buildings

Article

Comparing the Standards of Life Cycle Carbon Assessment of Buildings: An Analysis of the Pros and Cons

Yahong Dong [1,2,*], Tingyi Yang [2], Peng Liu [3] and Zhenyan Xu [4]

[1] Department of Environmental Science and Engineering, Macau Environmental Research Institute, Macau University of Science and Technology, Macao 999078, China
[2] Qingdao Research Center for Green Development and Ecological Environment, Qingdao University of Science and Technology, Qingdao 266000, China
[3] Faculty of Innovation Engineering, Macau University of Science and Technology, Macao 999078, China
[4] Faculty of Humanities and Arts, Macau University of Science and Technology, Macao 999078, China
* Correspondence: yhdong@must.edu.mo

Abstract: Buildings play a substantial role in carbon emissions and contribute to approximately 37% of global carbon emissions. In order to control and reduce the carbon emissions of buildings, a report of life cycle carbon assessment (LCCA) has been mandated for all the new buildings in China since 1 April 2022. As a technical support for carbon accounting efforts in China, it is important to adhere to the national standards for conducting an LCCA report. In this context, the GB/T51366-Standard for Building Carbon Emission Calculation is the designated national standard that should be followed. However, GB/T51366 has several deficiencies, including incomplete life cycle processes, impractical calculation methods, the unrepresentativeness of default emission factors, and so forth. Therefore, it is essential to critically analyze the pros and cons of employing an LCCA methodology adhering to GB/T51366. To fulfill the research aim, this study develops a computational toolkit based on GB/T51366. We propose two data collection methods and conduct a case study of a residential building in China. GB/T51366 was also used as the baseline scenario and compared with the European standard EN15978. The results show that GB/T51366 is less comprehensive than EN15978, leading to a 2.9% reduction in the total life cycle emissions. Notably, up to 26.7% difference was observed in the comparison of the emission factors of the main construction materials. Based on the research outcomes, it is suggested to improve the national standard in terms of the scope and data availability, as well as to promote the harmonization of existing national LCCA standard of buildings with international standards.

Keywords: carbon emission calculations; comparative analyses; quantitative analyses; EN15978

check for updates

Citation: Dong, Y.; Yang, T.; Liu, P.; Xu, Z. Comparing the Standards of Life Cycle Carbon Assessment of Buildings: An Analysis of the Pros and Cons. *Buildings* **2023**, *13*, 2417. https://doi.org/10.3390/buildings13102417

Academic Editor: Md Morshed Alam

Received: 29 August 2023
Revised: 14 September 2023
Accepted: 20 September 2023
Published: 22 September 2023

1. Introduction

The intensive consumption of fossil fuels has led to excessive emissions of greenhouse gases (GHGs) [1]. As one of the major sectors of energy consumption, the building industry accounts for 37% of total global carbon emissions [2]. China is presently experiencing rapid development, with an annual growth rate of four billion square meters in completed building area between 2013 and 2021 [3]. As stated in the "2022 China Building Energy Consumption and Carbon Emission Research Report" published by the China Building Energy Conservation Association, the cumulative carbon emissions from the entire building process in 2020 amounted to 5.08 billion tons of carbon dioxide (CO_2), representing 50.9% of China's total carbon emissions [4]. In addition, maintaining a huge amount of building area and operating a large size of population's life in buildings can consume abundant energy and emit significant GHGs. Therefore, ensuring controlled and reduced life cycle carbon emissions of buildings in a scientifically informed manner holds utmost significance for China to successfully attain its national target of carbon neutrality by 2060 [5,6].

A wide array of strategies and policies have been implemented to effectively reduce carbon emissions within the building industry in China. In 2020, the "Action Plan for the Construction of Green Buildings" was introduced, setting a target for new urban buildings to achieve a minimum of 70% green floor space by 2022 [7]. The 2021 "Action Plan for Carbon Peaking by 2030" highlighted various targets to be achieved. These include a 20% proportion of non-fossil energy consumption, a 13.5% decrease in energy consumption per unit of GDP, the transformation of building energy use structure, and the promotion of green building material products through certification and application initiatives by 2025 [8]. Furthermore, in 2021, the "National Standards Development Outline" declared the intent to expedite the establishment of a robust standard system pertaining to carbon peaking and carbon neutrality [9]. The national standard, GB/T55015 "General Specification for Building Energy Efficiency and Renewable Energy Utilization", made it mandatory for all new buildings, renovation projects, and expansion works in China since 1 April 2022 to undergo a mandatory life cycle carbon assessment (LCCA) [10]. The national standard, GB/T51366 "Carbon Emission Calculation Standard for Buildings", serves as a crucial reference for the building industry in accurately calculating the life cycle carbon emissions of buildings, providing essential guidance [11,12].

Life cycle assessment (LCA), as the scientific basis of GB/T51366, is an efficient instrument to assess the environmental impacts of a product throughout its life cycle [13]. The analysis of life cycle stages allows for the identification of hotspots where carbon emissions are significant, enabling the formulation of optimization solutions that can be validated to effectively reduce carbon emissions [14–16]. Recently, LCA has been implemented intensively in the building industry to evaluate the environmental impacts of various building types and multiple life cycle stages. Existing studies investigated the embodied carbon emissions of buildings [17,18] and emissions of various building types [19–22]. In addition, studies analyzed variations caused by different system boundaries [23–25]. Recent studies focused on new technologies for carbon reduction [26]. Moreover, the emergence of new construction methods and green construction materials has attracted the attention of researchers. Assembly buildings and green buildings are superior to traditional buildings in many aspects [27,28]. The use of bio-materials in the retrofitting of traditional buildings can facilitate the reduction of carbon emissions of buildings [29,30]. There are also researchers focusing on the variability of LCA structures due to differences in life cycle databases [31]. Therefore, LCA has been recognized as an indispensable method in evaluating a building's life cycle carbon emissions.

Although recent scientific studies adopted GB/T51366 as the reference to conduct LCCA [32,33], none of the existing studies comprehensively examined the pros and cons of GB/T51366, especially concerning its scope, calculation methods, feasibility in practical implementation, and other related factors. However, GB/T51366 is a relatively new standard. There have been no studies investigating the advantages and disadvantages of GB/T51366 nor comparing it with other widely accepted international standards. Furthermore, considering the increasing demand for carbon calculations in the Chinese building sector [34–38] and the need for international compatibility in carbon emissions reporting [39–42], it is crucial to assess whether the scope and calculation methods outlined in GB/T51366 are aligned with other widely recognized international standards, such as the EN15978 standard [43]. The lack of such an analysis undermines the comprehensive international understanding of the significant efforts undertaken in carbon calculation within the building industry, resulting in communication deficiencies. LCA is now included in the Green Building Rating System (GBRS) as part of its assessment. For instance, undertaking LCA in Leadership in Energy and Environmental Design (LEED) earns 5 points out of a total score of 4.5% [44], while undertaking LCA in Building Research Establishment Environmental Assessment Method (BREEAM) carrying out an LCA can earn 6 points, or 5.9% of the total score [45]. It is shown that performing LCA is essential in selecting the best LEED certification strategy in order to achieve sustainable development [46]. However, as two different environmental impact assessment tools, there are limitations in the ability of GBRS to deal with LCA, such as the contradiction between LCA and the credits granted by LEED for the same building material [47]. Sartori et al. [48] compared the LCA and GBRS assessment methods and reviewed the LCA software tools (https://www.openlca.org) for GBRS-compliant buildings, mainly focusing on the impact categories. eToolLCD (https://etoollcd.com) was the software tool that was applied to all the rating systems analyzed in their study, as it considered all the impact categories specified in EN15978. Therefore, due to the growing demand for LCCA in China and the mandatory implementation of GB/T51366, it is of utmost importance to conduct a comprehensive exploration of the pros and cons associated with adopting GB/T51366 in the construction and building industry. Furthermore, it is crucial to discuss the gaps between GB/T51366 and international standards, enabling the provision of recommendations for the implementation, interpretation, and enhancement of GB/T51366.

This study aims to investigate the pros and cons of GB/T51366 through a comprehensive analysis of a residential building and to compare GB/T51366 with EN15978, both qualitatively and quantitatively. This study is conducted through four steps (Figure 1). Step 1 is to define the research objectives and interpret GB/T51366 for the preparation of Step 2, in which a calculation toolkit is developed in accordance with GB/T51366. A case study is conducted in Step 3, and sensitivity analysis and comparison with EN15978 are carried out. In Step 4, the pros and cons of GB/T51366 are discussed, and suggestions are provided in terms of insights on how to promote the implementation of LCCA in China and how to interpret results from GB/T51366 and international standards. This study fulfills the research gap by comparing GB/T51366 with international standards and analyzing the advantages and disadvantages of GB/T51366. The study outcome can improve the understanding of the LCCA practice in China, promote the LCCA standard system, and facilitate communication with international industries.

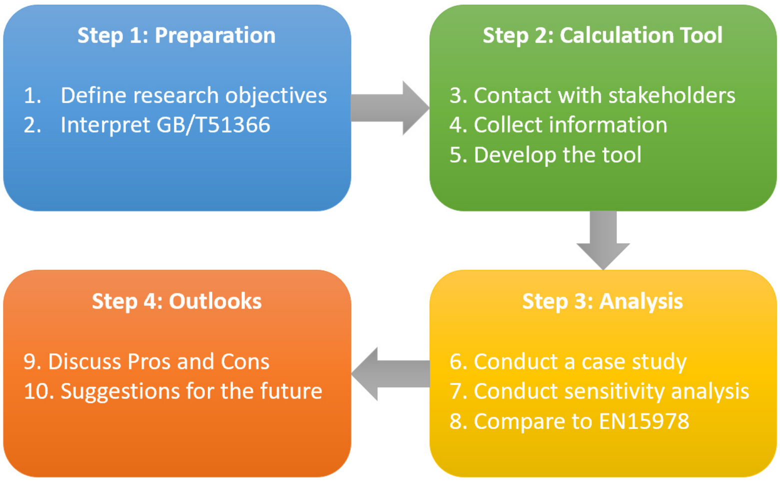

Figure 1. Research design of this study.

2. Material and Methods

2.1. Scope and Methods of GB/T51366

In response to the growing necessity for carbon accounting in the building industry, the Ministry of Housing and Urban–Rural Development (MOHURD) has commissioned the China Academy of Building Research to formulate the GB/T51366-2019 Carbon Emission Calculation Standard for Buildings, which was officially released on 1 December 2019 [12]. Through rigorous scientific methodologies and comprehensive evaluation criteria, it aims to provide a systematic framework for measuring and managing the carbon footprint of buildings in an accurate and reliable manner. The functions of GB/T51366 are (i) to regulate the calculation of building carbon emissions, (ii) to provide guidance for the industry to consider the whole life cycle of buildings for energy saving and carbon reduction, (iii) to enhance the awareness of suppliers of construction and building materials with respect to carbon accounting, reporting, monitoring, and verification, (iv) to technically support the industry to participating in carbon emission trading, carbon tax, carbon footprint assessment, and (v) to provide technical support for buildings to participate in the carbon market and carry out international comparisons [12].

GB/T 51366 is capable of evaluating new buildings, refurbishment, and expansion works. The life span of a building in this standard is assumed to be 50 years. As shown in Figure 2, GB/T51366 analyzes five life cycle stages, including production, transportation, construction, operation, and demolition. The operation stage should include heating, ventilation, and air conditioning (HVAC), domestic hot water, lighting and lifts, renewable energy, and carbon sink.

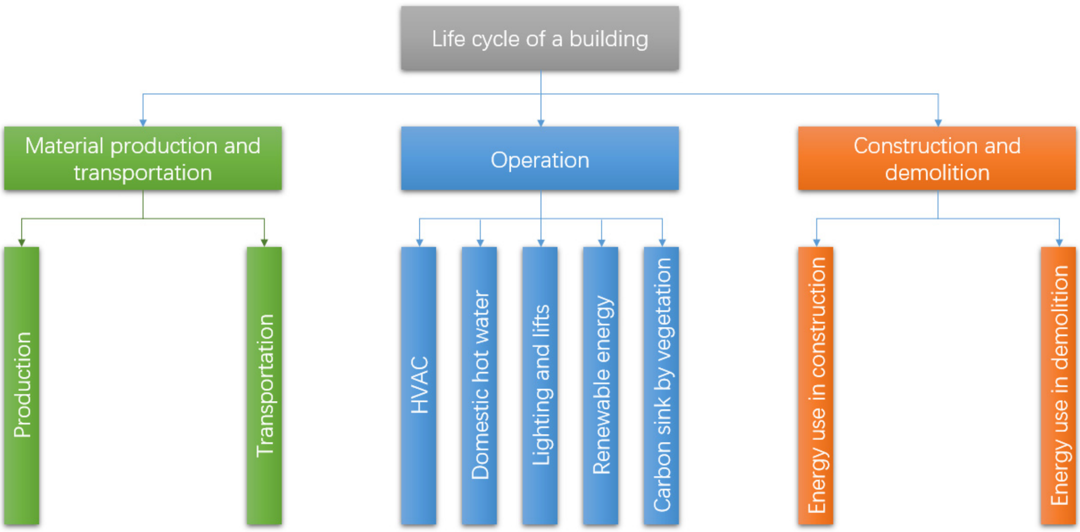

Figure 2. Life cycle stages assessed by GB/T51366.

The standard's calculation methods are based on emission factors. The emission factors for building materials are taken from the China Life Cycle Database (CLCD), and the calculation of the emission factors for building materials is based on the LCA model in accordance with ISO 14040-2006. Due to the dependency of building material emission factors on the specific type of material and their temporal variability, it is advisable to prioritize the utilization of carbon footprint data supplied by building material manufacturers. As the primary data source for calculating building carbon emissions, the carbon footprint data should be checked through third-party auditing. Subsequently, reference values provided within the established standard can be employed as a secondary option. This approach ensures the reliability and accuracy of carbon emission calculations by considering verified and validated data sources. It also enables accounting for variations in building material compositions and associated emission factors over time.

The standard also includes building operating characteristics for different types of buildings, encompassing various parameters, such as lighting hours, humidity design, ventilation requirements, and others. Through pre-defined formulas and parameters, GB/T51366 can be used to compare the carbon emissions of different building design options, energy systems, building materials, etc. [12].

2.2. Development of a Calculation Toolkit Based on GB/T51366

2.2.1. Model Structure

Based on GB/T51366, a calculation toolkit is developed in Microsoft Excel, and its structure is shown in the first worksheet of "Introduction" (Figure 3). Fourteen worksheets are developed with various functions for data input, calculation, documentation of parameters, and results outputs. The calculation toolkit is attached in the Supplementary Material S1. The basic building information input screen in this toolkit is provided in the "Input" worksheet, containing information on the building type, geographical location, construction area, life span, etc. Through several rounds of telephone interviews and face-to-face interviews with architects, HVAC engineers, and water supply and drainage engineers, it is found that the format of data documentation is different among the stakeholders, and the data format is not standardized since data are usually not shared between stakeholders. For example, at the design stage, the specifications on HVAC, electrical appliances, water supply, and drainage equipment are not provided in an exact number. Instead, rough information like types of these parameters are provided. The exact parameters are usually determined by the contractor later in the construction stage.

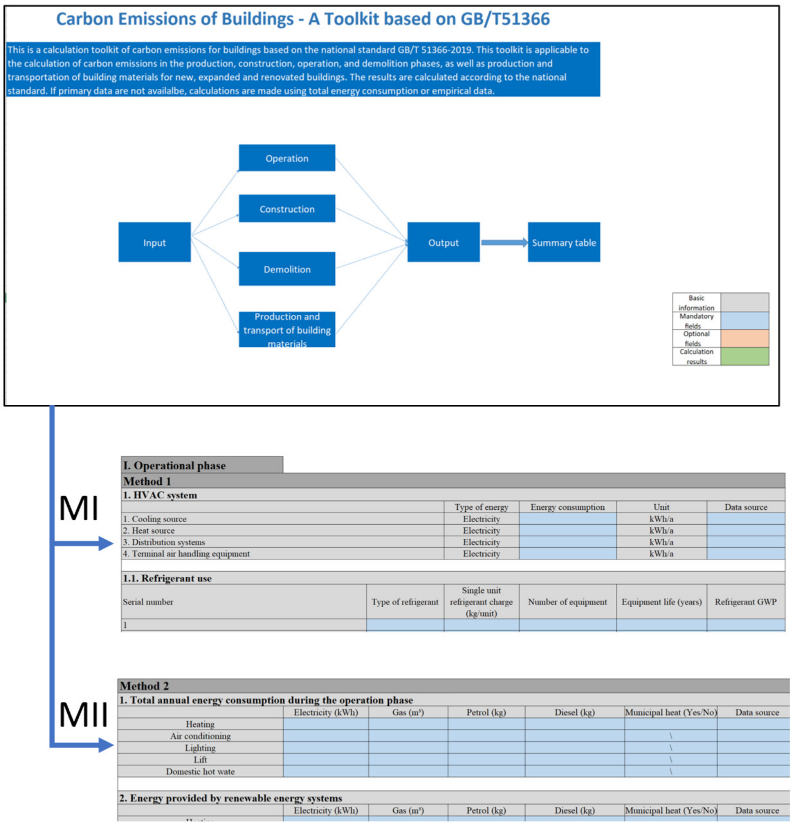

Figure 3. A snapshot of the worksheet "Introduction" of the calculation toolkit and the two calculation methods.

In order to further understand the industrial practice of data communication among the stakeholders, an in-depth interview was carried out with an architect in a local design company, where it was found that a design company conducts a design project as a one-off. When the design project is completed, the design protocol is submitted to the developer. A contractor is hired by the developer to be responsible for the construction processes and arrangement of purchasing from suppliers. Therefore, detailed information on the required data by GB/T51366 is not available at the design stage. In addition, it is often difficult to obtain all the required data on a building's life cycle from one stakeholder. Given difficulties in data collection, GB/T51366 allows the adoption of empirical data as a substitute for the unavailable data.

2.2.2. Two Methods of Calculation Based on GB/T51366

The GB/T51366 standard enables the calculation of carbon emissions at various stages throughout the life cycle of a building, which can be aggregated to derive a comprehensive assessment of its overall carbon footprint. However, in practice, it is very difficult to collect all the required data for GB/T51366. First, it is common for different stakeholders involved in the building industry, such as designers, developers, contractors, and suppliers, to possess their own sets of information relevant to the project, and there is often a lack of an information-sharing mechanism among these stakeholders [49]. In addition, the required data in GB/T51366 for the operation and construction stages are too specific to be obtained. For example, the assessment of a domestic hot water system requires data on cold water and hot water temperature, water density, daily hot water use hours, and transmission and distribution efficiency; however, these data are usually not available, particularly in the design and construction stages. Similar problems also exist in the assessment of the Heating, Ventilation, and Air Conditioning (HVAC) system, refrigerant use, lighting, renewable energy systems, and construction machinery.

In response to the difficulties of data collection of GB/T51366, we provide two methods in the calculation toolkit for data input and calculation algorithm. The setups of the two methods are given in Table 1. Method I (MI) adopts the methods provided in GB/T51366 with additional reference to IPCC2006/2019 for the operation phase and GB/T2589 for the construction and demolition phases. On the other hand, Method II (MII) is a simplified method referring to third-party reports and estimations for unavailable data. The main difference between the two methods is the source of activity data. MI follows GB/T51366 throughout all stages of its life cycle, whereas MII deviates from GB/T51366 by simplifying the data input required during the operation, construction, and demolition stages. The development of the two approaches helps stakeholders provide sufficient input for LCCA modeling.

Table 1. The setups of two calculation methods: Method 1 (MI) and Method 2 (MII).

LC Stage	MI	MII
Production	GB/T51366	GB/T51366
Transportation	GB/T51366	GB/T51366
Operation	GB/T51366, IPCC2006, IPCC2019	Third-party report *, GB/T51366, IPCC2006, IPCC2019
Construction	GB/T51366, GB/T2589	Third-party report *, empirical data, GB/T51366, GB/T2589
Demolition	GB/T51366, GB/T2589	Third-party report *, empirical data, GB/T51366, GB/T2589

* Third-party report refers to a report issued by a third-party agency for carbon footprint certification.

In the operation stage, MI requires detailed lighting specifications, HVAC, lifting, etc. MII requires data on total energy consumption, which can be obtained from existing documents, such as a low-energy certification report and an energy consumption simulation report of a building project. In the construction and demolition stages, MI requires the energy consumption data for each construction process, as well as the specifications of construction machinery. MII only requires the data of different energy consumptions, such as electricity, diesel, and petrol. The two methods require the same input data and adopt the same calculation methods for the production and transportation stages. It should be noted that both methods can calculate the carbon emissions of the life cycle stages of a building project as required by GB/T51366, while MII is applicable when detailed information is missing. Participators can choose MI or MII based on data availability in case of insufficient data at the early design stage.

3. Case Study

3.1. Description of the Study Case

The studied building is a new residential building in Qingdao, eastern China (Figure 4). The building consists of eighteen floors and one basement floor underground. Each floor of the building consists of 4 three-bedroom apartments, a lift lobby, and a staircase, and there are 72 apartments in total. The height of the building is 55.2 m, and the construction area is 6969.91 m^2. The designed service life is 50 years. The building fulfills the requirements of low-energy buildings in China and was named a 2-star building in accordance with the Green Building Evaluation Standard (GB/T 50378-2019).

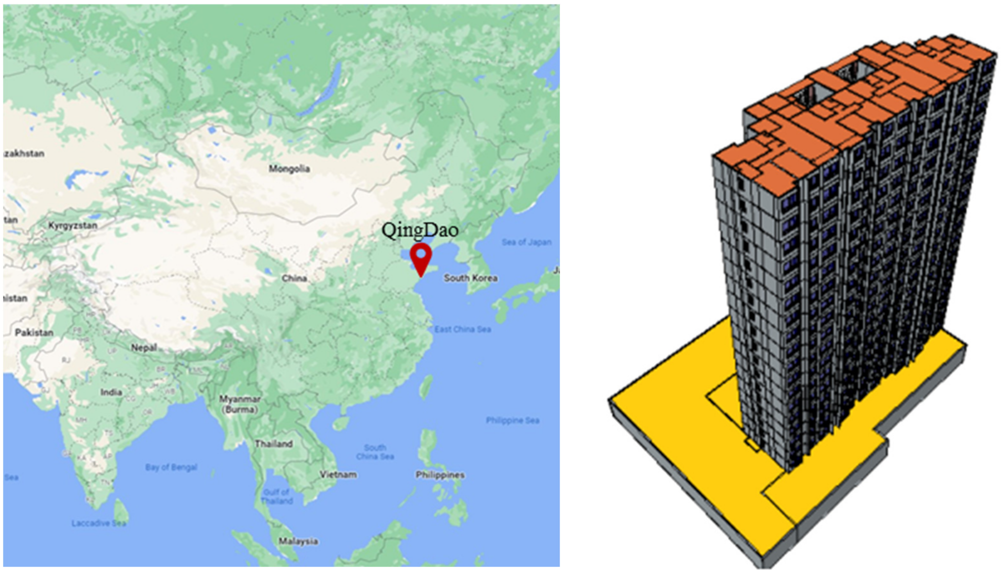

Figure 4. Location of the studied building and the architectural model of the studied residential building (Sources: Google Maps; the project design document).

3.2. Data Collection

Primary data of the LCCA model of the studied building are obtained from the developer, contractor, and designer. Since the construction project involves multiple stakeholders, it is difficult for the developer to provide a complete list of activities. Therefore, a hybrid approach of MI and MII was adopted for data collection. The details of data collection at various stages of the LCA are articulated below.

In the production and transportation stages, data of construction materials are acquired from the bill of quantities of construction materials provided by the developer and contractor (Table 2). The upstream embodied carbon emissions of building services, such as air conditioners, lighting, and lifts, are excluded in this study as they are not required by GB/T51366. The information on road transportation is provided by the developer and contractor.

Table 2. Data for the production and transportation of construction materials.

Construction Material	Amount	Unit	Transport Mode	Transportation Distance (km)
Steel	373.84	t	Light diesel truck (load 2 t); Medium diesel truck (load 8 t); Heavy diesel wagon transport (46 t load)	150
Concrete	951.59	t	Heavy diesel wagon transport (46 t load)	150
Portland cement	491.95	t	Heavy diesel wagon transport (46 t load)	150
Lime	53.69	t	Heavy diesel wagon transport (46 t load)	150
Natural sand	765.64	t	Heavy diesel wagon transport (46 t load)	150
Gravel	544.02	t	Heavy diesel wagon transport (46 t load)	150
Northeast pine, imported pine	0.05	m^3	Heavy diesel wagon transport (46 t load)	20
Specification material	40.27	m^3	Heavy diesel wagon transport (46 t load)	20
Clay bricks	68.39	m^3	Heavy diesel wagon transport (46 t load)	20
Mechanized red bricks	30.34	m^3	Heavy diesel wagon transport (46 t load)	20
Floor tile cylinder bricks	783.05	m^3	Heavy diesel wagon transport (46 t load)	20
External brick	119.77	m^3	Heavy diesel wagon transport (46 t load)	20

Table 2. *Cont.*

Construction Material	Amount	Unit	Transport Mode	Transportation Distance (km)
Doors and windows	1410.18	t	Medium diesel trucking (load 8 t), Heavy duty diesel trucking (30 t capacity)	30
Roofing polystyrene foam board	66.867	t	Heavy diesel wagon transport (46 t load)	30
Extruded plastic insulation board	1420.45	t	Heavy diesel wagon transport (46 t load)	50
Copper pipes	2.883	m^3	Light diesel truck (load 2 t)	40
Cable	7.11	m^3	Light diesel truck (load 2 t)	40
Reddan anti-rust paint	6.47	m^3	Light diesel truck (load 2 t)	35
Plastic drainage pipe	3.64	t	Light diesel truck (load 2 t)	35
Steel-plastic composite pipe	53.71	m^3	Light diesel truck (load 2 t)	30
Granite strips	17.44	m^3	Light diesel truck (load 2 t)	30
Chlorinated polyethylene coil plane	117.15	m^3	Light diesel truck (load 2 t)	30
Petroleum asphalt (No.30)	0.891	m^3	Medium diesel truck (load 8 t)	30
Polyurethane coated film	4.855	m^2	Medium diesel truck (load 8 t)	2000

The energy consumption data in the operation stage were obtained from the Building Energy Efficiency Report (the Energy Report) provided by the developer. In the Energy Report, data on energy consumption were simulated using PKPM, which refers to its two early modules of frame design (Pai jia Kuang jia She ji, PK) and floor plan design (Ping Mian she ji, PM) [50]. As shown in Table 3, the energy consumption of the heating and air conditioning, lighting, lift, and hot water system was obtained from the Energy Report, and the energy consumption per construction area was calculated. Since the collected data cannot meet the data requirement of MI, the operation phase was analyzed using MII.

Table 3. Annual energy consumption in the operation phase.

Emission Source		Annual Electricity Consumption (kWh/a)	Energy Consumption per Unit Area (kWh/m^2/a)
Heating and air conditioning	Heating	101,954	14.62
	Air conditioning	38,201	5.481
Lighting		38,803	5.567
Lift and hot water	Elevator	5010	0.719
	Domestic hot water	2059	0.295
Total		186,027	26.69

Input data for the construction phase were obtained from the Energy Report of the project, including diesel consumption and electricity consumption. Since the data on the demolition phase are not available, we followed a recent study [51] and assumed the demolition phase accounts for 90% of the energy consumption of the construction phase. The input data of the two stages are provided in Table 4. As detailed information on construction machinery is not available, MII was used for the analysis of the construction and demolition stages.

Table 4. Energy consumption of construction and demolition stages.

Stage	Area	Unit	Energy Consumption of Small Construction Equipment (kWh)	Gasoline Consumption (kg)	Diesel Consumption (kg)	Electricity Consumption (kWh)
Construction	6969.91	m^2	500	N.A.	5852	16,724
Demolition	6969.91	m^2	500	N.A.	5267	15,052

3.3. Results of the Case Study

The results of the life cycle carbon emissions of the studied building are shown in Table 5. The whole life cycle carbon emission is 10,381.6 tCO_2e, and the carbon emission per unit of construction area is 1.49 tCO_2e/m^2. The carbon emissions are mainly from operation (79.2%) and production (20.2%), while the other life cycle stages of transportation, construction, and demolition account for only 0.68%. According to the analysis of 105 buildings, the median of end-of-life demolition emission is 28.9 kg CO_2e/m^2 [52], which is apparently larger than 4.47 kg CO_2e/m^2 of the studied building, implying that several processes in the demolition (and construction) stage are not involved in GB/T51366. In this study, due to the lack of updated regional electricity emission factors, we adopted the electricity emission factors published in 2012, which is probably larger than the real situation since more renewable energy is used in the current electricity mix. Electricity emission factors are critical to the LCCA calculation. Adjusting electricity emission factors can lead to significant changes in the carbon emissions of buildings [53]. As electricity emission factors alter temporally [54–56], up-to-date electricity emission factors should be employed.

Table 5. Results of GHG emissions of the studied residential building.

Life Cycle Stage	Amount	Unit	Amount	Unit	Contribution
Material production	2,093,082	$kgCO_2e$	300.3	$kgCO_2e/m^2$	20.2%
Material transportation	4129	$kgCO_2e$	0.592	$kgCO_2e/m^2$	0.04%
Operation	8,217,637	$kgCO_2e$	23.6	$kgCO_2e/m^2/yr$	79.2%
Construction	33,371	$kgCO_2e$	4.79	$kgCO_2e/m^2$	0.32%
Demolition	30,043	$kgCO_2e$	4.47	$kgCO_2e/m^2$	0.29%
Total	10,381,153	$kgCO_2e$	1489	$kgCO_2e/m^2$	100%

The contributions from detailed processes in the operation and production stages are further analyzed in Figure 5. It is found that the material production stage accounts for 20.2% of the total carbon emissions. For the production stage, the primary materials with large emission proportions are steel (42%), cement (17%), concrete (14%), windows and doors (12%), and insulation materials (4%), which account for about 90% of the carbon emissions in the production stage. On the other hand, the largest contributor in the operation stage is the HVAC system (59.6%), with air conditioning accounting for 16.2% and heating for 43.4%. The studied building is located in Qingdao, where domestic heating from coal combustion is supplied from November to March. Hence, the carbon emissions caused by heating have the largest share of emissions. However, there are a few neglected processes in the operation stage in GB/T51366, including maintenance, repair, water supply, etc. It can be shown that the life cycle assessment lacks completeness. The missing processes will be analyzed in Section 4.2.1 in comparison with international standards.

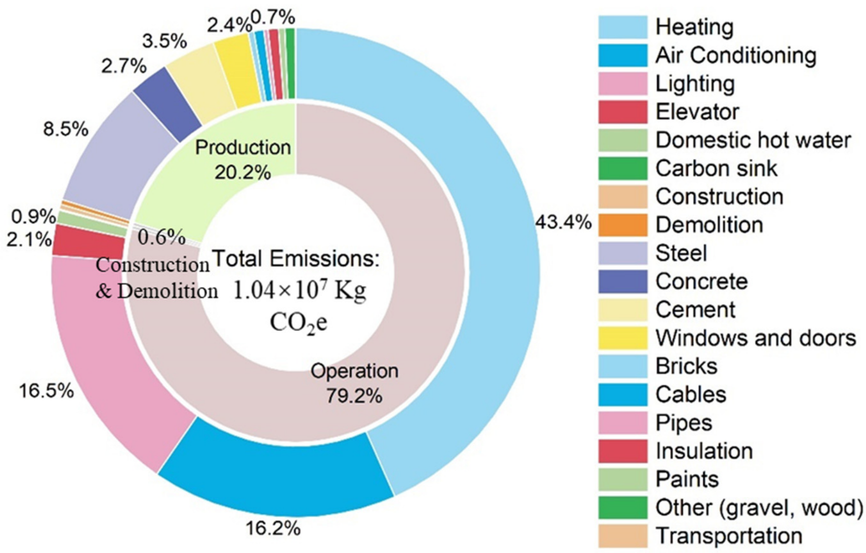

Figure 5. Contributions from life cycle stages and processes to the LCCA results of the studied building.

4. Comparing GB/T51366 and EN15978

4.1. Descriptive Comparison

GB/T51366 has been recognized as the calculation guidance for carbon emission accounting in China. It is crucial to understand whether this standard is comparable to international practices so that the results of LCCA for a large volume of buildings in China can be communicated with the international building industry. In order to facilitate the comparison, EN15978-2011 Sustainability in Building Construction—Building Environmental Performance Assessment—Calculation Methods is referred to as the international standard. EN15978 is selected as the reference standard since it has been proven to be a reliable and widely adopted standard for LCA of buildings and has been applied in many previous studies [57,58]. A descriptive comparison between GB/T51366 and EN15978 is given in Table 6.

Table 6. Descriptive comparison of GB/T51366 and EN15978.

Standard	GB/T51366	EN15978
Scope of buildings	Civil buildings	All buildings
Building types	New, refurbishment, and extension works	New, refurbishment, and extension works
Calculation methods	Emission factor method	Emission factor method
Impact categories	Single category of climate change	Various impact categories *
System boundary	Whole life cycle, some processes are excluded (maintenance, renovation, water)	Whole life cycle
Data quality	Strict requirement	Strict requirement
Reporting	Not specified	Specified
Scenario description	Not detailed	Detailed
Accounting for the gross amount	Not specified	Consideration of losses due to multiple factors (transport, processing, design, etc.)

* Impact categories, such as acidification, eutrophication, ecotoxicity, particulate matter, etc.

The scopes are different between the two standards. GB/T51366 assesses civil buildings, including residential buildings, commercial buildings, schools, etc., while factory plants, industrial buildings, warehouses, village buildings, etc., are not covered. For these building types, there is currently no standard available in China to quantify their carbon emissions. The lack of carbon calculation standards for non-civil buildings in China may hinder the building industry from achieving the carbon-neutral target. Therefore, it is inevitable to develop carbon calculation standards for non-civil buildings. On the other hand, EN15978 is applicable for all buildings. With respect to impact categories, GB/T51366 focuses on a single impact category, i.e., climate change, while EN15978 does not limit the emission assessment to climate change. However, the selection of life cycle impact assessment (LCIA) methods is not specified in the standard.

Both standards encompass the "cradle-to-grave" life cycle stages of buildings. However, GB/T51366 ignores a few processes as compared to EN15978. As a new standard, GB/T51366 is limited in several aspects. The incompleteness of the scope of GB/T51366 can lead to a lack of accuracy in calculating life cycle carbon emissions. In the production and transportation of construction materials, the two standards have no significant differences. In the construction stage, GB/T51366 does not include the transportation of construction machinery to the construction site. In addition, transportation and disposal of construction wastes are not accounted for in GB/T51366. In the operation stage, GB/T51366 involves carbon emissions generated from energy consumption caused by HVAC, domestic hot water, lighting, and lifts. Different from EN15978, GB/T51366 does not account for water consumption, maintenance, renovation, replacement, etc. Carbon reduction caused by renewable energy and carbon sinks of green areas are requested in GB/T51366. Unfortunately, the details of the carbon sink calculation are missing in GB/T51366. Therefore, this study refers to IPCC 2006 and IPCC 2019 for calculation methods of carbon sinks. EN15978 considers the environmental benefits at Stage D, "Benefit and loads beyond the boundary". In the demolition stage, GB/T51366 provides the calculation methods for energy consumption and transportation of demolition construction wastes. However, the description of waste disposal scenarios is lacking.

4.2. Quantitative Comparison

4.2.1. Difference in Scopes

In order to further explore the missing parts in GB/T51366, an alternative scenario is explored. Additional processes are complemented in the alternative scenario according to EN15978. First, the carbon emissions from the transportation of construction waste are involved. With reference to the on-site construction material wastage rates identified in the fifth edition of the Building Construction Manual and studies of similar residential projects [59,60], the estimated construction material wastage rates for on-site construction are shown in Table 7. Because there is no detailed information on the transportation of construction machinery, we do not make any changes to this process. In the operation stage, carbon emissions from building maintenance, replacement, renovation, and water consumption are included in the alternative scenario. For repairs, replacements, and refurbishments, since there is no specific supplier of the relevant building materials, the service life of the building components and services that are commonly used in the building industry in China are acquired through consultation with relevant stakeholders. Information on the assumed replacement building materials is shown in Table 8. With respect to water consumption, due to the difficulty of obtaining site-specific data at the design stage, the national standard GB/T 55015-2021 "General Specification for Energy Conservation and Renewable Energy Use in Buildings" is used to calculate a daily water consumption of 0.01 m^3 per person in a residential building. The water consumption for 50 years is estimated to be 19,710 m^3.

Table 7. Loss rate of on-site construction materials.

Building Materials	Concrete	Brick or Brock	Steel	Wood	Finishing Materials	Other
Wastage rate (%)	1.5	5	3	5	2.5	5.5

Table 8. Information on construction materials assumed to be replaced.

Building Materials	Service Life	Number of Replacements
Fire doors	10	4
Aluminum doors and windows	30	1
Plastic doors and windows	30	1

Figure 6 shows the results of the baseline scenario (GB/T51366) and the alternative scenario, which adds more processes based on EN15978. It was found that the carbon emissions increased by 3.7%, from 23.58 $kgCO_2e$ to 24.45 $kgCO_2e$ per square meter during the operation stage. In the construction stage, the increase was 1.2%, from 4.79 $kgCO_2e$ to 4.85 $kgCO_2e$. In total, the increase rate of the alternative scenario is 2.9% throughout the entire life cycle of the studied building. The results demonstrate that the missing processes in GB/T51366 do not have significant impacts on the total carbon emissions. However, the accuracy of evaluation based on GB/T51366 is questionable since not all the processes are involved. It is suggested to revisit the system boundary and involve significant processes to enhance the accuracy of LCCA.

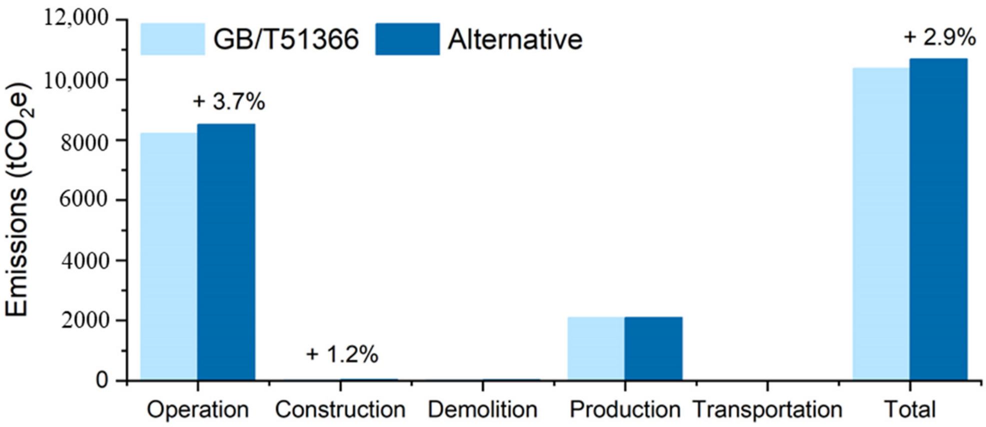

Figure 6. Change in carbon emissions using the alternative scenario as compared to GB/T51366.

4.2.2. Sensitivity to Emission Factors

Both standards adopt the emission factor method, in which the emission factor is multiplied by activity data to calculate environmental impacts. This approach heavily relies on emission factors, while the lack of emission factors for construction materials and processes is one of the key limitations of LCCA in China. On the other hand, Ecoinvent has been recognized as one of the most comprehensive databases in the world, with over 30,000 datasets covering a variety of categories. Here, we compare the results of the production stage by replacing the emission factors in the baseline model with the emission factors from Ecoinvent 3. As aforementioned, the high-impact materials of the studied building are steel, concrete, and cement. Therefore, the emission factors of these building materials are changed. The materials selected for comparison are shown in Table 9.

Table 9. Comparison of carbon emission factors for building materials.

Material	Emission Factor (Ecoinvent)	Unit	Emission Factor (GB/T51366)	Unit
Reinforcing Steel	2150	$kgCO_2/t$	2340	$kgCO_2/t$
Hot rolled steel	1950	$kgCO_2/t$	3110	$kgCO_2/t$
Concrete	329	$kgCO_2/m^3$	295	$kgCO_2/m^3$
Cement	657	$kgCO_2/m^3$	735	$kgCO_2/m^3$

As shown in Figure 7, the carbon emissions of the baseline model of the studied building during the production stage are 560 tCO_2e higher than that of the Ecoinvent scenario, with a 26.7% increase. The increase in carbon emissions relative to the whole life cycle is 5.4%. Of these, the carbon emissions of reinforcement steel, hot-rolled steel sheets, and cement are higher than the Ecoinvent scenario value, while the carbon emissions of concrete are lower than the Ecoinvent scenario value. This is due to the fact that carbon emission factors of materials vary geographically [61], the differences in production processes [62], energy mix [63], and level of economic development [64]. The differences in material production stages found in this study are mainly attributed to the high energy consumption of building materials in China since the energy structure is currently dominated by fossil fuels [65]. The significant difference caused by emission factors may obscure the understanding of LCCA of buildings when the results are compared with overseas.

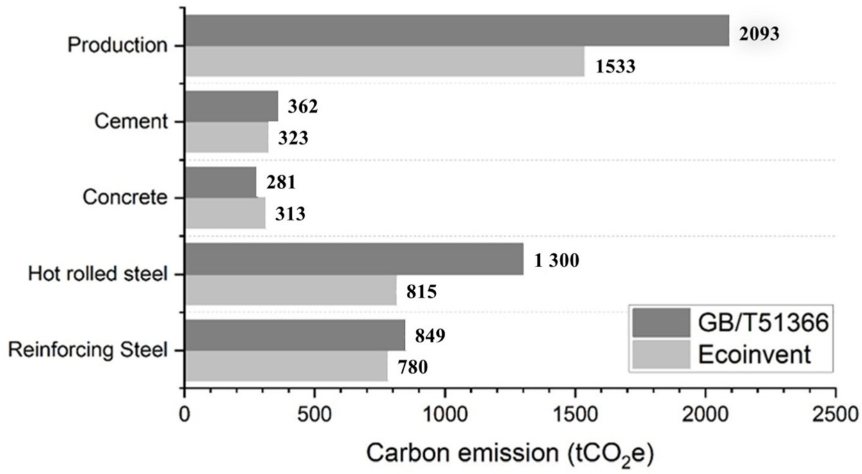

Figure 7. Comparison of impacts from carbon emission factors of building materials in GB/T51366 and Ecoinvent.

5. Discussion

Carbon emission calculation standards of buildings are essential for accurate quantification of LCCA and serve as a technical basis for the building industry to achieve carbon neutrality. This study develops a calculation toolkit following GB/T51366 and conducts descriptive and quantitative analyses to compare GB/T51366 with a widely adopted LCA standard of buildings, EN15978.

5.1. Summary of the Pros and Cons of GB/T51366

The national standard GB/T51366 provides a reference for consistent life cycle carbon assessment in China, with potential application in comparing the carbon emissions of buildings in China and overseas. Based on the outcomes of this study, the pros and cons of GB/T51366 are summarized in Table 10. It is suggested to improve the standard in terms of the completeness of the study scope. The method adopted in EN15978 can be a good reference as it has been widely implemented in the building industry. Carbon sinks should be included in the standard, as the green areas of landscapes, green roofs, and walls are the tendency of future low-carbon buildings. Difficulties with data collection in accordance with GB/T51366 are found in this study. More research should be conducted in this aspect to improve the feasibility and accuracy of the standard.

Table 10. The summary of pros and cons of GB/T51366.

Aspects	Pros	Cons
Scope	The standard covers full life cycle of a building, including material production, transportation, construction, operation, and demolition.	Several processes are not involved: Production: the emissions from manufacturing of building equipment; Construction and demolition: transportation of machinery, transportation of workers, water consumption; Operation: maintenance, refurbishment, replacement, repairing, water supply.
Calculation method	Detailed calculation methods for each process are provided.	Calculation method of carbon sink is not provided.
Data collection	Default data of emission factors are provided.	Very difficult to collect all the required data by the standard.
Application	There are many reports and software based on the standard.	Difficult for the industry to use without adjustments of data and calculation methods.
Others	The first life cycle standard for buildings in China.	The accuracy is not comparable to overseas standards.

5.2. Challenges in Data Collection

During the process of data collection, it was found that obtaining all the data required by GB/T51366 is very difficult, especially at the early design stage. Detailed data on all the life cycle stages are not available, and data communication among stakeholders is lacking. In order to unveil the existing challenges of data collection for LCCA in China, we conducted a set of non-structured interviews with architects, contractors, suppliers, third-party agencies, and government departments from February to June 2022. We designed a data collection sheet based on the "Input" worksheet of the calculation tool and sent it to the above stakeholders. The interviewees were asked the following questions: (i) What data in the worksheet can you provide? (ii) Which method do you prefer: MI or MII?

For question (i), we summarize the feedback from the stakeholders into a relationship diagram, as shown in Figure 8. At the early design stage, only three stakeholders are mainly involved, i.e., the developer, architect, and government. On the one hand, a developer should seek approval from the government for the building construction project. On the other hand, an architect provides the drawing and design for the tender process to fulfill the requirements of the developer. If the LCCA is conducted at the design stage, building information modeling (BIM) can be established based on the building design to obtain an inventory of construction materials. For the operational data, energy modeling can be performed to generate data on energy consumption by different building services. Data on construction, transportation, and demolition can only be estimated according to previous projects or existing literature. At the construction stage, accurate data on construction materials, machinery, and labor are available. If the LCCA is required at the design and construction stages, the carbon emissions generated from demolition are not available, and the data have to be estimated.

For question (ii), all the interviewees indicated that MII is preferred, although MII does not restrict following GB/T51366. As there is no standard data collection guidance for GB/T51366, MI is not feasible in the LCCA practice for the building industry. Not surprisingly, MII is adopted for the operation, construction, and demolition stages in our case study. Based on the research findings of this study, it is suggested to adopt a hybrid method that combines MI and MII. When data are available, MI should be used. If detailed data are missing, MII can be adopted.

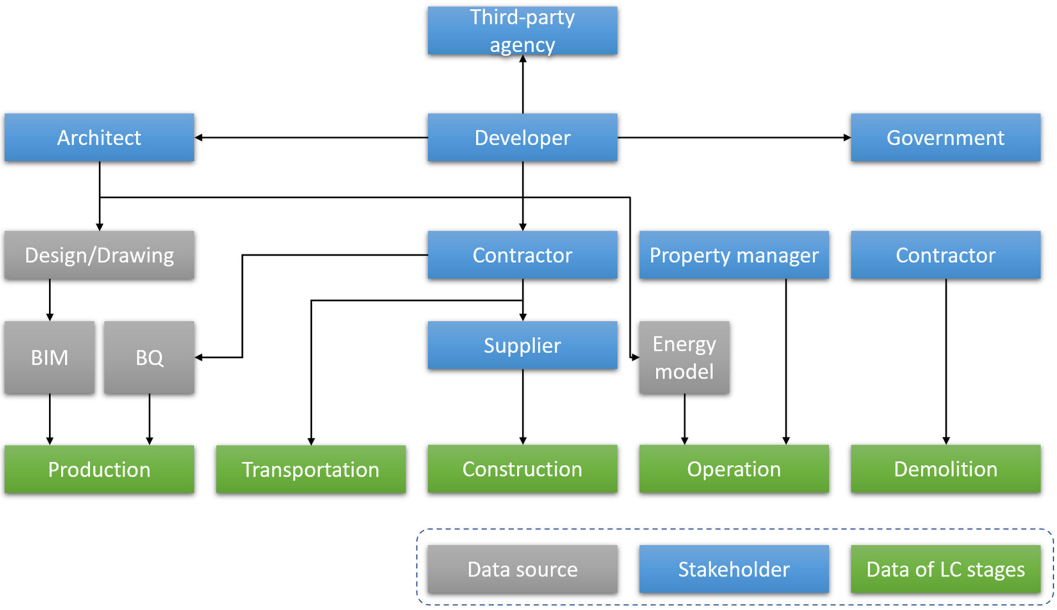

Figure 8. Links among stakeholders and data sources for the life cycle stages of a building.

5.3. Carbon Sink

GB/T51366 requires the calculation of carbon sinks by vegetation within the building project area, but no calculation methods are provided. While EN15978 involves the environmental benefits in module D, the details on carbon sinks are not available. In this study, IPCC 2006 and 2019 are referred to calculate the carbon sinks of the building project [66,67]. It should be noted that with the increasing demand for high living standards, green areas in future building projects tend to increase as well. Consequently, carbon sinks in the vegetation of the green areas will be inevitable [68]. Therefore, detailed specifications for carbon sinks should be provided in the GB/T51366.

6. Conclusions

This study focuses on an emerging issue of the pros and cons of the national standard GB/T51366 for life cycle carbon assessment (LCCA) of buildings. We established a calculation toolkit based on GB/T51366 and performed an LCCA of a residential building in Qingdao, China. In addition, GB/T51366 is compared with EN15978, and the challenges in important topics of data collection, emission factors, completeness, and carbon sinks are discussed. Considering the difficulty in data collection, two methods are provided in the calculation toolkit. The simplified method of MII is preferred by relevant stakeholders, and a hybrid method that combines MI and MII is suggested.

It is found that GB/T51366 is not as complete as EN15978. The carbon emissions of the baseline model are 2.9% less than the alternative model. Although the difference is not significant in the case study, the accuracy of evaluation based on GB/T51366 should be further improved to involve additional processes. By changing the emission factors of building materials, the difference in results can be as large as 26.7%. The significant difference caused by emission factors may obscure the understanding of LCCA of buildings when the results are compared with overseas.

Suggestions are provided for the LCA participators in the building industry. Although the proposed two methods can solve the problem of data unavailability to some extent, difficulties in data collection may hinder the application of LCCA in the industry. Therefore, it is suggested to establish a mechanism to facilitate communication among stakeholders for LCCA data sharing. In addition, comprehensive databases should be established, and the datasets should be updated regularly to meet the emerging data demand. This study is based on a residential building project, while other building typologies are not investigated. Future research is needed to involve more building typologies, such as commercial buildings and public buildings, for the analysis, thus paving the way for a comprehensive LCCA standard of buildings.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings13102417/s1. File S1: Calculation toolkit; File S2: Life cycle carbon assessment of buildings based on the national standard—GB/T51366: the pros and cons. Ref. cited [12].

Author Contributions: Y.D. conceived and designed the analysis and wrote and revised the manuscript. T.Y. wrote the manuscript and developed models. P.L. reviewed and revised the manuscript. Z.X. provided the resources. All authors have read and agreed to the published version of the manuscript.

Funding: This study is funded by the Natural Science Foundation of Shandong Province, China (No. ZR2021MG035), the Science and Technology Development Fund of Macao SAR (FDCT/0146/2022/A), and Macau University of Science and Technology (No. FRG-22–091-FIE).

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article and materials cited.

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

References

1. Ali, K.A.; Ahmad, M.I.; Yusup, Y. Issues, Impacts, and Mitigations of Carbon Dioxide Emissions in the Building Sector. *Sustainability* **2020**, *12*, 7427.
2. United Nations. 27th United Nations Climate Change Conference. 2022. Available online: https://news.un.org/zh/story/2022/11/1112252 (accessed on 10 December 2022).
3. National Bureau of Statistics of the People's Republic of China. China Statistical Yearbook 2021. 2021. Available online: http://www.stats.gov.cn/tjsj/ndsj/2021/indexch.html (accessed on 6 January 2023). (In Chinese)
4. China Association of Building Energy Efficiency. 2022 Series of Research Reports on Carbon Emissions in China's Urban and Rural Construction Sector. 2023. Available online: https://www.cabee.org/site/content/24420.html (accessed on 4 January 2023). (In Chinese).
5. Wu, Y.; Zhang, S.; Jiang, L. Discussion on the current situation of carbon emission and carbon neutral path of China's buildings. *Chongqing Archit.* **2021**, *20*, 66–68.
6. Xu, T.T.; Kang, C.Y.; Zhang, H. China's efforts towards carbon neutrality: Does energy-saving and emission-reduction policy mitigate carbon emissions? *J. Environ. Manag.* **2022**, *361*, 115286. [CrossRef] [PubMed]
7. Ministry of Housing and Urban-Rural Development of the People's Republic of China. Green Building Creation Action Plan. 2020. Available online: http://www.gov.cn/zhengce/zhengceku/2020-07/24/content_5529745.htm (accessed on 6 January 2023). (In Chinese)
8. General Office of the State Council of the People's Republic of China, 2021. Available online: http://www.gov.cn/zhengce/content/2021-10/26/content_5644984.html (accessed on 5 December 2022). (In Chinese)
9. General Office of the State Council of the People's Republic of China. National Standardisation Development Framework. 2021. Available online: http://www.gov.cn/zhengce/2021-10/10/content_5641727.html (accessed on 5 December 2022). (In Chinese)
10. Ministry of Housing and Urban-Rural Development of the People's Republic of China. GB/T 55015-2021 General Specification for Energy Efficiency and Renewable Energy Use in Buildings. 2021. Available online: https://www.mohurd.gov.cn/gongkai/fdzdgknr/zfhcxjsbwj/202110/20211013_762460.html (accessed on 6 January 2023). (In Chinese)
11. Dong, Y.; Liu, J.; Dong, H.; Luo, G.; Sun, H. Analysis of carbon emission of buildings and research on carbon reduction path. *Chongqing Archit.* **2023**, *22*, 5–8.
12. Ministry of Housing and Urban-Rural Development of the People's Republic of China. GB/T 51366-2019 Standard for Calculating Carbon Emissions from Buildings. 2019. Available online: https://www.mohurd.gov.cn/gongkai/fdzdgknr/tzgg/201905/20190530_240723.html (accessed on 20 November 2022).
13. Kloepffer, W. Life cycle sustainability assessment of products. *Int. J. Life Cycle Assess.* **2008**, *13*, 89–94. [CrossRef]
14. 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]
15. Kumanayake, R.; Luo, H. A tool for assessing life cycle carbon emissions of buildings in Sri Lanka. *Build. Environ.* **2018**, *128*, 272–286. [CrossRef]
16. Oh, B.K.; Glisic, B.; Lee, S.H.; Cho, T.; Park, H.S. Comprehensive investigation of embodied carbon emissions, costs, design parameters, and serviceability in optimum green construction of two-way slabs in buildings. *J. Clean. Prod.* **2019**, *222*, 111–128. [CrossRef]

17. Wu, X.; Peng, B.; Lin, B. A dynamic life cycle carbon emission assessment on green and non-green buildings in China. *Energy Build.* **2017**, *149*, 272–281. [CrossRef]
18. Luo, Z.; Cang, Y.; Zhang, N.; Yang, L.; Liu, J.P. A Quantitative Process-Based Inventory Study on Material Embodied Carbon Emissions of Residential, Office, and Commercial Buildings in China. *J. Therm. Sci.* **2019**, *28*, 1236–1251. [CrossRef]
19. Mao, C.; Shen, Q.P.; Shen, L.Y.; Tang, L.Y.N. Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: Two case studies of residential projects. *Energy Build.* **2013**, *66*, 165–176. [CrossRef]
20. Zhang, X.; Wang, F. Life-cycle assessment and control measures for carbon emissions of typical buildings in China. *Build. Environ.* **2015**, *86*, 89–97. [CrossRef]
21. Teng, Y.; Li, K.; Pan, W.; Ng, T. Reducing building life cycle carbon emissions through prefabrication: Evidence from and gaps in empirical studies. *Build. Environ.* **2018**, *132*, 125–136. [CrossRef]
22. Ding, Z.K.; Liu, S.; Luo, L.W.; Liao, L.H. A building information modeling-based carbon emission measurement system for prefabricated residential buildings during the materialization phase. *J. Clean. Prod.* **2020**, *264*, 121728. [CrossRef]
23. Fenner, A.E.; Kibert, C.J.; Woo, J.; Morque, S.; Razkenari, M.; Hakim, H.; Lu, X.S. The carbon footprint of buildings: A review of methodologies and applications. *Renew. Sustain. Energy Rev.* **2018**, *94*, 1142–1152. [CrossRef]
24. Chastas, P.; Theodosiou, T.; Kontoleon, J.; Bikas, D. Normalising and assessing carbon emissions in the building sector: A review on the embodied CO_2 emissions of residential buildings. *Build. Environ.* **2018**, *130*, 212–226. [CrossRef]
25. Pan, W.; Li, K.; Teng, Y. Rethinking system boundaries of the life cycle carbon emissions of buildings. *Renew. Sustain. Energy Rev.* **2018**, *90*, 379–390. [CrossRef]
26. Erdogan, S. Dynamic nexus between technological innovation and buildings Sector's carbon emission in BRICS countries. *J. Environ. Manag.* **2021**, *293*, 112780. [CrossRef]
27. Jayawardana, J.; Sandanayake, M.; Jayasinghe, J.A.S.C.; Kulatunga, A.K. A comparative life cycle assessment of prefabricated and traditional construction—A case of a developing country. *J. Build. Eng.* **2023**, *72*, 106550. [CrossRef]
28. Zhao, Y.; Liu, L.; Yu, M. Comparison and analysis of carbon emissions of traditional, prefabricated, and green material buildings in materialization stage. *J. Clean. Prod.* **2023**, *406*, 137152. [CrossRef]
29. Llorach-Massana, P.; Cirrincione, L.; Sierra-Perez, J.; Scaccianoce, G. Environmental assessment of a new building envelope material derived from urban agriculture wastes: The case of the tomato plants stems. *Int. J. Life Cycle Assess.* **2023**, *28*, 813–827. [CrossRef]
30. Sheep, L.; Allacker, K.; Rock, M. Bio-based building material solutions for environmental benefits over conventional construction products-Life cycle assessment of regenerative design strategies (1/2). *Energy Build.* **2023**, *280*, 112767.
31. Teng, Y.; Li, C.Z.; Shen, G.Q.P.; Yang, Q.W. The impact of life cycle assessment database selection on embodied carbon estimation of buildings. *Build. Environ.* **2023**, *243*, 110648. [CrossRef]
32. Yang, X.; Zhang, S.; Wang, K. Quantitative study of life cycle carbon emissions from 7 timber buildings in China. *Int. J. Life Cycle Assess.* **2021**, *26*, 1721–1734. [CrossRef]
33. Dong, J. Quantitative Study on the Life-Cycle Carbon Emissions of a Nearly Zero Energy Building in the Severe Cold Zones of China. *Sustainability* **2022**, *14*, 1148.
34. Li, J. Energy performance heterogeneity in China's buildings sector: A data-driven investigation. *Renew. Sustain. Energy Rev.* **2016**, *58*, 1587–1600. [CrossRef]
35. Huang, L.Z.; Krigsvoll, G.; Johansen, F.; Liu, Y.P.; Zhang, X.L. Carbon emission of global construction sector. *Renew. Sustain. Energy Rev.* **2018**, *81*, 1906–1916. [CrossRef]
36. Abeydeera, L.H.U.W.; Mesthrige, J.W.; Samarasinghalage, T.I. Global Research on Carbon Emissions: A Scientometric Review. *Sustainability* **2019**, *11*, 3972. [CrossRef]
37. Li, C.Z.; Lai, X.L.; Xiao, B.; Tam, V.W.Y. A holistic review on life cycle energy of buildings: An analysis from 2009 to 2019. *Renew. Sustain. Energy Rev.* **2020**, *134*, 110372. [CrossRef]
38. Yan, J.Y.; Lu, Q.C.; Tang, J.Q.; Chen, L.; Hong, J.K.; Broyd, T. Digital Tools for Revealing and Reducing Carbon Footprint in Infrastructure, Building, and City Scopes. *Builds* **2022**, *12*, 1097. [CrossRef]
39. Williams, J.; Mitchell, R.; Raicic, V.; Vellei, M. Less is more: A review of low energy standards and the urgent need for an international universal zero energy standard. *J. Build. Eng.* **2016**, *6*, 65–74. [CrossRef]
40. De Wolf, C.; Pomponi, F.; Moncaster, A. Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. *Energy Build.* **2017**, *140*, 68–80. [CrossRef]
41. Rasmussen, F.N.; Malmqvist, T.; Moncaster, A.; Wiberg, A.H. Analysing methodological choices in calculations of embodied energy and GHG emissions from buildings. *Energy Build.* **2018**, *158*, 1487–1498. [CrossRef]
42. Piccardo, C.; Gustavsson, L. Implications of different modelling choices in primary energy and carbon emission analysis of buildings. *Energy Build.* **2021**, *247*, 111145. [CrossRef]
43. BSI. EN-15978 (2011) Sustainability of Construction Works. Assessment of Environmental Performance of Buildings. Calculation Method. 2011. Available online: https://standards.iteh.ai/catalog/standards/cen/62c22cef-5666-4719-91f9-c21cb6aa0ab3/en-15978-2011 (accessed on 10 September 2023).
44. USGBC. LEED v4.1 Building Design and Construction. In Getting Started Guide for Beta Participants. 2019. Available online: http://refhub.elsevier.com/S2352-710200036-X/sref42 (accessed on 10 September 2023).

45. BRE. 2016 BREEAM International New Construction. In Technical Manual SD233 2.0. Building Research Establishment Group. Available online: http://refhub.elsevier.com/S2352-710200036-X/sref44 (accessed on 10 September 2023).
46. Pushkar, S. Life-Cycle Assessment of LEED-CI v4 Projects in Shanghai, China: A Case Study. *Sustainability* **2023**, *15*, 5722. [CrossRef]
47. Lessard, Y.; Anand, C.; Blanchet, P. LEED v4: Where Are We Now? Critical Assessment through the LCA of an Office Building Using a Low Impact Energy Consumption Mix. *J. Ind. Ecol.* **2018**, *22*, 1105–1116. [CrossRef]
48. Sartori, T.; Drogemuller, R.; Omrani, S.; Lamari, F. A schematic framework for Life Cycle Assessment (LCA) and Green Building Rating System (GBRS). *J. Build. Eng.* **2021**, *38*, 10. [CrossRef]
49. Li, C.Z.; Xue, F.; Li, X.; Hong, J.; Shen, G.Q. An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction. *Autom. Constr.* **2018**, *89*, 146–161. [CrossRef]
50. China Academy of Building Research. 1988. Available online: https://www.pkpm.cn/ (accessed on 20 December 2022). (In Chinese).
51. Yang, X.N.; Hu, M.M.; Wu, J.B.; 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]
52. Dong, Y.; Ng, S.T.; Liu, P. A comprehensive analysis towards benchmarking of life cycle assessment of buildings based on systematic review. *Build. Environ.* **2021**, *204*, 108162. [CrossRef]
53. Lou, Y.Y.; Ye, Y.Y.; Yang, Y.Z.; Zuo, W.D. Long-term carbon emission reduction potential of building retrofits with dynamically changing electricity emission factors. *Build. Environ.* **2022**, *210*, 108683. [CrossRef]
54. Du, Q.; Shao, L.; Zhou, J.; Huang, N.; Bao, T.N.; Hao, C.C. Dynamics and scenarios of carbon emissions in China's construction industry. *Sustain. Cities Soc.* **2019**, *48*, 101556. [CrossRef]
55. Yang, H.H.; Li, X.; Ma, L.W.; Li, Z. Using system dynamics to analyse key factors influencing China's energy-related CO_2 emissions and emission reduction scenarios. *J. Clean. Prod.* **2021**, *320*, 128811. [CrossRef]
56. Huo, T.F.; Ma, Y.L.; Xu, L.B.; Feng, W.; Cai, W.G. Carbon emissions in China's urban residential building sector through 2060: A dynamic scenario simulation. *Energy* **2022**, *254*, 124395. [CrossRef]
57. Braulio-Gonzalo, M.; Jorge-Ortiz, A.; Bovea, M.D. How are indicators in Green Building Rating Systems addressing sustainability dimensions and life cycle frameworks in residential buildings? *Environ. Impact Assess. Rev.* **2022**, *95*, 106793. [CrossRef]
58. Vandervaeren, C.; Galle, W.; Stephan, A.; De Temmerman, N. More than the sum of its parts: Considering interdependencies in the life cycle material flow and environmental assessment of demountable buildings. *Resour. Conserv. Recycl.* **2022**, *177*, 106001. [CrossRef]
59. China Architecture and Building Press. *Building Construction Handbook*, 5th ed.; China Architecture and Building Press: Beijing, China, 2012. (In Chinese)
60. Zhang, X.; Wang, F. Analysis of embodied carbon in the building life cycle considering the temporal perspectives of emissions: A case study in China. *Energy Build.* **2017**, *155*, 404–413. [CrossRef]
61. Pan, X.F.; Uddin, M.K.; Ai, B.W.; Pan, X.Y.; Saima, U. Influential factors of carbon emissions intensity in OECD countries: Evidence from symbolic regression. *J. Clean. Prod.* **2019**, *220*, 1194–1201. [CrossRef]
62. Geng, Y.B.; Wang, Z.T.; Shen, L.; Zhao, J.N. Calculating of CO_2 emission factors for Chinese cement production based on inorganic carbon and organic carbon. *J. Clean. Prod.* **2019**, *217*, 503–509. [CrossRef]
63. Wen, L.; Bai, L.; Zhang, E. System dynamic modeling and scenario simulation on Beijing industrial carbon emissions. *Environ. Eng. Res.* **2016**, *21*, 355–364. [CrossRef]
64. Xu, P.Y.; Zhu, J.J.; Li, H.T.; Xiong, Z.H.; Xu, X.X. Coupling analysis between cost and carbon emission of bamboo building materials: A perspective of supply chain. *Energy Build.* **2023**, *280*, 112718. [CrossRef]
65. Ouyang, X.L.; Lin, B.Q. An analysis of the driving forces of energy-related carbon dioxide emissions in China's industrial sector. *Renew. Sustain. Energy Rev.* **2015**, *45*, 838–849. [CrossRef]
66. Intergovernmental Panel on Climate Change. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. 2006. Available online: https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html (accessed on 25 November 2022).
67. Intergovernmental Panel on Climate Change. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. 2019. Available online: https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/ (accessed on 25 November 2022).
68. Han, J.; Meng, X.; Zhou, X.; Yi, B.L.; Liu, M.; Xiang, W.N. A long-term analysis of urbanization process, landscape change, and carbon sources and sinks: A case study in China's Yangtze River Delta region. *J. Clean. Prod.* **2016**, *141*, 1040–1050. [CrossRef]