buildings

MDPI

Article

Life Cycle Carbon Emission Analysis of Buildings with Different Exterior Wall Types Based on BIM Technology

Yuelong Lyu *, Nikita Igorevich Fomin *, Shuailong Li, Wentao Hu, Shuoting Xiao, Yue Huang and Chong Liu

Ural Federal University Named After the First President of Russia B.N. Yeltsin (UrFU), St. Mira, 19, Yekaterinburg 620002, Russia

* Correspondence: iuelun.lui@urfu.me (Y.L.); ni.fomin@urfu.ru (N.I.F.); Tel.: +7-(912)-616-4631 (Y.L.)

Abstract: Building energy conservation and emission reduction are crucial in addressing global climate change. High-performance insulated building envelopes can significantly reduce energy consumption over a building's lifecycle. However, few studies have systematically analyzed carbon reduction potential through a life cycle assessment (LCA), incorporating case studies and regional differences. To address this, this study establishes an LCA carbon emission calculation model using Building Information Modeling (BIM) technology and the carbon emission coefficient method. We examined four residential buildings in China's cold regions and hot summer–cold winter regions, utilizing prefabricated concrete sandwich insulation exterior walls (PCSB) and autoclaved aerated concrete block self-insulating exterior walls (AACB). Results indicate that emissions during the operational phase account for 75% of total lifecycle emissions, with heating, ventilation, and air conditioning systems contributing over 50%. Compared to AACB, PCSB reduces lifecycle carbon emissions by 18.54% and by 20.02% in hot summer–cold winter regions. The findings demonstrate that PCSB offers significant energy-saving and emission-reduction benefits during the construction and operation phases. However, it exhibits higher energy consumption during the materialization and demolition phases. This study provides a practical LCA carbon calculation framework that offers insights into reducing lifecycle carbon emissions, thereby guiding sustainable building design.

Keywords: building life cycle analysis; carbon emissions; BIM; insulated exterior walls; energy conservation and emission reduction

check for updates

Academic Editor: Theodosiou Theodoros

Received: 3 December 2024
Revised: 31 December 2024
Accepted: 3 January 2025
Published: 5 January 2025

Citation: Lyu, Y.; Fomin, N.I.; Li, S.; Hu, W.; Xiao, S.; Huang, Y.; Liu, C. Life Cycle Carbon Emission Analysis of Buildings with Different Exterior Wall Types Based on BIM Technology. *Buildings* **2025**, *15*, 138. https://doi.org/10.3390/buildings15010138

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Global climate change, driven by global warming, has become a focal point of widespread concern. As a significant contributor to global energy consumption (36%) and greenhouse gas emissions (39%), the construction industry plays a crucial role in addressing global warming and promoting sustainable development [1].

To address this challenge, the Paris Agreement has set targets for achieving carbon neutrality in new buildings by 2030 and full carbon neutrality by 2050 [2]. The increasing number of construction activities has accelerated resource depletion and exacerbated climate change threats. As a crucial tool for quantifying environmental impacts, carbon footprint analysis is increasingly employed to assess and mitigate climate risks. Life cycle assessment (LCA) is a widely recognized environmental evaluation method used to quantify carbon emissions throughout a building's life cycle, from production to demolition [1,3,4].

Studies have shown that the operational phase accounts for the largest proportion of energy consumption throughout a building's lifecycle [5,6]. Thus, reducing lifecycle carbon

emissions during this phase has become a key focus in building energy efficiency research. Optimizing building design plays a significant role in reducing energy consumption and improving energy efficiency. Effective energy-saving measures lower a building's energy demand, directly decreasing fossil fuel consumption and consequently reducing greenhouse gas emissions such as carbon dioxide [7]. Data indicate that optimizing building envelope materials and construction techniques can reduce building energy consumption by 28–66% [8].

By controlling the selection of exterior wall materials, the dimensions of the building envelope, and its thermal performance, the use of air conditioning and heating can be effectively reduced. Hence, carbon emissions can be lowered during the building's operational phase [9]. Therefore, improving building envelope performance holds significant potential for energy conservation and carbon emission reduction, attracting widespread attention from scientists.

Some researchers have analyzed the energy consumption of building envelopes to evaluate their impact on the overall building carbon emissions. For instance, Adem Atmaca's study on two Turkish buildings revealed that installing an 80 mm insulation layer reduced carbon emissions by 23.4% over the building's life cycle, from construction to demolition [10]. Similarly, based on a thermoeconomic analysis of rural residential walls, Li et al. determined that using phase change materials saved 12.8% of energy and significantly reduced carbon emissions [11].

Other studies used Building Information Modeling (BIM) technology to simulate building envelopes and optimize energy-saving strategies. Karami et al. analyzed the impact of different insulated exterior walls on carbon emissions during the embodied and operational phases and showed that vacuum insulation panels reduced emissions [12]. Using an orthogonal experimental design, Yue et al. investigated energy-efficient envelope designs for public buildings in cold regions and demonstrated that an optimal insulation material thickness significantly lowers energy consumption [13]. Song evaluated innovative and traditional hollow brick wall materials using simulation models and proposed optimal energy-saving strategies [14].

However, some scholars have highlighted limitations in existing research. First, the comprehensiveness of building lifecycle carbon footprint analysis remains insufficient. Mostafaei et al. highlighted that the construction industry is a key contributor to carbon emissions, with impacts extending across the entire lifecycle of construction projects [1]. Therefore, a thorough examination and comprehensive assessment of the carbon footprint within this sector are essential [15]. Building lifecycle carbon emissions include operational and embodied emissions. However, most studies focus more on energy consumption and carbon emissions during the operational phase, with relatively less attention focused on embodied carbon. Based on a statistical analysis of 85 previous building carbon footprint studies, Huang et al. found that only seven studies (8.2%) covered all stages from material production to demolition and recycling [1]. However, research indicates that the importance of embodied emissions is gradually increasing, which are often underestimated in lifecycle emission analyses. This oversight may lead to a fragmented understanding of the research results [16].

Second, insufficient engineering validation limits the practical application of the research findings. Numerous studies are theoretical and lack validation in real-world scenarios. This reduces the applicability of the findings and renders them less useful as direct references for designers and engineers [17].

Finally, the lack of analysis on climate zone adaptability remains a significant issue. The importance of regional climate adaptability optimization is closely tied to energy-efficient building design [18]. Different climate zones exhibit significant differences in requirements

for exterior wall material selection, design thickness, and construction techniques. However, many studies focus on a single climate zone, lacking cross-regional comparisons. This gap prevents a comprehensive understanding of the strengths, weaknesses, and adaptability of exterior wall design schemes across different regions [19].

In summary, the existing research mainly focuses on the thermodynamic properties of exterior wall materials and carbon emissions during the operational and embodied phases. However, a systematic examination of the carbon reduction potential of building exterior walls from a lifecycle perspective across multiple regions remains underexplored.

This study investigates four residential buildings in China's cold and hot summer–cold winter regions, featuring prefabricated concrete sandwich-insulated exterior walls (PCSB) and autoclaved aerated concrete block self-insulated exterior walls (AACB). Using BIM technology, a calculation model was established based on the carbon emission factor method with the building life cycle as the boundary. This study analyzes the main differences and influencing factors of lifecycle carbon emissions for buildings with different exterior walls in various regions to provide strategies for building energy conservation and carbon reduction.

With the rapid advancement of urbanization, accurately and efficiently calculating building carbon emissions has become increasingly important to achieve the energy-saving and emission-reduction goals of the construction industry. Owing to the complexity of materials and tools involved throughout a project's lifecycle, traditional assessment methods often rely on the bill of quantities (BOQ) approach, requiring manual calculation and data input. This process is not only time-consuming and labor-intensive but also prone to omissions and errors. BIM technology integrates architectural data, material information, and other relevant parameters to analyze energy consumption and carbon emissions [20]. Therefore, employing BIM technology to study the impact of different exterior wall types on the lifecycle carbon footprint of buildings holds significant importance.

2. Methodology

This study selects four buildings located in cold and hot summer–cold winter regions of China, featuring PCSB and AACB. A calculation model is established based on BIM technology, employing the carbon emission factor method as the calculation approach and defining the building's entire lifecycle as the research boundary. The study analyzes the key differences and influential factors of lifecycle carbon emissions in buildings with different exterior walls across distinct regions, aiming to provide effective strategies for building energy conservation and carbon emission reduction.

2.1. Calculation Model

2.1.1. Structure of Building Exterior Walls

A traditional autoclaved aerated concrete block self-insulated exterior wall (CBW) is a form of wall construction that integrates structural and insulation functions, making it widely used for building exteriors [21].

Conversely, a prefabricated concrete sandwich-insulated wall panel (PSW) is a composite wall comprising multiple layers of materials. Its defining feature is the inclusion of an insulation material sandwiched between structural or protective layers, resembling a "sandwich" structure, hence its name. Owing to its excellent thermal insulation performance, structural strength, and the use of prefabricated panels, this type of wall is commonly employed in modern energy-efficient buildings. Prefabrication allows for the production of panels in factories and their direct transportation to construction sites, offering advantages such as ease of construction, consistent quality, and improved efficiency [22].

2.1.2. Climate Zoning

According to the current Chinese national standards, including the Code for the Design of Civil Buildings (GB 50352), the Standard for Climatic Regionalization of Buildings (GB 50178), and the Code for the Thermal Design of Civil Buildings (GB 50176), China's building climate zones are classified into seven main types, including cold regions and hot summer–cold winter regions [23–25].

- Cold Region: Characterized by extremely cold winters and short, mild summers, building designs in these regions focus on insulation and heating systems. The emphasis is placed on improving thermal insulation performance and ensuring energy efficiency in building envelopes.
- Hot Summer-Cold Winter Region: This region experiences hot, humid summers and cold winters, with significant seasonal temperature variations. Building designs prioritize thermal insulation and energy efficiency in air-conditioning systems while also enhancing heating efficiency during winter [26].

Qingdao and Wuhan represent the aforementioned two climate zones, respectively. The annual average temperature distributions for these cities are shown in the accompanying Figure 1 [27,28].

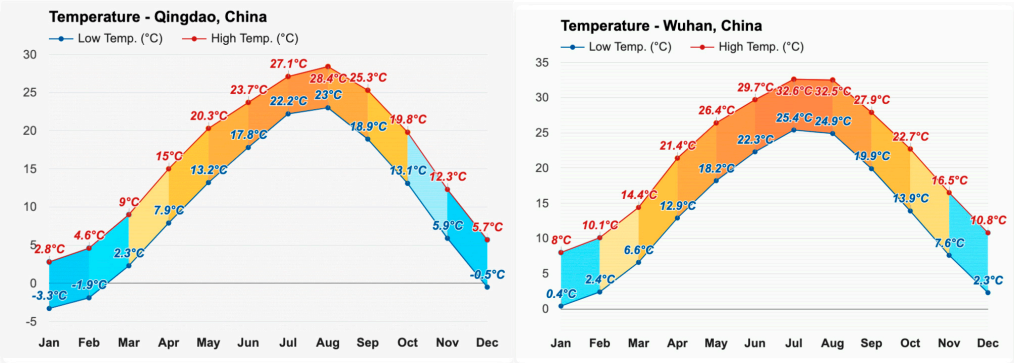


Figure 1. Average annual temperatures in Wuhan and Qingdao.

2.1.3. Project Overview

A comparative analysis of four residential building models with PCSB and AACB in different regions was conducted. The basic parameters of each project are listed in Table 1, and the building model and wall sections are shown in Figure 2.

Table 1. Project details.

Project	Project A	Project B	Project C	Project D
Region	Huangdao District, Qingdao	Shibei District, Qingdao	Qingshan District, Wuhan	Hancheng District, Wuhan
Climate Type	Cold Region	Cold Region	Hot Summer–Cold Winter Region	Hot Summer–Cold Winter Region
Area (m^2)	9743.24	14,533.89	18,870.75	540.33
Number of Floors	17	33	45	5
Building Exterior Wall Type	PCSB	AACB	PCSB	AACB

Table 1. *Cont.*

Project	Project A	Project B	Project C	Project D
Exterior Wall Material	Reinforced Concrete, Expanded Polystyrene Foam	Cement Mortar, Autoclaved Aerated Concrete Blocks	Reinforced Concrete, Rock Wool Board	Cement Mortar, Autoclaved Aerated Concrete Blocks
Exterior Wall Construction (from outside to inside)	First Layer: Reinforced Concrete (60.0 mm) Second Layer: Expanded Polystyrene Foam (50.0 mm) Third Layer: Reinforced Concrete (200.0 mm)	First Layer: Cement Mortar (8.0 mm) Second Layer: AACB B06 (235.0 mm) Third Layer: Cement Mortar (10.0 mm)	First Layer: Reinforced Concrete (60.0 mm) Second Layer: Rock Wool Board (50.0 mm) Third Layer: Reinforced Concrete (200.0 mm)	First Layer: Cement Mortar (10.0 mm) Second Layer: AACB B06 (200.0 mm) Third Layer: Cement Mortar (10.0 mm)

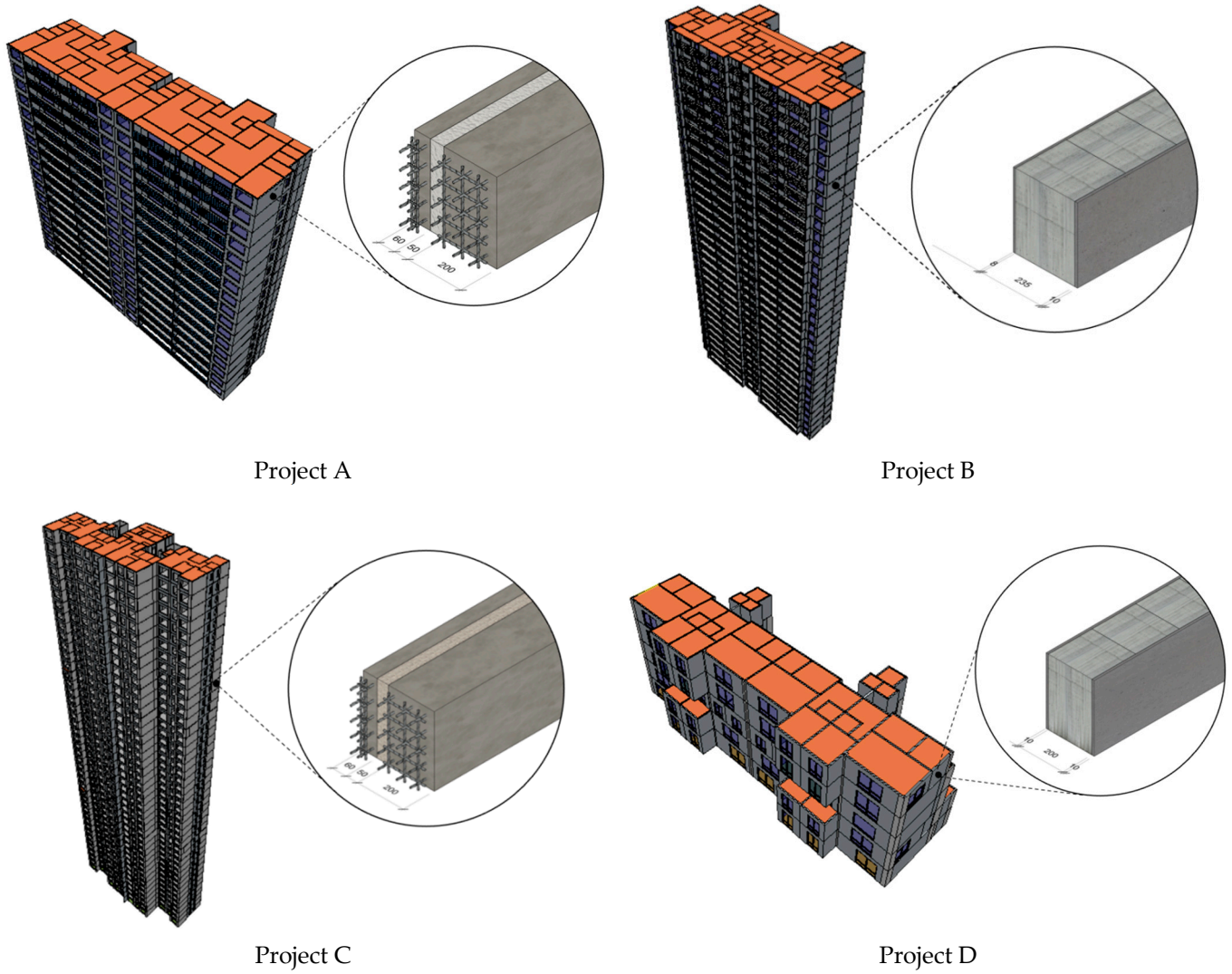


Figure 2. Building models and wall sections.

Regional and structural differences in building models offer a comprehensive basis for analyzing lifecycle carbon emissions across varying climates and exterior wall configurations.

2.2. Calculation Methods

2.2.1. Algorithm Logic

This study utilizes the PKPM-GBP 2024 software developed by Beijing Glory Technology Co., Ltd., from the China Academy of Building Research. This software supports the DOE and IBE cores to calculate building energy consumption and carbon emissions. The software enables 3D modeling, operational simulation, and energy consumption calculations, providing a relatively accurate platform for building carbon emission research and foundational building data [29].

In this study, BIM technology is employed to digitize building drawings, material information, and calculation parameters. This modeling process integrates data such as building geometry, structure, and materials. Subsequently, the built-in simulation calculation engine of the BIM software (PKPM-GBP 2024) is used to generate building energy consumption lists, mechanical equipment operating hours, transportation volume schedules, and material lists. Finally, by matching the carbon emission factor database and following the provisions of the *Standard for Building Carbon Emission Calculation* (GB/T 51366-2019) [30] and *General Specification for Building Energy Efficiency and Renewable Energy Utilization* (GB 55015-2021) [31], the carbon emissions of buildings at different lifecycle stages are calculated. The algorithmic logic based on BIM is illustrated in Figure 3.

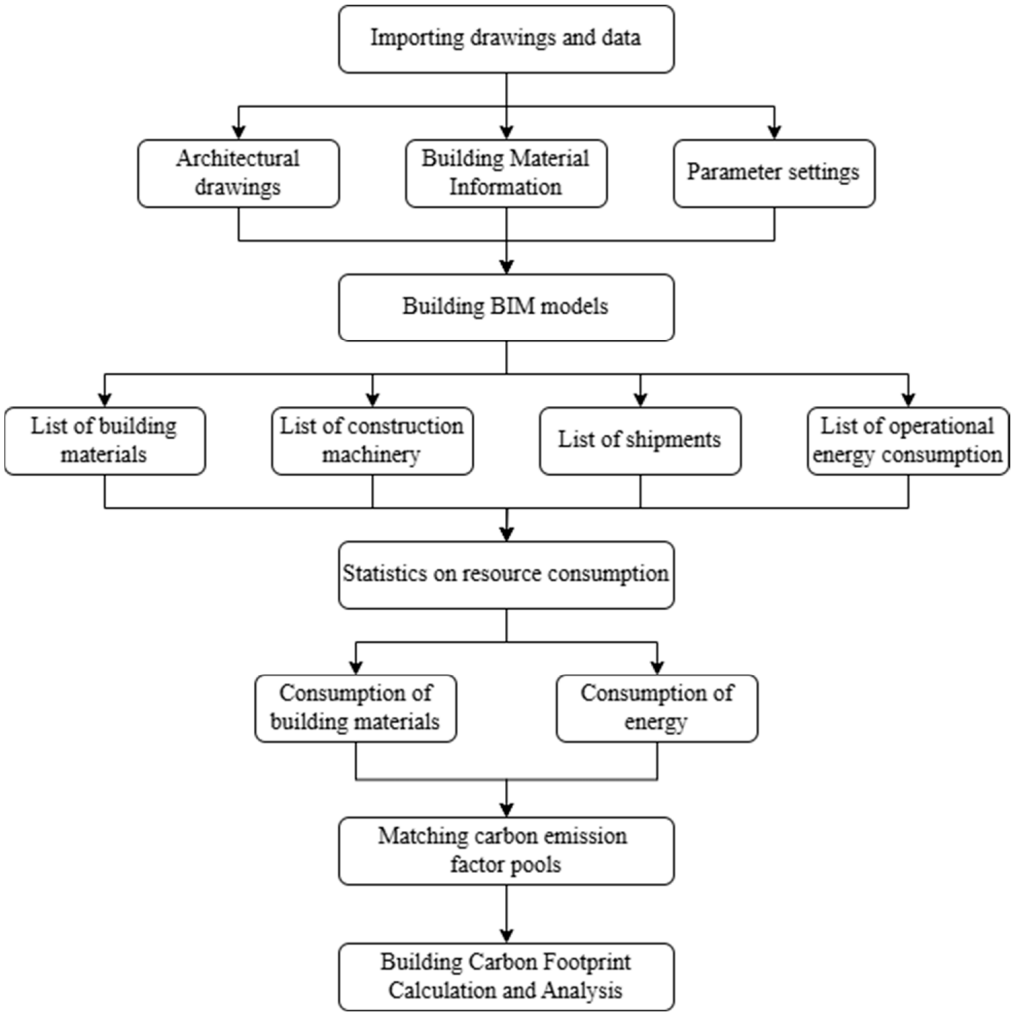


Figure 3. Algorithm logic of the carbon emission factor method based on BIM technology.

2.2.2. Carbon Emission Factor Analysis

Currently, three methods are commonly used for calculating building carbon emissions: carbon emission factor, material balance, and direct measurement methods. The carbon emission factor method, proposed by the Intergovernmental Panel on Climate Change (IPCC), establishes a database of carbon emission factors for each emission source. The total carbon emissions of a project are calculated as the product of activity data and carbon emission factors [32].

The carbon emission factor is a coefficient that correlates energy and material consumption with CO_2 emissions, enabling the quantification of carbon emissions associated with activities during various building lifecycle stages [30]. Compared to other methods, the carbon emission factor method is advantageous because of its simplicity and rapid calculation, making it suitable for this study. This study applies the carbon emission factor method to analyze case studies using project bill data to calculate emissions.

The analyses included commonly used energy sources, building materials, construction machinery, and transportation. The grid carbon factor is based on the 2022 national average of China's power grid [33], while other carbon emission factors are derived from values specified in the "Standard for Calculation of Building Carbon Emissions" (GB/T 51366-2019) [30]. The specific carbon emission factors used in this study are listed in Tables 2–7.

2.2.3. Calculation Boundary

The system boundary is defined according to ISO 21930 [34], which divides the building lifecycle into six stages: material production, material transportation, construction, building operation, building demolition, and material recycling.

The material-production, transportation, and construction stages are collectively referred to as the embodied stage, whereas the demolition and material recycling stages are collectively referred to as the demolition and recycling stage. CO_2 emissions from the embodied and demolition stages are classified as embodied carbon, while those from the operational stage are classified as operational carbon [35].

Given that each stage involves distinct energy consumption and CO_2 emissions, the calculations must be conducted individually. The calculation boundaries are shown in Figure 4. Carbon emission sources and recoverable carbon sinks at each stage are shown in Figure 5.

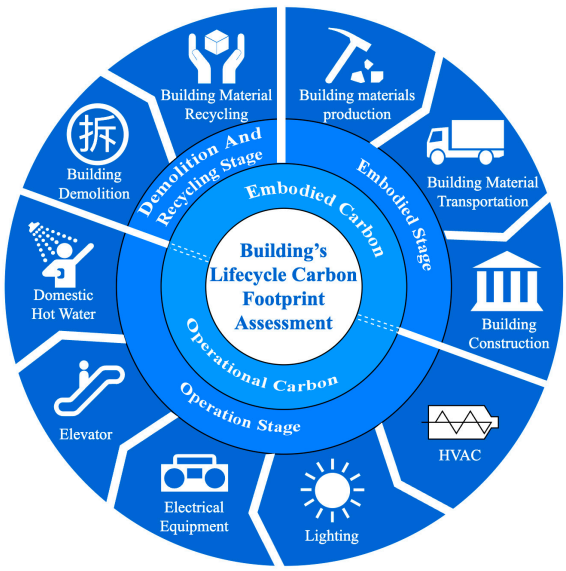


Figure 4. Calculation boundary for building life cycle carbon emissions.

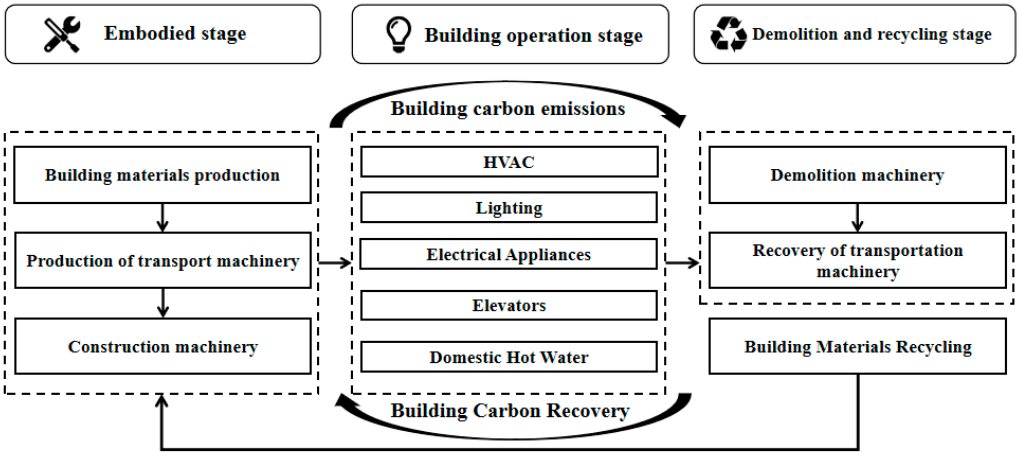


Figure 5. Boundary map of carbon source and sink systems.

2.2.4. Calculation Formulas

The average carbon emission per unit area of a building's LCA can be calculated as follows (unit: $kgCO_2e/m^2$):

$$P_L = P_M + P_T + P_C + P_O + P_D + P_R \quad (1)$$

Here,

- P_M: Average carbon emissions during the material-production phase.
- P_T: Average carbon emissions during the material-transportation phase.
- P_C: Average carbon emissions during the construction phase.
- P_O: Average carbon emissions during the operational phase.
- P_D: Average carbon emissions during the demolition phase.
- P_R: Average carbon emissions during the material recycling phase.

The calculation formulas for each stage are as follows [30].

Material-Production Phase

The average carbon emissions during the material-production phase were calculated based on the material list.

$$P_M = \sum_{i=1}^{n} M_i MF_i / A \quad (2)$$

Here,

- M_i: Consumption of the i-th main building material (t).
- MF_i: Carbon emission factor of the iii-th main building material ($kgCO_2e/t$).
- A: Building area (m^2).

Material-Transportation Phase

The average carbon emissions during the material-transportation phase can be calculated using transportation schedules:

$$P_T = \sum_{i=1}^{n} M_i D_i TF_i / A \quad (3)$$

Here,

- M_i: Consumption of the i-th main building material (t).
- D_i: Average transportation distance of the i-th material (km).

- TF_i: Carbon emission factor of the i-th material for the transportation method used [$kgCO_2e/(t \cdot km)$].

Construction Phase

The average carbon emissions during the construction phase are calculated using construction machinery schedules:

$$P_C = \sum_{i=1}^{n} E_i EF_i / A \tag{4}$$

Here,

- E_i: Energy consumption of the i-th type of machinery (kg or kWh).
- EF_i: Carbon emission factor of the ith type of energy ($kgCO_2e$/kWh or $kgCO_2e$/kg).

Operational Phase

The average carbon emissions during the operational phase were calculated based on the following operational energy consumption list:

$$P_O = \sum_{i=1}^{n} EY_i EF_i Y / A \tag{5}$$

Here,

- EY_i: Annual consumption of ith type of energy (kg or kWh).
- EF_i: Carbon emission factor of the ith type of energy ($kgCO_2e$/kWh or $kgCO_2e$/kg).
- Y: Building design lifespan (a).

Demolition Phase

If detailed demolition machinery schedules were available, then the calculation method could be followed by the PC formula.

Otherwise, demolition-phase emissions can be estimated using an empirical formula from the "Guangdong Building Carbon Emission Calculation Guidelines" [36]:

$$P_D = 0.06X + 2.01 \tag{6}$$

Here,

- X: Number of above-ground floors.

Material Recycling Phase

The carbon footprint during the material recycling phase includes emissions from transportation and carbon reductions from material recycling. Average carbon emissions were calculated as follows:

$$P_R = (C_{TR} - C_{MR}) / A \tag{7}$$

Here,

- C_{TR}: Carbon emissions during the recycling transportation process ($kgCO_2e$).
- C_{MR}: Carbon reductions from material recycling ($kgCO_2e$).

Transportation emissions for recyclable materials are calculated as:

$$C_{TR} = \sum_{i=1}^{n} M_{r,i} D_{r,i} TF_i \tag{8}$$

Here,

- $M_{r,i}$: Quantity of recyclable material i (t).
- $D_{r,i}$: Average transportation distance for recyclable material i (km).
- TF_i: Carbon emission factor for the transportation method used [$kgCO_2e/(t \cdot km)$].

Carbon reductions from material recycling are calculated as:

$$C_{MR} = \sum_{i=1}^{n} M_{r,i} \eta_i RF_i \quad (9)$$

Here,

- $M_{r,i}$: Quantity of recyclable material i (t).
- η_i: Recycling rate of material i (%).
- RF_i: Recycling factor of material i ($kgCO_2e/t$).

3. Case Study and Results

Project A is a 17-story residential building constructed in 2023 in Huangdao District, Qingdao, China, with a building area of 9743.24 m^2. A model was developed based on Project A to calculate the carbon emissions for each lifecycle stage, and the results are as follows.

3.1. Carbon Emissions in the Material-Production Phase

Using BIM, a material list was generated, and the main building materials were selected. The quantities and carbon emission factors of these materials are obtained and are listed in Table 2. By applying Equation (2), the carbon emissions during the material-production phase were calculated as 2575.97 tCO_2e.

Table 2. Carbon emission calculations for the material-production and transportation phases.

Material Type	Quantity	Unit	Material Carbon Emission Factor (tCO_2e/unit)	Transport Distance (km)	Production Carbon Emissions (tCO_2e)	Transportation Carbon Emissions (tCO_2e)
Reinforced Concrete	3649.66	m^3	0.295	40	1076.65	121.90
Expanded Polystyrene Foam	10.85	t	5.02	500	54.45	1.81
Metal Profiles	446.24	m^2	0.254	500	113.34	14.08
Glass	54.74	t	2.84	500	155.45	9.14
Cement Plaster	24.36	t	0.735	500	17.91	4.07
Fine-Stone Concrete	27.07	m^3	0.295	40	7.99	0.90
Cement Mortar	278.36	m^3	0.7302	500	203.26	83.67
Waterproof Coating	1.35	t	0.9514	500	1.29	0.23
Lime Cement Mortar	400.48	m^3	0.7302	500	292.43	113.70
AAC Block B06	1666.25	m^3	0.25	500	416.56	166.96
Single-Layer Solid Door	875.16	m^2	0.254	500	222.29	27.62
Crushed Concrete	92.27	t	0.126	40	11.63	1.23
Waterproof Membrane	2.87	t	0.9514	500	2.73	0.48
Total	--	--	--	--	2575.97	545.80

3.2. Carbon Emissions in the Material-Transportation Phase

The transportation phase includes direct carbon emissions from transporting construction materials from production sites to the construction site and emissions generated during the production of energy consumed during transportation.

The transportation distances for major materials are based on the default values provided in Appendix E of the "Standard for Calculation of Building Carbon Emissions" (GB/T 51366-2019) [30]. Considering that the materials were sourced locally within Shandong Province, suppliers located within a 500 km range were selected. All materials were transported by road using gasoline-powered trucks, with a carbon emission factor of 0.000334 $tCO_2e/(t{\cdot}km)$. The transportation distances for each material are listed in Table 2. Using Equation (3), the carbon emissions for the material-transportation phase were calculated as 545.80 tCO_2e.

3.3. Carbon Emissions in the Construction Phase

The mechanical energy consumption during the construction phase was calculated based on the quantities extracted from the BIM-generated project BOQ. Construction machinery is classified into three categories based on energy type: electric, diesel, and gasoline-powered equipment.

Electric machinery includes construction elevators, concrete pumps, mortar mixers, rebar cutters, and arc-welding machines.

Diesel machinery comprised tracked excavators, diesel pile drivers, and cranes.

Gasoline machinery primarily included heavy-duty and dump trucks used during construction.

The total energy consumption was calculated by multiplying the energy consumption per unit of operation by the total number of operational hours of the equipment. The energy consumption and carbon emission factors are listed in Table 3. Using Equation (4), carbon emissions during the construction phase were calculated as 129.49 tCO_2e.

Table 3. Carbon emission results for energy consumption in the construction phase.

Energy Type	Consumption	Emission Factor (tCO_2/unit)	Carbon Emissions (tCO_2)
Gasoline	4288.25 kg	0.0029286	12.55
Diesel	11,363.71 kg	0.0031	35.23
Electricity	89,699.83 kWh	0.0005703	51.16
Total	--	--	129.49

3.4. Carbon Emissions in the Building Operational Phase

To standardize the variables, carbon emissions during the operational phase were calculated for heating, ventilation, and air conditioning (HVAC) systems; domestic hot water; electrical appliances (sockets); lighting; and elevators. Reductions in renewable energy and carbon sinks were not considered. The designed lifespan of the building was assumed to be 50 years.

The energy consumption of the HVAC systems was calculated using energy simulation software, and lighting and domestic hot water were converted into equivalent electricity consumption. The HVAC energy-consumption parameters were set according to Appendix C of the General Code for Building Energy Conservation and Renewable Energy Utilization (GB 55015-2021) [31]. For severe cold and cold regions, the HVAC system coefficient of performance (COP) was set to 3.60 for cooling and 2.18 for heating, following the Design Standard for Energy Efficiency of Residential Buildings in Severe Cold and Cold Regions (JGJ26-2010) [37]. For hot summer–cold winter regions, the COPs were set to 3.60 for cooling

and 2.60 for heating, based on the Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Cold Winter Regions (JGJ134-2010) [38].

The elevator energy consumption was standardized according to the Technical Conditions for Elevators (GB/T 10058-2009) [39], and domestic hot water was supplied via electric boilers. The per capita daily water usage was set at 50 L, with a temperature difference of 45 °C, and hot water supply was assumed to be year-round.

The total annual electricity consumption and associated carbon emissions for all the building systems are summarized in Table 4. Using Equation (5), the carbon emissions during the operational phase were calculated to be 10,684.16 tCO_2e.

Table 4. Summary of electricity consumption and carbon emissions in the operational phase.

Energy Use Type	Annual Equivalent Electricity Consumption (kWh)	Energy Form	Energy Consumption	Carbon Emission Factor (tCO_2/unit)	Carbon Emissions (tCO_2)
HVAC (Cooling)	8781.67	Electricity (kWh)	8781.67	0.0005703	250.41
HVAC (Heating)	201,601.21	Electricity (kWh)	201,601.21	0.0005703	5748.66
Lighting	48,892.84	Electricity (kWh)	48,892.84	0.0005703	1394.18
Electrical Appliances	67,340.52	Electricity (kWh)	67,340.52	0.0005703	1920.22
Elevators	16,730.12	Electricity (kWh)	16,730.12	0.0005703	477.06
Domestic Hot Water	31,339.16	Electricity (kWh)	31,339.16	0.0005703	893.64
Total	--	--	--	--	10,684.16

3.5. Carbon Emissions in the Demolition Phase

As the project is still under construction, actual data on the demolition machinery are unavailable. Therefore, an empirical formula was used to estimate carbon emissions during the demolition phase. Using Equation (6), the unit area carbon emissions were calculated using an empirical formula. The total carbon emissions for the demolition phase were derived by multiplying the unit area emissions by the building area. The results are shown in Table 5, and the total carbon emissions during the demolition phase are calculated as 29.52 tCO_2e.

Table 5. Carbon emissions in the demolition phase.

Building Area (m^2)	Number of Above-Ground Floors	Unit Area Carbon Emissions ($kgCO_2/m^2$)	Total Demolition Carbon Emissions (tCO_2)
9743.24	17	3.03	29.52

3.6. Carbon Emissions in the Material Recycling Phase

The material recycling phase includes carbon emissions from energy consumption during the transportation of recyclable materials and carbon reduction achieved through the reuse of recycled materials. The recyclable material types, recycling factors, and recycling rates were determined using a material list and data from Chen et al. [40] (refer to Table 6).

For consistency, transportation during the recycling phase was assumed to be conducted using gasoline-powered trucks over a distance of 10 km, with a carbon emission

factor of 0.000334 $tCO_2e/(t{\cdot}km)$. Using Equations (7)–(9), the total carbon reduction during the material recycling phase was calculated to be 311.65 tCO_2e.

Table 6. Carbon emission and reduction statistics in the material recycling phase.

Material Type	Quantity	Unit	Recycling Factor (tCO_2e/unit)	Recycling Rate	Transport Factor [$tCO_2e/(t{\cdot}km)$]	Carbon Reduction (tCO_2e)
Reinforced Concrete	3649.66	m^3	0.0149841	0.70	0.0003340	7.81
Metal Profiles	446.24	m^2	0.0597971	0.80	0.0003340	21.07
Fine-Stone Concrete	27.07	m^3	0.0149841	0.70	0.0003340	0.06
Waterproof Layer	1.35	t	0.7905933	0.70	0.0003340	0.74
AAC Block (B06)	1666.25	m^3	0.2077447	0.70	0.0003340	238.97
Single-Layer Solid Door	875.16	m^2	0.0597971	0.80	0.0003340	41.31
Crushed Concrete	92.27	t	0.0064000	0.70	0.0003340	0.11
Waterproof Membrane	2.87	t	0.7905933	0.70	0.0003340	1.58
Total	--	--	--	--	--	311.65

3.7. Results

Owing to space limitations, the calculation methods for Projects B–D were the same as those for Project A, and the detailed calculations were omitted. The calculation models and parameters for all the projects are listed in Table 1. The average carbon emissions per unit area for each LCA stage is shown in Table 7.

Table 7. Carbon emissions per unit area for each stage ($kgCO_2/m^2$).

Stage	Project A	Project B	Project C	Project D
Material-production stage	264.39	278.87	317.88	304.57
Material-transportation stage	56.02	71.29	111.92	182.37
Construction stage	13.29	28.96	13.95	31.04
Building operation stage	1096.57	1358.02	1004.18	1278.03
Building demolition stage	3.03	3.99	4.71	2.31
Material recycling stage	−31.98	−53.07	−30.35	−19.92
Total	1401.32	1688.06	1422.29	1778.40

The proportion of unit area carbon emissions at each stage of the LCA for the four projects is shown in Table 8.

Table 8. Proportion of carbon emissions by stage.

Stage	Project A	Project B	Project C	Project D
Building materials production and recycling stage	16.58%	13.37%	20.22%	16.01%
Material-transportation stage	4.00%	4.22%	7.87%	10.25%
Construction stage	0.95%	1.72%	0.98%	1.75%
Building operation stage	78.25%	80.45%	70.60%	71.86%
Building demolition stage	0.22%	0.24%	0.33%	0.13%
Total	100.00%	100.00%	100.00%	100.00%

4. Analysis and Discussion

Based on the aforementioned calculations, a detailed analysis and discussion of the results were conducted. Through the analysis of buildings with different wall types and in

different regions, the carbon emission characteristics at each stage of the building's LCA were explored, and the key factors influencing building carbon emissions were identified.

4.1. Analysis of the Proportion of Average Carbon Emissions Across LCA Stages

Figure 6 illustrates the proportions of average carbon emissions across the LCA stages for the four projects. The results show that the operational phase accounts for the largest share of average carbon emissions, comprising 75.29%. This was followed by the material-production and recycling phase, which accounted for 16.55%, whereas the demolition phase contributed the smallest share at 0.23%.

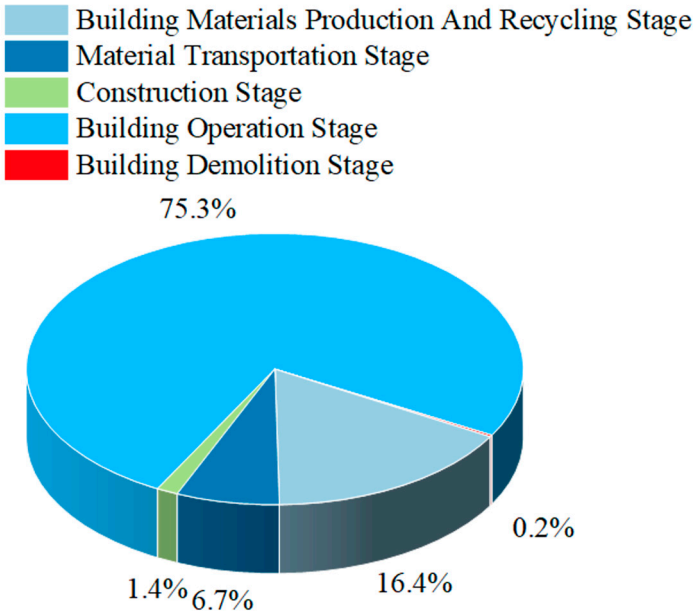


Figure 6. Average unit carbon emission share of project LCA by stage.

These findings corroborate previous research conclusions that "the operational phase accounts for the largest proportion of energy consumption in a building's life cycle" [5,6,41]. This highlights the critical role of emission-reduction measures during the operational phase and warrants further investigation.

4.2. Analysis of Carbon Emissions in the Embodied Phase

Figure 7 illustrates the average carbon emissions per unit area across the different stages for the PCSB and AACB buildings. The data show that in the embodied phase, the carbon emissions per unit area for PCSB are 498.06 $kgCO_2e/m^2$, while those for AACB are 448.55 $kgCO_2e/m^2$, indicating that PCSB emits 49.51 $kgCO_2e/m^2$ more than AACB during this phase.

This result differs from those of previous studies, and this discrepancy is due to the relatively complex PSW production process. These panels require high-strength concrete, insulation materials, and steel reinforcements, all of which result in inherently higher carbon emissions during production. Conversely, CBW uses simpler materials and consumes less energy during manufacturing.

Figure 8 illustrates the average carbon emissions per unit area and their proportions in the LCA for the PCSB and AACB buildings during the construction phase. The results indicate that the average carbon emissions per unit area for PCSB is 13.62 $kgCO_2e/m^2$, accounting for 1.23% of the LCA, while for AACB, the values are 30 $kgCO_2e/m^2$ and 1.73%, respectively.

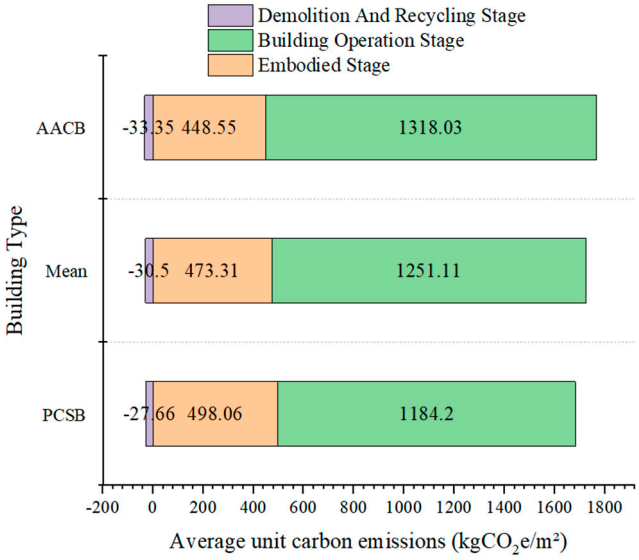


Figure 7. Average unit carbon emissions of different building LCA stages.

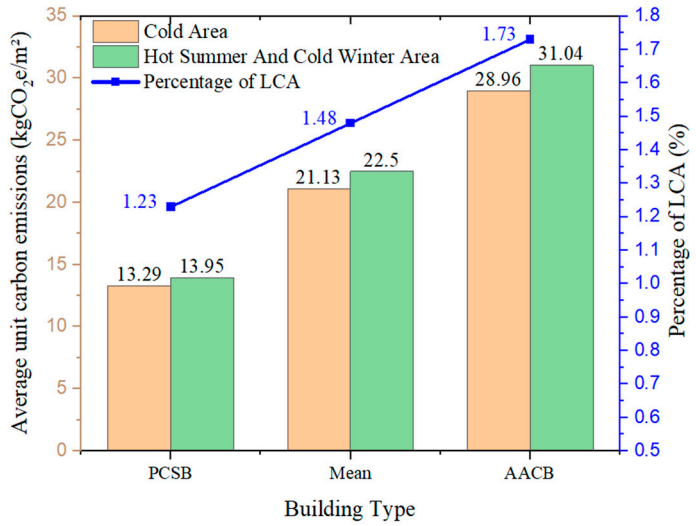


Figure 8. Average carbon emissions per unit area of different buildings at the construction stage and LCA share.

These results show that PCSB reduces the average carbon emissions per unit area by 54.6% when compared with AACB and decreases the proportion of the construction phase in the LCA by an average of 28.9%, demonstrating significant carbon reduction benefits.

The primary cause of this reduction was that the PSW in the PCSB was prefabricated offsite, allowing it to be transported directly to the construction site for installation. This reduces on-site energy consumption and machinery usage time, thereby reducing carbon emissions during the construction process [42]. Conversely, CBW requires on-site construction, which involves higher usage of construction machinery and greater fuel consumption, increasing carbon emissions.

Based on this analysis, promoting prefabricated construction and adopting smart construction practices can significantly enhance construction efficiency and provide ample opportunities for reducing carbon emissions during the embodied phase of buildings.

4.3. Analysis of Carbon Emissions in the Operational Phase

Figure 9 illustrates the annual average carbon emissions per unit area during the operational phase for buildings in different regions, along with their proportions in the

LCA. Figure 10 shows the comparison of the annual average carbon emissions per unit area and LCA proportions for different building types.

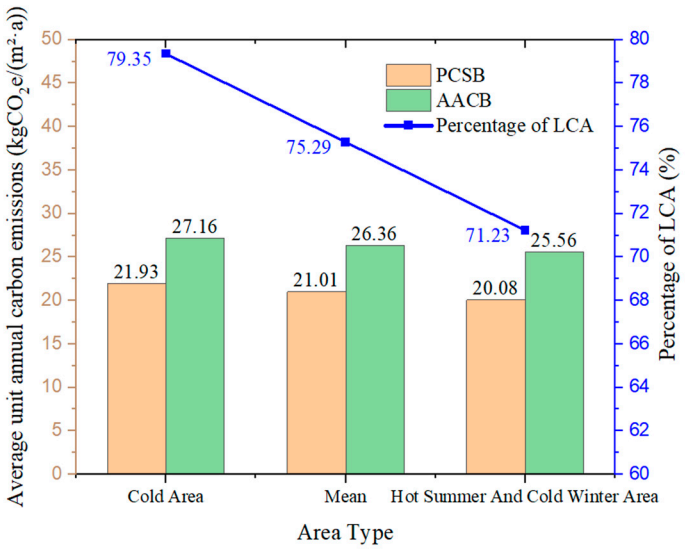


Figure 9. Average annual carbon emissions per unit area of different buildings in the operation stage and share of LCA in different regions.

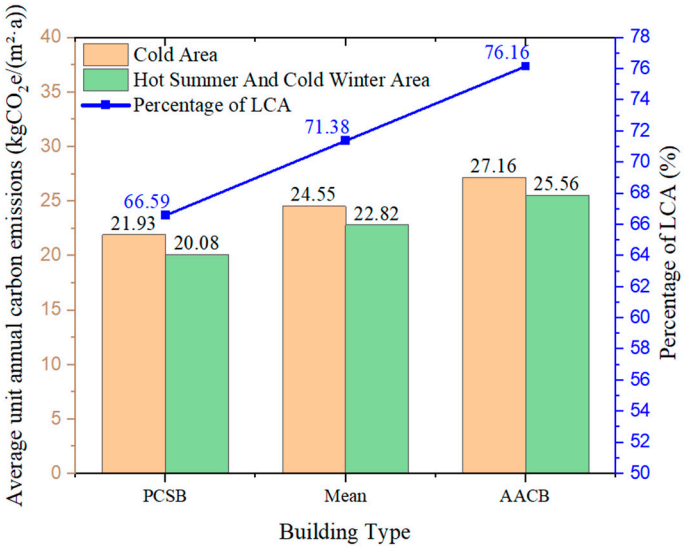


Figure 10. Average annual carbon emissions per unit area of different buildings in the operation stage and LCA share.

The results indicate that:

- In cold regions, the annual average carbon emissions per unit area during the operational phase is 24.55 $kgCO_2e/(m^2 \cdot a)$, accounting for 79.35% of the LCA.
- In hot summer–cold winter regions, the annual average carbon emissions per unit area is 22.82 $kgCO_2e/(m^2 \cdot a)$, accounting for 71.23% of the LCA.

The findings show that buildings in cold regions have a 1.73 $kgCO_2e/(m^2 \cdot a)$ higher annual average carbon emissions per unit area when compared to buildings in hot summer–cold winter regions, with the operational phase contributing an additional 10.23% to the LCA proportion.

This difference is primarily attributed to longer heating periods in cold regions, where continuous heating is required to maintain indoor temperatures during winter. Buildings in cold regions often rely on centralized heating systems or the combustion of high-energy

fossil fuels (such as coal or natural gas) for heating, which have higher carbon emissions and result in greater overall energy consumption.

Conversely, buildings in hot summer–cold winter regions, although requiring heating, have shorter heating durations and relatively lower annual heating energy consumption. These regions predominantly use electricity-driven alternating conditioning systems. Although summer cooling increases energy consumption, the carbon emissions per unit area are still lower than those from heating in cold regions.

4.4. Energy Consumption Analysis in the Operational Phase

Table 9 presents a detailed comparison of the energy consumption of various categories during the operational phase of the PCSB and AACB buildings.

Table 9. Energy consumption analysis by category during the operational phase.

Energy Category	Carbon Emissions per Unit Area for Each Energy Consumption Item ($kgCO_2e/m^2$)		Proportion of Total Carbon Emissions (%)	
	PCSB	AACB	PCSB	AACB
HAVC	563.08	714.32	53.49%	54.09%
Lighting	142.04	165.69	13.54%	12.59%
Electronic Equipment	194.87	228.00	18.58%	17.34%
Elevators	45.83	56.65	4.36%	4.31%
Domestic Hot Water	104.56	153.37	10.03%	11.67%
Total	1050.38	1318.03	100.00%	100.00%

As shown in Figure 10, the annual average carbon emissions per unit area during the operational phase for PCSB is 21.01 $kgCO_2e/(m^2 \cdot a)$, accounting for 66.59% of the LCA. In comparison, AACB has annual average carbon emissions of 26.36 $kgCO_2e/(m^2 \cdot a)$, representing 76.16% of the LCA. The results indicate that PCSB reduces the average carbon emissions per unit area during the operational phase by 20.31% compared to AACB, with an average reduction of 12.57% in the LCA operational phase proportion. According to the calculations in Table 9, PCSB reduces the average carbon emissions from heating and air conditioning by 151.24 $kgCO_2$ per unit area, representing a relative reduction of 21.17%, demonstrating its significant carbon reduction potential.

The data support that PCSB offers superior thermal insulation performance. The prefabricated concrete sandwich walls effectively reduce heat transfer through the walls, enhancing the overall thermal insulation of the building [43]. This improved insulation translates into lower energy consumption for heating and air conditioning, thereby reducing carbon emissions during the operational phase. Conversely, traditional block walls have poorer insulation performance, leading to higher energy losses and increased heating and cooling demands. These findings confirm that the effective use of prefabricated insulated exterior walls can significantly improve the thermal performance of building envelopes.

Figure 11 lists the primary recyclable materials and their average carbon reduction per unit area for different building types during the recycling phase. The results indicate that the main recyclable materials in residential buildings, ranked from highest to lowest in terms of contribution, are AACBs, doors and windows, reinforced concrete, and lightweight aggregate concrete.

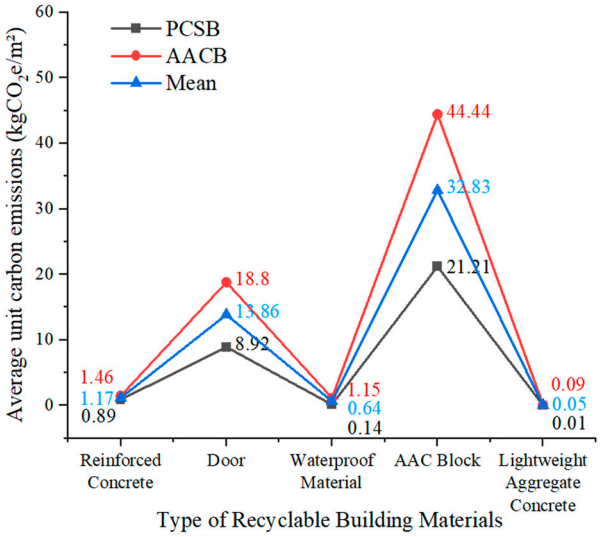


Figure 11. Average unit carbon reduction for major recyclable materials in the recycling phase.

Based on the data in Figure 7, it can be observed that during the demolition and recycling phase, the average carbon reduction per unit area for AACB is 5.69 $kgCO_2e/m^2$ higher than that for PCSB.

This discrepancy can be attributed to the material composition of the following two wall types.

CBW are constructed from brick, mortar, and other simpler materials. These materials are relatively easy to sort after demolition and can be directly reused or processed into other building materials, resulting in a higher recycling rate and greater carbon reduction potential.

Conversely, PSW comprises multiple materials, including steel reinforcements, insulation layers, and concrete. The complexity of their composition makes demolition and material sorting more challenging, reducing the efficiency of recycling and resulting in a lower carbon reduction rate when compared with traditional masonry materials.

This analysis highlights the importance of improving the design and recycling strategies of prefabricated walls to enhance their carbon reduction potential during the recycling phase.

4.5. Analysis of Average Carbon Emissions in Building LCA

Figure 12 illustrates the average carbon emissions per unit area in the LCA for buildings located in different regions.

Overall, under the LCA framework, the following results are found:

- The average carbon emissions per unit area for PCSB and AACB are 1411.81 $kgCO_2e/m^2$ and 1733.23 $kgCO_2e/m^2$, respectively, resulting in a reduction of 321.43 $kgCO_2e/m^2$, or an 18.54% decrease for PCSB when compared to AACB.
- In cold regions, the carbon emissions per unit area for PCSB are reduced by 286.74 $kgCO_2e/m^2$, representing a 16.99% decrease.
- In hot summer–cold winter regions, the carbon emissions per unit area are reduced by 356.11 $kgCO_2e/m^2$, corresponding to a 20.02% decrease.

The results demonstrate that PCSB achieves a significant reduction in carbon emissions when compared to AACB under the LCA framework, with even more pronounced effects in hot summer–cold winter regions.

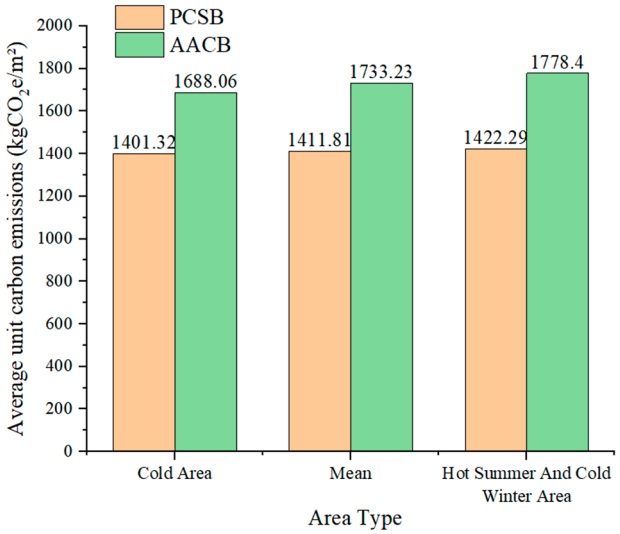


Figure 12. Average carbon emissions per unit area in the LCA for buildings located in different regions.

5. Limitations and Research Outlook

Several limitations were identified during the implementation of this study. First, calculating carbon emissions over a building's full lifecycle involves multiple stages. Furthermore, various lifecycle assessment methods (e.g., ISO 14040, EN 15978) differ in their scope and level of detail, lacking a unified standard. Consequently, differences in research boundaries may result in discrepancies in data processing and calculation methods. Second, this study adopts China's current calculation standards; however, the existing carbon emission factor data remains insufficient, limiting its applicability. Third, this study uses a static method to conduct quantitative assessments of the full lifecycle without accounting for carbon emissions from building maintenance and occupant activities. Additionally, the operational phase of a building is influenced by multiple factors, such as climatic conditions, user behavior, and equipment usage, leading to significant uncertainties.

Future efforts should focus on establishing a more unified and reliable carbon footprint database while promoting international data standardization. Developing unified calculation boundaries and evaluation mechanisms would enhance data accuracy and comparability [44]. Furthermore, future studies should consider dynamic factors during the building usage phase, incorporating long-term factors such as climate change, building retrofitting, renewable energy, and carbon sinks into carbon footprint calculation models to provide more comprehensive predictions and evaluations [45].

6. Conclusions

This study focused on PCSB and AACB exterior walls, utilized BIM technology to construct a computational model, and employed the carbon emission factor method to analyze the LCA carbon emission differences and their main influencing factors for four residential buildings in China's cold and hot summer–cold winter regions.

The findings reveal the following trends in LCA carbon emissions for residential buildings:

- The operational phase accounts for the largest share of carbon emissions, comprising 75% of the total, with HVAC systems consuming more than 50% of the annual energy.
- The embodied phase contributed 27%, whereas the demolition and recycling phase contributed approximately 2% "negative carbon emissions".
- Regional differences indicate that buildings in cold regions have an annual average carbon emission per unit area in the operational phase that is 1.73 $kgCO_2e/(m^2 \cdot a)$ higher than those in hot summer–cold winter regions, with the operational phase accounting

for an additional 10.23% of the LCA emissions. This highlights the significantly higher energy consumption in the cold regions during the operational phase.

- In phase-specific comparisons like the following.
- During the construction phase, PCSB reduces average carbon emissions per unit area by 16.38 $kgCO_2e/m^2$, achieving a 54.6% reduction when compared to AACB.
- In the operational phase, PCSB reduces average carbon emissions per unit area by 5.35 $kgCO_2e/m^2$, a relative decrease of 12.57%. Specifically, for HVAC systems, PCSB reduced annual carbon emissions per unit area by 151.24 $kgCO_2$, a 21.17% reduction, and saved 265.19 kWh/m^2 of electricity, demonstrating its advantages in shortening construction periods. This in turn reduces machinery energy consumption and enhances insulation performance.

However, during the embodied phase, PCSB emits 49.51 $kgCO_2e/m^2$ more than AACB. In the recycling phase, PCSB achieves 5.69 $kgCO_2e/m^2$ less carbon reduction than AACB. This implies that PCSB has lower energy efficiency in material production and recycling, highlighting the need to improve carbon emission factor databases and enhance material recycling efficiency to reduce emissions.

From an overall LCA perspective:

- PCSB reduced carbon emissions per unit area by 321.43 $kgCO_2$, an 18.54% decrease when compared to AACB.
- On average, this corresponds to a saving of 563.62 kWh of electricity per square meter.
- In cold regions, emissions decreased by 16.99%, whereas in hot summer–cold winter regions, the reduction reached 20.02%.

These results confirm the significant carbon reduction benefits of PCSB in LCA, fulfilling energy-saving objectives, particularly in hot summer–cold winter regions.

The innovation of this study lies in integrating current building LCA carbon emission calculation methods based on BIM technology and developing a comprehensive and practical calculation model. This model covers carbon emissions across all stages, from material production to demolition and recycling, while analyzing the carbon emission characteristics of each stage. Future research can further enhance this framework by establishing unified carbon emission calculation boundaries and evaluation mechanisms, improving material recycling efficiency, and incorporating dynamic factors and renewable energy generation into the LCA model [45]. These advancements aim to provide more effective emission-reduction strategies for building designers and construction practitioners. This study offers new perspectives for future energy-saving and emission-reduction research in building LCA while serving as a valuable reference for emission-reduction efforts in architectural design and construction practices.

Author Contributions: Conceptualization, Y.L. and N.I.F.; methodology, Y.L.; software, Y.L., S.L. and S.X.; validation, N.I.F., S.X. and W.H.; formal analysis, Y.L.; investigation, Y.H.; resources, S.L. and S.X.; data curation, Y.L. and Y.H.; writing—original draft preparation, Y.L., S.L. and Y.H.; writing—review and editing, N.I.F., W.H., S.X. and C.L.; visualization, S.L., S.X. and C.L.; supervision, N.I.F.; project administration, Y.L. and N.I.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by [China Scholarship Council] grant number [202310380022].

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author(s).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Mostafaei, H.; Rostampour, M.A.; Chamasemani, N.F.; Wu, C. An In-Depth Exploration of Carbon Footprint Analysis in the Construction Sector with Emphasis on the Dam Industry. In *Carbon Footprint Assessments*; Muthu, S.S., Ed.; Environmental Footprints and Eco-Design of Products and Processes; Springer Nature: Cham, Switzerland, 2024; pp. 45–80, ISBN 978-3-031-70261-7.
2. Þórólfsdóttir, E.; Árnadóttir, Á.; Heinonen, J. Net Zero Emission Buildings: A Review of Academic Literature and National Roadmaps. *Environ. Res. Infrastruct. Sustain.* **2023**, *3*, 042002. [CrossRef]
3. Yang, X.; Hu, M.; Wu, J.; Zhao, B. Building-Information-Modeling Enabled Life Cycle Assessment, a Case Study on Carbon Footprint Accounting for a Residential Building in China. *J. Clean. Prod.* **2018**, *183*, 729–743. [CrossRef]
4. Allen, S.R.; Hammond, G.P.; Harajli, H.A.; Jones, C.I.; McManus, M.C.; Winnett, A.B. Integrated Appraisal of Micro-Generators: Methods and Applications. *Proc. Inst. Civ. Eng. Energy* **2008**, *161*, 73–86. [CrossRef]
5. Peng, C. Calculation of a Building's Life Cycle Carbon Emissions Based on Ecotect and Building Information Modeling. *J. Clean. Prod.* **2016**, *112*, 453–465. [CrossRef]
6. Cho, S.-H.; Chae, C.-U. A Study on Life Cycle CO_2 Emissions of Low-Carbon Building in South Korea. *Sustainability* **2016**, *8*, 579. [CrossRef]
7. Kneifel, J. Life-Cycle Carbon and Cost Analysis of Energy Efficiency Measures in New Commercial Buildings. *Energy Build.* **2010**, *42*, 333–340. [CrossRef]
8. Kumar, D.; Alam, M.; Memon, R.A.; Bhayo, B.A. A Critical Review for Formulation and Conceptualization of an Ideal Building Envelope and Novel Sustainability Framework for Building Applications. *Clean. Eng. Technol.* **2022**, *11*, 100555. [CrossRef]
9. Ionescu, C.; Baracu, T.; Vlad, G.-E.; Necula, H.; Badea, A. The Historical Evolution of the Energy Efficient Buildings. *Renew. Sustain. Energy Rev.* **2015**, *49*, 243–253. [CrossRef]
10. Atmaca, A. Life-Cycle Assessment and Cost Analysis of Residential Buildings in South East of Turkey: Part 2—A Case Study. *Int. J. Life Cycle Assess.* **2016**, *21*, 925–942. [CrossRef]
11. Li, Q.; Ma, L.; Li, D.; Arıcı, M.; Yıldız, Ç.; Wang, Z.; Liu, Y. Thermoeconomic Analysis of a Wall Incorporating Phase Change Material in a Rural Residence Located in Northeast China. *Sustain. Energy Technol. Assess.* **2021**, *44*, 101091. [CrossRef]
12. Karami, P.; Al-Ayish, N.; Gudmundsson, K. A Comparative Study of the Environmental Impact of Swedish Residential Buildings with Vacuum Insulation Panels. *Energy Build.* **2015**, *109*, 183–194. [CrossRef]
13. Yue, J.; Lu, J.; Yan, C.; Liu, J.; Pan, Y. Dynamic Simulation Analysis of Influencing Factors of Energy Consumption of Public Building Envelope in Central China. *Sustainability* **2023**, *15*, 14982. [CrossRef]
14. Song, Y.; Zhang, H.; Mithraratne, N. Research on Influences of Wall Design on Embodied and Operating Energy Consumption: A Case Study of Temporary Building in China. *Energy Build.* **2023**, *278*, 112628. [CrossRef]
15. Huang, Z.; Zhou, H.; Miao, Z.; Tang, H.; Lin, B.; Zhuang, W. Life-Cycle Carbon Emissions (LCCE) of Buildings: Implications, Calculations, and Reductions. *Engineering* **2024**, *35*, 115–139. [CrossRef]
16. Ibn-Mohammed, T.; Greenough, R.; Taylor, S.; Ozawa-Meida, L.; Acquaye, A. Operational vs. Embodied Emissions in Buildings—A Review of Current Trends. *Energy Build.* **2013**, *66*, 232–245. [CrossRef]
17. Pomponi, F.; Piroozfar, P.A.E.; Southall, R.; Ashton, P.; Farr, E.R.P. Life Cycle Energy and Carbon Assessment of Double Skin Façades for Office Refurbishments. *Energy Build.* **2015**, *109*, 143–156. [CrossRef]
18. Wang, Q.; Li, T.; Yang, W. Climate-Responsive Building Design and Its Impact on Energy Consumption and Carbon Emissions. Renew. *Sustain. Energy Rev.* **2019**, *101*, 235–248.
19. Zu'an, L.; Jiawen, H.; Lili, Z.; Dewancker, B.J.; Meng, X.; Hou, C. Research on Energy-Saving Factors Adaptability of Exterior Envelopes of University Teaching-Office Buildings under Different Climates (China) Based on Orthogonal Design and Energy Plus. *Heliyon* **2022**, *8*, e10056. [CrossRef]
20. Li, X.; Xie, W.; Xu, L.; Li, L.; Jim, C.Y.; Wei, T. Holistic Life-Cycle Accounting of Carbon Emissions of Prefabricated Buildings Using LCA and BIM. *Energy Build.* **2022**, *266*, 112136. [CrossRef]
21. Michelini, E.; Ferretti, D.; Miccoli, L.; Parisi, F. Autoclaved Aerated Concrete Masonry for Energy Efficient Buildings: State of the Art and Future Developments. *Constr. Build. Mater.* **2023**, *402*, 132996. [CrossRef]
22. O'Hegarty, R.; Kinnane, O. Review of Precast Concrete Sandwich Panels and Their Innovations. *Constr. Build. Mater.* **2020**, *233*, 117145. [CrossRef]
23. *GB 50352-2019*; Unified Standard for Design of Civil Buildings. China Architecture & Building Press: Beijing, China, 2019.
24. *GB 50178-2017*; Standard for Building Climate Zone Classification. China Architecture & Building Press: Beijing, China, 2017.
25. *GB 50176-2016*; Code for Thermal Design of Civil Buildings. China Architecture & Building Press: Beijing, China, 2016.
26. Yu, J.; Tian, L.; Xu, X.; Wang, J. Evaluation on Energy and Thermal Performance for Office Building Envelope in Different Climate Zones of China. *Energy Build.* **2015**, *86*, 626–639. [CrossRef]
27. Weather Atlas. Qingdao Climate. Available online: https://www.weather-atlas.com/zh/china/qingdao-climate (accessed on 29 December 2024).

28. Weather Atlas. Wuhan Climate. Available online: https://www.weather-atlas.com/zh/china/wuhan-climate (accessed on 29 December 2024).
29. Liu, P.; Wang, Y.; Zhu, F.; Jiang, L.; Lei, Y.; Zhu, Z.; Sun, M.; Wang, X. Analysis of Carbon Emissions in Prefabricated Residential Buildings Based on BIM. *Build. Energy Eff.* **2024**, *52*, 19–23.
30. *GBT 51366-2019*; Standard for Building Carbon Emission Calculation. China Architecture & Building Press: Beijing, China, 2019.
31. *GB 55015-2021*; General Specification for Building Energy Conservation and Renewable Energy Utilization. China Architecture & Building Press: Beijing, China, 2021.
32. Liu, M.; Meng, J.; Liu, B. Research Progress on Carbon Emission Accounting Methods at Home and Abroad. *Trop. Geogr.* **2014**, *34*, 248–258.
33. Ministry of Ecology and Environment of the People's Republic of China. Notice on Managing Greenhouse Gas Emission Reporting for Power Generation Enterprises from 2023 to 2025. Available online: www.mee.gov.cn/xxgk2018/xxgk/xxgk06/202302/t20230207_1015569.html (accessed on 26 November 2024).
34. *ISO 21930*; Sustainability in Buildings and Civil Engineering Works—Core Rules for Environmental Product Declarations of Construction Products and Services; ISO: Geneva, Switzerland, 2017.
35. Ding, G. The Development of a Multi-Criteria Approach for the Measurement of Sustainable Performance for Built Projects and Facilities. Ph.D. Thesis, University of Technology, Sydney, Australia, 2004.
36. Guangdong Provincial Department of Housing and Urban-Rural Development. *Guidelines for Building Carbon Emission Calculation (Trial)*; Guangdong Provincial Department of Housing and Urban-Rural Development: Guangzhou, China, 2021.
37. *JGJ 26-2010*; Design Standard for Energy Efficiency of Residential Buildings in Severe Cold and Cold Zones. China Architecture & Building Press: Beijing, China, 2010.
38. *JGJ 134-2010*; Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Cold Winter Zones. China Architecture & Building Press: Beijing, China, 2010.
39. *GB/T 10058-2009*; Standardization Administration of China. Technical Specifications for Elevators. China Standards Press: Beijing, China, 2009.
40. Chen, J. *Carbon Footprint of Buildings Throughout the Life Cycle*; China Architecture & Building Press: Beijing, China, 2021.
41. Liu, M.; Liu, C.; Xie, H.; Zhao, Z.; Zhu, C.; Lu, Y.; Bu, C. Analysis of the Impact of Photovoltaic Curtain Walls Replacing Glass Curtain Walls on the Whole Life Cycle Carbon Emission of Public Buildings Based on BIM Modeling Study. *Energies* **2023**, *16*, 7030. [CrossRef]
42. Sah, T.P.; Lacey, A.W.; Hao, H.; Chen, W. Prefabricated Concrete Sandwich and Other Lightweight Wall Panels for Sustainable Building Construction: State-of-the-Art Review. *J. Build. Eng.* **2024**, *89*, 109391. [CrossRef]
43. Yu, S.; Liu, Y.; Wang, D.; Bahaj, A.S.; Wu, Y.; Liu, J. Review of Thermal and Environmental Performance of Prefabricated Buildings: Implications to Emission Reductions in China. *Renew. Sustain. Energy Rev.* **2021**, *137*, 110472. [CrossRef]
44. Xu, J.; MacAskill, K. Carbon Data and Its Requirements in Infrastructure-Related GHG Standards. *Environ. Sci. Policy* **2024**, *162*, 103935. [CrossRef]
45. Chen, L.; Hu, Y.; Wang, R.; Li, X.; Chen, Z.; Hua, J.; Osman, A.I.; Farghali, M.; Huang, L.; Li, J.; et al. Green Building Practices to Integrate Renewable Energy in the Construction Sector: A Review. *Environ. Chem. Lett.* **2024**, *22*, 751–784. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.