

Estimation of Building's Life Cycle Carbon Emissions Based on Life Cycle Assessment and Building Information Modeling: A Case Study of a Hospital Building in China

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Abstract

Throughout the life cycle, the buildings emit a great deal of carbon dioxide into the atmosphere, which directly leads to aggravation in the greenhouse effect and becomes a severe threat to the environment and humans. Researchers have made numerous efforts to accurately calculate emissions to reduce the life cycle carbon emissions of residential buildings. Nevertheless, there are still difficulties in quickly estimating carbon emissions in the design stage without specific data. To fill this gap, the study, based on Life Cycle Assessment (LCA) and Building Information Modeling (BIM), proposed a quick method for estimating Building's Life Cycle Carbon Emissions (BLCCE). Taking a hospital building in Chuzhou City, Anhui Province, China as an example, it tested its possibility to estimate BLCCE. The results manifested that: 1) the BLCCE of the project is 40,083.56 tCO₂-eq, and the carbon emissions per square meter per year are 119.91 kgCO₂-eq/(m²·y); 2) the stage of construction, operational and demolition account for 7.90%, 91.31%, and 0.79% of BLCCE, respectively; 3) the annual carbon emissions per square meter of hospital are apparently higher than that of villa, residence, and office building, due to larger service population, longer daily operation time, and stricter patient comfort requirements. Considering the lack of BLCCE research in Chinese hospitals, this case study will provide a valuable reference for the estimated BLCCE of hospital building.

Keywords

Carbon Emissions, Life Cycle Assessment, Building Information Modeling, Hospital Building

1. Introduction

The global warming effect has attracted increasing attention all over the world (Gustavsson, Joelsson, & Sathre, 2010), among which carbon emissions are considered to be one of the underlying causes of global warming. Therefore, carbon emissions are progressively being used to quantify human impact on the environment (Wiedmann & Minx, 2008). As a core industry, the construction industry makes up 30% - 40% of all industries' carbon emissions (Baek, Tae, Kim, & Shin, 2016; Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014; Cubi, Doluweera, & Bergerson, 2015). For the sake of slashing building's life cycle carbon emissions (BLCCE), BLCCE calculation needs to be addressed first (Lee, Tae, & Kim, 2018).

Among the existing methods, Life Cycle Assessment (LCA) is extensively used to measure and evaluate the environmental impact of a particular product throughout its life cycle (Klüppel, 2005). The development of the Building Information Model (BIM) has contributed rapid and efficient methods for the implementation of LCA in the recent years (Rezaei, Bulle, & Lesage, 2019; Santos, Costa, Silvestre, & Pyl, 2019). Many scholars used BIM and LCA to calculate building carbon emissions, and have achieved immense advance (Gan et al., 2018; Peng, 2016; Yang, Hu, Wu, & Zhao, 2018). The purpose of calculating carbon emissions is to reduce carbon emissions, while carbon emission reduction needs to adopt abatement measures at the design phase of the building (Häkkinen, Kuittinen, Ruuska, & Jung, 2015; Zhu, Chew, Lv, & Wu, 2013). However, for the engineering design phase with limited data, it is still problematic to estimate the BLCCE.

In terms of building types, many scholars studied the BLCCE of villas (Yang et al., 2018), residential building (Li, Cui, & Lu, 2016; Zhang & Wang, 2015; Zhang, Zheng, Zhang, Chen, & Wang, 2016), office buildings (Peng, 2016; Zhang & Wang, 2015). However, the hospital building, as a building that is saddled with the urban medical system, has undergone tremendous variations in architectural nature compared with civil buildings or ordinary public buildings. But regrettably, the study of hospital building's BLCCE is unprecedented.

Based on these above, this paper applied LCA theory and BIM technology to put forward the estimation theory of the BLCCE. Simultaneously, a hospital building in Chuzhou City, Anhui Province, China, was taken as an example to estimate its BLCCE by using the theoretical method proposed in this paper. This study will help to estimate carbon emissions during the design phase with partial data deficiencies and conduct theoretical support for the adoption of low-carbon design and low-carbon decision-making. It will also make a contribution to serve as references for analyzing the BLCCE of the hospital building.

2. Literature Review

2.1. Building's Life Cycle Carbon Emissions

Building's life cycle carbon emissions (BLCCE) refers to the carbon emissions

generated by the building throughout its life cycle. The accounting of Carbon emissions (also can be converted into greenhouse gas emission or CO₂ emissions) often uses Carbon dioxide equivalent (CO₂-eq) as the accounting unit (Turner & Collins, 2013). The calculation of carbon dioxide equivalent (CO₂-eq) takes into account the collective contribution of greenhouse gases (including CO₂, CH₄, NO₂, etc.) (Gan et al., 2018). Thereby, carbon dioxide equivalent was employed as the calculation unit in this paper.

The BLCCE consists of three stages: 1) construction stage; 2) operational stage; 3) demolition stage (Peng, 2016). The carbon emissions at the construction stage mainly include material production, material transportation, and construction on site (Wan Omar, Doh, & Panuwatwanich, 2014; Yang et al., 2018). The carbon emissions at the operational stage originate within the energy consumption are produced by HVAC (heating, ventilation, air conditioning), lighting, water supplying, and equipment use (Roh & Tae, 2017), as well as refurbishment (Yang et al., 2018). Moreover, it varies drastically with climatic conditions, comfort requirements, and operating schedules (Ramesh, Prakash, & Shukla, 2010). Carbon emissions at the demolition stage are chiefly derived from demolition and refurbishment. The composition of BLCCE is as shown in Figure 1.

Although there were a multitude of studies have concerned calculations of life cycle carbon emissions, estimating the BLCCE remains obstructive due to the lack of data or complexity of information processing (Gustavsson et al., 2010). These research gaps are accompanied by the entire life cycle of the building. Firstly, at the construction stage, diverse materials, various types of machines, and chaotic construction techniques are mixed together in a dense time period (Li, Zhu, & Zhang, 2010). Secondly, energy consumption at the operational stage is challenging to calculate due to the disparate lifestyle and comfort requirements of different residents (Yang et al., 2018). Thirdly, at the demolition stage,

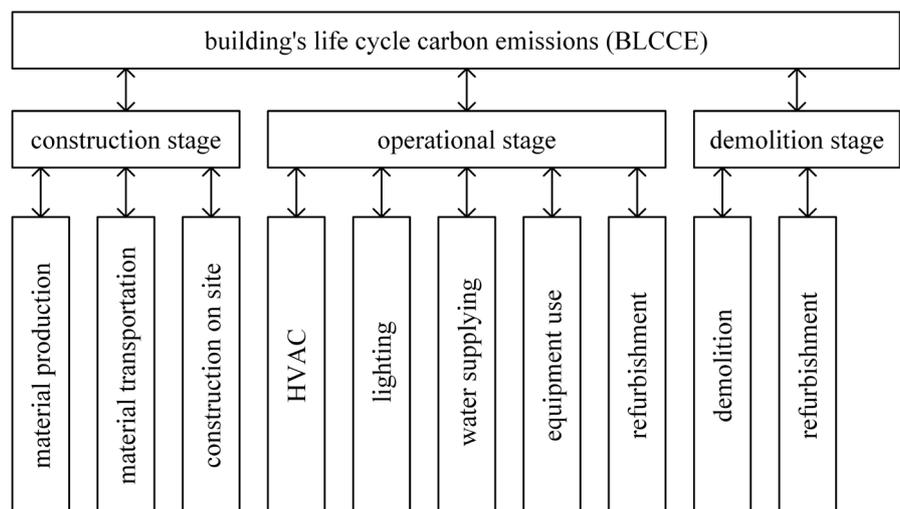


Figure 1. Composition of building's life cycle carbon emissions (Peng, 2016; Yang et al., 2018).

the means of demolition and the method of recovery are often fail to predict, and the estimation at this stage is full of obstacles.

2.2. Application of LCA and BIM in BLCCE

Life Cycle Assessment (LCA) is a method of assessing environmental and social impacts (Norris, 2001). According to the ISO 14041 Standard, LCA research is divided into four steps (Klüppel, 1998): 1) goal and scope definition; 2) inventory analysis; 3) environment impact assessment; 4) interpretation.

In the past few years, BIM has become a highly popular term and concept in architecture, engineering, and construction (Shin & Cho, 2015). The definition of BIM is “a set of interrelating policies, processes and technologies” that have resulted in a systematic approach to the management of key information about building design and project data appeared in a digital format throughout the building life cycle (Penttilä, 2006; Wong & Zhou, 2015).

Many researchers have tried to apply BIM to LCA (Shin & Cho, 2015). Many scholars presumed that connecting BIM and LCA software will eliminate the need for manual data input and remarkably accelerate the establishment of LCA model (Santos et al., 2019; Yang et al., 2018). Based on the rapidity of BIM, BIM is frequently adopted in LCA analysis of building carbon emissions. Basbagill et al. (2013) attempted to significantly reduce the actual carbon footprint with material and thickness decisions made through “BIM-enabled embodied impact feedback and prescription”. Han et al. (2014) proposed a building system optimization framework aimed at minimizing the life cycle cost of BIM-based energy consumption analysis. Shadram et al. (2016) constructed a model to evaluate the embodied energy of the material through the integration of BIM. Peng (2016) presented a calculation method for BLCCE based on Ecotect and BIM. D. Li et al. (2016) developed an automatic estimation system for life cycle carbon emissions of residential buildings. Yang et al. (2018) undertook a case study on carbon footprint accounting of a residential building based on BIM and LCA.

From the above literature review, it can be concluded that some scholars have offered methods for calculating carbon emissions based on BIM and LCA. Furthermore, there were also known the approaches to estimate carbon emissions. However, on the one hand, the estimation method of carbon emission based on BIM and LCA theory has not been formed. On the other hand, most of the current research was focused on villas, residential buildings, and office buildings. There is no research has been carried out on the BLCCE of a hospital building that consumes a vast amount of energy.

3. Methods

3.1. Overview

According to the above analysis, the BLCCE is composed of carbon emissions at the construction stage, the operational stage, and the demolition stage. The total BLCCE is calculated by the Formula (1). C_{top} , C_{con} , C_{ope} , and C_{dem} are corres-

ponding to the carbon emissions of the life cycle, the construction stage, the operational stage, and the demolition stage, respectively.

$$C_{\text{tot}} = C_{\text{con}} + C_{\text{ope}} + C_{\text{dem}} \quad (1)$$

A building involves various fields of expertise, such as architecture, structure, facility, equipment, electricity, and water supply system (Maia, Mêda, & Freitas, 2015), all of which have an impact on the amount of material and fuel in building's life cycle. The quantitative data on materials and fuels is decisive for the final outcome of BLCCE, as a result, the data sources are crucial in particular (Shin & Cho, 2015). In addition, the characteristics of each material should be listed and described, including material density, unit of measurement, manufacturing process, and production site. Only with this data can the corresponding carbon emission coefficient be matched. Therefore, the corresponding carbon emission coefficient database should be established before calculating the carbon emission.

At the construction stage, carbon emissions can be estimated by the bill of quantities method. Construction quotas are used to account for resource consumption and construction costs in China (Yang et al., 2018). Therefore, BIM5D software and construction quota can be employed to calculate the amount of engineering consumed at the construction stage, so as to calculate carbon emissions at the construction stage. Carbon emissions at the operational stage mainly come from the energy consumption generated by HVAC (heating, ventilation, air conditioning), lighting, water supplying, and equipment use. This energy consumption is represented by fuel consumption and electricity consumption. Carbon emissions at the demolition stage are estimated according to the carbon emissions at the construction stage. The information required for each stage and its sources are shown in Table 1.

3.2. Estimation Method at the Construction Stage

The bill of quantities is used to estimate carbon emissions at the construction stage. The carbon emissions at the construction stage are composed of sub-item project and measure project (Formula (2)). The carbon emission of sub-item project or measure project is equal to the carbon emissions coefficient of quota multiplied by the quantity of quota (Formula (3)). The carbon emission coefficient

Table 1. Information required and its data sources.

Stage	Information required for LCA	Data sources
construction	amount of materials	BIM5D software
	amount of working days	bill of quantities
	amount of mechanical class	life cycle database
operational	amount of fuel consumption	BIM operation simulation software
	amount of electricity	life cycle database
demolition	carbon emissions at construction stage	literature review

of quota is the carbon emission produced by the unit quota, and its value is equal to the number of man-days, material and mechanical multiplied by their carbon emission coefficient (Formula (4)). The quantities of sub-item project, measure project, and quota come from BIM5D software. Carbon emission coefficient is selected from the carbon emission coefficient database.

$$C_{\text{con}} = \sum C_{\text{sp}} + \sum C_{\text{mp}} \quad (2)$$

$$C_{\text{sp,mp}} = \sum CC_{\text{q}} \times Q_{\text{q}} \quad (3)$$

$$CC_{\text{q}} = \sum CC_{\text{md}} \times Q_{\text{md}} + \sum CC_{\text{mat}} \times Q_{\text{mat}} + \sum CC_{\text{mech}} \times Q_{\text{mech}} \quad (4)$$

In the Formulas (2)-(4): C_{sp} and C_{mp} represent carbon emissions generated by sub-item project and measure project separately; CC_{q} , CC_{md} , CC_{mat} , and CC_{mech} represent the carbon emission coefficient of quota, man-days, material, and machine class separately; Q_{q} , Q_{md} , Q_{mat} , and Q_{mech} represent the amount of quota, man-days, material, and machine class separately.

3.3. Estimation Method at the Operational Stage

As an estimation method, the energy required for refurbishment at the operational stage is negligible, as it accounts for only about 5 per cent of the life cycle energy consumption (Sartori & Hestnes, 2007; Yang et al., 2018). Carbon emissions at the operational stage mainly come from the energy consumption generated by HVAC, lighting, water supplying and equipment use. This energy consumption is represented by fuel consumption and electricity consumption. If sustainable energy is used at the operational stage, this part should be deducted. The estimation formulas of carbon emissions at the operational stage are listed in the Formulas ((5), (6)).

$$C_{\text{ope}} = C_{\text{sy}} \times Y \quad (5)$$

$$C_{\text{sy}} = C_{\text{e}} + C_{\text{f}} + C_{\text{re}} \quad (6)$$

In the Formulas ((5), (6)), C_{sy} represents the annual carbon emissions generated during the building use phase; C_{e} represents the annual carbon emissions generated by building electricity; C_{f} represents carbon emissions generated by the annual fuel consumption of the building; C_{re} represents the annual reduction in carbon emissions from sustainable energy use; Y is the service life at the operational stage, generally 50 years.

3.4. Estimation Method at the Demolition Stage

At the demolition stage, the bill of quantities method should be used to calculate the carbon emissions, and the calculation method should be the same as the construction stage. However, at the demolition stage, the data on the demolition workload stays unspecified at times. Many scholars deemed that the carbon emissions at the demolition stage can be approximately equal to 10% of the construction stage (Cai, Wang, & Fu, 2010; Hua et al., 2014; Zhong, 2005). Besides, researchers pointed out that the demolition stage accounts for about only 1% of

BLCCE (Sartori & Hestnes, 2007; Zhang & Wang, 2015), thus the estimation at this stage would not affect the estimation of BLCCE (Zhang & Wang, 2015). For convenience, this calculation can be simplified to the form of Formula (7) to estimate the carbon emissions at the demolition stage.

$$C_{\text{dem}} = C_{\text{con}} \times 10\% \quad (7)$$

4. Case Study and Results

4.1. Background Information of the Target Building

Mingguang People's Hospital Building is located in Chuzhou City, Anhui Province, China. It is a public building supported by a reinforced concrete frame structure system with a gross floor area (GFA) of 6367 m² and a base area of 1703 m². The building has 4 stories with a height of 15.9 m, can accommodate 102 beds, and has a design service life of 50 years. The construction engineering grade is two, the building fire resistance grade is two, and the seismic fortification intensity is 6 degree. The building is heated in winter by fossil energy.

4.2. Carbon Emissions Coefficient Database

Before calculating carbon emissions, establishing carbon emissions coefficient database is necessary. According to carbon emission coefficient mentioned in the literature and the "standard for measuring, accounting and reporting of carbon emission from building, CECS 374, 2014" authorized by China Engineering Construction Industry Association, the database of carbon emissions coefficient was established. Since the case is located in Anhui Province, China, the carbon emission coefficient selected gave priority to the actual local situation. Partial carbon emission coefficients in the database are shown in **Table 2**.

4.3. Establishment of Building Information Model

The core modeling software of BIM selected in this paper is Revit2017 (see **Figure 2**). Revit2017 is developed by Autodesk Company, which is regarded by

Table 2. Partial carbon emission coefficient in the database.

Type	Characteristics	Unit	Carbon coefficient
electricity	Anhui province	kgCO ₂ -eq/kW·h	0.928
diesel		kgCO ₂ -eq/kg	3.096
concrete	C20	kgCO ₂ -eq/m ³	239.190
concrete	C25	kgCO ₂ -eq/m ³	289.440
brick	hollow brick	kgCO ₂ -eq/100 blocks	150.980
steel	reinforced	kgCO ₂ -eq/kg	2.103
man-day	moderate labour	kgCO ₂ -eq/day	2.420
concrete mixer	350 L	kgCO ₂ -eq/class	72.295
unloading car	4 t	kgCO ₂ -eq/class	46.340

many experts as the most commonly used BIM modeling software in the field of architecture, engineering, and construction (Inyim, Rivera, & Zhu, 2014; Wong & Kuan, 2014). It should be noted that BIM should qualify the required level of details so that the relevant information can be extracted directly and accurately. Typically, the level of details of BIM should range from 200 to 300 in the study of LCA (Soust-Verdaguer, Llatas, & García-Martínez, 2017). Therefore, the level of details of BIM in this case was 300. Glondon GTJ2018 was selected as BIM quantities software in this case. In order to improve the data interoperability between Autodesk Revit2017 and Glondon GTJ2018, the BIM model was constructed according to the BIM Guide by Glondon Company.

When Revit2017 was imported into GTJ2018, there was component loss due to the compatibility of data. Therefore, it is necessary to supplement the graphics information and steel bar data of the building. The BIM quantities model in GTJ2018 was checked and modified to ensure it is right (see Figure 3). Glondon

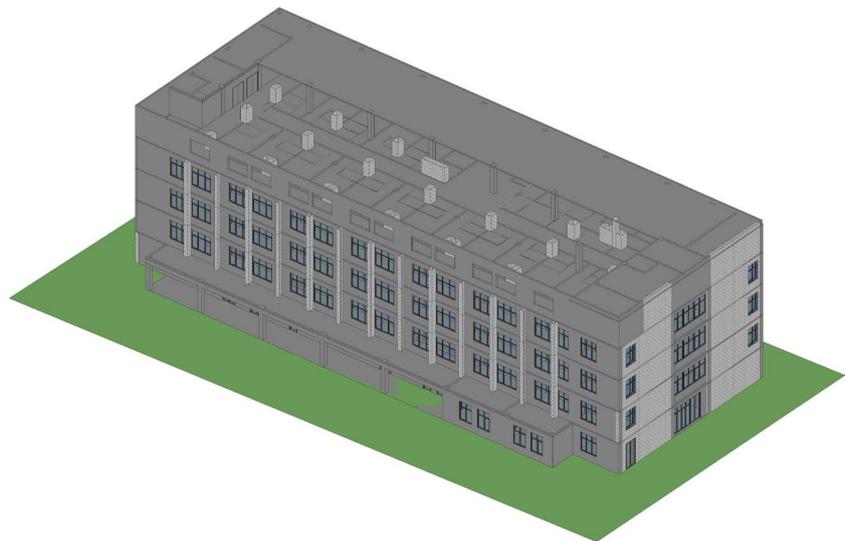


Figure 2. Building information modeling created by Revit2017.

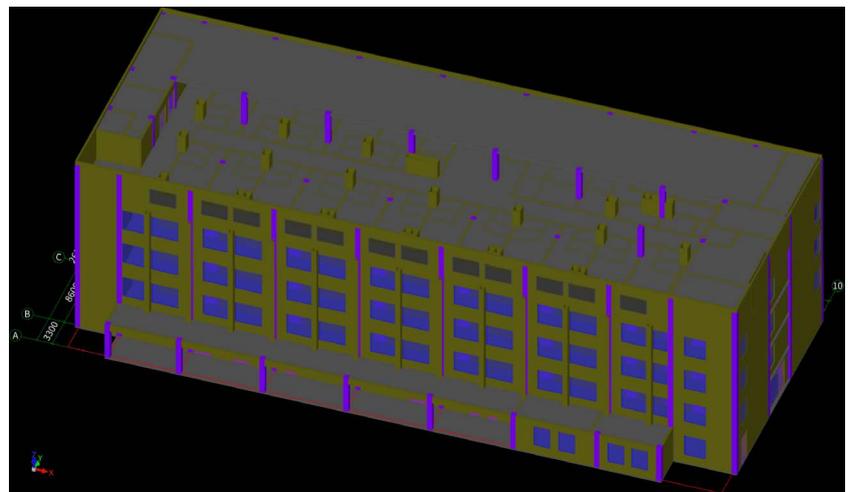


Figure 3. BIM quantities model in GTJ2018.

software is a commonly used software for calculating engineering quantities in China. It can calculate engineering quantities and export bill of quantities. This study followed the “2013 Code of Valuation with Bill Quantity of Construction Works” released by China’s Ministry of Housing and Urban-Rural Development, the “2013 Construction Engineering Valuation Quota of Anhui” and the “2013 Construction Machinery Cost Quota of Anhui” released by Anhui Provincial Construction Department.

4.4. Estimated Carbon Emissions at the Construction Stage

Before calculating the carbon emissions at the construction stage, the study needed to calculate the quota carbon emission coefficient (CC_q), which represents the carbon emissions generated by unit quota. Taking the quota A4-17 (see **Table 3**) and A10-31 (see **Table 4**) as examples, how to calculate the quota carbon emission coefficient CC_q is presented.

Table 3. Quota A4-17 carbon emission coefficient.

Quota number	A4-17					Unit: m ³
Quota name	Single beam, continuous beam, frame beam					
Kind	Name	Unit	Consumption	CO ₂ -eq coefficient	Total	
man-day	man-day	day	1.43	2.42	3.46	
material	concrete C20	m ³	1.02	239.19	242.78	
	water	m ³	1.20	0.91	1.09	
machinery	concrete mixer 350 L	class	0.06	72.29	4.56	
	Concrete vibrator plug in	class	0.13	4.04	0.51	
Total (kgCO ₂ -eq/m ³)					252.39	

Table 4. Quota A10-31 carbon emission coefficient.

Quota number	A10-31					Unit: 10 m ²
Quota name	Rectangular beam composite wood formwork					
Kind	Name	Unit	Consumption	CO ₂ -eq coefficient	Total	
man-days	man-days	day	3.187	2.42	7.71	
material	composite wood form	m ²	2.200	0.19	0.42	
	Steel support	kg	6.699	2.00	13.40	
	wooden support	m ³	0.015	0.19	0.003	
	steel nails	kg	0.819	2.00	1.64	
	galvanized iron wire	kg	0.030	2.00	0.06	
machinery	unload truck 4 t	class	0.017	46.34	0.79	
	truck crane 5 t	class	0.014	23.40	0.33	
	woodworking circular saw 500	class	0.033	42.44	1.40	
Total (kgCO ₂ -eq/10m ²)					25.75	

After the quota carbon emission coefficient was calculated, the carbon emission of the sub-item project or measure project can be calculated through the quota carbon emission coefficient, project quantities, and quota quantities (project quantity and quota quantity come from GTJ2018). Examples of carbon emissions from the sub-item project and measures project are shown in **Table 5** and **Table 6**, respectively.

Table 5. Calculation of carbon emissions from sub-item project 10101003001.

Project number	10101003001	Project quantities: 1143.88			
Project name	Earth excavation of foundation	Unit: m ³			
Quota number	Quota name	Unit	Quota quantities	Quota coefficient	Subtotal
A1-143	hydraulic crawler excavator (put it)	m ³	456.87	1.87	853.03
A1-144	hydraulic crawler excavator (not put in)	m ³	842.57	1.46	1233.78
A1-181	dump truck transport soil 8 t	m ³	456.87	14.59	6663.88
Total (kgCO ₂ -eq)					8750.69

Table 6. Calculation of carbon emissions from measure project 60108000001.

Project number	60108000001	Project quantities: 1			
Project name	Formwork and bracket	Unit: item			
Quota number	Quota name	Unit	Quota quantities	Quota coefficient	Subtotal
A10-1	concrete cushion composite steel formwork	10 m ²	8.46	30.35	256.65
A10-7	independent foundation, pile cap composite wood formwork	10 m ²	59.31	24.06	1427.11
A10-29	foundation beam composite wood formwork	10 m ²	113.15	23.66	2677.61
A10-11	beamless wood formwork for full floor foundation	10 m ²	0.43	21.21	9.09
A10-1	concrete cushion composite steel formwork	10 m ²	1.72	30.35	52.21
A10-26	structure column composite formwork	10 m ²	216.76	22.76	4934.61
A10-21	rectangular column composite wood formwork	10 m ²	130.11	29.60	3851.39
A10-37	ring beam composite wood formwork	10 m ²	13.64	16.21	221.08
A10-39	beam compound wood formwork	10 m ²	8.52	21.09	179.69
A10-42	straight wall composite wood formwork	10 m ²	6.13	29.07	178.11
A10-44	elevator shaft wall composite wood formwork	10 m ²	10.59	30.72	325.44
A10-50	beam board composite wood formwork	10 m ²	1195.92	22.30	26665.53
A10-31	rectangular beam composite wood formwork	10 m ²	78.48	25.75	2020.74
A10-65	bar board composite wood formwork	10 m ²	14.30	30.96	442.74
A10-60	cantilever board straight composite wood formwork	10 m ²	0.56	46.10	25.60
A10-67	gutter timber formwork with overhanging eaves	10 m ²	38.30	24.98	956.73
A10-58	stair composite wood formwork	10 m ²	31.80	41.93	1333.44
A10-71	top pressing composite wood formwork	10 m ²	22.22	26.18	581.71
A10-66	small component wooden formwork	10 m ²	26.50	24.50	649.09
A10-74	bench board	10 m ²	4.46	8.12	36.25
Total (kgCO ₂ -eq)					46824.83

After calculating the carbon emissions of each sub-item project and measure project, these carbon emissions were aggregated to acquire the total carbon emissions at the construction stage (see **Table 7**). The project coefficient in **Table 7** is the evaluation index obtained by dividing the subtotal of the project by the project quantities, and it represents the carbon emissions generated by the unit sub-item project or measure project. In this case, the estimated carbon emissions at the construction stage are 3,166,873.38 kgCO₂-eq, namely, 3166.87 tCO₂-eq.

4.5. Estimated Carbon Emissions at the Operational Stage

Carbon emissions at the operational stage come from refurbishment and the energy consumption generated by HVAC, lighting, water supplying, and equipment use. Among them, refurbishment can be ignored according to the above analysis. The energy consumption generated by HVAC, lighting, water supplying,

Table 7. Summary of carbon emissions at the construction stage.

Project number	Project name	Unit	Project quantities	Project coefficient	Subtotal
(sub-item project)					
010101001001	flat ground	m ²	1563.40	0.45	710.07
010101003001	earth excavation of foundation	m ³	1143.88	7.65	8750.69
010103001001	foundation earthwork backfill	m ³	706.36	2.37	1670.58
010103001002	indoor earthwork backfill	m ³	107.22	2.13	227.92
010301001001	brick foundation	m ³	4.50	319.89	1439.49
010302004001	filler wall (mixed-water brick)	m ³	15.97	338.98	5413.56
010302004002	filler wall (thickness 180)	m ³	972.46	187.96	182778.78
010401002001	isolated footing	m ³	281.07	299.18	84089.48
010403001001	foundation beam	m ³	143.23	356.79	51103.60
010402001003	rectangular column	m ³	56.92	453.41	25808.34
010402001001	constructional column	m ³	184.11	262.67	48359.54
010405001001	beam slab	m ³	361.00	361.80	130610.20
010403002001	rectangular beam	m ³	81.66	361.57	29525.41
010416001001	steel bar	t	225.84	2223.24	502104.11
010702001001	roofing rolls are waterproof	m ²	356.74	96.89	34562.83
.....
(measure project)					
060108000001	formwork and bracket	item	1.00	46824.83	46824.83
060201000001	vertical transportation and ultra-high transportation	item	1.00	8892.63	8892.63
.....
Total (kgCO ₂ -eq)					3166876.38

and equipment use at the operational stage can be converted into fossil energy and electric energy accounting. Considering the case building uses rooftop solar power as sustainable energy, the electricity generated can be supplied to the building, thus the resulting reduced carbon emissions should be deducted.

The operation simulation software called Green Building Studio in Revit2017 was harnessed to simulate and analyze the energy consumption at the operational stage, and the results of simulated fuel consumption and electricity consumption are shown in **Figure 4** and **Figure 5**.

According to the algorithm above, the simulation result of Green Building Studio depicted that the carbon emissions consumed every year at the operational stage are 732 tCO₂-eq (see **Figure 6**). During the 50 years of operational stage, the carbon emissions are expected to be 36,600 tCO₂-eq.

4.6. Estimated Carbon Emissions at the Demolition Stage

Carbon emissions at the demolition stage are approximately estimated to be 10% of carbon emissions at the construction stage (based on Formula (7)). Many

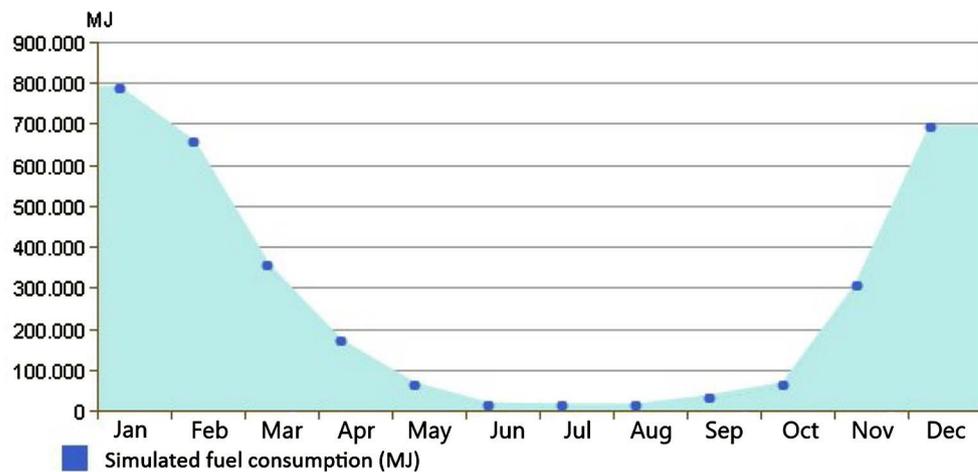


Figure 4. Simulated fuel consumption required for each month at the operational stage.

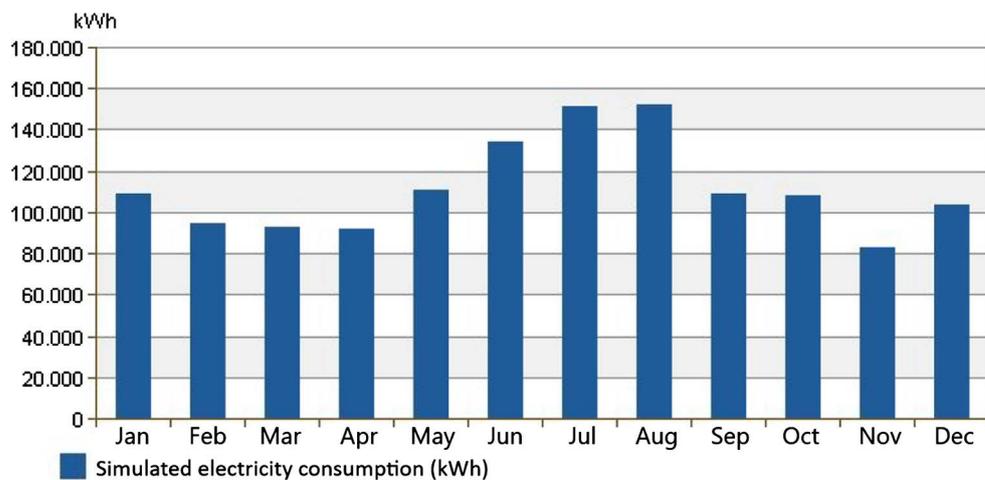


Figure 5. Simulated electricity consumption required for each month at the operational stage.

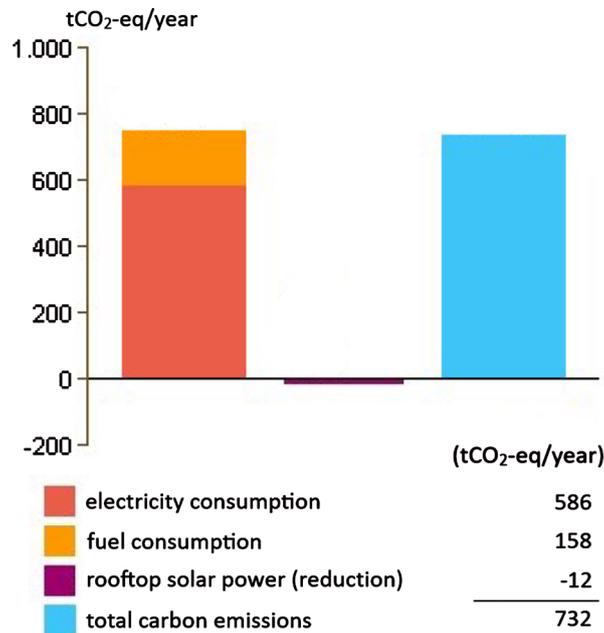


Figure 6. Carbon emissions from case building per year.

scholars maintained that the ratio of carbon emissions at the demolition stage to BLCCE is about 1% (Sartori & Hestnes, 2007; Zhang & Wang, 2015), as a consequence, the estimation of carbon emissions at this stage does not affect the results of BLCCE. According to Formula (7), the estimated value of carbon emissions at the demolition stage is 316.68 tCO₂-eq.

$$C_{\text{dem}} = 3166.87 \times 10\% = 316.69 \text{ tCO}_2\text{-eq}$$

4.7. Summary and Discussion

Peng (2016) believed that average carbon emissions per working area per year of each building stage C_{At} (kgCO₂-eq/(m²·y)) is an important evaluation index of BLCCE, the formula for calculating C_{At} is concluded in Formula (8). In China, the expected year (Y) of the construction, operational, and demolition stage of buildings is usually 2 years, 50 years, and 0.5 years, respectively (Peng, 2016; Wu, Yuan, Zhang, & Bi, 2012; Zhang, Shen, & Zhang, 2013).

$$C_{\text{At}(\text{con,ope,dem,tot})} = \frac{C_{(\text{con,ope,dem,tot})}}{Y \times GFA} \quad (8)$$

The estimated results of carbon emissions at each stage were summarized and calculated, and the total estimation of BLCCE is 40,083.56 tCO₂-eq. In addition, average CO₂-eq emissions per working area per year of construction, operational, demolition stage and life cycle (respectively is $C_{\text{At,con}}$, $C_{\text{At,ope}}$, $C_{\text{At,dem}}$, $C_{\text{At,tot}}$) were calculated and listed in Table 8.

In BLCCE, the carbon emissions at operation stage account for the largest proportion (91.31%) of the life cycle, while the $C_{\text{At,con}}$ at the construction stage is the highest, that is, the carbon emissions at the construction stage are the most concentrated. Therefore, in terms of low-carbon engineering design, engineers

Table 8. Case building's life cycle carbon emissions.

Stage	Carbon emission (tCO ₂ -eq)	Percentage (%)	C_{At} (kgCO ₂ -eq/(m ² ·y))
construction stage	3166.87	7.90	248.69
operational stage	36600.00	91.31	114.97
demolition stage	316.69	0.79	99.48
total	40083.56	100.00	119.91

should focus on carbon emissions at the operational stage and the construction stage.

5. Discussion

5.1. Application Scope and Limitations

As a hot spot in the field of architecture, engineering, and construction, BIM will be the mainstream delivery option in the future (Cao et al., 2015). Combined with BIM and LCA, this paper proposed an estimation of BLCCE method, which is rapidness and convenience. As long as the BIM designed by engineers can be acquired, the simulation results of the bill of quantities and operational energy consumption can be quickly obtained, and then the BLCCE can also be simulated.

However, creating BIM takes a long time. Due to various other factors, the current delivery option in China is still stuck in the CAD drawings (Cao et al., 2015). Secondary creating BIM based on CAD drawings will also lead to more serious work delays. Moreover, there is component loss in the introduction of Revit2017 into GTJ2018, and repairing BIM engineering quantities model also result in a waste of time and effort. These factors may reduce the rapidity of the method of this paper.

It is particularly noteworthy that there is still a certain gap between the estimation method and the actual carbon emission calculation, which is mainly evidenced by follows: 1) since the data of refurbishment is difficult to obtain, the carbon emission of this part is neglected in the estimation model; 2) in the case, the design phase lacks the design scheme of facilities and equipment, so the carbon emission of this part is ignored; 3) there are many uncertainties during operation (such as operation schedule, HVAC parameters, thermal conductivity of insulation material) which will lead to distortion of energy consumption simulation; 4) the missing carbon emission coefficient of some materials in China is also the reason for the deviation of the estimation results.

5.2. Comparison with Other Studies

In previous studies, many scholars have studied the BLCCE of villas, residences and office buildings. In order to grasp the characteristics of the hospital building's life cycle carbon emissions, the study compared the hospital building in this case with the other studies of some scholars. To avoid the differences of carbon emission coefficient caused by different countries, the scopes of cases

were all framed in China. Additionally, the selected cases met the following conditions: 2 years in the construction stage, 50 years in the operational stage, and 0.5 years in the demolition stage, which guaranteed the comparability between these cases.

According to the studies on villas (Yang et al., 2018), residential building (Li, Cui, & Lu, 2016; Zhang & Wang, 2015; Zhang, Zheng, Zhang, Chen, & Wang, 2016), office buildings (Peng, 2016; Zhang & Wang, 2015), the percentage Per (%) and carbon emissions per working area per year C_{At} (kgCO₂-eq/(m²·y)) at each stage were calculated. The calculation results are shown in Table 9.

In terms of the percentage of carbon emissions at each stage, carbon emissions account for 7.9% to 35.32% of the BLCCE at the construction stage, 63.26% to 91.31% at the operational stage, and 0.27% to 1.94% at the demolition stage, respectively. The demolition stage account for a small slice of BLCCE (almost negligible), while the construction stage and operational stage constitute 98.06% to 99.73% of BLCCE in total. Hence the low-carbon design should be optimized at the construction stage and the operational stage.

In the aspect of the average carbon emissions per working area per year at the construction stage ($C_{At,con}$), the $C_{At,con}$ of hospital is in the middle range of all case. The highest $C_{At,con}$ indicator is 357.33 kgCO₂-eq/(m²·y) of Case 2, which is mainly because Case 2 is a villa with luxurious and complicated decoration. Correspondingly, the $C_{At,con}$ of low-rise residential building with general decoration (see Case 5) is lowest within all case. Also, as the number of layers adds, the structural design grows harder, which leads to a growth in the amount of material used per square and an increase in $C_{At,con}$.

From the perspective of $C_{At,ope}$, the hospital building in this study is obviously higher than villas, residences, and office buildings (see Case 2 - 9). This may be due to the following factors: 1) the hospital building, as a public building that bears the burden of the whole city's medical system, serves the population of the entire city. As a result, it carries far more customers per construction area than that of villas, residences, and office buildings; 2) patients in hospital have higher

Table 9. Percentage and C_{At} at each stage.

Authors	Architectural type	Structure system	Floor	Per _{con}	Per _{ope}	Per _{dem}	$C_{At,con}$	$C_{At,ope}$	$C_{At,dem}$	$C_{At,tot}$
1 this study	hospital	reinforced concrete	4	7.90	91.31	0.79	248.69	114.97	99.48	119.91
2 Yang et al. (2018)	villa	brick-concrete	2	23.87	75.35	0.78	357.33	45.11	46.42	57.02
3 Peng (2016)	office building	reinforced concrete	15	12.64	85.43	1.94	321.00	86.76	196.59	96.73
4 Y. Zhang et al. (2016)	residential building	reinforced concrete	15	27.17	72.56	0.27	191.18	20.42	7.70	26.80
5 D. Li et al. (2016)	residential building	masonry-concrete	4	35.32	63.26	1.42	168.04	12.04	27.02	18.12
6 X. Zhang and Wang (2015)	residential building	brick-concrete	6	17.16	82.48	0.36	310.50	59.70	26.00	68.93
7 X. Zhang and Wang (2015)	residential building	masonry-concrete	6	14.52	85.16	0.31	254.50	59.70	22.00	66.76
8 X. Zhang and Wang (2015)	residential building	reinforced concrete	16	16.41	83.29	0.30	322.00	67.70	24.00	77.41
9 X. Zhang and Wang (2015)	office building	reinforced concrete	28	14.82	84.91	0.27	307.50	70.46	22.00	79.03

requirements for temperature and ventilation, which increases the energy consumption and carbon emissions; 3) some departments of the hospital (for example, the emergency department) are open in 24 hours, which cause more energy consumption and produce more carbon emissions than other building that are dormant at night.

$C_{At,tot}$ is heavily affected by carbon emissions at the operational stage, so the $C_{At,tot}$ of the hospital building is still higher than other cases. The explanation is that the operational stage is 50 years, while the construction stage and demolition stage are only 2 years and 0.5 years, respectively.

6. Conclusion

BIM and LCA were applied to estimate the BLCCE in this study, which is proved to be quickly and effectively in the engineering design stage. In addition, this paper took a Chinese hospital building as an example to test the feasibility of the method and filled the research gap of the BLCCE among hospital buildings. The results of this case study provided a reference value for similar hospitals under the same climate and economic situations.

In the calculation results of this study, the BLCCE of case building is 40083.56 tCO₂-eq, and average carbon emissions per working area per year are 119.91 kgCO₂-eq/(m²·y) in the building's life cycle. The carbon emissions at the construction stage, the operational stage, and the demolition stage constitute 7.90%, 91.31% and 0.79% of BLCCE, separately. The $C_{At,ope}$ of hospital is apparently higher than that of villas, residences, and office buildings. This study ascribed this finding to the following three principal elements: 1) large population in need of service; 2) long daily operational hours; 3) high comfort requirement of the patient.

The estimation method in this paper is rapid and effective. However, as an estimation method, it has certain limitations, and mainly include: 1) due to the information lack of refurbishment and facilities, this part of carbon emission is neglected in estimation; 2) there are component losses in process of Revit2017 into GTJ2018, and this issue consumes plenty of time to check and replenish the modeling; 3) the carbon emissions coefficient of some materials in China is missing, or greatly different from the international standard, which leads that estimated result is quite at odds with the actual value.

To compensate for the above shortcomings, future studies need to develop an estimation method about refurbishment. The problems of incompatibility between BIM software also need to be settled. Furthermore, horizontal comparisons of BLCCE between more building type (school, shopping mall, urban complex, etc.) are also the focus of our attention henceforward.

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name: research on building's carbon emission and integrated system based on city perspective.

Conflicts of Interest

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

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