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Comparative life cycle assessment of a reinforced concrete residential building with equivalent cross laminated timber alternatives in China

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ABSTRACT

With the development of mass timber, cross laminated timber (CLT) has gradually become a sustainable alternative to conventional building materials to alleviate the increasing energy consumption and carbon emissions by the building sector. This study aims to explore the life cycle greenhouse gas emissions (LCGHGE) and life cycle primary energy (LCPE) of three high-rise residential buildings in the cold region of China through a life cycle assessment approach. The three buildings are conventional reinforced concrete (RC), CLT and hybrid CLT buildings. The results show that CLT and hybrid CLT buildings produce 15.00% and 10.77% lower LCGHGE, respectively, compared to the RC building within a 50-year service life. A clear difference in greenhouse gas (GHG) emissions and primary energy (PE) in the product and construction stages is visible, with 46.52% and 37.24% of embodied GHG emissions reduced in CLT and hybrid CLT buildings, respectively, compared to the RC building. In the operational stage, RC building has lower PE and GHG emissions to CLT alternatives. The thermal mass effect has led to a 2.25% and 2.12% PE increase for space heating and cooling in CLT and hybrid CLT buildings, respectively, compared to the RC building. For the End-of-Life (EoL) stage, CLT demonstrates great recycling potential and biomass residues. The sensitivity analysis shows that the design of the low U-value of the building envelope and high-efficiency energy systems has a significant relationship with energy reduction during the operational phase of the three buildings, magnifying the impacts of the initial and EoL stages.

1. Introduction

According to the International Energy Agency, the building sector has become a major component of global energy consumption and greenhouse gas (GHG) emissions, accounting for more than one-third of global final energy consumption and contributing to nearly 40% of total carbon emissions [1]. Moreover, the number of houses and infrastructure are expected to increase in North America, China and Europe over the next decade [2]. In developing countries, the demand for energy in the building industry continues to increase with urbanization and population growth [3]. Therefore, the building sector has become an urgent and essential component of mitigating global warming and achieving sustainability.

As the world's largest coal consumer, China's policies to reduce coal and GHG emissions in households play a vital role in

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mitigating climate impacts [4]. In 2018, building energy consumption in China accounted for 46.5% of the total energy consumption, whereas building carbon emissions contributed to 51.3% of the national carbon emissions [5]. China's urbanization rate is expected to reach 70% by 2030, meaning that 1.02 billion people will live in cities [6]. This will inevitably lead to a sharp increase in the number of high-rise residential buildings in China, and it is foreseeable that GHG emissions and energy consumption of such buildings will increase significantly.

Wood is considered a sustainable material, and it has been reported that a 17% increase in wood usage leads to a 20% reduction in carbon emissions from building materials [7], promoting the development of the wood industry to mitigate global warming. Widely used in Europe for more than 20 years, engineered wood products have attracted increasing attention for residential and non-residential construction in several countries [8]. Cross laminated timber (CLT) is one of the most common types of mass timber among engineered wood products. CLT consists of an uneven number of layers of timber boards (usually 3, 5, or 7 layers), with adjacent layers glued to each other in orthogonal directions [9]. Easy to handle construction, high-level prefabrication, good strength and thermal performance make CLT an alternative to reinforced concrete (RC) [8,10].

With the advancement of engineered wood, many countries have revised regulations for wood-structured buildings. In Australia, the National Construction Code 2019 allows fire-proof timber buildings, including traditional lightweight timber framing and mass timber construction, of up to 25 m [11]. Sweden repealed legislation that prohibited multi-storey wood frame buildings in 1994 [12,13]. In the United States, the 2021 International Building Code (IBC) allows the mass timber construction of up to 18 storeys [14]. The Ministry of Housing and Urban-Rural Development of the People's Republic of China issued a new regulation in 2017 to promote the development of mass timber construction [15]. The regulation amended the maximum structural height limit of mass timber construction in non-seismic areas to 12 stories or 40 m, and that of the hybrid CLT building with an RC core to 18 stories or 56 m.

This study aims to compare the life cycle greenhouse gas emissions (LCGHGE) and life cycle primary energy (LCPE) of high-rise RC, CLT, and hybrid CLT buildings in Tianjin, China, as well as investigate the impact of the parameters on LCGHGE and LCPE. The life cycle assessment (LCA) results of the three buildings can be used to support government regulations and promote the development of mass timber construction, ultimately reducing the LCGHGE and LCPE of the building sector in China.

2. Literature review

Life cycle assessment has been applied in the building sector to determine the environmental impacts of buildings since 1990 [16]. The boundary of the LCA often consists of three main stages: product and construction (P&C), operational, and End-of-Life (EoL) stages based on ISO 14040 and EN 15978 standards [17,18]. With the emergence and development of CLT worldwide, LCA studies that focus on the environmental impacts of mass timber in the building sector (Table 1) are increasing each year [19,20].

It should be emphasized that the system boundaries and data are of vital importance to the results of the LCA [61]. In cradle to grave research, a couple of studies compare the building structural materials such as CLT, RC, and steel [13,21–25,32]. For instance, Jayalath et al. [24] found that mid-rise residential CLT buildings emitted 30%, 34%, and 29% less GHG than RC buildings through 50-year LCA in Melbourne, Sydney and Brisbane, respectively. Tettey et al. [33] analyzed the LCPE of RC, CLT, and prefabricated timber modules and showed that CLT produced lower primary energy (PE) and higher biomass residues. Liu et al. [21] found that CLT buildings reduced LCPE and LCGHGE by more than 30% and 40%, respectively, compared to RC mid-rise residential buildings. Moreover, different building typologies, including residences, offices, and stadiums [23,25,32], and energy-efficiency levels of buildings are included in these studies. For instance, Dodoo et al. [13] compared the GHG emissions of the conventional and low-energy versions of three low-rise buildings (CLT, beam-and-column, and prefabricated modules) and found that the low-energy version of the CLT building had the lowest carbon footprint.

Some studies have focused on the cradle to gate stage [39–52]. Nakano et al. [39] provided generic LCA data for CLT production in Japan and recommended the reuse of CLT panels to delay the release of biogenic carbon into the environment. Pierobon et al. [42] showed that two hybrid CLT buildings reduced carbon emissions by an average of 26.5% compared with RC buildings from cradle to gate analysis in the United States. Robertson et al. [44] analyzed the cradle to gate LCA of RC and hybrid mass timber office buildings. Li et al. [45] focused on the embodied energy and carbon of three buildings (RC, RC with timber non-structural elements, and CLT with an RC core).

The operational stage that dominates the environmental impact has also been extensively studied [53,54]. For instance, Guo et al. [53] evaluated heating and cooling energy consumption and carbon emissions of RC and CLT buildings in China's 31 main cities, revealing that CLT buildings result in a 29.4% energy savings and a 24.6% carbon emission reduction compared with RC buildings at the operation stage at the national level. The reuse, recycling, and recovery phases of CLT are often overlooked in LCAs, including reuse and incineration with energy recovery, which are highly related to sustainability [19].

Furthermore, the LCA of building components for mass timber construction has also received attention. D'Amico et al. [56] conducted research on using CLT to replace RC floors, resulting in a 1.5% reduction in annual GHG emissions related to construction. Larivière-Lajoie et al. [60] investigated the environmental impacts of eight wall assemblies, including light-frame construction, lightweight steel framing, CLT, and Glulam, showing that embodied impacts accounted for 40–66% of all environmental impacts.

In summary, studies on the LCA of mass timber construction have increased since the last two decades. The current research focuses on the comparison of the environmental impacts of CLT buildings with different structures such as RC, steel, and light wood frames, most of which focus on cradle to grave and cradle to gate assessments. Moreover, there are studies focusing on CLT in building components. However, to the best of our knowledge, limited research is available on cradle to grave LCA of hybrid CLT buildings. The operational stage accounts for more than 50% of the GHG emissions and 70% of the energy used in conventional buildings [62,63], and the EoL scenario of mass timber demonstrates a great impact on environmental impacts [19]. A comprehensive analysis of the LCA for

Table 1
Overview of the literature on the life cycle assessment of mass timber.

	LCA boundary	Building	LCGHGE	LCE	EP	AP	ODP	SFP	LCC	Others	Region	Building Type	Reference
The whole building	Cradle to grave	CLT/beam-and-column/modular buildings.	•	•							Sweden	residential	[13]
		RC/CLT	•	•							China	residential	[21]
		RC/CLT	•	•							China	residential	[22]
		RC/CLT	•	•							China	Stadium	[23]
		RC/CLT	•	•					•		Australia	residential	[24]
		RC/CLT	•		•	•	•	•		•	United States	mixed-use	[25]
		CLT	•	•	•	•	•		•	•	Spain	residential	[26]
		RC/CLT/Increased bio design	•								Sweden	residential	[27]
		Laminated timber	•	•	•	•	•		•	•	Canada	commercial and residential	[28]
		CLT/GLT	•	•			•		•	•	Malaysia	residential	[29]
		RC/CLT	•		•	•	•			•	Norway	residential	[30]
		GLT	•	•							Sweden	residential	[31]
		GLT/Steel	•	•					•		Norway	airport	[32]
		Precast concrete/CLT/modular buildings		•							Sweden	residential	[33]
		LVL wall with CLT elevator shaft	•	•							Germany	residential	[34]
		RC\CLT\Steel		•					•		Finland	residential	[35]
		Light weight timber/CLT/RC/Autoclaved aerated concrete/Brick/Steel		•							Finland	residential	[36]
		RC/light frame/massive timber (CLT)/beams& column timber/modular timber	•	•							Norway	residential	[37]
		RC/CLT							•		United States	mixed-use office and apartment	[38]
	Cradle to gate	CLT	•		•	•	•		•	•	Japan	/	[39]
		CLT	•	•	•	•	•	•			Canada	/	[40]
		Glulam	•	•	•	•	•	•		•	Canada	/	[41]
		CLT (1 fireproofing & 2 charring design)/RC	•	•	•	•	•	•			United States	commercial	[42]

(*continued on next page*)

Table 1 (*continued*)

	LCA boundary	Building	LCGHGE	LCE	EP	AP	ODP	SFP	LCC	Others	Region	Building Type	Reference
		CLT	•	•	•	•	•	•			United States	office	[43]
		RC/Hybrid mass timber (Glulam frame with concrete core)	•	•	•	•	•	•		•	Canada	office	[44]
		RC/RC and timber non-structural element/CLT with RC core	•	•							Australia	commercial	[45]
		RC/Glulam beam and CLT wall	•								Norway	/	[46]
		Precast concrete/CLT/Light weight timber	•								Finland	/	[47]
		RC/CLT	•								Australia	residential& commercial	[48]
		GLT	•	•	•	•	•	•		•	United States	/	[49]
		RC/CLT	•		•	•	•	•		•	China	residential	[50]
		Precast concrete/Steel/Post-Tension concrete/ CLT	•	•							United States	Parking garages	[51]
		RC/CLT	•								Australia	Commercial/Mixed use	[52]
	Operational	RC&CLT	•	•							China	residential	[53]
		RC&CLT		•							China	office	[54]
	cradle to gate& operational stage	CLT/GLT	•								Norway, Sweden	residential	[55]
Building component	Floor	CLT/Concrete floor	•								Globe	/	[56]
	Floor	Steel-concrete composite floors/Steel-timber composite floors/Steel-timber composite floors with CLT shear walls/RC		•							Australia	office	[57]
	Floor	CLT/Concrete floor	•						•		Sweden	/	[58]
	Wall	CLT/brick wall	•				•			•	Italy	residential	[59]
	Wall	Eight wall assemblies	•		•	•	•			•	Canada	office	[60]

LCGHGE: Life cycle greenhouse gas emissions, LCE: Life cycle energy, EP: Eutrophication potential, AP: Acidification potential, ODP: Ozone depletion potential, SFP: Smog formation potential, LCC: Life cycle cost.

hybrid CLT buildings needs to include the various building life cycle activities. Therefore, it is necessary to determine the cradle to grave LCA of hybrid CLT buildings. The study aims to fill the existing knowledge gap by exploring the LCGHGE and LCPE of high-rise hybrid CLT buildings in Tianjin, China. Mass timber products have recently developed in China as sustainable alternatives to RC. The development of CLT buildings in China is restricted by fire protection regulations. Hybrid CLT structures with RC cores provide advantages in fire protection and structure over CLT buildings and are a feasible way to boost mass timber construction in China. The results of the research could also provide information for decision-making and can be used to support government regulations.

3. Case study buildings and LCA

3.1. Case study buildings

The RC building was modeled based on an existing residential building in Tianjin (latitude 39° 10′ N; longitude 117° 10′ E), a northern coastal metropolis in the cold region of China. Tianjin has a humid continental *Dwa* climate within the Köppen–Geiger climate classification, with hot, humid summers and cold, windy, and dry winters [64]. The RC building was composed of an RC framed structure, RC slabs, and infill walls. The 11-storey residential building was a common type of high-rise building in China and was selected as the prototype for this study.

The redesign of the three buildings referred to the requirements for residential building regulation in Tianjin [65]. The design of mass timber construction referred to the dataholz.eu database, which covers many construction components for engineered wood products [66]. To compare the LCAs, three models were designed with the same functions, layout, height, and size as the ground floor built in the RC (Fig. 1). The insulation in each building was set to a different thickness to meet the same U-value of the envelope in all three buildings, thus making the buildings compared functionally equivalent. Furthermore, structural design was based on existing research to meet the same load conditions [21,24,42,54]. The CLT building replaced the concrete with CLT boards, and the hybrid CLT building was modeled with an RC core and CLT walls and slabs. Although the fire performances of RC and CLT are different, the CLT design should meet the fire resistance rating of 2 h. Table 2 lists the details of the three models. The foundations of CLT and hybrid CLT buildings are redesigned, taking into account that mass timber construction is lighter than RC buildings [58]. The number of piles in the foundation in CLT (i.e., 41) and hybrid CLT buildings (i.e., 43) is less than that of the RC alternative (i.e., 49).

3.2. Life cycle assessment

This study used a process-based approach, which is the conventional methodology for assessing the environmental impacts of each process involved in the system [67]. The scope of this study was within the boundary from cradle to grave to investigate the environmental impacts of three buildings in China, including the P&C, operational, EoL and benefits stages (Fig. 2).

The initial embodied energy and GHG emissions can account for up to 46% of the life cycle environmental impacts in the context of low environmental impacts of the energy mix [60]. The product stage focuses on the main materials, such as structure materials, envelope materials, and building components. The environmental impacts of material transport, building installation, and construction have often not been studied. It should be noted that transportation and construction activities account for 6–8% and 6–9% of the P&C stage, respectively [68]. Thus, the studies included all the modules (A1-A5) in the P&C stage.

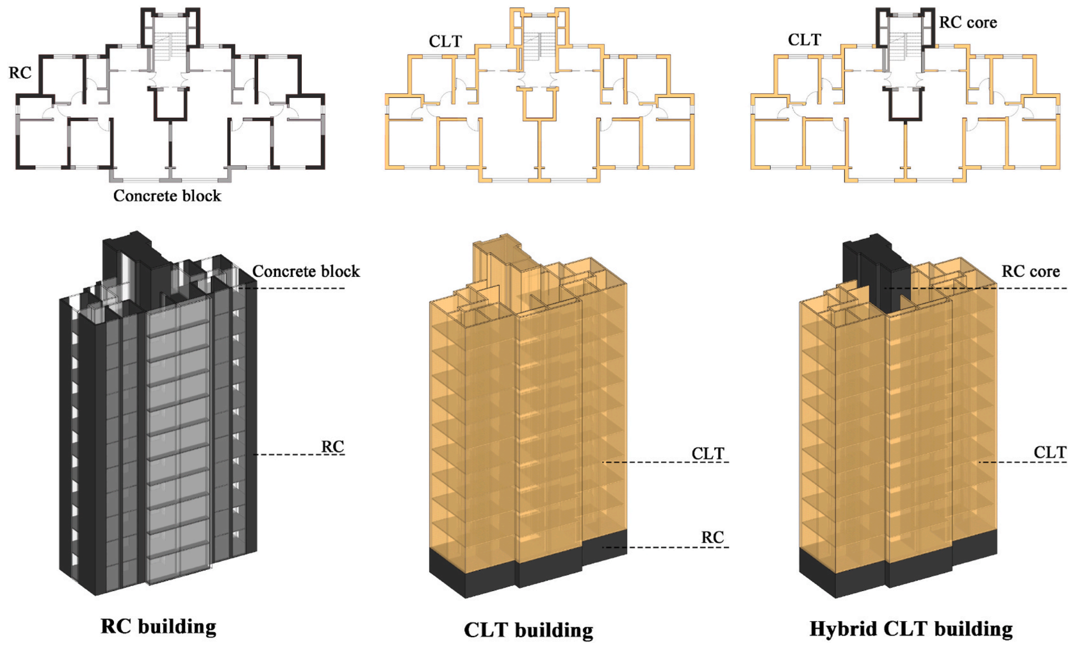
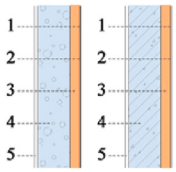
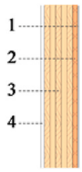
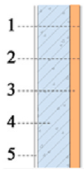
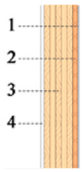
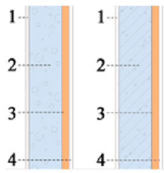
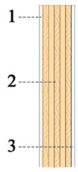
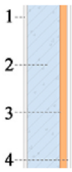
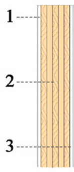
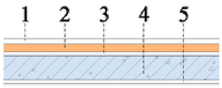
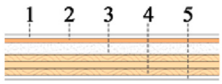
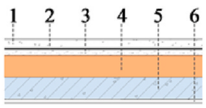
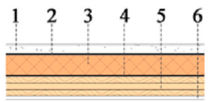


Fig. 1. Case study buildings.

Table 2
Details of RC, CLT, and hybrid CLT building models.

	RC	CLT	Hybrid CLT	
Structure	RC sheer walls	CLT walls	RC core and CLT walls	
Exterior wall	 1, 7 mm outdoor plaster 2, 3 mm cement mortar 3, 70 mm EPS insulation 4, 200 mm RC/concrete block 5, 20 mm gypsum board	 1, 7 mm outdoor plaster 2, 40 mm mineral wool 3, 175 mm CLT 4, 20 mm gypsum board	 1, 7 mm outdoor plaster 2, 3 mm cement mortar 3, 70 mm EPS insulation 4, 200 mm RC/concrete block 5, 20 mm gypsum board	 1, 7 mm outdoor plaster 2, 40 mm mineral wool 3, 175 mm CLT 4, 20 mm gypsum board
U-value (W/m^2 K)	0.396			
Separating Wall	 1, 20 mm gypsum board 2, 100/200 mm RC/concrete block 3, 40 mm EPS insulation 4, 20 mm gypsum board	 1, 20 mm gypsum board 2, 105/175 mm CLT 3, 20 mm gypsum board	 1, 20 mm gypsum board 2, 100/200 mm RC/concrete block 3, 40 mm EPS insulation 4, 20 mm gypsum board	 1, 20 mm gypsum board 2, 105/175 mm CLT 3, 20 mm gypsum board
U-value (W/m^2 K)	0.586			
Floors	 1, 20 mm particle board 2, 40 mm EPS 3, 20 mm cement mortar 4, 120 mm RC 5, 20 mm gypsum board	 1, 20 mm particle board 2, 20 mm mineral wool 3, 60 mm elastic bonded fill 4, 105 mm CLT 5, 20 mm gypsum board		
U-value (W/m^2 K)	0.453			
Roof	 1, 40 mm concrete 20 2, 3 mm water proof material 3, 30 mm cement mortar 4, 100 mm EPS insulation 5, 120 mm RC 6, 20 mm gypsum board	 1, 40 mm concrete 20 2, 3 mm water proof material 3, 90 mm mineral wool 4, 3 mm water proof material 5, 105 mm CLT 6, 20 mm gypsum board		
U-value (W/m^2 K)	0.287			

Note: The ground floor of three buildings is made of RC, not shown in the table.

Product and construction stage					Use stage							End-of-Life stage				Benefits and loads
Raw material supply	Transport	Manufacturing	Transport	Construction installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	Reuse, Recovery, Recycling potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
√	√	√	√	√				√		√		√	√	√		√

Fig. 2. Building life cycle stages according to EN15804 and EN15978.

The operational stage can contribute more than 50% of the GHG emissions and up to 80% of the energy in the LCA [62]. According to EN 15978, the use stage comprises the following modules: B1 Installed products in use, B2 Maintenance, B3 repair, B4 Replacement, B5 Refurbishment, B6 Operational energy use, and B7 Operational water use. B6 consists of heating, cooling, lighting, ventilation, hot water supply, and so on. In China, residential buildings are assumed to operate for a lifespan of 50 years [69]. Replacement (B4), heating and cooling (B6) were considered and analyzed in this study.

The demolition stage is still a process that has not yet occurred and can only be estimated based on assumptions. During the construction and demolition of residential buildings, energy consumption accounts for less than 1% of the total energy consumption [70]. Some studies have calculated that the demolition energy consumption is approximately 90% of the energy consumption in the construction process [21,22,71]. Studies have also calculated energy consumption through the demolition energy of each material [26,72]. In recent years, the recycling, recovery, and reuse of building materials has attracted increasing attention. The conversion of building demolition materials into resources will help reduce carbon emissions, save energy and be environmentally friendly. The use of recycled materials in building construction reduces the building materials' energy consumption by at least 10% [73]. Compared to concrete alternatives, CLT buildings have great potential for recycling and energy reduction [33]. The reuse, recovery and recycling potential (D) is included in the EoL stage.

Three separate LCAs were applied and compared to determine the LCGHGE and LCPE of high-rise buildings, combined with a sensitivity analysis. To perform LCA, the following assumptions were made:

1. CLT was imported from Quebec, Canada, as CLT is in its infancy in China, where the import of mass timber from North America is common.
2. The transportation distance of common building materials, such as concrete, was 40 km, and that of other building materials was 500 km [74].
3. Preliminary factors, such as land use, labor costs, and transportation, were not included because they were highly uncertain and had great variability.
4. The ground floors of the three buildings were all made of RC.
5. The recyclable materials include concrete, steel and wood products [26].
6. The RC door and window frames were made of polyvinyl chloride (PVC), and those of the CLT and hybrid CLT buildings were made of wood.

4. Research method

4.1. Research framework

This study could be divided into four main steps (as shown in Fig. 3): 1) To compare the LCAs of the three buildings, a real 11-storey residential building in Tianjin was chosen as the prototype, and CLT and hybrid CLT alternatives were redesigned based on the RC building and regulations; 2) Three buildings were modeled using *Revit* and *DesignBuilder 4.6*; 3) The environmental impacts in all stages were calculated, and the LCA results for the three buildings were analyzed. Bill of quantities was exported from Revit and prepared for the cradle to gate stage (A1-A3). For the operational stage, the operational energy consumption of space heating and cooling was simulated based on key parameter settings (Table 3) in *Designbuilder*; 4) A sensitivity analysis was adopted to explore the impact of variables and uncertainties in the key parameters. Conclusions and suggestions were provided based on the comparison and sensitivity analysis.

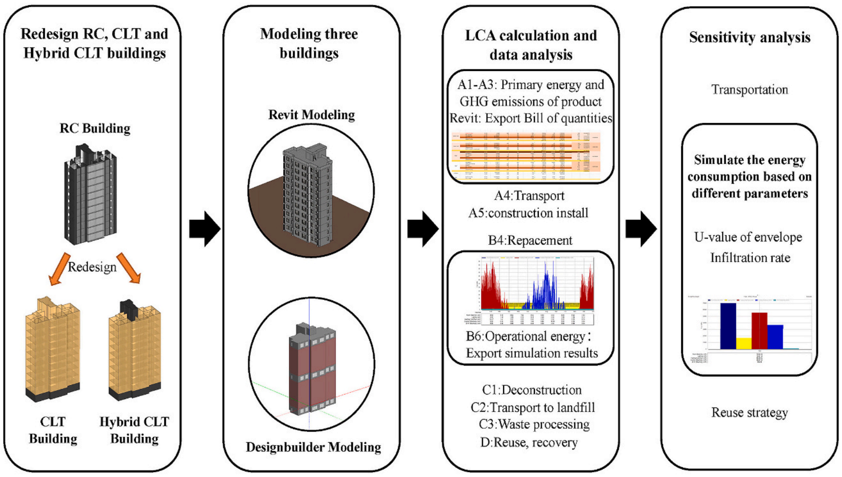


Fig. 3. Flowchart of the research.

Table 3
Key parameter settings in Designbuilder.

Parameter	Value
Building area	2347.5 m^2
Life span of the buildings	50 years
Infiltration rate	0.3 (l/s m2@ 50 Pa)
Natural ventilation	5 ac/h
Heating set point	18 °C (kitchen 15 °C)
Cooling set point	26 °C (kitchen 30 °C)
Seasonal coefficient of performance (COP)	4.5
Heating and cooling area	Living room, kitchen, bedroom, toilet

4.2. Calculation method

When considering the entire life cycle environmental impacts of the building, the LCGHGE was calculated using Eq (1), which included GHG emissions of the product and construction stage ($C_{P\&C}$), operational stage (C_O), and EoL stage (C_E). The LCPE was calculated based on Eq (2).

$$LCGHGE = CP\&C + CO + CE \quad \text{Eq (1)}$$

$$LCPE = EP\&C + EO + EE \quad \text{Eq (2)}$$

GHG emissions ($C_{P\&C}$) and energy consumption ($E_{P\&C}$) related to the product and construction stage include raw material supply (A_1), transport to manufacture (A_2), manufacturing (A_3), transportation of the material to the construction site (A_4), and construction installation (A_5).

The GHG emissions in the product stage were calculated via Eq (3), and the quantities of building materials were accessed from *Revit* where Mi (kg, m^3, …) is the quantity of building material i, and Ci (kg CO_2 -eq/Unit) is the GHG emissions coefficient of material i.

$$CA1 - A3 = \sum_{i=1}^{n} MiCi \quad \text{Eq (3)}$$

The PE in the product stage was similar to the calculation of GHG emissions, as shown in Eq (4), where Mi (kg, m3, …) is the quantity of building material i, and EE_i (MJ/unit) is the PE coefficient of material i.

$$EEA1 - A3 = \sum_{i=1}^{n} MiEEi \quad \text{Eq (4)}$$

Table 4 shows the quantity, embodied energy and GHG emissions of building materials. The PE and GHG emission coefficients of building materials were obtained from the Chinese Life Cycle Database (CLCD) as much as possible [75]. Global data from generic databases such as Ecoinvent was obtained for those missing in the local database [76,77]. The LCA data for the CLT was obtained from the Athena Sustainable Materials Institute [41].

Transport to the site stage (A_4) comprises all the transportation of building materials from manufacturing to the building

Table 4
Quantity, embodied energy intensity and embodied greenhouse gas intensities of construction materials.

Materials	Database Unit	Data source	GHG coefficient (kg CO_2-eq/unit)	Energy coefficient (MJ/unit)	Density (kg/m^3)	RC (t)	CLT (t)	Hybrid CLT(t)
Elastic bonded fill	m^3	ÖKOBAUDAT	160.10	3115.10	350.00	0.00	88.72	88.72
Cement mortar	kg	Ecoinvent 3.1	0.31	2.35	1800.00	176.22	0.00	0.00
outdoor plaster	kg	Ecoinvent 3.1	0.27	5.65	1600.00	22.72	22.72	22.72
Particle board	m^3	Ecoinvent 3.1	436.07	13816.95	600.00	25.35	25.35	25.35
Gypsum board	kg	Ecoinvent 3.1	0.41	6.06	1050.00	260.05	259.38	259.80
Autoclaved Aerated Blocks	m^3	CLCD	514.66	3738.28	500.00	173.28	32.03	47.99
Concrete 50	m^3	CLCD	401.63	2773.67	2300.00	3171.78	1117.95	1513.08
Steel	kg	CLCD	2.63	39.00	7800.00	253.55	70.62	115.45
Concrete 20	m^3	CLCD	322.80	2296.40	2300.00	288.18	288.18	288.18
EPS insulation	kg	CLCD	4.57	96.10	20.00	6.22	0.00	0.00
Mineral wool	m^3	ÖKOBAUDAT	173.40	2537.90	152.00	0.00	28.51	28.51
Waterproofing membranes	kg	ÖKOBAUDAT	4.79	124.71	1334.00	0.49	0.98	0.98
Sound insulation plasterboard	kg	Ecoinvent 3.1	0.41	6.06	1050.00	6.91	6.22	5.18
PVC	kg	ELCD	2.78	56.11	1380.00	12.25	0.00	0.00
Wood	kg	ELCD	0.03	10.80	360.00	0.00	3.20	3.20
Low-e glass	kg	CLCD	1.08	12.50	2500.00	11.17	11.17	11.17
CLT	m^3	Athena	79.99	3336.58	500.00	0.00	500.73	409.66

construction site. Notably, CLT was imported from Canada. Manufactured in Quebec, Canada, the mass timber was set to be transported 21,594 km by sea from Canadian port to Tianjin port based on the software NETPAS DISTANCE, and 530 km by diesel truck (65 km from Tianjin port to the construction site, and 465 km from manufacture to the port in Canada according to Google maps). The GHG emissions from transport to the site (C_{A4}) were calculated using Eq (5).

$$\mathbf{CA4} = \sum_{i=1}^{n} \boldsymbol{MiDiTi} \qquad \text{Eq(5)}$$

where C_{A4} (kg CO_2 -eq) is the total GHG emissions related to the transportation of building materials to the site, Mi (kg, m3, …) is the quantity of building material i, Di (km) is the distance between the factory and the construction site, and Ti (kg CO_2 -eq/(t · km)) is the emission factor for transportation. The building materials were assumed to be transported by heavy diesel vehicles with a load of 18 t. The GHG emission coefficient for truck transportation (Ti) obtained from the CLCD was 0.122 kg CO_2 -eq/(t.km).

The PE of transportation (EE_{A4}) was calculated via Eq (6), where f_e is the fuel energy used factor of the truck, and the value is set to be 1.18 MJ/(t · km) according to the CLCD database.

$$\mathbf{EEA4} = \sum_{i=1}^{n} \boldsymbol{MiDif}\mathbf{e} \qquad \text{Eq (6)}$$

Construction installation A_5 includes the equipment and machines used at the site. Table 5 lists the main machinery and equipment used in three buildings. The GHG emissions and PE of the construction installation of the RC building were based on the machines used in the real building construction process in Tianjin. The electricity data was based on the average electricity in north China. The usage of diesel and electricity per machine shift is based on *Standard for building carbon emission calculation* in China [74]. As for the machines utilized for the CLT and hybrid CLT buildings, the shifts of the machines related to the materials were calculated based on the quantity of materials used in Table 4. For example, for machinery utilized for steel processing, the number of shifts was decided depending on the quantity of steel used in the three buildings. 253.55, 70.62 and 115.45 tons of steel (1: 0.28: 0.46) were used for the RC, CLT and hybrid CLT buildings, respectively. This ratio was used to determine the machine shifts for steel processing for the CLT and Hybrid CLT buildings. The machinery used to process the site is the same in all three buildings. The details of the machine shifts in the three buildings are provided in Table 5.

The operational phase covers the period from the completion of the construction to the deconstruction of the building. GHG emissions in the operation stage (C_B) are mainly indirect GHG emissions caused by various energy consumption and the replacement of materials.

The replacement module (B4) includes the production of components and recycled products. From the scale of the entire building, the impact of installation, transport, and deconstruction of the replacement were considered insignificant and were not considered. The interior wall and floor finishes of CLT and hybrid CLT buildings were replaced more frequently than those of RC buildings [24]. Material life expectancy may vary greatly for buildings according to different geographical locations, climates, exposure conditions, etc. Therefore, the life expectancy of building components was set according to previous studies in China [78,79] (Table 6). The GHG emissions (C_{B5}) and incurring energy (E_{B5}) in the replacement stage were calculated based on Eq (3) and Eq (4).

Electricity is utilized for cooling over a building's 50-year life cycle. Occupancy schedules (Table 7) for heating and cooling were set in the simulation [80]. Weather data was obtained from EnergyPlus. The energy consumption was obtained from the simulation

Table 5
Machinery and equipment used for three buildings.

Description	Shift of the machine			Details	Shifts for CLT/RC buildings	Shifts for Hybrid CLT/RC buildings
	RC	CLT	Hybrid CLT			
Bulldozer	0.02	0.02	0.02	Related to the processing site	1.00	1.00
Excavator	0.21	0.21	0.21			
Electric compactor	16.99	16.99	16.99			
Leveling machinery	0.10	0.10	0.10			
Truck crane/8t	27.84	15.51	17.81	Related to material weight	0.56	0.64
Jack-up tower crane	116.93	65.14	74.80			
Truck/6t	58.52	32.60	37.43			
Dump Truck	1.34	0.75	0.86			
Mortar mixer	104.09	11.89	11.89	Related to mortar and plaster usage	0.11	0.11
Reinforcement straightener	33.92	9.45	15.44	Related to steel usage	0.28	0.46
Steel bar cutter	18.77	5.23	8.55			
Rebar bending machine	51.96	14.47	23.66			
AC arc welding machine	154.25	42.96	70.24			
Butt welding machine	17.52	4.88	7.98			
Electric welding machine	0.42	0.12	0.19			
Woodworking circular saw	12.00	250.57	207.45	Related to wood products usage	20.88	17.29

Table 6
The replacement of building components in the operation stage.

Building	Replacement	Life expectancy	Replacement times
RC	PVC windows	30	1
	PVC doors	30	1
	Floor finishes	10	4
	Exterior wall finishes	20	2
	Interior wall finishes	10	4
	Roof finishes	20	2
CLT	Wood windows	30	1
	Wood doors	30	1
	Floor finishes	7	7
	Exterior wall finishes	20	2
	Interior wall finishes	7	7
	Roof finishes	20	2
Hybrid CLT	Wood windows	30	1
	Wood doors	30	1
	Floor finishes	7	7
	Exterior wall finishes	20	2
	Interior wall finishes	7	7
	Roof finishes	20	2

Table 7
Occupancy schedules of rooms.

Room	Cooling set point(°C)	Heating set point(°C)	Time											
			1	2	3	4	5	6	7	8	9	10	11	12
Bedroom	26	18	1	1	1	1	1	1	0.5	0.5	0	0	0	0
Living room	26	18	0	0	0	0	0	0	0.5	0.5	1	1	1	1
Kitchen	30	15	0	0	0	0	0	0	1	0	0	0	0	1
Toilet	26	18	0	0	0	0	0	0.5	0.5	0.1	0.1	0.1	0.1	0.1
Stair	–	–	0	0	0	0	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Room	**Cooling set point(°C)**	**Heating set point(°C)**	**Time**											
			13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Bedroom	26	18	0	0	0	0	0	0	0	0	0.5	1	1	1
Living room	26	18	1	1	1	1	1	1	1	1	0.5	0	0	0
Kitchen	30	15	0	0	0	0	0	1	0	0	0	0	0	0
Toilet	26	18	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.5	0	0	0
Stair	–	–	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0	0

results, and the GHG emissions were calculated via Eq (7), where C_{B6} ((kg CO_2-eq) is the total carbon emissions of the energy consumption, Ei (MJ) is the annual consumption of energy i, and EF_i (kg CO_2-eq/MJ) presents the emission factor for energy i.

$$\mathbf{CB6} = \sum_{i=1}^{n} \boldsymbol{EiEF}\mathbf{i} \tag{Eq(7)}$$

The EoL stage starts when the building is about to be deconstructed. In this study, the deconstruction (C1), transport (C2), waste processing (C3) and recycling (D) processes were considered.

The deconstruction stage includes on-site operations and activities undertaken off-site for deconstruction process. The primary energy (E_{C1}) and GHG emissions (C_{C1}) come from the on-site use of construction machinery and equipment. Only the materials listed in Table 8 were considered for demolition [81]. It is assumed that the energy consumption of CLT and concrete block demolition is the same as that of bricks. GHG emissions were calculated based on the assumption that the energy used for demolition was diesel. The discarded materials were transported to a recycling site or landfill within 15 km by diesel trucks. The GHG emissions (C_{C2}) and primary

Table 8
Energy used by the machines for the demolition process.

Material demolished	Demolition energy (MJ/kg)
Reinforce concrete	0.0612
Concrete	0.0437
Cement mortar	0.0437
Gypsum plaster	0.0359
Concrete Block	0.0359
Particleboard	0.0359
CLT	0.0359

energy (E_{C2}) were calculated based on Eq (5) and Eq (6). In addition, the carbonation process is also considered in the EoL. The energy (E_{C3}) for crushing concrete is considered to be 88 MJ for oil and 9 MJ of electricity per ton based on Pommer et al. [82].

Where the materials are recycled and flow out of the system boundary and have an economic value or substitute another product, the impacts are calculated in the recycling module D. In this study, the following materials were considered for recovery or recycling: concrete, wood products, and metal with a 10% loss of mass [13]. In the EoL scenario, steel is assumed to be separated from concrete and recycled as a raw material for new steel production and is considered for smelting and reformation. However, research has shown that concrete cannot be fully recycled and often requires downcycling [83]. In the recycling process, the concrete is crushed into aggregate to form the raw material of crushed stones [13], with 71% of the concrete being recycled in the subsequent material and 29% used for landfilling [26]. Concrete products were crushed to enhance the surface area for CO_2 uptake and exposed to the atmosphere for 4 months to increase carbonation [84]. The aggregate was assumed to have a particle size of 10 mm and a surface area of 0.5 m^2/kg [30]. The uptake of CO_2 was modeled using the method proposed by Pade et al. [85]. Wood waste contains a large amount of bio-energy, which can be recycled and used as an alternative to fossil fuels. Landfilling wood is banned in several countries because of the methane it emits [13]. However, some sources claimed that landfill gases were being captured and used as fuel [97]. Santos et al. suggested that incineration with energy recovery was the best option at present as wood degradation in landfills was uncertain [81]. In China, used CLT belongs to Class I and II waste wood according to the *Code for recycling utilization of waste wood* [86], and its EoL scenario has reuse, regenerative utilization and energy recovery. However, Wang et al. [87] reported that wood is subjected to temperature, humidity, chemical and biological decay during use, which makes the used wood less strong and also affects its gluing properties. In addition, CLT is more prone to breakage when separated from insulation, finishes and structural materials, leading to a reduction in its reuse value. Therefore, CLT was considered to be incinerated for recovered bioenergy at the EoL stage (with a 10% loss of mass). The minimum thermal efficiency of boilers using biomass fuel in China is 91% for Class 1 level [88], which was also considered in this research. The PE and GHG emissions savings were deducted from the LCGHGE and LCPE of buildings. The reduced GHG emissions and PE of recoverable biomass residues of incineration CLT to replace fossil fuels with recovered biofuel were based on the following Eq (8) [89] and Eq (9) [90].

$$\mathbf{Cav} = \sum_j (M_j H_j) C_f \varphi_f - (C_{diesel} D_{diesel}) \qquad \text{Eq(8)}$$

$$\mathbf{Eav} = \sum_j \{ M_j H_j [1 - \beta_j (1 + \alpha_{diesel})] \} \qquad \text{Eq(9)}$$

where C_{av} (kg CO_2 -eq) is net reduced GHG emissions, j is the type of biomass residues, M(kg) presents the mass of recovered residue (oven dry tones), H (GJ/t) is the lower heating value of the residue, Ci(kg CO_2 -eq/GJ) is the carbon intensity of the reference fossil fuel, φ_f is the relative conversion efficiency of biofuel versus reference fossil fuel; C_{diesel} (kg CO_2 -eq/GJ) and D_{diesel}(GJ) are the carbon intensity and quantity of diesel fuel used for recovering and transporting the biomass. E_{av} is the net energy from recovered biomass residues (GJ); β is the diesel fuel energy required to recover and transport the residue expressed as a proportion of the heat energy contained in the residue; α is the fuel cycle energy requirement of the diesel fuel. The values were obtained from previous studies [74, 84,89,91,92].

5. Results and discussion

This section analyzes the LCPE and LCGHGE in RC, CLT, and hybrid CLT buildings and compares the P&C, operational, and EoL stages of three buildings.

5.1. Product and construction stage (A1-A5)

The GHG emissions and PE for the product and construction stages (A1-A5) of the three buildings are presented in Fig. 4, which consists of materialisation, transport to site, and on-site construction. The functional unit of this study is 1 m^2 of total floor area. The embodied GHG emissions (A1-A5) of CLT and hybrid CLT buildings are 411.39 kg CO_2-eq/m2 and 482.77 kg CO_2-eq/m^2, emitting 46.52% and 37.24% less GHG in the P&C stage compared to the RC building (769.20 kg CO_2-eq/m^2), respectively. The embodied GHG emissions of the CLT in the P&C stage are a little higher than in previous work (327.53–333.52 kg CO_2-eq/m^2) [42], which is mainly due to the omission of the foundation structures from previous analysis. Moreover, a similar result was found in that CLT and hybrid CLT buildings reduce embodied energy by 32.48% and 24.99%, respectively, compared to the RC building. The GHG emissions of materials accounted for 94.47%, 78.54%, and 83.56% of RC, CLT, and hybrid CLT buildings, respectively. When the building is designed as a mass timber construction, the transportation GHG emissions and PE in the P&C stage increase more than four times compared to the RC building on account of the fact that CLT is imported from Canada rather than produced locally, resulting in a surge in transportation GHG emissions.

5.1.1. Product stage (A1-A3)

The GHG emissions of RC building materials (A1-A3) are 124.92% and 80.13% higher than those of CLT and hybrid CLT buildings, respectively. Therefore, increasing the use of wood products can reduce energy consumption and GHG emissions in the P&C phase, which is consistent with previous studies [33,44,46,71,93]. Fig. 5 shows the GHG emissions and PE from the production of the materials (A1-A3). Reinforced concrete (Steel and Concrete 50) dominated the GHG emissions in the RC (71.58%), CLT (50.24%), and hybrid CLT (59.98%) buildings. A high proportion of GHG emissions in mass timber construction is mainly due to the large amount of

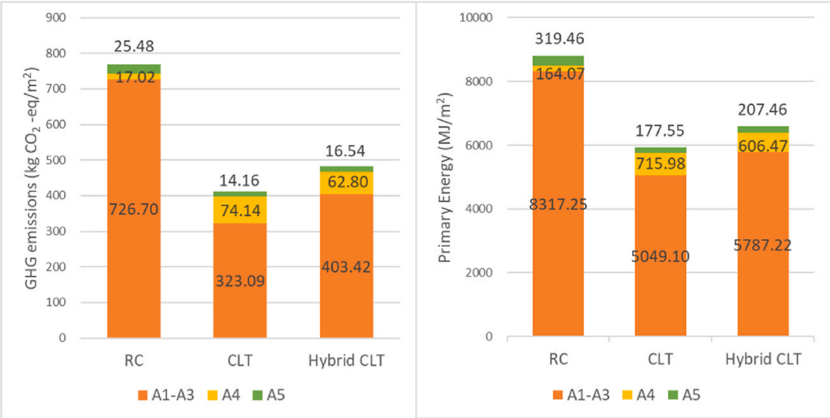


Fig. 4. GHG emissions and primary energy breakdown in the P&C stage (A1-A5).

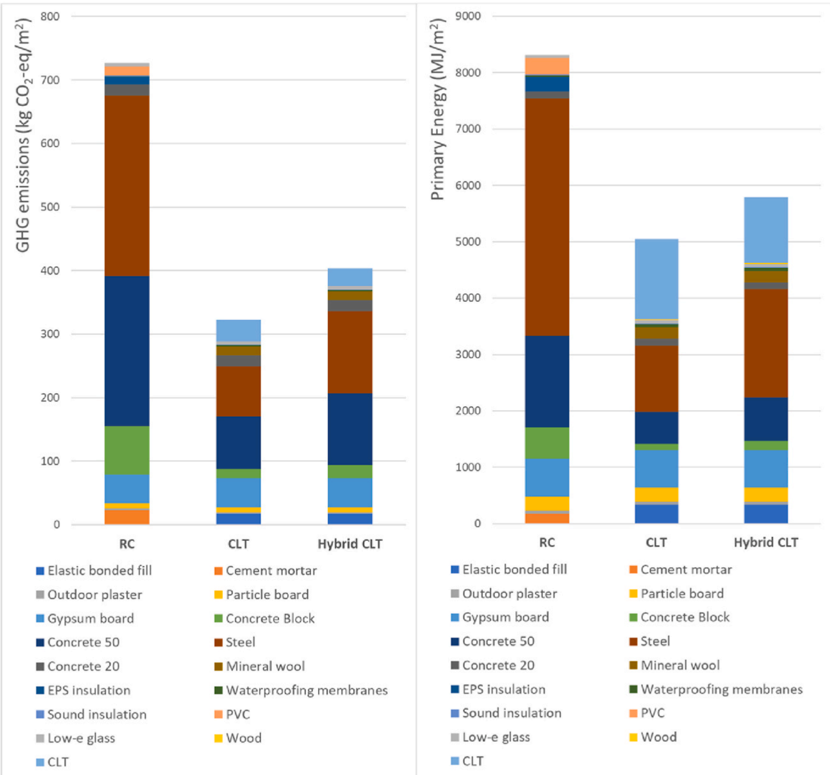


Fig. 5. Primary energy and GHG emissions breakdown in the production of materials (A1-A3).

RC used in the foundation and ground floor. Furthermore, the GHG emissions of CLT only accounted for 10.56% and 6.92% in CLT and hybrid CLT buildings, respectively, and contributed to 28.19% and 20.12% of PE in CLT and hybrid CLT buildings, respectively. One possible reason for this is that mass timber has a low carbon footprint and a high PE or biomass residue.

5.1.2. Construction process stage (A4-A5)

One interesting finding is that the A4 stage accounts for 13–19% of the GHG emissions and 9%–13% of PE in the P&C stage of CLT alternatives, while that of the RC building is less than 3% for both GHG emissions and PE. This is predominant because of the much greater transportation distance for importing CLT as compared to concrete production, resulting in increased transportation energy consumption and environmental burden in mass timber buildings. The on-site construction process represents 2%–4% of the environmental impacts in the P&C stage of the three buildings. The RC building (25.48 kg CO_2-eq/m^2) emits 79.91% and 54.01% more GHG than CLT (14.16 kg CO_2-eq/m^2) and hybrid CLT (16.54 kg CO_2-eq/m^2) buildings, respectively, in the on-site construction.

5.2. Operational stage (B4 & B6)

Fig. 6 shows operational GHG emissions and PE (B4 & B6), including the replacement of building components (B4) and heating and cooling consumption (B6) over a 50-year service life. CLT and hybrid CLT buildings have 12.57% and 12.45% greater GHG emissions than RC, respectively, in the operational stage. As for the PE, the values are 12.93% and 12.82%.

5.2.1. Replacement (B4)

The replacement (B4) breakdown of the GHG emissions and recurring energy is shown in Fig. 7. The replacement scenarios and results in the CLT and hybrid CLT buildings were the same. It showed that CLT and hybrid CLT buildings (344.20 kg CO_2-eq/m^2) produced 57.94% more GHG emissions than the RC building (217.92 kg CO_2-eq/m^2) during the replacement stage. The recurring energy of the CLT alternatives was 5211.89 MJ/m^2. The replacement of wall finishes in CLT alternatives had the greatest environmental impact, which is mainly due to the much more frequent replacement of interior wall finishes.

5.2.2. Operational energy use (B6)

Table 9 presents the annual heating and cooling demand in three buildings (B6). In the operational stage, space cooling was powered by electricity while space heating was provided by natural gas-fired boiler plants with an overall efficiency of 85%. Heating energy demand dominates the operational energy demand in three buildings. The cooling energy loads accounted for 12–14% of the total energy loads but contributed to 40–42% of the operational GHG emissions and 34–36% of the operational PE. This is mainly due to the fact that the method for space heating is more effective than that for space cooling. Furthermore, although the U-value of the envelope in all three buildings was set to be the same, the total heating and cooling PE consumption of CLT (296.97 MJ/year/m^2) and hybrid CLT (296.57 MJ/year/m^2) buildings were 2.25% and 2.21% higher than that of the RC building (290.43 MJ/year/m^2) due to the thermal mass effect. Conventional materials like concrete have a clear advantage over low thermal mass timber products [54]. The lower space heating demand of RC buildings compared to CLT buildings has already been reported in a study conducted by Dodoo et al. [37]. The overheating of mass timber is consistent with previous studies [54,94,95]. In particular, when global warming occurs, mass timber buildings require more cooling energy demand than in the current climate, which can be mitigated by increasing natural ventilation and shading [95].

5.3. End of life (C1–C3 & D) stage

The LCA results for the EoL (C1–C3 & D) are listed in Table 10. At the EoL stage, the GHG emissions and PE of all buildings were negative. CLT alternatives (−173.12 and −164.47 kg CO_2-eq/m^2) benefited much more from the GHG emissions in EoL than the RC building (−101.91 kg CO_2-eq/m^2). The EoL stage of PE of the CLT building (−5171.19 MJ/m^2) was 278.12% and 13.67% higher than that of RC and hybrid CLT buildings, respectively. The environmental impacts of demolition and transport accounted for a small part of the EoL stage. When the building was designed as a mass timber construction, it showed greater potential for biomass recovery.

The recycling (D) is calculated based on a scenario in which wood, concrete, and steel are recycled. The recycling of demolition materials in this study was based on the common practices of concrete, steel, and wood waste. The avoided GHG emissions for recycling steel for the RC building (−88.40 kg CO_2-eq/m^2) demonstrated a greater advantage over CLT alternatives (−24.62 and −40.25 kg CO_2-eq/m^2) owing to the large amount of steel used in the structure. The carbon benefits of bioenergy were the most significant in CLT (−146.45 kg CO_2-eq/m^2) and hybrid CLT (−121.11 kg CO_2-eq/m^2) buildings. The carbonation and down-recycling of concrete were −28.22, −11.42 and −14.65 kg CO_2-eq/m^2 in RC, CLT and Hybrid CLT buildings, respectively. In terms of avoided PE of biomass recovery, the CLT building (−4886.85 MJ/m^2) and hybrid CLT (−4041.22 MJ/m^2) buildings showed a greater advantage than the RC building (−196.20 MJ/m2). Therefore, biomass recovered from dismantled mass timber brings greater GHG and energy benefits.

5.4. Life cycle GHG emissions and life cycle primary energy (A1-A5, B4, B6, C1–C3 and D)

Fig. 8 shows a breakdown of the LCGHGE and LCPE for the three buildings (A1-A5, B4, B6, C1–C3 and D). Positive numbers indicate that GHG emissions and energy flow to the environment, while negative values indicate reduced or avoided GHG emissions and PE. The CLT building results in a 15.00% lower LCGHGE and a 17.32% lower LCPE than the RC building. For the hybrid CLT building, the values are 10.77% and 12.32%, respectively. This is mainly because of the beneficial carbon balance and greater potential for recycling

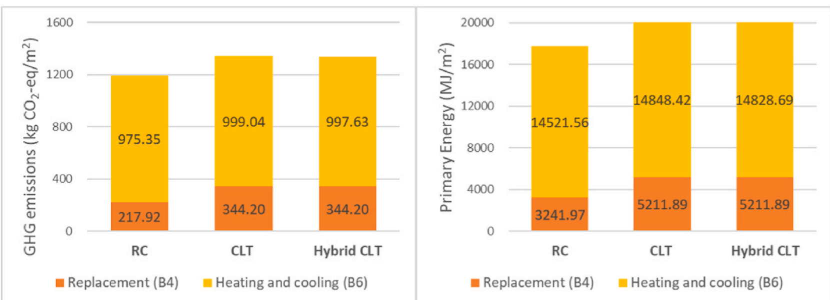


Fig. 6. Operational primary energy and GHG emissions for a service life of 50 years (B4 & B6).

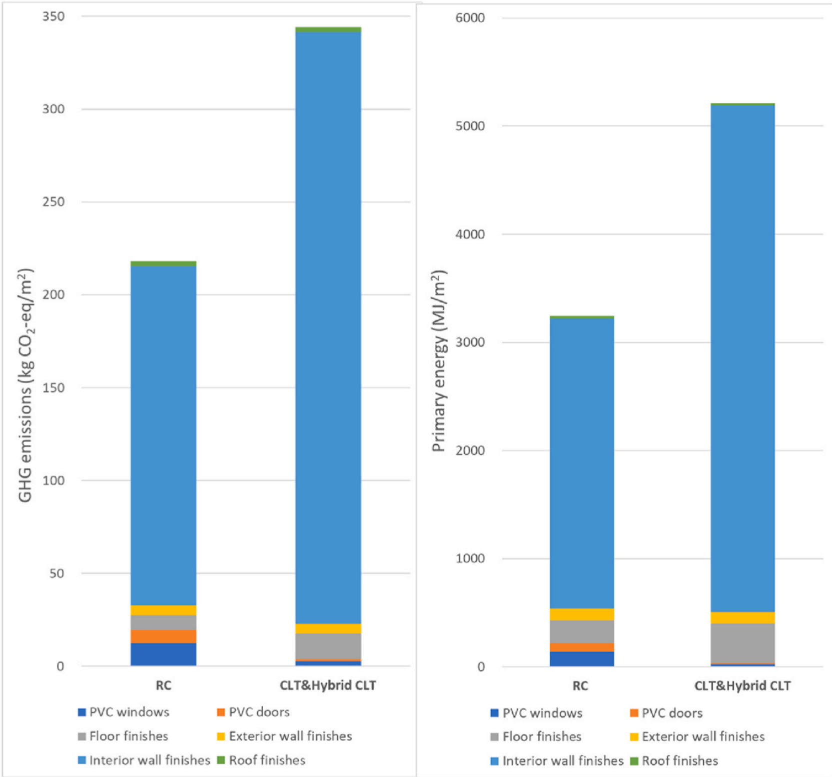


Fig. 7. The recurring energy and GHG emissions in the replacement module (B4).

Table 9
Annual operational energy consumption and GHG emissions in three buildings.

	Simulation results (kWh/year/m^2)		Primary energy (MJ/year/m^2)		GHG emissions (kg CO_2-eq/year/m^2)	
	Space heating	Space cooling	Space heating	Space cooling	Space heating	Space cooling
RC	45.99	6.76	189.03	101.40	11.53	7.98
CLT	46.55	7.04	191.33	105.64	11.67	8.31
Hybrid	46.51	7.03	191.16	105.41	11.66	8.29

Table 10
The life cycle assessment results of the EoL stage in three buildings.

	GHG emissions (kg CO_2 -eq/m^2)			Primary energy (MJ/m^2)		
	RC	CLT	Hybrid CLT	RC	CLT	Hybrid CLT
De-construction(C1)	7.62	3.63	4.43	104.96	50.01	61.07
Transport (C2)	3.70	1.99	2.30	35.71	19.18	22.31
Waste processing (C3)	9.26	3.75	4.81	109.97	44.47	57.07
End-of-life benefits (D)						
Concrete recycling and carbonation	−28.22	−11.42	−14.65	−15.21	−6.18	−7.92
Steel recycling	−88.40	−24.62	−40.25	−1406.83	−391.82	−640.58
Biomass recovered	−5.88	−146.45	−121.11	−196.20	−4886.85	−4041.22
Total EoL	−101.91	−173.12	−164.47	−1367.60	−5171.19	−4549.28

and biomass recovery of mass timber, offsetting the additional environmental impacts of the CLT alternatives during the operational phase. In previous studies, Guo et al. [22] showed that CLT building led to 9.9% and 13.2% declines in LCPE and LCGHGE, respectively, compared to the RC building. Jayalath et al. [24] found that the LCGHGE of a CLT building was 30% lower than that of RC. This was mainly due to system boundary and energy consumption in the operational stage, which was closely related to the thermal performance of the building envelope, building efficiency, geographical location, and climatic conditions [95,96].

The P&C stage accounts for 26–30% of LCGHGE and LCPE in CLT alternatives, whereas it contributes for 41.34% of LCGHGE and 34.93% of LCPE in the RC building. However, operational GHG emissions and PE in CLT and hybrid CLT buildings are higher than

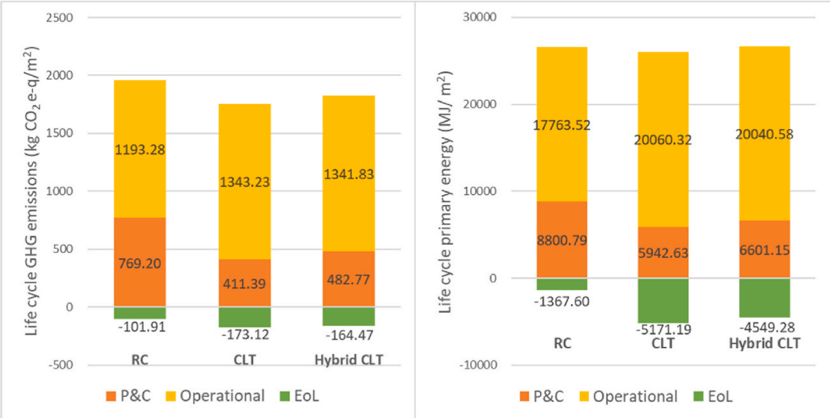


Fig. 8. Breakdown of the LCGHGE and LCPE of three buildings (A1-A5, B4, B6, C1–C3 and D).

those of the RC building, and dominate LCGHGE and LCPE. But CLT building still gives the lowest LCGHGE (1581.50 kg CO_2 -eq/m^2) and LCPE (20831.76 MJ/m^2). For the EoL stage, the three buildings reduce approximately 5–11% of LCGHGE, and the CLT and hybrid CLT buildings save around 20–25% LCPE compared to around 6% savings in RC. The reduction in LCGHGE and LCPE in the RC building is mainly due to the recycled steel, while CLT alternatives benefit more from the biomass recovery of mass timber.

6. Sensitivity analysis

LCGHGE and LCPE were highly related to the variables. A sensitivity analysis is applied to explore the impacts of variables and uncertainties in key parameters, such as thermal performance of the building envelope and infiltration rate. Table 11 shows the effects of varying parameters on the GHG emissions and PE for the three buildings.

6.1. *Transportation*

The CLT is imported from Canada and shipped by sea over long distances. To explore the impact of transport distance on LCGHGE and LCPE, all building materials were considered to be produced locally. The transportation distance was set at 40 km in the sensitivity analysis. The material transportation distance decreased the LCGHGE for the RC, CLT, and hybrid CLT buildings by 0.39%, 4.35% and 3.41%, respectively. For CLT alternatives, the development of locally engineered wood products can reduce the adverse impact of transportation on the environment.

6.2. *U-value of the building envelope*

The operational stage was significantly related to the thermal performance of the building envelope. The U-value of the building envelope was improved from the reference setting to the ultra-low-energy building envelope standard. The operational energy consumption is sensitive to the thermal performance of the envelope, with a maximum of 5.28% LCGHGE and 6.40% LCPE reduction for RC (−1612.57 MJ/m^2). The CLT and hybrid CLT buildings reduce 1575.53 MJ/m^2 and 1583.38 MJ/m^2 in the same scenario, accounting for 7.56% and 7.17% of LCPE. However, it is worth highlighting that the low U-value of the building envelope will increase the consumption of building materials, resulting in a rise in environmental impacts and costs in the P&C stage.

Table 11
Effects of varying parameters on GHG emissions and PE.

Description	Parameters	Output variation GHG emissions (kg CO_2-eq/m^2)			Output variation primary energy (MJ/m^2)			Stage of change
Buildings	/	RC	CLT	Hybrid CLT	RC	CLT	Hybrid CLT	
Reference	Life span: 50 years Infiltration rate: 0.3	0 (1860.57)	0 (1581.50)	0 (1660.13)	0 (25196.71)	0 (20831.76)	0 (22092.45)	
Transport distance	40 km between the factory to the site	−0.39%	−4.35%	−3.41%	−0.28%	−3.19%	−2.48%	P&C stage
U-value for building envelope	0.1 Exterior wall/0.10 roof	−5.28%	−6.06%	−5.80%	−6.40%	−7.56%	−7.17%	Operational stage
	0.2 Exterior wall/0.16 roof	−3.45%	−3.93%	−3.78%	−4.18%	−4.91%	−4.67%	
	0.3 Exterior wall/0.22 roof	−1.69%	−1.89%	−1.82%	−2.04%	−2.37%	−2.26%	
Infiltration rate	0.236	−1.46%	−1.69%	−1.64%	−1.81%	−2.16%	−2.07%	
	0.171	−2.99%	−3.46%	−3.32%	−3.69%	−4.40%	−4.18%	
	0.107	−4.49%	−5.22%	−4.98%	−5.54%	−6.64%	−6.27%	
	0.042	−6.02%	−7.03%	−6.72%	−7.45%	−8.93%	−8.45%	
Reuse strategy	Demolition of CLT and other timber to landfill	0.32%	9.26%	7.29%	0.78%	23.46%	18.29%	EoL stage

6.3. Infiltration rate

Buildings with poor airtightness produce excessive indoor and outdoor air exchanges, resulting in unnecessary energy loss. When the thermal insulation performance of a building envelope is sufficiently high, outdoor air infiltration becomes the main factor affecting the indoor environment. The infiltration rate was assumed to be 0.042 (l/s m^2@ 50 Pa) when the building was designed as a passive house according to regulations in China [97]. We explored the LCGHGE and LCPE of the four scenarios by improving the infiltration from 0.3 to 0.042 (l/s m^2@ 50 Pa). Table 11 shows that RC, CLT, and hybrid CLT buildings have reduced LCGHGE by 6.02%, 7.03% and 6.72%, and LCPE by 7.45%, 8.93% and 8.45%, respectively, when the infiltration rate meets the passive-house criterion.

The sensitivity analysis indicates that a more efficient energy system and a low U-value of the building envelope should be considered for the improvement of the RC, CLT, and hybrid CLT buildings, which can significantly reduce energy consumption during the use phase. The operational energy of the CLT and hybrid CLT buildings will always be higher than that of the RC building due to the thermal mass effect. This should be taken into account in the development of mass timber construction. When the building is designed as a passive or zero-energy building, the operational phase accounts for a small part of the environmental impacts in life cycle assessment, which makes the P&C and EoL phases the main influences.

6.4. Reuse strategy

At the end of their service life, wood products are sent to landfills to determine the consequences of practices in countries where landfills may be prevalent [13]. The results showed a clear difference between the three buildings. The GHG emissions of the CLT and hybrid CLT buildings increased by 9.26% and 7.29%, respectively. Furthermore, PE shows greater sensitivity than GHG emissions to the parameter, with increases of 23.46% and 18.29% in CLT and hybrid CLT buildings, respectively. The effect of this parameter on the RC building was quite small. In the future, the disassembly design of CLT buildings may promote the benefit of mass timber as a re-use material, which will gain additional value before it is burnt for biomass recovery [31]. This will prolong the lifespan of the wood materials and lead to a lower climate effect when considering the timing of emissions and biogenic forest carbon [27].

7. Conclusion

The study explored the GHG emissions and PE of three buildings in a cold region of China through a 50-year LCA, including the P&C, operational and EoL stages. The buildings consisted of conventional RC, CLT, and hybrid CLT buildings.

Significant differences were observed in the P&C phases of the three buildings. The embodied GHG emissions of CLT and hybrid CLT buildings were reduced by 46.52% and 37.24% in the P&C stage, while the PE was reduced by 32.48% and 24.99%, respectively. RC dominates the GHG emissions in PE compared with other materials in three buildings. Through a sensitivity analysis of the transportation distance of building materials, it is known that the localized production of building materials can reduce LCGHGE by approximately 3%–5% in mass timber construction.

Operational energy consumption dominates the LCGHGE and LCPE. The operational GHG emissions and PE of CLT and hybrid CLT buildings were 12–13% higher than those of the RC building. During the operational phase, the space heating and cooling PE of the CLT alternative was 2.21–2.25% higher than that of the RC building due to the low thermal mass of mass timber compared to conventional materials like concrete. Especially with a tendency like global warming, the overheating in mass timber construction should be severely considered. Sensitivity analysis indicated that the energy demand of the three buildings was significantly reduced by improving the thermal performance of the building envelope and airtightness. The selection of building materials combined with the design of low-energy buildings and high-efficiency energy systems plays an essential role in reducing energy consumption during the operational phase.

When a building is designed as an ultra-low-energy or zero-energy building, the energy consumption in the operation phase is significantly reduced, which magnifies the impact of the P&C and EoL phases [98,99]. Section 6.4 shows that when the wood is sent to landfill without considering the biomass recovery at the EoL stage, the GHG emissions of CLT and hybrid CLT buildings will rise by 9.26% and 7.29%, respectively, whereas LCPE will increase by 23.46% and 18.29%, respectively. This proves that mass timber has a large amount of biomass residue during the EoL stage [13].

The 50-year life cycle GHG emissions of CLT and hybrid CLT buildings were 1581.50 kg CO_2-eq/m^2 and 1660.13 CO_2-eq/m^2, respectively, 15.00% and 10.77% lower than that of the RC building (1860.57 kg CO_2-eq/m^2). The lower GHG emissions in the P&C stage and greater EoL benefits of the CLT alternatives offset their additional operational GHG emissions compared to RC building. In addition, the LCPE of the CLT and hybrid CLT buildings were 17.32% and 12.32% lower than those of the RC building, respectively. The results show that replacing RC with mass timber can reduce LCGHGE and LCPE.

Advancements in building technology and mass timber have made it possible to construct high-rise mass timber buildings. The results showed that the CLT building outperformed the RC and hybrid CLT buildings in a 50-year life cycle assessment. However, the code for fire protection design restricts the development of CLT buildings in China, where mass timber is still in its infancy. The hybrid CLT buildings with RC cores show advantages in fire protection and structure for CLT buildings and are a feasible way to promote mass timber buildings in China. Although the environmental impacts of the hybrid CLT building are higher than those of the CLT building, they are significantly lower for the RC building. Therefore, hybrid CLT buildings can be regarded as a practical way of achieving more sustainable buildings to decrease the environmental impacts of the building sector in China. The LCA results of this study can be used to support government regulations and policies in the process of rapid urbanization in China.

Future work could address some of the limitations of this paper's research, such as considering renewable and non-renewable energy sources in LCA in the Chinese context and the relationship between life cycle costs and environmental impacts.

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CRediT author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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