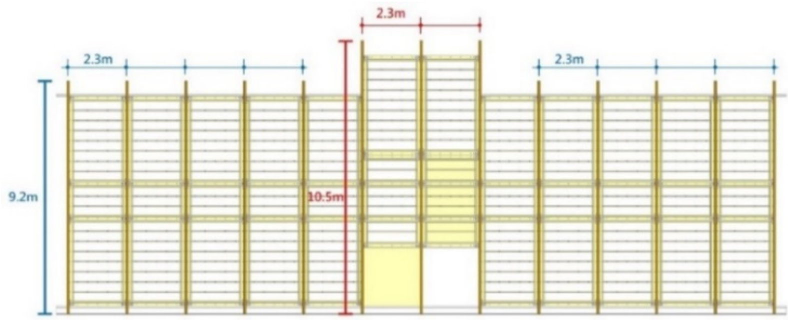

Figure 6: Single-slope roof.

5.3 Modular residential space configuration

Vertical service core and corridors: The designed modular system can be extended into diverse configurations for living units. Thus, the interfaces of every modular unit are important. The vertical service core module (Fig. 7) consists of three parts: elevator, staircase, and stairwell. In the composition of a single floor, the 'elevator and stairwell' are integrated, while the 'staircase' is a separate entity. Additionally, all module spaces comply with the dimensions required for accessibility: indoor width of 1.2 m and outdoor width of 1.6 m.

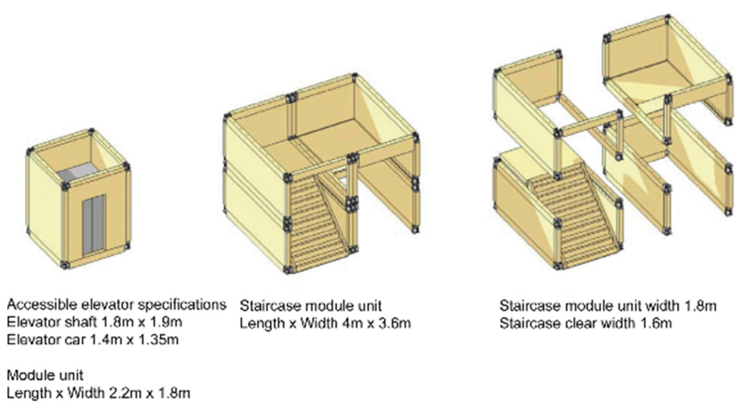

Figure 7: Vertical service units.

6 STUDY OBJECTIVES AND SCOPE

6.1 Scope definition

This study primarily focuses on assessing the carbon footprint of the production and construction stages of modular wood construction homes throughout their entire life cycle. The production stage includes processes from raw material extraction to the manufacturing of finished products in the processing plant. The construction stage includes energy consumption during construction. The study only considers carbon emissions at these stages and does not account for transportation.

6.2 Residential space types

The residential living arrangements include single-person households, couples living together, and small families consisting of couples and children. The modular spatial units are categorized based on their functional spaces, including bedrooms, bathrooms, living rooms, kitchens, and dining areas. For this study, the residential composition consists of four single-person households, one couple household, and one small family household.

6.3 Carbon emission inventory analysis

Prior to assessing the carbon emissions during the production phase of building materials, a fundamental carbon inventory analysis is conducted in accordance with the ISO 14040 series standards. In this study, the LCA software SimaPro is utilized to classify all building materials used in modular timber construction into four categories: wood materials, metal materials, cement materials, and other materials. A carbon emission inventory analysis is then performed for each category during the production phase, using data from the Ecoinvent 3 database and the IPCC 2013 GWP 100a method for calculation.

7 MATERIAL DESCRIPTION

7.1 Wood materials

The modular timber construction of the housing utilizes various wood materials, including glued laminated timber (GLT), CLT, and plywood. These materials are applied to different components/modules based on their specific characteristics and dimensions. The total volume of all components is calculated and then entered into the LCA software to determine the unit carbon emissions for the wood materials category.

7.2 Metal materials

In the modular wood construction of residential buildings, the main structural system is a framed system. Apart from the reinforcing bars used in the foundation, most of the metal materials used are metal connectors for connecting the wooden structures. The following summarizes the total weight of the reinforcing rebars, metal connectors, door and window hardware, and elevator boxes. The weight of all components is calculated and then the materials are input into the LCA system database to calculate the unit carbon emissions of metal materials.

7.3 Cement

The foundation utilizes precast concrete blocks at the factory, which are placed and connected on-site after excavating and levelling the earthwork. The concrete foundation consists of continuous footings and foundation columns. The volume and quantity of concrete foundation components are organized, and the total volume of all components is calculated. Subsequently, the material data is inputted into the LCA system database to calculate the unit carbon dioxide emissions of cement-based building materials.

7.4 Other materials

In addition to the three aforementioned building material categories, other materials used include glass, glass fibre, sound insulation cotton, SPC waterproof flooring, PMMA waterproof panels, calcium silicate boards, and gypsum boards. The total weight of all components is calculated and summed up. Subsequently, the material data is inputted into the LCA system database to calculate the unit carbon dioxide emissions of metal materials.

8 CARBON FOOTPRINT ASSESSMENT IN THE PRODUCTION STAGE

8.1 Total material quantities

To assess the carbon footprint in the production stage, the total quantities of all materials used in the modular wood structure, along with the unit material carbon emissions obtained from the LCA system analysis can be mutually incorporated into corresponding items for carbon footprint evaluation calculations.

8.2 Carbon footprint assessment in the production stage

Taking GLT as example, through system analysis and calculation, it is determined that 1 m^3 of GLT generates 110 $kgCO_2$ eq in terms of carbon dioxide equivalent emissions. In the case of modular timber-framed houses, GLT utilizes approximately 139.78 m^3. Multiplying 139.78 m^3 by 110 $kgCO_2$ eq yields a carbon footprint of approximately 15,375.8 $kgCO_2$ eq in the production stage for GLT. The carbon footprints of other building materials can be calculated using the same method (see Table 3).

8.3 Carbon footprint assessment of the construction stage

In calculating the carbon emissions during the construction stage of modular timber-framed houses, this study focuses solely on the assessment of construction activities. The following items are not included in the assessment:

- Energy consumption for material transportation: Since the assessment scope of this study is limited to the carbon emissions from construction activities, changes in resource allocation or construction processes generally do not affect the amount of materials used. Therefore, the transportation of materials is not considered to increase during construction, and the carbon emissions resulting from material transportation are excluded.
- Construction site workers: In this study, the carbon emissions from construction activities are calculated, specifically assessing the energy consumption of machinery.

Table 3: Carbon footprint of materials in the production stage.

Material	Quantity	Unit	Database material	Unit carbon footprint	Carbon footprint ($kg\ CO_2$ eq)
GLT	139.78	m^3	Sawn wood, softwood, dried (u=10%)	110	15,375.80
CLT	118.153	m^3	GLT for indoor use	238	28,120.41
Plywood	6.272	m^3	Plywood, for indoor use	394	2,471.17
Reinforcing steel	1136.68	kg	Reinforcing steel	2.35	2,671.20
Hot-dip galvanized steel	12661.97	kg	Steel, low-alloyed	1.81	22,918.17
Copper	3.532	kg	Copper	8.32	29.39
Aluminium alloy	0.1188	kg	Aluminium, cast alloy	6.39	0.76
Zinc alloy	0.2178	kg	Steel, low-alloyed	1.81	0.39
Stainless steel	10392.93	kg	Iron-nickel-chromium	4.71	48,950.70
Concrete	55.0672	m^3	Concrete, sole plate and foundation	362	19,934.33
Low-E glass	1976	kg	Flat glass, coated	1.2	2,371.20
Glass fibre insulation	109.76	kg	Glass fibre	2.52	276.60
SPC waterproof flooring	3294	kg	Polycarbonate	8.24	27,142.56
PMMA waterproof panels	1178.82	kg	Polymethyl methacrylate, sheet	8.79	10,361.83
Calcium silicate board	6361.6	kg	Limestone, crushed, for mill	0.00285	18.13
Gypsum board	12106.8	kg	Cover plaster, mineral	0.154	1,864.45
Total carbon footprint					182,507.09

Modular timber-framed houses are prefabricated in factories and installed using hoisting operations during construction. Compared to traditional construction methods, these operations save significant human resources. Therefore, the carbon emissions from on-site construction workers are excluded.

Total construction energy consumption: this study assumes a construction period of 3 days for modular timber-framed houses, with 8 hours of work per day. A 150 kVA generator operates at full load for 7 hours and standby for 1 hour. The total energy consumption from fuel-powered and electricity-powered equipment during construction is obtained. The total energy consumption is then multiplied by the unit carbon dioxide emissions of diesel fuel and electricity to determine the carbon footprint of the construction stage.

To assess the carbon footprint of the construction stage, the total fuel consumption and total electricity consumption are multiplied by the corresponding carbon dioxide emission factors for fuel combustion and electricity usage. This enables the calculation of carbon emissions for each respective item.

8.4 Analysis results for total carbon emissions

$$\text{Carbon storage per unit area of wood} = (1/2) \times (\text{Carbon emission per unit area of wood}) \tag{1}$$

Carbon emission per unit area of wood = (Total wood volume) × (wood density)/(Total floor area) = (264.205 m^3 × 450 kg/m^3)/703.75 m^2 = 168.94 kg CO_2/m^2. Hence, from eqn (1), wood carbon storage per unit area = 84.47 kg CO_2/m^2.

$$\text{Carbon emission per unit area} = \text{Total carbon emission}/\text{Total floor area} \tag{2}$$

where total carbon emission = carbon emission in production stage + carbon emission in construction stage = 182,507.09 kg CO_2 + 10,988.95 kg CO_2 = 193,496.04 kg CO_2. Hence, carbon emission per unit area = 193,496.04 kg CO_2/703.75 m^2 = 274.95 kg CO_2/m^2.

$$\text{Net carbon emission per unit area} = \text{carbon emission per unit area} - \text{wood carbon storage per unit area} \tag{3}$$

Hence, net carbon emission per unit area = 190.48 kg/m^2.

9 CONCLUSIONS

This study focused on the life cycle of modular wood construction systems and assessed the carbon emissions generated during the material production and construction stages. Based on the statistical data obtained from these two stages, the following conclusions are presented:

(1) Material production stage: the calculated carbon emissions in the material production stage for modular wood construction homes are as follows: Structural system (GLT columns and beams, panel walls, GLT roof trusses, CLT exterior walls, and floors) account for 55,698.47 kg CO_2 eq (57%); Galvanized iron components used to connect all modular units contribute 22,918.17 kg CO_2 eq (23%); Prefabricated continuous foundations (rebar + concrete) emit 19,934.33 kg CO_2 eq (20%).

(2) Construction stage: The carbon emissions from energy consumption during the construction stage were calculated based on a 3 day construction period. The carbon emissions from fuel combustion amount to 3,150.79 kg CO_2 eq (7%), while the carbon

emissions from electricity usage amount to 7,838.16 kg CO_2 eq (93%). These results indicate that electricity consumption has the highest carbon emissions during the construction stage.

(3) Net carbon emissions of modular wood construction: The carbon storage per unit area of wood in modular wood construction homes is 84.47 kg/m^2, and the carbon emissions per unit area are 274.95 kg/m^2. Consequently, the net carbon emissions per unit area for modular wood construction are calculated to be 190.48 kg/m^2.

Based on the research findings and process, the following recommendations are proposed to guide future studies and promote the practical implementation of modular wood construction systems as socially applicable products:

(1) Scope and conditions of definition: to enhance the accuracy of carbon emission calculations, future studies should evaluate the complete life cycle of modular wood construction, including transportation energy consumption and carbon emissions from on-site construction personnel, in addition to the material production and construction stages assessed in this study.
(2) Importance of material selection and construction methods: while there is a global focus on promoting the development of green buildings, with an emphasis on energy efficiency and sustainability during the operational stage of the life cycle, the overall life cycle process is often overlooked. Green building designs typically consider only specific stages, resulting in limited benefits. By selecting low-carbon wood during the material production stage and utilizing the simplified construction process enabled by modular design, a more comprehensive perspective on sustainable construction can be achieved.
(3) Optimization of modular wood construction design: the carbon emission data obtained in this study were relatively higher compared to the values presented in the literature review conducted in Section 2.3. Upon review, it was found that the excessive use of metal components at junctions in the designed modular wood construction system contributed to the overall increase in carbon emissions. To reduce carbon emissions, it is recommended to optimize the system design by minimizing the use of connecting metal components.

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