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A Comparison of the Energy Saving and Carbon Reduction Performance between Reinforced Concrete and Cross-Laminated Timber Structures in Residential Buildings in the Severe Cold Region of China

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Abstract: This paper aims to investigate the energy saving and carbon reduction performance of cross-laminated timber residential buildings in the severe cold region of China through a computational simulation approach. The authors selected Harbin as the simulation environment, designed reference residential buildings with different storeys which were constructed using reinforced concrete (RC) and cross-laminated timber (CLT) systems, then simulated the energy performance using the commercial software IES^{TM} and finally made comparisions between the RC and CLT buildings. The results show that the estimated energy consumption and carbon emissions for CLT buildings are 9.9% and 13.2% lower than those of RC buildings in view of life-cycle assessment. This indicates that the CLT construction system has good potential for energy saving when compared to RC in the severe cold region of China. The energy efficiency of residential buildings is closely related to the height for both RC and CLT buildings. In spite of the higher cost of materials for high-rise buildings, both RC and CLT tall residential buildings have better energy efficiency than low-rise and mid-rise buildings in the severe cold region of China.

Keywords: carbon reduction; energy saving; severe cold region; cross-laminated timber (CLT); residential building

1. Introduction

1.1. Energy Consumption and Carbon Emissions in the Building Sector

At present, the construction industry is the most resource-intensive industrial sector in the global economy [1]. The construction and occupation of buildings is a substantial contributor to global CO_2 emissions, with almost a quarter of total global CO_2 emissions attributable to energy use in buildings [2]. The building sector is responsible for approximately 40% of the total energy consumption and carbon emissions in many developed countries [3]. In Europe, the existing building stock is responsible for the consumption of 33% of raw materials and 50% of electricity generated, with residential buildings accounting for 16% of final energy use and commercial buildings accounting for 10% [4]. In the United States, buildings account for 40% of energy use which is equivalent to 7.7% of global carbon emissions [5]. In the UK, buildings account for 50% of total CO_2 emissions [6]. In China, buildings also make a significant contribution to China's total energy consumption, especially residential buildings.

Eighteen percent of the overall Chinese greenhouse gas (GHG) emissions are from the building sector [7]. In 2010, residential buildings accounted for 84% of total energy consumption by the building sector [8]. Reducing the energy consumption and carbon emissions attributed to buildings is clearly an essential function of the government's energy policy.

In China, there is no specific building energy data available from official sources. As a result, it is difficult to accurately assess the total amount of energy consumed by buildings in China. Some energy consumed by buildings may be counted more than once by different government sectors. Some references point out that the energy consumption per unit of floor area of buildings in China is much higher than that of developed countries [9]. The IAE reported in 2007 that China's building sector consumed 31% of China's total final energy [10]. The building sector was expected to be responsible for the consumption of 35% of China's total primary energy supply (TPES) by 2020. China is undergoing a period of rapid development characterised by fast urbanisation. The Chinese government plans to increase urbanisation to 60% by 2030, and to 70% over the next 25 years. This means that 880 million people will be urban dwellers by 2030, requiring more residential buildings for this urbanisation [11]. The construction of new buildings China amounts to a cumulative area of approximately two billion square metres annually, which accounts for nearly 50% of construction in the world [12,13]. It can be predicted that residential buildings in China will consume more energy and release more carbon emissions in the coming decades.

With development of new technology, new construction materials are increasingly more energy efficient and environmentally-friendly. The existing studies have shown that the energy performance of different building materials may vary significantly. Paolo et al. pointed out the relationship between different building materials by simulation. For the 40-story building, the embodied energy (EE) of the steel rigid frame with a steel–concrete floor is 43% greater than the EE of the RC frame with RC slabs, while for the 70-story building, the former is 88% greater than the latter [14]. Treloar et al. compared the energy embodied in office buildings varying in height from three storeys to 52 storeys. The result showed that the high-rise buildings have approximately 60% more energy embodied per unit gross floor area (GFA) in their materials than the low-rise buildings. The 52-story building with a structure composed of a RC core and steel columns has an EE of 18.4 GJ/m^2 [15].

1.2. CLT and Its Development in China

Timber is one of the most environmentally-friendly building materials available and has been used as a basic construction material for millennia. The adoption of new techniques and behaviour by a traditionally conservative industry has enabled continuous improvement in timber construction [1]. New wood products, such as plywood, glue-laminated timber, and cross-laminated Timber, are frequently used as building materials in recent years. Plywood is a sheet material manufactured from thin layers of wood veneer that are glued together with adjacent layers having their wood grain rotated up to 90 degrees to one another. In China, this product is widely used as a non-structure building material for decoration. Glued laminated timber, also called glulam, is a type of structural engineered wood product comprising a number of layers of dimensioned lumber bonded together with durable, moisture-resistant structural adhesives. Among these wood products, cross-laminated timber (CLT) is one of the most recent innovations that have spread throughout Europe and worldwide. CLT construction technology originated from Europe in the early 1990s, and in the last two decades it has been used for a wide range of buildings worldwide, including single and multi-story residential buildings, office buildings, and other low-rise commercial buildings [16]. CLT production rose from 25,000 m^3 in 1996 to 340,000 m^3 in 2010. In 2014, the global annual production of CLT was 600,000 cubic metres, and this is expected to reach 1,000,000 cubic metres by 2016 [17]. CLT was introduced to the UK in 2001 and the material use is growing at a rate of 25% per annum [1]. CLT based construction has also experienced rapid market growth more recently in the Australian, US, and Canadian markets. At present, the CLT production factories are mainly located in central Europe and these accounted for 80% of the global installed production capacity in 2015 [18].

As shown in Figure 1, cross-laminated timber (CLT) is an integrated building system which is constituted similarly to plywood, with boards that are glued side by side in a single layer and then glued to another layer of boards arranged crosswise to each other at an angle of 90° with the adjacent layers [19]. Usually, CLT is composed of an uneven number of layers with at least three layers. Although CLT has been developed for 20 years, the product standard has only been introduced recently [20]. As a result, the determinations of CLT panels vary significantly between producers. Different methods have been adopted for the basic mechanical properties of CLT [21]. The thickness of a single layer is between 20 and 50 mm, and whole panels are available in thicknesses from 60 to 500 mm [22]. The width and length of the panel are typically 4.8 m by 20 m. Due to its layered configuration, CLT possesses uniform mechanical and physical properties. The material can be used not only as load-bearing panels (walls, floors and roofs) and shear walls, but also for partitions and linear structural components in buildings [23]. When CLT is used as a linear structural element, it shows promising resistance against shear in-plane and tension perpendicular to the grain [24].

Figure 1. CLT panels and its use in buildings.

As a building material, timber has better energy saving and carbon reduction performance than other traditional building materials, such as bricks, RC, and steel. Although the energy and carbon emissions during the operational stages of a building constitute the majority of the energy and emissions over the building's lifetime, there is also significant carbon emissions involved in the initial construction of a building. During construction, the extraction of materials, processing, manufacture, and transportation consume significant energy and have an environmental impact, which includes CO_2 emissions [2]. When compared to wood framed buildings, RC-framed buildings consume approximately 80% more energy during the material production stages and release about 100–200% more net GHG emissions [25]. However, wood may store approximately 1.10 tons of CO_2 per cubic metre. Even after wood harvesting, much of the carbon stored in forest products may not be released for decades [26]. Gong et al. made a comparison between concrete and timber as materials for frameworks in Beijing in various scenarios, and showed that concrete frames consume 30% more energy than timber frames [12]. During the operational phase, Guo et al. pointed out that, in China, the effects of energy saving and carbon reductions by CLT buildings show little relationship to the climate zone. On a national level, a seven-storey CLT building may result in a 29.4% energy saving, which is equivalent to a 24.6% carbon reduction, when compared with a concrete building in the operational stage [17]. Liu et al. made comparisons between two seven-storey buildings constructed using RC and CLT in the severe cold region of China. They found that the energy consumption for heating and cooling was 338 MJ/m^2 and 231.2 MJ/m^2 per annum, respectively [27].

The cost of CLT buildings may be a fundamental factor that affects the development and adoption of this material. The existing references indicate that the cost of CLT buildings is close to that of traditional building materials such as concrete, bricks, and steel [28]. Currently, CLT is widely used for residential or commercial buildings between eight and 20 floors high, a range of buildings which is generally dominated by concrete and steel frame structural systems. Sellen showed that in the Pacific Northwest, the cost of a CLT design option can be as cost-effective as reinforced concrete. The costs of a 26 m high CLT building (eight storeys) and 38 m high CLT building (14 storeys) are approximately 32.5 US dollars and 31 US dollars per square foot, which is slightly higher than the cost of the same buildings in RC [29]. Mahlum Architects et al. also indicated that the use of CLT as the construction material for a 10-storey building may result in a slightly lower cost than the concrete alternative (4%) [28]. Pei et al. highlighted that equivalent or better performance than current code and existing concrete and steel structures is expected from tall CLT buildings. The cost of tall CLT buildings is comparable or less expensive than concrete and steel options in the US [28]. Tall residential buildings are often believed to be high-energy consumers, mainly due to the large amount of materials required for the structure during construction [14]. However, the total energy consumed by the building during its lifespan is not limited to the amount of material used, but also includes the energy consumed during the operational stage.

At present, reinforced concrete (RC) frames are the most frequently used structural material for buildings in China. Although the CLT system has not been well adopted and there are only a few demonstration projects for scientific research, there is growing interest in this material. The Chinese government also made a series of improvements to encourage the development of timber buildings. In 2017, the Ministry of Housing and Urban-Rural Development of China (MOHURD) revised the regulation of timber construction and published a new building code (GB/T 51226-2017). The new code extended the height of timber buildings to 56 m or no more than 18 storeys in non-seismic regions. It can be expected that the timber buildings in China will develop rapidly over the next few decades.

The aforementioned context has raised several questions. So far, limited references are available for the comparison of energy consumption between high-rise and low-rise residential buildings in China. Studies concerning the implementation of carbon emissions reductions by altering current carbon-intensive construction materials are scarce in China. Furthermore, the use of CLT in China is in its initial phase, and there is limited availability of studies of the energy saving performance of this sustainable material. This paper considers the energy consumption of residential buildings and addresses the following questions: (1) is using CLT as a sustainable material for construction an efficient way to lower energy consumption in China? (2) Do tall residential buildings have lower energy efficiency than low-rise and mid-rise buildings? (3) Do CLT buildings have a lower energy cost than RC buildings when performing a life-cycle assessment?

2. Description of Studied Buildings and Its Environment

2.1. Simulation Environment

In this work, Harbin was selected as the simulation environment for the concrete and CLT buildings. Harbin is the capital and the largest city of Heilongjiang province which is located in the severe cold region of Northeast China. According to the Code for Design of Civil Buildings (GB 50352-2005), there are five climate zones in China. These are the severe cold region, the cold region, the hot-summer cold-winter region, the hot-summer warm-winter region, and the temperate region. Furthermore, the standard can be divided into A, B, C, and D sub-regions when necessary. Harbin is located in the severe cold region and the envelope criteria and insulation levels of opaque constructions, together with the thermal and optical performance of windows and skylights of the buildings here should follow the code designated IB. The values for Harbin are shown in Table 1.

Table 1. Climate zone of Harbin City.

Climate Zone	Temperature		U-Value (Regulation)
	Coldest	Hottest	
Severe Cold (IB)	≤ −10 °C	≤ 25 °C	Roof: 0.25
			Wall: 0.33

Data Source: Code for Design of Civil Buildings (GB 50352-2005).

2.2. Details of RC Buildings

In this paper, four actual residential buildings (4, 7, 11, and 17 storeys high) which had already been constructed in Harbin were selected as the objects of study. The reference RC buildings considered in the analysis presented in this paper are composed of a RC-framed structure, RC slabs (full weight), and brick infill walls, with dimensions and detailing for buildings from 4 to 17 storeys high. According to China's code for fire protection design, residential buildings with more than 18 storeys must have outdoor corridors between each unit. In order to examine whether energy efficiency is closely related to the height of the residential building, the four reference buildings selected have similar floor plans. Figure 2 illustrates the floor plan of the four buildings: There are two flats with a shared staircase in each unit, and the building consists of three dwelling units. The internal storey height of the structure is 2.70 m, which is a representative value for residential buildings in China. The detailed design parameters of the four case study RC buildings are presented in Tables 2–4.

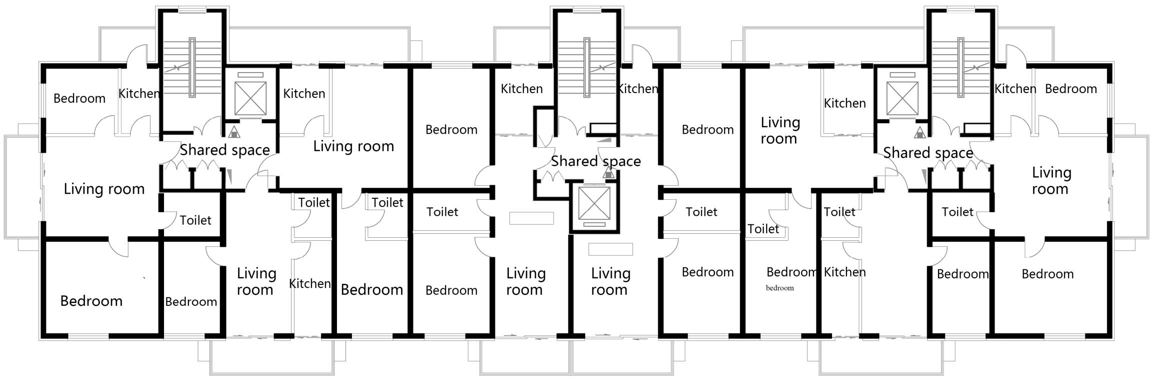

Figure 2. Floor plan of the buildings.

Table 2. Details of RC roof design.

Material ID	Thickness (mm)	Conductivity (W/(mK))	Specific Heat Capacity (J/(kgK))	Density (kg/m^3)	Resistance (m^{2}K/W)
Concrete	40	1.51	920	2300	0.026
Cement mortar 01	10	0.81	1050	1600	0.012
SBS waterproof material	1	0.23	1620	900	0.004
Cement mortar 02	20	0.93	1050	1800	0.022
EPS insulation	100	0.03	1647	28.5	3.333
SBS waterproof material	1	0.23	1620	900	0.004
Cement mortar 02	20	0.93	1050	1800	0.022
Reinforced concrete	100	1.74	920	2500	0.057
Composite mortar	20	0.87	1050	1700	0.023
Total R-value					3.644
Total U-value					0.274

Table 3. Details of RC external wall design.

Material ID	Thickness (mm)	Conductivity (W/(mK))	Specific Heat Capacity (J/(kg K))	Density (kg/m^3)	Resistance (m^{2}K/W)
Cement mortar 02	20	0.93	1050	1800	0.022
EPS insulation	100	0.03	1647	28.5	3.333
Cement mortar 02	20	0.93	1050	1800	0.022
Reinforced concrete	200	1.74	920	2500	0.115
Cement mortar 01	10	0.81	1050	1600	0.012
Total R-value					3.674
Total U-value					0.272

Table 4. Details of RC external window design.

Material ID	Thickness (mm)	Conductivity (W/(mK))	Gas	Convection Coefficient (W/(m^{2}K))	Resistance (m^{2}K/W)
Out pane	6	1.06			0.006
Cavity	8		Air	3.12	0.299
Inner pane	6	1.06			0.006
U-value (glass only)					2.082
Net U-value (Including frame)					2.344

2.3. Details of CLT Buildings

As mentioned earlier, the market for CLT construction in China is still quite limited at present. As a result, there is no CLT design standard available in China. In this study, Eurocode 5 and relevant documents [30,31] are adopted as the design standards for CLT structures. The dimensions of the buildings, such as the structural height, the building orientation, floor areas and the floor plan remain the same as for the reference concrete buildings. What should be noted is that the stairs of the CLT reference buildings are still built up with concrete. The detailed design parameters of the four case study CLT scenarios are presented in Tables 5–7 and Figure 3.

Table 5. Details of CLT roof design.

Material ID	Thickness (mm)	Conductivity (W/(mK)	Specific Heat Capacity (J/(kgK))	Density (kg/m^3)	Resistance (m^{2}K/W)
Cement mortar 01	25	0.81	1050	1600	0.031
SBS waterproof material	3	0.23	1620	900	0.013
Cement mortar 02	20	0.93	1050	1800	0.022
EPS insulation	50	0.03	1647	28.5	1.667
SBS waterproof material	3	0.23	1620	900	0.013
Plaster board	15	0.16	840	950	0.094
CLT panel	170	0.13	1500	500	1.308
Plaster board	15	0.16	840	950	0.094
Total R-value					3.380
Total U-value					0.296

Table 6. Details of CLT external wall design.

Material ID	Thickness (mm)	Conductivity (W/(mK)	Specific Heat Capacity (J/(kgK))	Density (kg/m^3)	Resistance (m^{2}K/W)
Plaster board	15	0.16	840	950	0.094
EPS insulation	50	0.03	1647	28.5	1.667
CLT panel	135	0.13	1500	500	1.038
Plaster board	15	0.16	840	950	0.094
Total R-value					3.084
Total U-value					0.324

Table 7. Details of CLT external window design.

Material ID	Thickness (mm)	Conductivity (W/(mK))	Gas	Convection Coefficient (W/(m^{2}K))	Resistance (m^{2}K/W)
Out pane	6	1.06			0.006
Cavity	8		Air	3.12	0.299
Inner pane	6	1.06			0.006
U-value (glass only)					2.082
Net U-value (Including frame)					2.344

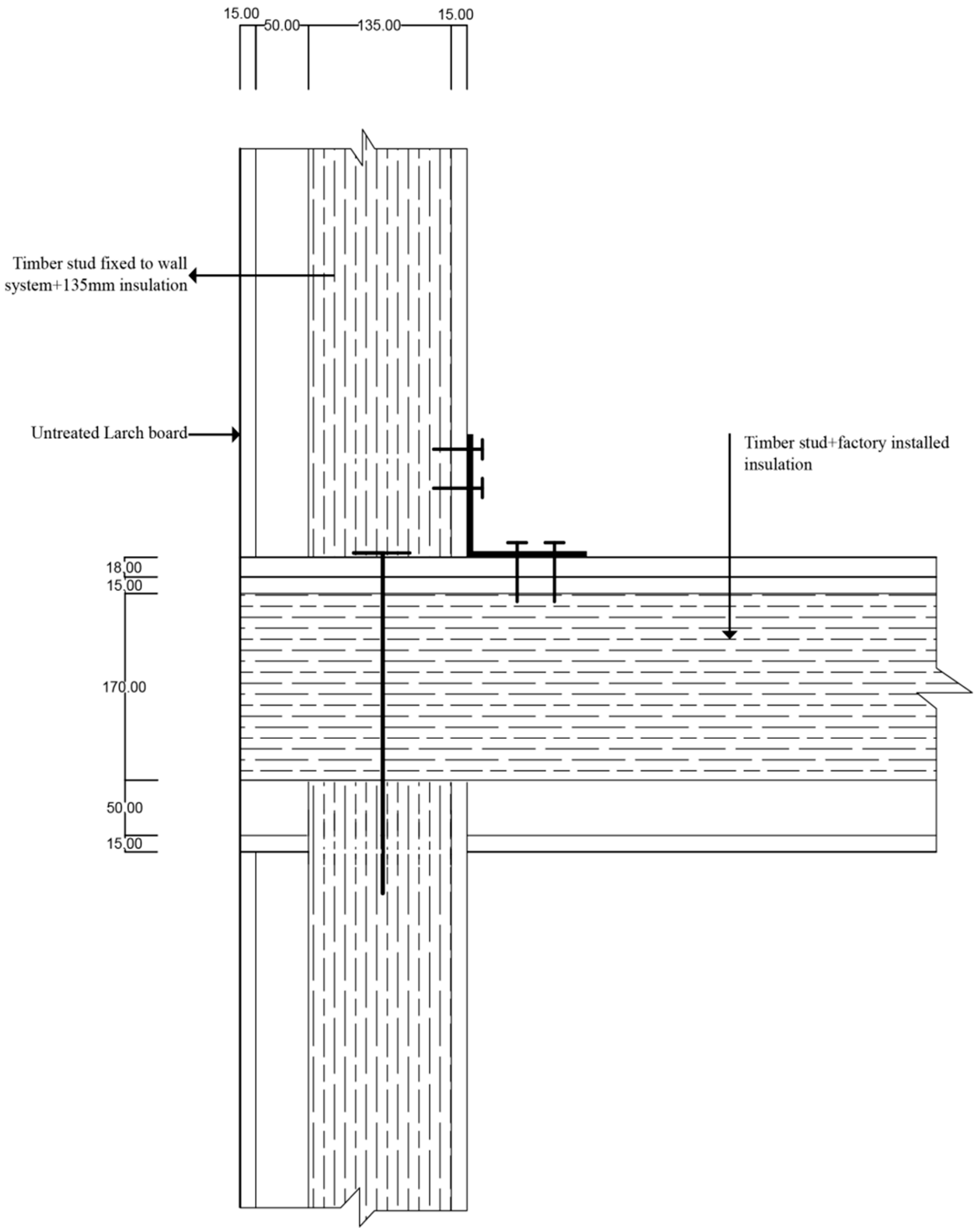

Figure 3. Configuration of the CLT external wall and roofs.

3. Methodologies

3.1. The Framework of the Study

Life-cycle assessment (LCA) is the method used to evaluate the energy consumption and carbon emission of the RC and CLT buildings [32]. Figure 4 presents a flowchart of the life-cycle assessment and the explicit study steps followed in this paper. When considering the whole life of the building, the energy consumption can be divided into three stages which are the construction stage, the operational stage, and the end of life stage.

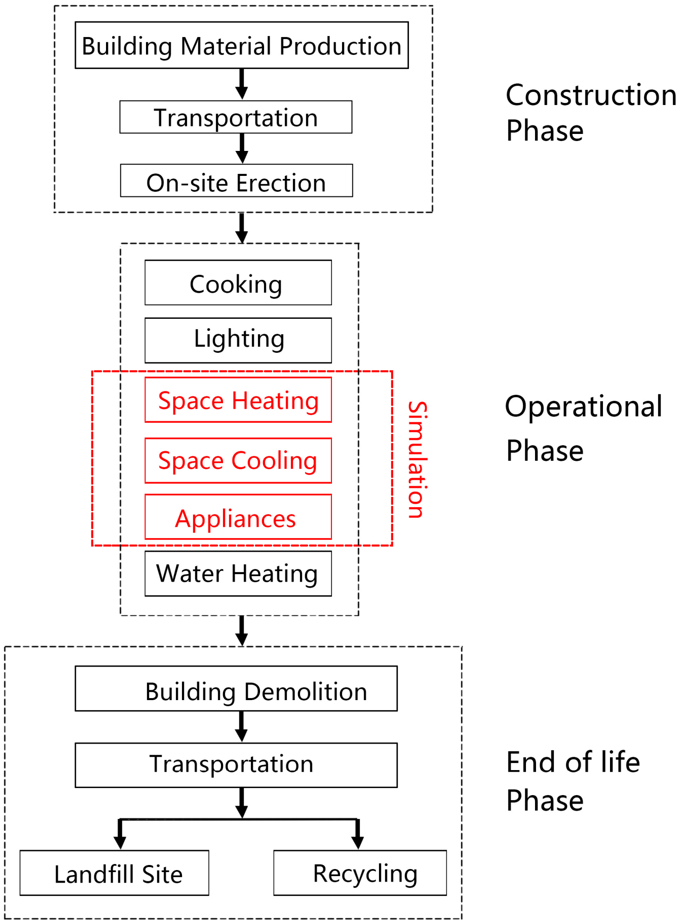

Figure 4. Flowchart showing the life-cycle assessment and the study scope.

The energy consumed in the construction phase includes material production, transportation, and on-site installation. The energy consumed in the operational phase includes all activities related to the use of the building over its life span which can be mainly summarised as space heating, space cooling, cooking, lighting, appliances, and water heating. In this paper, the energy consumed for space heating, space cooling, and appliances during the operational stage was calculated through simulation. Furthermore, in relation to these activities, energy consumed by space heating and space cooling is significantly related to the building envelope and materials, while energy used for cooking appliances, water heating and lighting is related to the activity of the inhabitants. The energy consumed in the end of life phase includes destruction of the building and transportation of dismantled materials to landfill sites or recycling plants.

3.2. Construction Phase

The construction phase comprises material production, transportation, and on-site erection. In this study, several assumptions were made when carrying out the LCA in this stage:

(1) The materials that were used for assessment included concrete, sand, cement, steel, brick, EPS insulation board, plaster board, and CLT panel. Other building materials were neglected due to their small amount. The details of RC and CLT design are presented in Tables 2–7.
(2) The energy consumption of the building materials are from the existing references [27], which are presented in Table 8.
(3) The carbon sequestration of CLT is considered in the assessment with the assumption that one cubic meter of timber would store 800 kg of CO_2 [17]. The mass and volume of CLT buildings are presented in Table 9.
(4) Erection of RC and CLT buildings are set to be 100 MJ/ m^2 and 20 MJ/m^2 [27].

Table 8. List of materials used for construction.

Materials	Units	Values
Concrete	GJ/t	0.764
Sand	GJ/t	0.029
Cement	GJ/t	3.186
Steel	GJ/t	19.520
Brick	GJ/t	0.218
EPS Insulation Board	GJ/t	94.000
Plaster Board	GJ/m^3	2.400
CLT Panel	GJ/m^3	0.545

Table 9. Mass and volume of CLT.

Floors	Total Timber Volume (m^3)	Total Material Mass (Ton)
4	835.0	417.5
7	1391.2	695.6
11	2132.9	1066.4
17	4520.7	2260.3

3.3. Operational Phase

3.3.1. Energy Scenario of the Operational Phase

The energy consumed in the operational stage was simulated using the commercial program IES^{TM} (Integrated Environmental Solutions), which is frequently and widely involved in all levels of research with respect to sustainable and environmental design for spaces, buildings, and cities. This software provides LCA tools within the virtual environment to allow users to evaluate the environmental impact of the model constructions. It is very convenient for the user to build up the intelligent model and make the simulation for fault detection and analysis. The models are allowed to set up some important simulation parameters, such as the building location, real-time occupation, and the environment temperature.

National and local building codes were used to set the basic information for the simulation. The basic parameters selected are presented in Table 10. The following assumptions were made for the purpose of the simulation:

(1) According to the building grade classification in China, the life span of the residential buildings is assumed to be 50 years.
(2) As mentioned earlier, only the energy used for heating, cooling and appliances is simulated.

(3) The indoor temperature is assumed to be controlled between 18 °C and 26 °C. The cooling and heating systems are operated automatically when the temperature is not in this range.
(4) According to previous studies, in the severe cold region of China, approximately 78% of total energy is used for space heating, space cooling and appliances in the residential buildings [17,33].

Table 10. Basic simulation parameters.

Room	No. of People	Occupied	Heating Time	Heating Set Point	Heating Month	Cooling Set Point	Ventilation Rate (When Occupied)
Bedroom (small)	1	21:00–8:00	24 h	18 °C	15 October to 15 April	26 °C	30 $m^3/h/per$
Bedroom (big)	2	21:00–8:00					30 $m^3/h/per$
Living room	2	8:00–21:00					30 $m^3/h/per$
Kitchen	2	10:00–12:00 16:00–18:00					300 m^3/h
Toilet	-	0:00–24:00					80 m^3/h

3.3.2. Carbon Emissions on the Operational Phase

The results obtained from the simulation of the operational stage are in the form of energy rather than carbon emissions. Conversion from energy into carbon emissions is done by multiplication of the carbon emission factors as per the following equation [34]:

$$E_t = \sum Q_{jt} C_j \eta_j \times \frac{11}{3} \quad (1)$$

where

E_t is the estimated amount of carbon emissions of the t-th studied city;
Q_{jt} is the j-th physical energy consumption of the t-th studied city;
C_j is the appropriate calorific value of j-th energy; and
η_j is the carbon emission factor of the j-th energy source.

As mentioned earlier, in this study electricity is used for cooling and appliances, while coal is used for heating. The values of C_j and η_j are summarised in Table 11 according to the existing references [34–36].

Table 11. C_j and η_j for coal and electricity.

Fossil Energy Items	C_j	η_j
Coal	20,934 kJ/kg	26.80 (t-C/TJ)
Electricity	3600 kJ/kWh	1.14 (t-CO_2/MWh, Northeast China)

3.4. End of Life Phase

The end-of-life stage consists of demolition, transportation, disposal, and recycling. Additionally, the estimated energy and carbon emissions were obtained on the following assumptions:

(1) According to the existing references, energy for demolition of a building can be assumed to be 90% of the energy required in the erection phase [27]. Demolition of RC and CLT buildings are set to be 90 MJ/m^2 and 18 MJ/m^2.
(2) For the concrete buildings, we assumed that all the concrete and steel materials would go into landfill after demolition. This is also the current practice in Northeast China. The recycle rate for the bricks is assumed to be 60%.
(3) For the CLT building, a recycle rate of 50% is assumed with 50% used for biomass energy.
(4) The energy consumption for transportation is neglected.

4. Results and Analysis

4.1. Results of Life-Cycle Assessment

The estimated LCA results of the comparative energy consumption and CO_2 emissions for RC and CLT buildings are presented in the Table 12. The results show that on construction phase, CLT buildings may result in approximately 46.5% energy saving than that of RC buildings on average. The CLT panels stored more CO_2 in itself than those emitted during the process of the construction phase, and more carbon reductions can be obtained if using CLT systems as an alternative to RC. The energy saving and carbon reduction performance of CLT systems are very remarkable.

Table 12. Estimated LCA results of the reference buildings (50 years).

Buildings	Floors	Energy Consumed (MJ/m^2)			CO_2 Emissions (kg/m^2)		
		Construction	Operation	End of Life	Construction	Operation	End of Life
RC buildings	4	1541.1	34,314.1	90.0	308.2	6916.7	18.0
	7	1463.2	33,320.5	90.0	292.6	6698.7	18.0
	11	1350.2	32,839.7	90.0	270.0	6596.2	18.0
	17	1326.6	32,538.5	90.0	265.3	6532.1	18.0
CLT buildings	4	847.5	31,455.1	18.0	−84.0	6314.1	45.6
	7	790.8	30,621.8	18.0	−85.7	6121.8	46.5
	11	711.3	30,160.2	18.0	−96.9	6025.6	52.0
	17	694.1	29,884.6	18.0	−97.4	5967.9	52.3

The results indicate that on operation phase, CLT systems also consume less energy than RC buildings. On average, the energy consumption of the RC framed buildings is approximately 8.2% more than that of the CLT buildings. When comparing carbon emissions, the former is 8.7% more than the latter. In the severe cold region of China, the energy required for space cooling, appliances and space heating accounts for approximately 78% of total energy consumption in Northeast China [17,33]. It is estimated that, on average, total energy consumption in residential building with RC frames and CLT system is approximately 665.1 MJ/m^2 and 610.6 MJ/m^2 per annum, respectively, during the operational stage. The estimated average value of CO_2 emissions during the operational stage in RC and CLT residential buildings is 133.7 kg/m^2 and 122.1 kg/m^2 per annum, respectively. These results reflect the outcomes from existing research [27,37,38]. In view of life-cycle assessment, on average, the CLT buildings may result in approximately 9.9% energy saving 13.2% carbon reduction comparing to RC-framed buildings.

4.2. Quality of Data

The dimensions of 4 concrete buildings were obtained directly from construction drawings. The reliability of the figures is considered as high, since it is official. While Eurocode 5 and relevant documents [30,31] are adopted as the design standards for CLT structures. The coefficients in Equation (1), such as C_j and η_j, are taken from relevant scientific references and China Energy Statistical Yearbooks published by China Statistics Press [35]. Some basic simulation settings, such as the range of room temperature, heating time and ventilation rate all followed the codes JGJ132-2001 and JGJ129-2000 for the severe cold regions in China.

5. Discussions

This paper focused on the comparisons of energy consumption and carbon emissions of residential buildings between RC framed and CLT systems in view of life-cycle assessment. The authors selected Harbin City in the severe cold region of China as the simulation environment, designed reference residential buildings ranging from 4 to 17 storeys, then simulated the energy performance using the commercial software IES^{TM} and finally made comparisons between the RC and CLT buildings.

Based on the results of this study, the following findings and policy suggestions are provided for policy-makers in China.

5.1. Relationship between Energy Consumption and Initial Cost

The results show that the CLT system consumes less energy than RC buildings. The energy consumption of the RC framed buildings is approximately 9.9% higher than that of CLT buildings. The carbon emissions are 13.2% more. The energy savings can increase if the thickness of the CLT panels is increased. For the purposes of this study the external wall was made up of 135 mm thick panels to meet the local energy code, but if this had to be increased to 150 mm thick CLT panels, the building with require 14.1% less energy than the RC building. The increased thickness would obviously increase the initial cost of the building, so the designer needs to balance the initial cost and the energy saving performance of the building. The optimisation of the building construction and performance could be the subject of further study.

The results also indicate that tall buildings consume less energy per square metre. In spite of the higher initial cost of the materials required for the structure in the construction phase, the results show that both RC and CLT high-rise residential buildings have higher energy efficiency than low-rise and mid-rise buildings in the severe cold region of China. High-rise buildings consume relatively less energy during the operational stage. The urbanisation level in China was approximately 56.10% in 2015, compared to 25.84% in 1990. According to the national policy in China, 880 million people will be living in urban areas by 2030 [9]. This means that more people will move to the cities from rural areas and more residential buildings will be needed to accommodate new dwellers. The residential land in the city is limited, and developing high-rise residential buildings will be an inevitable trend.

The initial construction cost of the CLT buildings may be a fundamental factor that affects the development and adoption of this material. As mentioned previously, existing data from the US and Europe shows that the cost of CLT residential buildings is approximately the same as that of traditional building materials such as concrete, bricks, and steel. In addition to the economic competiveness of the material, the faster on-site construction speed of CLT buildings may also help to reduce labour and drive down initial costs, while better energy performance and lower carbon emission may further reduce the cost during the operational stage. As a result, if it is necessary to import CLT panels from Europe at the initial stage, cost should not be an obstacle to the development of CLT in China. Currently, most timber buildings in China are light-weight frame buildings and the heights of these buildings are limited to three-floors. There is great potential for China to develop CLT system for the construction of eight to 18 storey residential or commercial buildings instead of traditional building materials.

5.2. Potential Carbon Absorption of Cement and RC

In this study, the carbonation and durability of cement and RC are not taken into consideration. The existing references have mentioned that carbonation of reinforced concrete is one of the causes of corrosion, however, it is also an effective way to sequester CO_2 [39]. More than half of the CO_2 emitted from the calcination of limestone during the production of cement, but this CO_2 would be reabsorbed during the life-cycle of cement products, such as concrete and mortars, in the carbonation process [40]. Tatiana et al. pointed that concrete made with Portland cement, FA blended cement (35% FA), and BFS blended cement (80% BFS) captures 47%, 41%, and 20% of CO_2 emissions, respectively [41]. Isabel et al. highlighted that increasing the amount of cement in the concrete, both the carbonation depth and the amount of CO_2 absorbed decrease, being the main cause for that the decrease in porosity. However, the material production parameters of RC buildings are not available in this study. If taking the carbonation process of cement and RC into consideration, the RC buildings would release less CO_2 than estimated. The potential carbon absorption of cement and RC requires further studies.

5.3. Potential Development of CLT Industry

The increasing forest area will also provide strong support for China to develop the CLT industry. China has made significant progress in afforestation and the conservation of forests. In 2008, the forest area was 195.5 million hectares, which accounted for 20.4% of the national land area, and this figure increased to 22.2% by 2015. The country plans to increase the forest storage to 16.5 billion cubic metres by 2020, which accounts for 23.04% of the national land area [17]. Harbin is the capital city of Heilongjiang Province located in Northeast China. As shown in Figure 5, the forest coverage in this region is approximately 38% in 2015, which is much higher than the national average. Timber storage in Heilongjiang accounts for a quarter of the national total in China. This region also possesses a complete industrial timber chain which covers harvesting, operation, and production. It can be predicted that it is definitely possible to develop the CLT industry in this region as an initial scheme which can then be extended to the whole country.

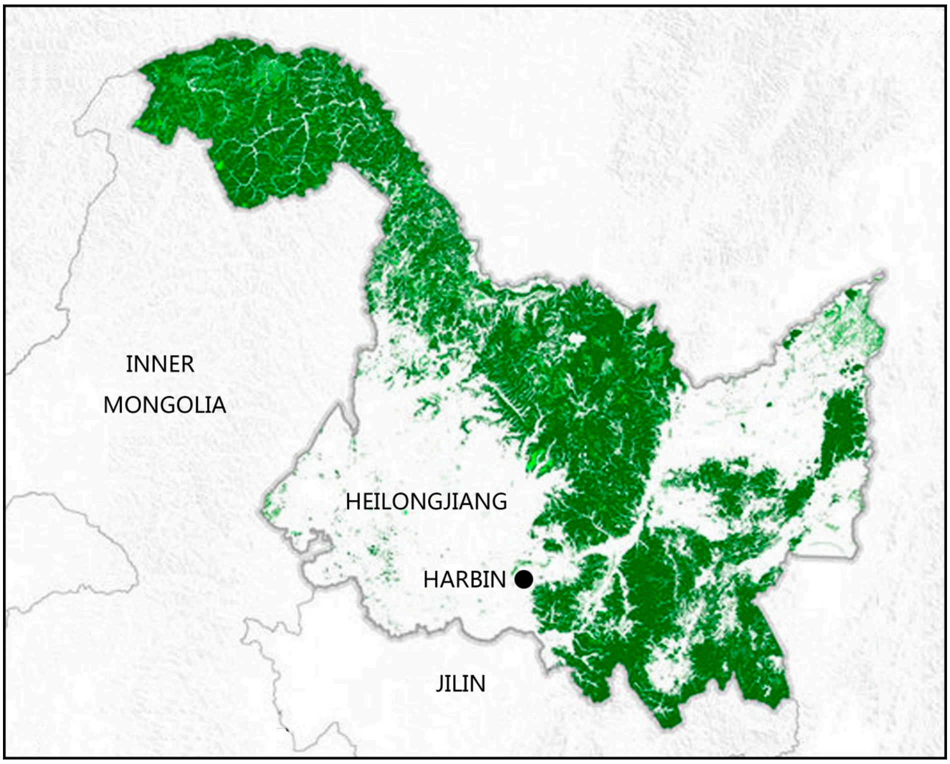

Figure 5. The forest distribution of Heilongjiang Province in Northeast China.

6. Conclusions

This paper assesses the energy consumption of residential buildings constructed in reinforced concrete (RC)-framed and CLT systems. The buildings considered range from 4 to 17 storeys. The conclusions drawn by this study enable policy makers to understand the energy saving performance of CLT in the severe cold region of China and to formula relative strategies to develop the CLT system. Based on the results of this study, the main findings can be summarised as follows:

(1) Energy efficiency is closely related to height for both RC and CLT residential buildings. Both RC and CLT tall residential buildings consume relatively less energy per square metre than low-rise and mid-rise buildings in the severe cold region of China.

(2) The estimated energy consumption and carbon emissions in CLT buildings are 9.9% and 13.2% lower than those of RC buildings in view of LCA, and energy savings can be increased further by increasing the initial thickness of the CLT panels.

(3) CLT systems have good potential for energy saving when compared to RC construction in the severe cold region of China. It deserves to be given adequate attention by policy-makers.

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