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Retraction

Retracted: Case Study of Carbon Emissions from a Building's Life Cycle Based on BIM and Ecotect

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Advances in Materials Science and Engineering has retracted the article titled "Case Study of Carbon Emissions from a Building's Life Cycle Based on BIM and Ecotect" [1]. The article was previously published as Peng C, "Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling," (2016), Journal of Cleaner Production, Part 1 112, pp. 453–465. doi: 10.1016/j.jclepro.2015.08.078.

References

[1] C. Peng and X. Wu, "Case study of carbon emissions from a building's life cycle based on BIM and Ecotect," *Advances in Materials Science and Engineering*, vol. 2015, Article ID 954651, 15 pages, 2015.

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Research Article

Case Study of Carbon Emissions from a Building's Life Cycle Based on BIM and Ecotect

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Using building information modeling (BIM) and Ecotect, this paper estimated carbon emissions during an office building's life cycle. This building's life cycle CO_2 emissions were divided into three parts: the construction, operation, and demolition stages. Among these, the statistics on the schedule of quantities were generated using BIM, and the energy consumption during the building's operational stage was obtained using ECOTECT simulation. Sensitivity analysis was performed by changing several alternative parameters, to identify which parameter has more impacts on building performance. The paper demonstrated that (1) BIM and Ecotect are very helpful in estimating carbon emissions from a building's life cycle, (2) the primary and effective measures to reduce the building's CO_2 emissions in hot and humid climate should be arranged as follows: (a) within the limits of comfort, reducing the fresh air volume; (b) extending the indoor temperature range; (c) improving the thermal insulation performance of exterior windows, walls, and roofs; (d) exploiting natural ventilation during transition seasons, and (3) currently there are some limitations in performing LCA based on BIM and Ecotect.

1. Introduction

The global warming caused by greenhouse gas (GHG) emissions has become a focus of concern to international society. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) has shown that global GHG emissions due to human activities have grown since preindustrial times, with an increase of 70% between 1970 and 2004. In the 100 years between 1906 and 2005, the average global temperature has increased by 0.74°C, while in the most recent 50 years the average temperature increase has been approximately 0.13°C every 10 years, double the temperature increase of the past 100 years. Model experiments show that the average global temperature will continue to increase at a speed of 0.2°C every 10 years in the next 20 years [1].

During China's industrialization and urbanization process, the construction industry has been charged with the building of a national infrastructure, consuming a large amount of resources and power and generating a large amount of waste, resulting in major impacts to the environment. The consumption of resources and energy and the solid waste treatment that occur during the process of building construction, operation, and demolition have been generating high GHG emissions [2].

Life-cycle analysis (LCA) is able to quantify energy consumption and environmental pollutant emission, by defining a scope of analysis for each type of building or fabrication method, for types of manufacturing or building material, and for each stage of its life cycle [3–5].

LCA has been applied to building systems on a variety of levels, such as building materials, building products, or the entire building [6]. Most building-related LCA studies have focused on a specific part of the building life cycle, and few have addressed the whole building throughout its life cycle [7] due to the difficulties of acquiring accurate building material quantities and building performance indicators such as energy use and indoor climate, especially in the design stage. Building information modeling (BIM) provides an effective platform for overcoming the difficulties of acquiring the necessary building data in LCA, so they provide great potential for conducting LCAs of entire buildings in the design stage. As a result, LCA could be used to enable better early-stage decision-making by providing feedback on the environmental impacts of BIM design choices [8]. Basbagill et al. [8] have presented a method for applying LCA to early-stage decision-making to inform designers of the relative environmental impact importance of building component materials and dimension choices. An impact allocation scheme was developed which showed the distribution of embodied impacts among building elements, and an impact reduction scheme illustrated which material and thickness choices achieved the greatest embodied impact reductions [7].

Life-cycle energy consumption and the CO_2 emissions of a university building in the Midwest have been calculated using Ecotect and BIM models [8, 9]. The study has compared life-cycle performance, such as CO_2 emissions and energy consumptions, among different design configurations, and their distributions over the stages of the building's lifetime. Sensitivity analysis was performed by varying several alternative parameters to identify which parameter had the most impact on building performance. Preliminary results indicated that the whole-building life-cycle performance was affected by several design parameters with different degrees of sensitivity. Adalberth has presented case studies of the total carbon emissions of three single-unit dwellings in Sweden, reporting that 85% of the total energy use was required during the operation phase, whereas the energy used in manufacturing the materials employed in construction, including erection and renovation, represented approximately 15% of the total energy use. The transportation and process energy used during the erection and demolition of the dwellings comprised approximately 1% of the total energy requirement [10]. However, for a low-energy family house (LEFH), the dramatic contribution of material-related impacts emerged. Structure and finishes materials represented the highest relative contribution. The contributions of equipment, construction stage, and transportation were minor. The important role of the recycling potential also emerged. Unlike standard buildings, where heating-related impacts overshadowed the rest of the life cycle, there was no single dominating item or aspect in LEFH. Rather, several of them played equally important roles [11].

Although embodied carbon constitutes only 10–20% of a building's life-cycle carbon, the opportunity for its reduction should not be ignored [12–14]. There is potential to reduce embodied carbon requirements through the use of building materials that require less carbon during manufacturing [15]. Oka et al. have quantified the energy consumption and carbon emissions produced by construction in Japan [16], while Buchanan has performed a detailed study on the embodied carbon of buildings and resulting CO_2 emissions from wood, concrete, and steel structures created for office and residential purposes in New Zealand and concluded that wood structures have less embodied carbon than concrete and steel structures [17]. Reddy and Jagadish have estimated the embodied carbon of residential buildings using different construction techniques and low carbon materials and obtained 30–45% reductions in embodied carbon [18]. Another opportunity for reducing embodied carbon is through the use of recycled materials in construction [19].

The purpose of this study was to present a method for calculating the carbon emissions generated over a building's life cycle, to perform quantitative analysis on these carbon emissions and gain a clear, precise understanding of the accounting process of building carbon emissions.

There have been similar studies conducted in other places, especially in developed regions. However, carbon emissions from a building's life cycle have distinct regional characteristics because of the different types of climates, management policies, and technological levels in different places. For example, carbon emissions from the building material construction in developed regions may be more than those in developing regions. However, carbon emissions from raw material procurement and building material production may be less than those in developing regions. Therefore, the simulation of carbon emissions from a building's life cycle becomes more complicated and the results of calculation appear more different. That is why the calculation methods used in developed regions cannot be applied mechanically in developing areas. Currently, the study of carbon emissions from a building's life cycle based on BIM and Ecotect in developing area of Nanjing has not yet been conducted. Therefore, this paper has some novelty in terms of results and recommendations.

2. Methods

This case study combined three types of methods to perform the case study. Firstly, life- cycle modeling of the building was executed based on its physical process from cradle to grave. BIM and Ecotect were then used to provide required information and tools for simulating the building performance.

2.1. Definition of a Building's Life-Cycle CO_2 ($LCCO_2$) Emissions. Based on life-cycle theory [20, 21], this study divided a building's $LCCO_2$ emissions into three stages: the construction stage (including processes such as procurement of raw materials, building material production, transportation, and construction), the operational stage, and the demolition stage (including processes such as building demolition and waste material recycling and processing). In this study, maintenance stage was excluded due to its lower weight in importance [22]. The carbon emissions of the operational stage primarily include those generated by heating, ventilation, and air conditioning (HVAC), lighting, office equipment, elevators, and water pumps. The sequestration from the surrounding greenery might also be considered. Figure 1 shows a flowchart of these phases.

2.2. BIM-Based Quantity Surveying. Quantity surveying is an essential part of life-cycle analysis of building carbon emissions. It is a profession that necessitates both a high degree of knowledge and finely honed deployment skills. It entails accurate interpretation of designs and numerical

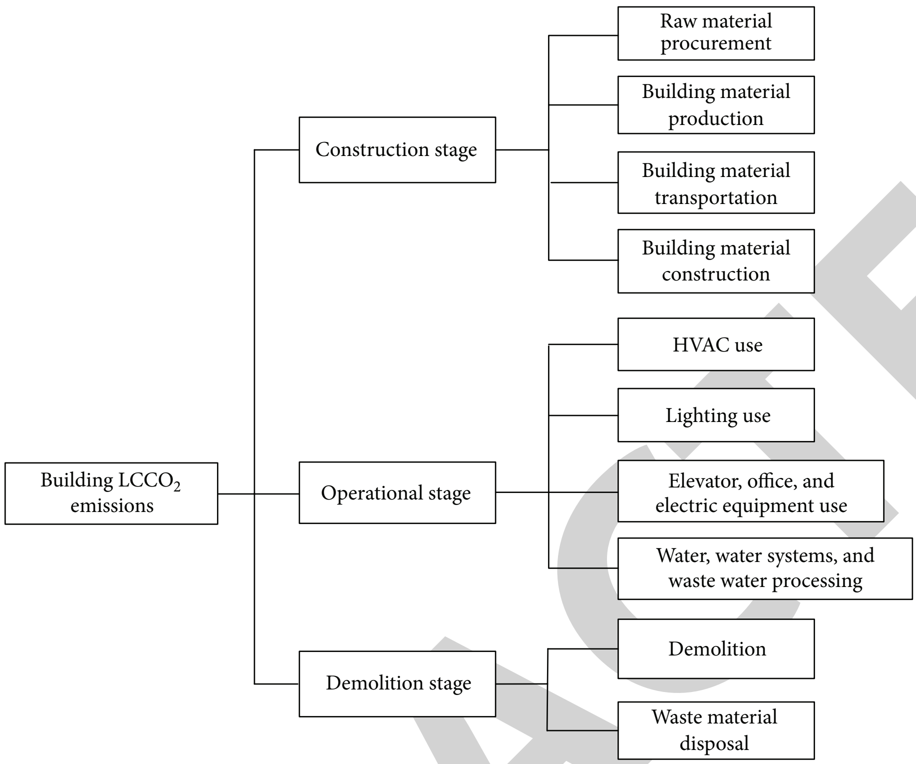

Figure 1: Building $LCCO_2$ emissions.

representation of component quantities. Because computer-aided design (CAD) software cannot store the necessary information to facilitate the automatic calculation of engineering project components, traditionally quantity surveying is a manual process and, as such, is prone to errors as well as being very time consuming. However, time issues can be addressed and errors eradicated by automating the process. BIM is a database containing rich engineering information that can provide realistic material quantity information [23–25]. With this information, BIM can automatically produce an accurate bill of quantities, thereby reducing the tedious manual operations required for the process and the associated potential errors.

The Run Run Shaw Architectural Building (RRSAB) used as an example in this study is constructed in 2000 and located at Southeast University in Nanjing and is an office building of reinforced concrete with a 16,873 m^2 gross floor area (GFA). Of this area, 15,419 m^2 is aboveground and 1,454 m^2 is underground. The elevation of basement floor is −3.4 m. There are 15 floors above the ground floor in the main building, three floors in the neighboring podium, and one floor underground. A BIM of the RRSAB was constructed using the Autodesk Revit Architecture and is shown in Figure 2.

After entering the densities of various materials into the program, Revit can then perform automatic statistical analysis on the quantities, and the quantities of the main building materials used for the entire building can be obtained after some organization, as shown in Table 1. Note that, firstly, we have to add those components, elements, or materials that we used into Revit database in advance if Revit does not cover them.

2.3. Detailed $LCCO_2$ Emission Calculation

2.3.1. Basic Measurement Method for Carbon Emissions. The “2006 IPCC national greenhouse gas inventory categories” [26] states that the GHG emissions generated by energy activities can be calculated using the formula below:

$$C = \sum_{i,j,k} AD_{i,j,k} \cdot \mathrm{EF}_{i,j,k},$$
$$\mathrm{EF}_{i,j,k} = c_k \cdot \eta_{i,j,k} \cdot \frac{44}{12}, \tag{1}$$

where C is the amount of carbon emissions, AD is the level of activity, and EF is the emission factor. i is the industry and region, j is the equipment and technology used, k is the type of fuel used, c_k is the carbon content, and $\eta_{i,j,k}$ is the oxidation rate.

AD is based on the amount of fuel burned and is usually taken from national energy statistics. EF is the average emission factor (default value). For CO_2, the emission factor is determined mainly by the fuel’s carbon content. The burning conditions (burning efficiency and carbon residual in the objects such as slag and ashes) are relatively unimportant. Therefore, the amount of carbon emissions can be accurately

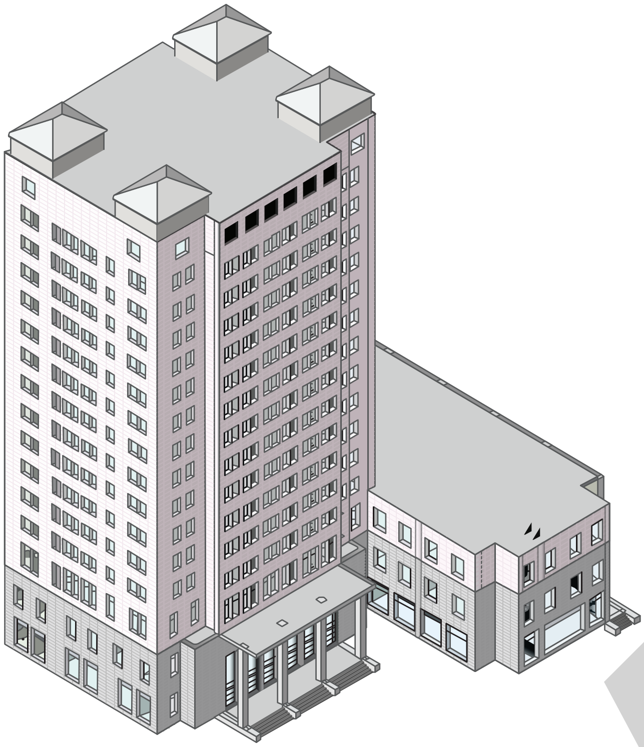

Figure 2: Three-dimensional rendering of the RRSAB created in Revit.

Table 1: Quantities of main building materials used in the RRSAB.

Material	Amount used in the entire building (t)
Concrete	11960.996
Brick	11424
Cement	762.9503
Lime	121.7998
Mortar	1895.9496
Gravel	384.44
Stone	440.265
Steel	527.122
Ceramic tile	169.0875
Paint	64.3755
Glass	48.525
Wood	29.38
Organic material	17.5553
Aluminum	1.16855
Copper	0.204
Total	27847.819

estimated based on the total amount of fuel burned and the average carbon content in the fuel [27].

2.3.2. Total Carbon Emission Computation for the Life Cycle of a Building. Based on Figure 1, the total amount of carbon emissions produced over the life cycle of a building was taken as the sum of the carbon emissions generated during the construction, operational, and demolition stages. The formula is

$$C = C_b + C_u + C_d - C_t, \tag{2}$$

where C is total amount of carbon emissions over the life cycle of the building, t; C_b is the total amount of carbon emissions during the construction stage, t; C_u is the total amount of carbon emissions during the operational stage, t; C_d is the total amount of carbon emissions during the demolition stage, t; and C_t is the total carbon sequestration by vegetation around the building, t.

(1) Total Carbon Emissions during the Construction Stage, C_b. The total amount of carbon emissions during the construction stage included processes such as material production, transportation, and construction; the formula is

$$C_b = C_{be} + C_{bt} + C_{bp}, \tag{3}$$

where C_{be} is the total carbon emissions generated by the building material production, t; C_{bt} is the total carbon emissions generated by the building material transportation, t; and C_{bp} is the total carbon emissions of building materials used during building construction, t.

(1.1) Total Carbon Emissions Generated by the Building Material Production, C_{be}. The amount of materials is multiplied by the corresponding emission factor using the following formula [26]:

$$C_{be} = \sum_i Q_{be,i} \cdot EF_{be,i}, \tag{4}$$

where $Q_{be,i}$ is the quantity of the ith building material used in the project, t, and $EF_{be,i}$ is the carbon emission factor for the ith building material, t/t.

The building material statistics were collected using Autodesk Revit Architecture and the data of energy consumption and CO_2 emission generated by the main building material production were looked up in the literature [28] and listed in Table 2.

(1.2) Total Carbon Emissions Generated by Building Material Transportation, C_{bt}. Transportation methods include trains, trucks, and ships. However, the main transportation means for building materials are generally trucks in China. Commonly used fuels for trucks include gasoline and diesel. The CO_2 emission factors for different transportation means are listed in Table 3 [29], and the use and transportation of building materials generally follow the principle of proximity. The factories manufacturing building materials in Nanjing are generally located in suburbs such as Jiangning, Pukou, or Liuhe. To simplify calculations, the transportation distances in this study were set as $D = 50$ km [28, 30, 31].

The calculation formula is [29]

$$C_{bt} = \sum_i Q_{bt,i} \cdot EF_{bt,i} \cdot D_i, \tag{5}$$

where $Q_{bt,i}$ is the weight of the ith building material, t; $EF_{bt,i}$ is the emission factor for the ith building material

TABLE 2: The data of unit energy consumption and unit CO_2 emissions generated by the main building material production.

Number	Main building materials	Unit	Unit energy consumption (kJ/unit)	Unit CO_2 emissions (kg/unit)
1	Concrete	Kg	1247.74	0.2420
2	Brick	Kg	2000	0.2
3	Cement	Kg	4464	0.894
4	Lime	Kg	4644	1.2
5	Mortar	Kg	3972	0.792
6	Gravel	Kg	23.8	0.002
7	Stone	Kg	12943	2.33
8	Steel	Kg	33906	2.208
9	Ceramic tile	Kg	15400	1.4
10	Paint	Kg	5837	0.89
11	Glass	Kg	16000	1.4
12	Wood	Kg	1800	0.2
13	Organic material	Kg	90353	17.07
14	Aluminum	Kg	12964	1.407
15	Copper	Kg	23579	1.01

Note: (a) the metal has already been considered for recycling. (b) From a life-cycle perspective, the renewability of the building material must be considered when calculating building material consumption and CO_2 emissions. The building materials associated with renewability include reinforced steel, steel, architectural glass, aluminum extrusion, and wood. Although architectural glass and wood can be totally or partially recycled, recycled glass generally cannot be used again for construction. Wood also cannot be used directly in construction without further processing. Therefore, there is no need to consider the recycling and reuse of glass and wood.

TABLE 3: CO_2 emission factors for different transportation methods.

Transportation method	Railroad	Road freight	Coastal vessel	Deep-sea transport
Emission factor (t/(t·km))	$2.04E-5$	$1.68E-4$	$3.46E-5$	$1.60E-5$

transportation method, $t/(t\cdot km)$; and D_i is the distance from the production site to the construction site, kilometers.

(1.3) Total Carbon Emissions of Building Materials Used during Building Construction, C_{bp}. The total carbon emissions produced by building materials used during building construction, C_{bp}, equal the sum of the carbon emissions produced by the construction site electricity use by construction equipment and office devices, and so forth, C_{bp1}, the carbon emissions produced by various construction crafts, C_{bp2}, and the carbon emissions produced by the horizontal transportation occurring during the construction stage, C_{bp3}. The calculation formula is [28, 29]

$$C_{bp} = C_{bp1} + C_{bp2} + C_{bp3}. \tag{6}$$

(1) The electricity use at the construction site includes construction zone and living quarters electricity consumption; the former includes cranes, pile drivers, welding machines, and hoists, and the latter includes workers' living and office space. The statistics on the actual consumed quantities can usually be determined using the construction statements. Before construction, the electricity at the construction site was estimated based on project quotas. The margin emission factors [32] for various Chinese grids are shown in Table 4. In this study, the construction electricity consumption was taken as 10.069 kWh/m^2 [28, 30]. Nanjing belongs to the Eastern Chinese grid, so the operating margin (OM) emission factor of the electricity system was 0.8244 tCO_2/MWh. The computation equation is

TABLE 4: 2012 baseline emission factors for regional power grids in China (tCO_2/MWh).

	EF_{OM}	EF_{BM}
Northern Chinese regional grid	1.0021	0.5940
Northeast regional grid	1.0935	0.6104
Eastern Chinese regional grid	0.8244	0.6889
Mid-Chinese regional grid	0.9944	0.4733
Northwest regional grid	0.9913	0.5398
Southern regional grid	0.9344	0.3791

Note: OM is the operating margin emission factor and BM is the build margin emission factor.

$$C_{bp1} = \sum_i Q_{bp1,i} \cdot EF_{bp1,i}, \tag{7}$$

where $Q_{bp1,i}$ is the construction project quantities. The RRSAB's building area was 16873 m^2. $EF_{bp1,i}$ is the OM CO_2 emission factor for the construction site's electricity system, tCO_2/m^2.

(2) There are many pieces of fuel-consuming machinery at a construction site, and the main fuel-consuming processes include excavation, earth removal, earth work, and horizontal transportation. Current direct statistics data exist on the amount of fuel consumption during the construction stage. Nevertheless, the fuel consumption at this stage could be approximately estimated using "normal consumption quantities for construction projects" and "the construction machinery one-shift cost quota." This study adopted the data estimated from the literature of Zhang et al. [29] and Wang [33], which are shown in Table 5:

$$C_{bp2} = \sum_i Q_{bp2,i} \cdot EF_{bp2,i}, \tag{8}$$

where $Q_{bp2,i}$ is the project quantity for the ith construction process, m^3, and $EF_{bp2,i}$ is the carbon emission factor for the ith construction process, tCO_2/m^3.

(3) It can be very easy to confuse the amount of CO_2 emissions caused by horizontal transportation during

Table 5: CO_2 emission factors for different construction processes.

Construction process	Unit	Diesel consumption (kg)	Gasoline consumption (kg)	Emissions factor (kg/unit)
Excavation and earth removal	m^3	0.270	0.018	1.05
In situ earthwork	m^3	0.030	0	0.11
Earth filling, rolling, and smoothing	m^3	0.250	0.022	0.99
Horizontal transportation	t·km	0.052	0	0.19

the construction stage with the amount of transportation emissions produced during the building material preparation stage, which can result in double counting. Therefore, the carbon emissions caused by the transportation of various component materials should be counted in those generated by building material transportation, C_{bt}. Other transportation emissions generated by various machinery and materials are not part of the building but should be counted as construction emissions, such as concrete moldboard, earthwork from the site excavation or backfilling, and the off-site transportation of large machinery and equipment. The data for horizontal transportation are difficult to compute accurately. Based on the actual case conditions, this study performed estimation using the method of assumption, by assuming material weights for the horizontal transportation stage as 20000 tons and an average transportation distance of 20 km [29, 31]:

$$C_{bp3} = \sum_{i} Q_{bp3,i} \cdot D_i \cdot EF_{bp3,i}, \tag{9}$$

where $Q_{bp3,i}$ is the horizontal transportation project quantity of the ith building material or equipment, t, $EF_{bp3,i}$ is the carbon emission factor of the ith building material or piece of equipment, $kgCO_2/(t \cdot km)$, and D_i is the distance from the production site to the construction site, kilometers.

(2) Total Carbon Emissions during the Building Demolition Stage, C_d. The computation of the carbon emissions generated during the demolition stage includes the carbon emissions generated during the demolition process and the construction waste material treatment process:

$$C_d = C_{d1} + C_{d2}, \tag{10}$$

where C_{d1} is the carbon emissions generated during the demolition process and C_{d2} is the carbon emissions produced during the waste material treatment process.

(2.1) The Carbon Emissions Generated during the Demolition Process, C_{d1}. The carbon emissions generated during the demolition process were obtained by multiplying the demolition energy consumption by the corresponding regional grid alignment emission factors. Based on [28, 30, 31], the demolition energy consumption for the reinforced concrete structure was 107.7 kWh/m^2, which is a combination value of the gross floor area and gross height of the buildings of reinforced concrete. Therefore, the carbon emissions produced by the demolition process are

$$C_{d1} = A_{gfa} \times EF_{dc} \times EF_{OM}, \tag{11}$$

where A_{gfa} is gross floor area of the buildings, m^2; EF_{dc} is emission factor of the demolition energy consumption for the reinforced concrete structure, kWh/m^2; EF_{OM} is operating margin emission factor, tCO_2/MWh.

(2.2) The Carbon Emissions Produced during the Waste Material Treatment Process, C_{d2}. Building materials that cannot be recycled are transported to waste disposal sites for open dumping or landfilling after demolition. Therefore, the CO_2 emissions at this stage are mainly generated by the transportation process, when the waste materials are shipped to a waste disposal site. Assuming that the transportation distance was 30 km and the transportation method was a truck, based on Tables 1 and 3, the carbon emissions produced during the waste material treatment process are

$$C_{d2} = Q_r \times D_r \times EF_{dr}, \tag{12}$$

where Q_r denotes the quantity of waste transported to landfill, t; D_r denotes the distance between construction site and landfill, kilometers; EF_{dr} denotes the emission factor of emission due to waste transportation $t/(t \cdot km)$.

(3) Total Carbon Sequestration by Vegetation around the Building, C_t. The carbon sequestration by vegetation around the building was calculated based on a minimum value. Because the green area around the building in the study case was not very large, the following could be assumed: total amount of carbon sequestration by vegetation = annual sequestration per unit green area × green area × annual limit [26]:

$$C_t = G_1 \times G_2 \times A \times n \times \frac{44}{12}, \tag{13}$$

where G_1 is the carbon ratio of ground tree biomass, set as 0.47 t carbon/t dry matter; G_2 is the annual increase in the above ground biomass, set as 8 t dry matter/(acres · year); A is the green area, acres, for this study only 100 m^2 (0.025 acres); and n is useful lifetime of building, set as 50 years.

(4) Total Carbon Emissions during the Building Operational Stage, C_u. The case example for this study was located in Nanjing, China, which is hot in the summer and cold in the winter. The energy source during the building operational stage is electricity only (the building under study was an ordinary office building with very low water use, so this factor was ignored). Therefore, only the carbon emissions generated

by electricity consumption need to be calculated, using the following formula:

$$\begin{aligned} C_{\mathrm{u}} &= \left(C_{\mathrm{u}1} + C_{\mathrm{u}2} + C_{\mathrm{u}3}\right) \times n \\ &= \left(P_{\mathrm{u}1} + P_{\mathrm{u}2} + P_{\mathrm{u}3}\right) \times \mathrm{EF}_{\mathrm{electricity}} \times n, \end{aligned} \quad (14)$$

where $C_{\mathrm{u}1}$ is the carbon emissions generated by air conditioning, t; $C_{\mathrm{u}2}$ is the carbon emissions generated by lighting, t; $C_{\mathrm{u}3}$ is the carbon emissions generated by elevator, office, and electric equipment, t; $P_{\mathrm{u}1}$ is the total electricity used by air conditioning, MWh; $P_{\mathrm{u}2}$ is the total electricity used by lighting, MWh; $P_{\mathrm{u}3}$ is the total electricity used by elevator, office, and electric equipment, MWh; and n is the regulated building lifetime limit, which for land used for welfare purposes such as education, science, culture, and medicine is 50 years. Therefore, 50 years was used for this study.

Based on the annual average electricity consumption per unit area for Nanjing office buildings and the investigation of this case's actual conditions, the percentages of various energy consumption methods are listed in Table 6 [34].

In this study, the air conditioning energy consumption was simulated using Ecotect, and the electricity consumption for lighting, elevator, office, and electric equipment was calculated based on Table 6. The details of these calculations are given in Section 2.3.3.

2.3.3. Ecotect-Based Operational Carbon Emission Computation

(1) Ecotect. Autodesk Ecotect Analysis is an energy simulation tool, compatible with BIM software, such as Autodesk Revit Architecture, to perform comprehensive preliminary building energy performance analysis [9]. It combines an intuitive 3D design interface with a comprehensive set of performance analysis functions and interactive information displays. Ecotect provides thermal, lighting, and acoustic analysis which includes hourly thermal comfort, monthly space loads, natural and artificial lighting levels, acoustic reflections, reverberation time, and project cost and environmental impact as well [35, 36]. There are studies which show that Ecotect simulations are highly accurate [37–40]. Since the operation stage is usually significant in energy consumption and CO_2 emission [41, 42] in order to ensure the accuracy of the result, Ecotect was used to simulate the heating and cooling load in the operational stage of the building under its defined geometry, material properties, and local weather conditions.

This study used Ecotect to simulate air conditioning electricity consumption. The energy consumption percentage based on the RRSAB's air conditioning, lighting, and electric equipment was used to derive its total electricity consumption. Furthermore, the amount of carbon emissions was derived based on an electricity emission factor, and when multiplied by the annual limit, the carbon emissions produced during the building operational stage could be derived.

In fact, all of the results obtained by energy simulation software are just reference values. And the actual situations

Table 6: Percentages of energy consumption by various processes in the RRSAB.

Main energy consumption component	Air conditioning	Lighting	Elevator, office, and electric equipment
Percentage of total energy consumption	55	20	25

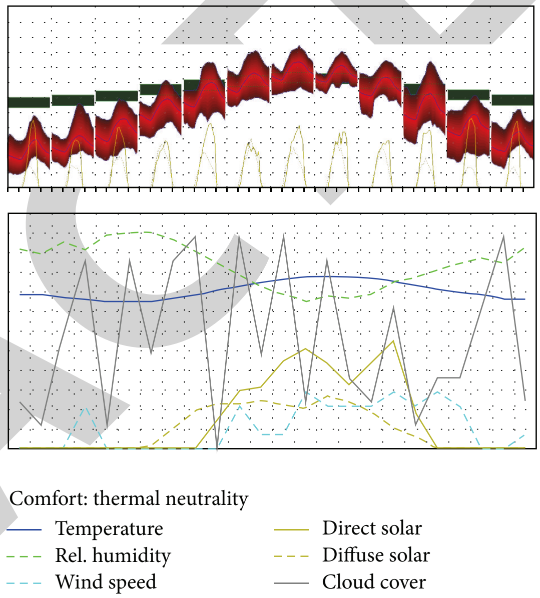

Figure 3: TMY data for Nanjing.

may be very different from the simulation conditions. As for the case of RRSAB, its energy consumption had been monitored by an energy monitoring system from 2010 to 2015. The actual energy consumption was 83.16 MWh. The energy consumption simulated by Ecotect and EnergyPlus was 97.30 MWh and 223.79 MWh, respectively. The reason for these situations may be that the RRSAB's air conditioning equipment was used intermittently and especially was not used in spring and autumn; moreover, the climate data used by Ecotect and EnergyPlus were typical meteorological year data that were not the same data of actual monitoring year. Therefore, Ecotect is more appropriate for modeling the thermal analysis of the RRSAB than EnergyPlus.

(2) Energy Consumption Computation for Building Air Conditioning. Nanjing is located at 32 degrees of latitude and 118.8 degrees of longitude and belongs to a weather zone associated with hot summers and cold winters. The city's typical meteorological year (TMY) data are shown in Figure 3 [43].

(i) Modeling. The model shown in Figure 4 was built by inputting the RRSAB's construction, structure, thermal engineering parameters, equipment parameters such as air

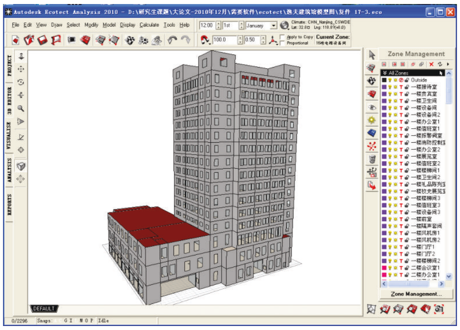

FIGURE 4: The RRSAB model built in Ecotect.

TABLE 7: Air conditioning energy consumption derived from the Ecotect simulation.

Month	Heating (Wh)	Cooling (Wh)	Total (Wh)
1	80041624	344520	80386144
2	49173116	300237	49473352
3	18099332	1305673	19405004
4	349045	22355044	22704090
5	25493	60105540	60131032
6	73738	118199608	118273344
7	191428	217340112	217531536
8	155983	217877424	218033408
9	57001	91019448	91076448
10	240023	40017400	40257424
11	11018536	6645343	17663880
12	41405076	317324	41722400
Total	200830384	775827648	976658048

conditioning and lighting, assumed conditions, and use plan into Ecotect.

(ii) Thermal Environment Analysis. The hourly temperature, hourly heat gain/loss, and hourly energy for the RRSAB were obtained using Ecotect. After organization, the annual energy consumption was summarized in Table 7.

2.3.4. Comparison of CO_2 Emissions in the Life Cycle. Because a building is constructed for working or living, we can use the following formulas to compare the CO_2 emissions in the life cycle:

$$\overline{C}_{\mathrm{At}\cdot i} = \frac{C_i}{A_{\mathrm{gfa}} \cdot t_i}, \tag{15}$$

where $\overline{C}_{\mathrm{At}\cdot i}$ is the average CO_2 emissions per working area per year of each building stage, $\mathrm{kgCO_2/(m^2 \cdot y)}$. C_i is the total CO_2 emissions of each building stage, $\mathrm{tCO_2}$. A_{gfa} is the gross floor area of buildings, $\mathrm{m^2}$. t_i is the duration time of each building stage, year.

3. Results and Discussion

3.1. Total Carbon Emissions during the Construction Stage, C_{b}. From (4), the carbon emissions generated from building material production, C_{be}, can be calculated as

$$\begin{aligned} C_{\mathrm{be}} &= C\,(\text{Concrete}) + C\,(\text{Brick}) + C\,(\text{Cement}) \\ &\quad + C\,(\text{Lime}) + C\,(\text{Mortar}) + C\,(\text{Gravel}) \\ &\quad + C\,(\text{Stone}) + C\,(\text{Steel}) + C\,(\text{Ceramic tile}) \\ &\quad + C\,(\text{Paint}) + C\,(\text{Glass}) + C\,(\text{Wood}) \\ &\quad + C\,(\text{Organic Material}) + C\,(\text{Aluminum}) \\ &\quad + C\,(\text{Copper}) \\ &= 11960.996 \times 0.2420 + 11424 \times 0.2 + 762.9503 \\ &\quad \times 0.894 + 121.7998 \times 1.2 + 1895.9496 \times 0.792 \\ &\quad + 384.44 \times 0.002 + 440.265 \times 2.33 + 527.122 \\ &\quad \times 2.208 + 169.0875 \times 1.4 + 64.3755 \times 0.89 \\ &\quad + 48.525 \times 1.4 + 29.38 \times 0.2 + 17.5553 \\ &\quad \times 17.07 + 1.16855 \times 1.407 + 0.204 \times 1.01 \\ &= 10369.01\ (\mathrm{t}). \end{aligned} \tag{16}$$

From (5), the carbon emissions generated by building material transportation, C_{bt}, are

$$C_{\mathrm{bt}} = 27847.819 \times 1.68 \times 10^{-4} \times 50 = 233.92\ (\mathrm{t}). \tag{17}$$

3.1.1. Total Carbon Emissions of Building Materials Used during Building Construction, C_{bp}. From (7), the carbon emissions produced by the construction site electricity use by construction equipment and office devices, and so forth, C_{bp1}, are

$$\begin{aligned} C_{\mathrm{bp1}} &= 16873\,\mathrm{m^2} \times 10.069\,\mathrm{kW \cdot h/m^2} \\ &\quad \times 0.8244\,\mathrm{t/MWh} = 140.06\ (\mathrm{t}). \end{aligned} \tag{18}$$

From (8), the carbon emissions produced by various construction crafts, C_{bp2}, are

$$\begin{aligned} C_{\mathrm{bp2}} &= 1454\,\mathrm{m^2} \times 3.4\,\mathrm{m} \times (1.05 + 0.11 + 0.99)\,\mathrm{kg/m^3} \\ &= 10.63\ (\mathrm{t}). \end{aligned} \tag{19}$$

From (9), the carbon emissions produced by the horizontal transportation occurring during the construction stage, C_{bp3}, are

$$C_{\mathrm{bp3}} = 20000\,\mathrm{t} \times 20\,\mathrm{km} \times 0.19\,\mathrm{kg/(t \cdot km)} = 76\ (\mathrm{t}). \tag{20}$$

From (6), the CO_2 emissions during the construction stage are

$$C_{\mathrm{bp}} = 140.06 + 10.63 + 76 = 226.69\ (\mathrm{t}). \tag{21}$$

Therefore, from (3), the total amount of CO_2produced during the construction stage is

$$C_b = 10369.01 + 233.92 + 226.69 = 10829.62\,(\mathrm{t}). \quad (22)$$

3.2. Total Carbon Emissions during the Building Demolition Stage, C_d. From (11), the carbon emissions produced by the demolition process are

$$C_{d1} = 16873\,\mathrm{m}^2 \times 107.7\,\mathrm{kWh/m}^2 \times 0.8244\,\mathrm{tCO_2/MWh} = 1498.12\,(\mathrm{t}). \quad (23)$$

From (12), the carbon emissions produced during the waste material treatment process are

$$C_{d2} = 27847.819\,\mathrm{t} \times 30\,\mathrm{km} \times 1.92\,\mathrm{t}/(\mathrm{t}\cdot\mathrm{km}) \times 10^{-4} = 160.4\,(\mathrm{t}). \quad (24)$$

From (10), the total carbon emissions produced during the building demolition stage were

$$C_d = C_{d1} + C_{d2} = 1498.12 + 160.4 = 1658.52\,(\mathrm{t}). \quad (25)$$

3.3. Total Carbon Sequestration by Vegetation around the Building, C_t. From (13), the amount of carbon sequestration by vegetation was

$$C_t = 0.47 \times 8 \times 0.025 \times 50 \times \frac{44}{12} = 17\,(\mathrm{t}). \quad (26)$$

It can be seen that if the green area around a building is relatively small, the carbon sequestration by vegetation is very limited. Compared to the total carbon emissions of the entire building life cycle, this impact is low compared to overall emissions.

3.4. Total Carbon Emissions during the Building Operational Stage, C_u. Table 6 shows that the air conditioning energy consumption in the office building accounted for 55% of the total energy consumption, the lighting energy consumption accounted for 20%, and the elevator, office, and electric equipment consumption accounted for 25%. Therefore, the total energy consumption during the building use stage was as follows:

Air condition energy consumption: P_{u1} = 976.66 MWh.

Lighting energy consumption: P_{u2} = 355.15 MWh.

Elevator, office, and electric equipment consumption: P_{u3} = 443.94 MWh.

From (14), the total carbon emissions produced during the building operational stage were

$$C_u = (976.66 + 355.15 + 443.94) \times 0.8244 \times 50 = 73196\,(\mathrm{t}). \quad (27)$$

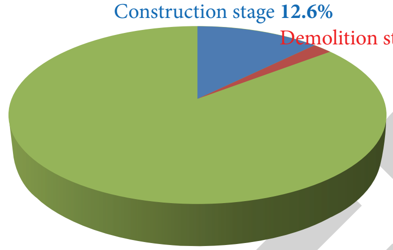

Figure 5: Percentage of CO_2 emissions produced in building life cycle.

3.5. Total LCCO$_2$ Emission Computation, C. From (2), the total CO_2 emissions produced during the building's life cycle were

$$C = C_b + C_u + C_d - C_t = 10829.62 + 73196 + 1658.52 - 17 = 85667.14\,(\mathrm{t}). \quad (28)$$

3.6. Comparison of CO_2 Emissions in the Life Cycle. Based on the above computation results, the carbon emissions produced during the building's operational stage made up the major portion of the building's emissions load, accounting for 85.4% of the total emissions. Next were the emissions produced during the construction stage, which accounted for 12.6% of the total emissions. Finally, the emissions produced during the demolition stage were the smallest, accounting for 2% of the total, as shown in Figure 5. It is obvious that the greatest proportion of carbon emissions was emitted during a building's operational phase to meet various needs such as heating, ventilation, and air conditioning (HVAC), water heating, and lighting. A smaller percentage of energy was consumed in materials manufacturing and transport, construction, and demolition. Governments can therefore achieve the greatest reductions in CO_2 emissions by targeting the operational phase of buildings.

However, the opportunity for nonoperational phase should not be ignored because the duration of nonoperational phase is much less than that of operational phase, but a disproportionately large amount of CO_2 is generated during the nonoperational stage.

The duration times of construction stage, operational stage, and demolition stage of office buildings in China are typically 2, 50, and 0.5 years, respectively [28–31].

The average CO_2 emissions per working area per year of construction stage of RRSAB were

$$\overline{C}_{\mathrm{At\cdot b}} = \frac{10829.62}{16873 \times 2} = 321\,\mathrm{kg}/\left(\mathrm{m}^2\cdot\mathrm{y}\right). \quad (29)$$

The average CO_2 emissions per working area per year of operational stage of RRSAB were

$$\overline{C}_{\mathrm{At\cdot u}} = \frac{73196}{16873 \times 50} = 86.8\,\mathrm{kg}/\left(\mathrm{m}^2\cdot\mathrm{y}\right). \quad (30)$$

TABLE 8: The sensitivity analysis of annual CO_2 emissions by altering design configurations.

Design ID	Changed to original design	Annual CO_2 emission (t)	Compared with D0	Decreased
D0	Existing design	1463.92	—	—
D1	Changing thermal transmittance coefficient, W/(m^2·K)	—	—	—
	(1) Exterior walls changed from 1.081 to 0.713	1361.45	0.93	0.07
	(2) Roof changed from 0.812 to 0.5	1452.21	0.992	0.008
	(3) Exterior windows changed from 5.700 to 2.100	1346.81	0.92	0.08
D2	Reducing the fresh air volume from 30 to 20 (unit, m^3/(h·p))	1258.97	0.86	0.14
D3	Using nighttime ventilation	—	—	—
	(1) Duration: June 1–September 30 Frequency of ventilation and air exchange: 2 times/h from 21:00 to 09:00 (the next morning); 0.5 times/h at all other times	1456.6	0.995	0.005
	(2) Duration: June 1–September 30 Frequency of ventilation and air exchange: 4 times/h from 21:00 to 09:00 (the next morning); 0.5 times/h at all other times	1452.21	0.992	0.008
D4	Extending the indoor temperature range from 18°C–26°C to 17°C–27°C	1317.53	0.90	0.10

The average CO_2 emissions per working area per year of demolition stage of RRSAB were

$$\overline{C}_{\mathrm{At\cdot d}} = \frac{1658.52}{16873 \times 0.5} = 196.6\,\mathrm{kg}/\left(\mathrm{m}^2 \cdot \mathrm{y}\right). \tag{31}$$

Therefore,

$$\begin{aligned} \frac{\overline{C}_{\mathrm{At\cdot b}}}{\overline{C}_{\mathrm{At\cdot u}}} &= 3.70, \\ \frac{\overline{C}_{\mathrm{At\cdot d}}}{\overline{C}_{\mathrm{At\cdot u}}} &= 2.27, \\ \frac{\overline{C}_{\mathrm{At\cdot b}}}{\overline{C}_{\mathrm{At\cdot d}}} &= 1.63. \end{aligned} \tag{32}$$

Thus, the chance to mitigate environmental impact for nonoperational stage, especially construction stage, should also be taken seriously. There are currently many new buildings being built in China every year, so the related environment pollution problems cannot be ignored. Policies should encourage property developers and construction companies to incorporate greenhouse gas emission considerations into the feasibility and design stages of buildings.

3.7. Sensitivity Analysis. In order to investigate the sensitivity of life-cycle CO_2 emissions from this building, design configurations were changed through an imaginary way.

As shown in the above analysis, operational stage is dominant in life-cycle CO_2 emission (= 85.4%). Annual CO_2 emissions in operation stage were chosen as the sole parameter to test the efficiency of different factors.

Several factors that affect the annual CO_2 emissions were chosen for sensitivity analysis, including (1) changing thermal transmittance coefficient for exterior walls, roofs, and windows; (2) reducing the fresh air volume; (3) using nighttime ventilation; and (4) extending the indoor temperature range. Table 8 displays the sensitivity analysis of annual CO_2 emissions on the factors by altering design configurations.

Table 8 reveals that the most sensitive factor for yearly CO_2 emissions of the building was “reducing the fresh air volume.” The air conditioning cooling load of the RRSAB consisted of the cooling load from the building envelope, that from the fresh air, the load from the occupants, and the illumination load. The simulation results indicated that the cooling load from the fresh air accounted for the majority of the air conditioning cooling load. The loads from the occupants and illumination together were second. The cooling load from the building envelope due to heat transfer was relatively small. Therefore, the air conditioning cooling load decreased significantly with changes in the thermal disturbance from the fresh air volume. The fresh air latent heating load (i.e., the load used for fresh air dehumidification) constituted a majority of the fresh air load because Nanjing is located in a region with hot and humid climate [44].

As shown in Table 8, the second sensitive factor for yearly CO_2 emissions of the building was “extending the indoor temperature range.” The enlarged temperature range reduces CO_2 emissions by lessening the cooling and heating loads in two ways: first, as a result of fewer heating and cooling hours and, second, as a result of a decrease in the magnitude of the difference between the set point and the outdoor temperature. The saving is about 10% for each degree Celsius increase or decrease in the set point [45].

The third sensitive factor for annual CO_2 emissions of the building was “changing thermal transmittance coefficient of exterior windows and walls.” The thermal performance of the building envelope in the existing RRSAB does not meet the mandatory requirements of the aforementioned design standard [34]. This increased the CO_2 emissions during the building operational stage. After altering the thermal transmittance coefficient of exterior windows and walls to meet the requirements of standard GB50189-2005, the CO_2 emissions during the building use stage decreased significantly. However, the effect of changing roof thermal transmittance coefficient was not obvious because the RRSAB's roof area was just the 6% of its gross floor area.

The fourth sensitive factor for annual CO_2 emissions of the building was "using nighttime ventilation." Although the effect of "using nighttime ventilation" was fewer than other measures mentioned above, its role to decrease CO_2 emissions should not be overlooked. A field investigation of the RRSAB during summer when the air conditioning was operating revealed that the lights were left on overnight, and many students worked in the offices during the nighttime, causing the air conditioning to run throughout the night. However, the doors and the windows of the rooms that were not used during the nighttime were often tightly closed. The outdoor temperature typically dropped at night. According to the meteorological data for Nanjing, the outdoor temperature could drop to 27°C (the temperature achieved with air conditioning) on most nights, even in July, the month with highest daily mean temperature. By increasing the frequency of ventilation and air exchange, the daytime base room temperature could be reduced, which in turn could help to reduce CO_2 emissions by decreasing the air conditioning energy consumption.

Thus, the primary and effective measures to reduce the building's CO_2 emissions in hot and humid climate such as Nanjing, China, should be arranged as follows: (1) within the limits of comfort, reducing the fresh air volume as much as possible or the time used to process fresh air and using new air dehumidification methods such as liquid desiccant dehumidifiers; (2) extending the indoor temperature range; (3) improving the thermal insulation performance of exterior windows, walls, and roofs; (4) exploiting natural ventilation, especially nighttime ventilation, during transition seasons.

3.8. Methods Limitations

3.8.1. LCA

(1) Limitations due to the Method, Assumptions, and Impact Coverage. There are many limitations for whole-building LCAs, but they can be consistently categorized across all building projects, and their relative importance evaluated for each case. Some projects will have less or lower quality data available, but for the purpose of creating a Goal Type library, it should be possible to quantitatively determine benchmarks in each category for Use-Cases and Deliverables according to the Cost Modeling phases discussed earlier [46].

The limitations of a whole-building LCA study can be summarized by the following categories:

(i) Data availability is limited in the early-design phases when building material specifications and detailed energy-use models have not been created. There is also limited LCA data available for building materials generally [46]. Therefore, the architects or LCA practitioners have to use multiple data sources and an increased number of assumptions. This limitation is being ameliorated as the databases enlarge their store of information and as more tools and more easily used tools become available [47].

(ii) Data quality is varied across many different sources and trades and therefore can be hard to determine for the overall model. As an aggregation of a number of smaller products and processes, the level of data quality is recommended to be measured at the product level, where environmental product declarations (EPDs) can be used as they are developed [46].

(iii) A functional lifespan is difficult to determine for a building because it must model both service life of building elements and the adaptability of the structure to market demand. There could be a situation where a building meets physical requirements, but the local market demands repurposing, a risk that is challenging to predict [46]. For example, though buildings have long lifetimes, even some more than 50 years, in China actually many buildings are deconstructed even no more than 30 years, which caused serious environmental impacts. Hence, the evaluated results in the studied building may be lower than that in fact [31].

(iv) Operational energy use represents the majority of impacts from a building over its lifespan—it must be modeled using standard occupancy assumptions—but will be largely determined by occupant behavior that is unpredictable [46]. For example, during the lifespan, the building may undergo many changes in its form and function, and the technology of producing materials, constructing, operating, and demolishing the building is also quickly developed. The evaluation is in accordance with the original building and the opportunity to minimize the environmental effects of changes is partly a function of the original design [31].

(v) Assumptions in materials production and demolition could not accurately reflect the environmental impact of the building. As the studied building is in operation when studying, the information from the survey is limited by the time, some assumptions are used in building materials production stage and demolition stage. The data in the stages are referred to by related literatures, building contractor, and site measurements. Also some assumptions are made. For example, it is assumed that the end-of-life materials are landfilled. Various other disposal alternatives are possible, including incineration, biological treatment, composting, and recycling. Such optimization of end-of-life materials disposal may become increasingly important in the future. In such a future scenario, the "design for disassembly" of buildings would become more prevalent to facilitate the removal of building materials with minimal energy consumption and CO_2 emission [31].

(2) Limitations due to Lack of Benchmarks. Another unresolved issue in the LCA analysis of buildings is the identification of benchmarks. Benchmarks are important in the building performance studies as they provide a basis for comparing the performance of a given project under consideration [47]. Benchmarking for carbon emissions can be completed in a variety of ways:

(i) Past performance—a comparison of current versus past performance.

(ii) Industry average—based on an established performance metric, such as the recognized average performance of a peer group.

(iii) Best in class—benchmarking against the best in the industry and not the average.

(iv) Best practices—a qualitative comparison against certain established practices considered to be the best in the industry.

Note that items (ii) and (iii) are part of the Energy Star method assessing the energy use of buildings. Similar methods can be adopted for benchmarking buildings for their overall environmental impact assessed by LCA. Some argue against benchmarking a building design based on its past performance or worst-case scenario, since it does not provide a sound basis for establishing a building's performance. Thus, national agencies and organizations, such as the Ministry of Environmental Protection of China, need to establish "industry average" LCA data to benchmark buildings.

3.8.2. BIM-Based LCA. LCA faces a fundamental dilemma: the largest impact an LCA can have is in the early-design phase, but this is when the necessary data is most scarce [48]. Reducing the time requirement for an LCA could potentially allow designers to check the impacts of their designs earlier, but with current tools, this is not possible. LCA and Environmental Impact Assessments (EIA) are carried out in later phases after most major design decisions have been made and serve primarily as a documentation of impacts rather than a strategic information source that can actually make an impact on design. The models more accurately identify "hotspots" in later stages, but they do much less to change the actual outcome [46, 48].

Another problem is that BIM does not allow alternative design options or the managing of "what if" scenarios [8, 49].

The third issue is the limited database of BIM. For example, some components, elements, or materials that designers used may not be covered by BIM database; therefore, users have to add this information into BIM database in advance.

The overarching issue for BIM-based LCA is that the two fields remain very separate worlds with virtually no overlap of tools, terminology, and data structure. LCA is a generic methodology, and for that reason, its tools have traditionally been developed to be generic and applicable to any sector. The result is that buildings must be modeled in both BIM and LCA software separately, and there is no direct information flow from one to the other.

Because of this software and modeling disconnect, whole-building LCAs remain too time consuming and esoteric for most user in the building industry and therefore remain a specialized field for academics and consultants. It is doubtful that the building industry will adapt its tools or processes to fit with the much smaller LCA industry, so if LCA practitioners wish to establish themselves within the AECOO (Architecture, Engineering, Construction, Owner Operator) workflow, they will be the ones responsible for closing the communication gap [46].

3.8.3. Ecotect. Ecotect is simplified energy modeling tools that are based on more complex simulation engines and therefore cannot be used for meeting codes or regulations. It is slightly different from EcoDesigner in that it is separate from the drafting software like ArchiCAD or Revit that is used to produce the geometry of the building [46]. Another limitation is long run times.

4. Conclusions

From this case study, it can be concluded that BIM and Ecotect can be very helpful in reducing the efforts of estimating carbon emissions from a building's life cycle, because they can provide the majority of the necessary information and calculation tools for performing LCA, which may alleviate the difficulty that when executing building LCA, there is not enough available information.

The $LCCO_2$ emissions of a building were divided into three parts, the construction (including processes such as raw material acquisition, building material production, transportation, and construction), operation, and demolition stages (including building demolition and construction waste recycling and processing stages). Life-cycle CO_2 emissions comparison showed the operational stage is the biggest contributor to CO_2 emissions. More than 85.4% of the total CO_2 emissions were generated during operation. About 12.6% of the total CO_2 emissions were produced during the construction stage. Approximately 2% of the total CO_2 emissions were yielded during the demolition stage. Compared to the total carbon emissions of the entire building life cycle, the carbon sequestration by vegetation was very limited. Governments can therefore achieve the greatest reductions in CO_2 emissions by targeting the operational phase of buildings. However, the opportunity for nonoperational phases should not be ignored because the average CO_2 emissions per working area per year of nonoperational stages are far more than those of use phase.

Sensitivity analysis indicated that the primary and effective measures to reduce the building's CO_2 emissions in hot and humid climate such as Nanjing, China, should be arranged as follows: (1) within the limits of comfort, reducing the fresh air volume as much as possible; (2) extending the indoor temperature range; (3) improving the thermal insulation performance of exterior windows, walls, and roofs; (4) exploiting natural ventilation, especially nighttime ventilation, during transition seasons.

Methods limitations discussion showed that currently there are some limitations in performing LCA based on Ecotect simulating energy and BIM collecting material quantities. The reasons are as follows: (1) LCA's limitations are due to the method, assumptions, impact coverage, and lack of benchmarks; (2) BIM cannot provide enough data in the very early-design phase for LCA performing, and the two fields of BIM and LCA remain very separate worlds; (3) Ecotect cannot be used for meeting codes or regulations and long run times.

Notations

A: Green area, acres
AD: Activity level
A_{gfa}: Gross floor area of buildings, m^2
C: Total carbon emissions during building life cycle, t
$\overline{C}_{\text{At}\cdot i}$: Average CO_2 emissions per working area per year of each building stage, $\text{kgCO}_2/(\text{m}^2\cdot\text{y})$
C_{b}: Total carbon emissions during the construction stage, t
C_{be}: Carbon emissions from building material production, t
C_{bt}: Carbon emissions produced by building material transportation, t
C_{bp}: Carbon emissions of building materials used during building construction, t
C_{bp1}: Carbon emissions produced by the construction site electricity use, t
C_{bp2}: Carbon emissions produced by various construction crafts, t
C_{bp3}: Carbon emissions produced by horizontal transportation during building construction, t
C_{d}: Total carbon emissions produced during the demolition stage, t
C_{d1}: Carbon emissions produced by the demolition process, t
C_{d2}: Carbon emissions produced by construction waste material processing, t
C_i: Total CO_2 emissions of each building stage, tCO_2
C_{u}: Total carbon emissions produced during the operational phase, t
C_{u1}: Carbon emissions produced by air conditioning, t
C_{u2}: Carbon emissions produced by lighting, t
C_{u3}: Carbon emissions produced by elevator, office, and electric equipment, t
C_{t}: Total carbon sequestration by vegetation, t
c_k: Carbon content
D_i: Distance building material travels from production site to construction site, km
D_{r}: Distance between construction site and landfill, km
EF: Emission factor
$\text{EF}_{\text{be},i}$: Carbon emission factor for the ith building material, t/t
$\text{EF}_{\text{bt},i}$: Emission factor for the ith building material transportation method, t/(t·km)
$\text{EF}_{\text{bp1},i}$: OM CO_2 emission factor for the construction site's electricity system, tCO_2/m^2
$\text{EF}_{\text{bp2},i}$: Carbon emission factor for the ith construction process, tCO_2/m^3
$\text{EF}_{\text{bp3},i}$: Carbon emission factor for ith building material or piece of equipment, t/(t·km)
EF_{OM}: Operating margin emission factor, tCO_2/MWh
EF_{BM}: Build margin emission factor, tCO_2/MWh
EF_{dc}: Emission factor of the demolition energy consumption for the reinforced concrete structure, kWh/m^2
EF_{dr}: Emission factor of emission due to waste transportation t/(t·km)
G_1: Carbon ratio of ground tree biomass, t carbon/t dry matter
G_2: Annual increase in the above ground biomass, t dry matter/(acres· year)
k: Types of fossil fuel used during the building material production process
n: Useful lifetime of building, years
P_{u1}: Total electricity consumption for air conditioning, MWh
P_{u2}: Total electricity consumption for lighting, MWh
P_{u3}: Total electricity consumption for elevator, office, and electric equipment, MWh
$Q_{\text{be},i}$: Quantity of the ith building material used in the project, t
$Q_{\text{bp1},i}$: Construction project quantities, m^2
$Q_{\text{bp2},i}$: Project quantity for the ith construction process, m^3
$Q_{\text{bp3},i}$: Horizontal transportation quantity of the ith building material or equipment, t
$Q_{\text{bt},i}$: Weight of the ith building material during the transportation stage, t
Q_{r}: The quantity of waste transported to landfill, t
t_i: Duration time of each building stage, year
$\eta_{i,j,k}$: Oxidation rate.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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