The following publication Zhu, H., Hong, J., Shen, G. Q., Mao, C., Zhang, H., & Li, Z. (2018). The exploration of the life-cycle energy saving potential for using prefabrication in residential buildings in China. Energy and Buildings, 166, 561-570 is available at https://doi.org/10.1016/j.enbuild.2017.12.045.

The exploration of the life-cycle energy saving potential for using prefabrication in residential buildings in China

Abstract: China's rapid urbanization along with the development of the modern economy is certain to result in a long-standing and substantial energy demand in the entire society. Therefore, industrialization in building construction is a vital strategy for alleviating adverse environmental burdens and accelerating urbanization with the current construction practice. An integrated method was employed to evaluate the life cycle energy performance of prefabricated buildings, using the process-based hybrid life cycle assessment and scenario-based energy simulation as the underlying methods. Results revealed the less obvious energy reduction potential of prefabricated buildings during the embodied phase. During the building operation phase, the scenario and comparative analyses from a life-cycle perspective indicate that prefabrication generates environmental gains by providing enhanced thermal performance. A regional level policy analysis reveals the backwards status quo of the precast construction in Northern and Western China. Given the significance of using prefabrication in building energy conservation, it is quite urgent and necessary to establish a mature construction market with highly evolved industrialization in these "backward" regions.

Keywords: Industrialization in building construction, Prefabrication, Life-cycle energy assessment, Hybrid LCA

1. Introduction

China is undergoing fast-tracked urbanization with the rapid development of the modern economy. By the end of The 13th Five-Year Plan (2016–2020), the urbanization rate in China is projected to exceed 60%, which will be a historic high for the country. Such an intensive construction process certainly generates a long-standing and substantial energy demand in the entire society. Therefore, the central government adopted key strategies to achieve energy conservation and emissions reduction nationally. Industrialization in building construction is a vital approach for alleviating adverse environmental burdens from the accelerated urbanization in the current construction practice. The central government has promulgated a wide range of policies at the national and industrial levels to promote industrialization. For instance, the National Plan on New Urbanization 2014–2020 [1] and the Plan on Green Building [2] focused on the active role of precast construction in developing sustainable construction and advancing urbanization in China.

Precast construction is a smart and innovative construction method that refers to the transfer of on-site construction work from sites to factories. The method includes manufacturing building components in a controlled condition, the transportation of complete or semi-complete components to the construction site, and the installation of prefabricated components to create buildings [3,4]. Precast construction is a resource-efficient and environmentally friendly method that does not compromise building shape and design. Compared with traditional construction technologies, not only does prefabrication improves construction productivity, building quality, and construction safety, it also reduces construction time, waste, dust, noise, and labor demand [[5], [6], [7], [8]].

The physical qualities and economic benefits (such as the schedule optimization and labor saving) have been extensively studied in the prefabrication research domain from both theoretical and practical perspectives [[9], [10], [11]]. However, knowledge of the life-cycle environmental benefits of prefabricated buildings remains insufficient. Especially given that the prefabrication technique is still in its infancy in the construction industry in China, there are few empirical studies of the ongoing projects proofing the sustainability of prefabrication through solid evidence. Mao et al. [12] compared the difference of greenhouse gas emissions (GHG) during the embodied phase between prefabricated and conventional buildings by using the process-based model. Their results explored the reduction potential of precast construction regarding GHG emissions. Aye et al. [13] conducted a similar comparative study to investigate the life-cycle energy use of prefabricated buildings. Their study focused on prefabricated steel and timber-frame buildings. By contrast, the concrete frame structure is the most common structural system adopted for prefabricated buildings in China, for which the composition of primary materials differs from those used in steel and timber-frame buildings. An input–output (I–O)-based hybrid analysis method to assess the embodied energy usage of six standard prefabricated components was developed by Hong et al. [14]. They also evaluated the effect of adopting prefabrication on the total embodied energy consumption of buildings. However, this study failed to explore operational energy performance. Therefore, another obstacle in the current prefabrication research domain is the extension of the system boundary to a wider scope by integrating the operational phase into a model with a life-cycle perspective. Moreover, regardless of current assessments achieved from previous research, there is still an urgent need to conduct a thorough investigation in Chinese context because the measurement of life-cycle energy is inconsistent in different contexts. In summary, previous studies provided limited support for a systematic exploration of the life-cycle energy saving potential of prefabricated buildings, especially in the context of China.

With regard to methods applied for embodied energy assessment in the building and construction field, most previous research employed process-based analysis. However, such method is dependent on a more specific and exhaustive database in resource and energy quantification, which involves time-intensive and costly data collection. Consequently, system boundary must be intuitively determined to alleviate the requirement of detailed inventory data through the upstream production process. By contrast, the I–O analysis investigates the entire system boundary by considering all upstream sectoral interactions but overlooks the measurement of the micro-level environmental impact due to the specificity loss in the project level. To retain the process specificity and eliminate the truncation errors, the present study employed a hybrid model to provide a more accurate assessment of environmental impacts. This study focuses on buildings built with the semi-prefabrication construction method. To achieve an accurate assessment of building operational energy consumption, several assumptions were made to incorporate the prefabrication-related characteristics into the simulation process.

Given the infancy of the prefabrication technique in China, the theoretical foundation and the empirical results provided in the present study are critical. In particular, the net environmental gains by adopting industrialization in building construction is a key concern for national policy makers, which, in turn, may significantly affect the delivery of prefabricated buildings. The results of this study can enhance the holistic understanding of potential environmental improvements in adopting prefabrication for the current construction practice. Moreover, such results benefit policy makers seeking to promote sustainable construction in China. The remainder of this paper is organized as follows. Section 2 introduces the fundamental models and data sources to simulate the energy consumption during the building's embodied and operational phases. Section 3 presents the life-cycle energy performance of prefabricated buildings and explores their environmental benefits in comparison with conventional buildings. In Section 4, the advantages and barriers for implementing precast construction are discussed based on the results obtained in the current study. Section 5 provides the conclusions and policy recommendations.

2. Methodology

2.1 The overview of assessment methods

Process-based methods aggregate specific data according to unit processes; however, they are subject to the errors induced by the subjective removal of the iterative effect from the upstream production system. Meanwhile, I–O analysis employs the national average data to quantify environmental impacts with a complete system boundary but without product-specific information [15]. By combining both process- and I–O-based methods, the hybrid model retains process specificity, as well as covers the inputs from the entire upstream supply chain. The fundamental theoretical foundation of the hybrid model was first proposed by Bullard et al. [16]. The computational framework is a simple integration where case-specific data for primary production processes were combined with I–O derived values from the higher-order upstream processes, use phases, and downstream processes. Such approach is a process-based hybrid model. A separate integration of process-based data and I–O-based results may cause unexpected inconsistency among multiple analytical tools. Therefore, it is vital to determine an appropriate interface for these two models to preclude double counting during calculation. Consequently, the I–O-based hybrid model promotes sector disaggregation in the I–O table [17]. The model directly incorporates detailed process-based data into the I–O transaction matrix, preventing truncation errors and retaining product specificity by running the updated I–O analysis within a complete system boundary [18]. Although the I–O-based hybrid technique facilitates ready access to integrate process specificity with the entire economy, it remains vulnerable regarding providing sufficient specific data on input and sale information for the newly-added sector [19,20]. Rebitzer et al. [21] indicated that the I–O-based hybrid method is distinct to the process-based hybrid model as it improves the structure of I–O analysis. The integrated hybrid model incorporates physical process-based flows into the I–O model with a consistent computational structure [20,22,23]. This model addresses the difficulties of interface selection and modelling interactions from the traditional hybrid analysis. However, the integrated hybrid method requires a high level and detailed data processing because of the inherent computational mechanism. This may result in difficulties in the practical application.

Thus, hybrid analysis enables a more accurate assessment by considering higher-order upstream production processes while retaining most of the valuable and specific process-based information. The process- and I–O-based hybrid models quantify environmental impacts with a high level of aggregation due to the use of the I–O model. The integrated model highlights the interaction between process-based and I–O-derived data by incorporating physical units into monetary transactions. In fact, the method utilized for a particular study is case specific, which depends on resource availability and accuracy requirement. In this study, the process-based hybrid model was employed to quantify the life-cycle energy consumption of prefabricated buildings according to the data availability and the research purpose.

2.2 Scope, system boundary, and functional unit

Prefabricated buildings were investigated in the present study to explore the difference between their life-cycle energy performances against those of current traditional buildings. Precast construction is a production process involving off-site manufacturing, factory to construction site transportation, and on-site installation of prefabricated components. The system boundary of process-based hybrid analysis covers the energy consumption during the building embodied phase including the extraction of raw materials, off-site manufacturing, transportation, and on-site construction process. Such analysis also involves the energy consumed during the building operational phase, including the cooling and heating loads, as well as lighting and appliance use.

The functional unit for the embodied energy quantification is per square meter of energy consumption of the target prefabricated buildings (GJ/m2). For the operational phase, the basic function unit is the energy consumption on a per square meter per year basis (GJ/m2 yr). Apart from the intensity-based measurement, the total energy consumption was also quantified (GJ) to reflect the relative proportion of energy consumption between the embodied and operational phases.

2.3 Embodied phase

The initial embodied energy use is the energy consumed by all of the processes, goods, and services associated with the building construction process, from the mining and processing of natural resources to manufacturing building materials, transport, and product delivery. This study utilized a process-based hybrid model to assess the embodied energy consumption of the investigated buildings.

The hybrid energy intensity for a certain material is equal to the sum of the process-based energy intensity of lower-order primary production process and the I–O derived energy intensity covering higher-order upstream processes. Therefore, it is essential to determine the interface and to avoid double counting during the integration process. The location of the interface is subjectively determined according to research purpose and data resource availability. Deciding the interface location is comparatively straightforward for practitioners because the cut-off rule in the conventional process-based model is also applicable to hybrid analysis [24]. The prevention of double counting requires the subtraction of duplicate process-based inventory data from the I–O-derived total energy consumption. Various approaches are used in the subtraction process in previous studies. The traditional method subtracts the monetary value of the process data from the final demand vector. [25] integrated process-based inventory data into the I–O-derived value by conducting structural path analysis in the upstream supply chain. [24] discovered an innovative approach by introducing the system incompleteness factor during subtraction. Considering the computing complexity and data availability, this study adopted the conventional approach to avoid double counting in the process-based hybrid analysis.

2.4 Operation phase

Heat transfer and air infiltration are the two principal factors influencing building operational energy consumption. They are physically associated with some building design parameters, including the shape coefficient, the specific materials used in the external walls, the window–wall ratio, and the shading coefficient. Consequently, the operational energy intensity varies due to the specific construction technologies and methods adopted for a certain building. Particularly for prefabricated buildings, given the superiority of the elaborate manufacturing process, the quality of building components is improved, which further enhances the airtightness and integrality of buildings. To further examine the effectiveness of operational energy consumption, this study established four scenarios for the in-depth analysis of the operational energy use of prefabricated buildings (see Table 1).

The first scenario involves a building constructed with prefabricated techniques, where the operational energy consumption is simulated based on the actual building parameters collected from real case studies. More specifically, the external wall of the target prefabricated building is a two-plate sandwich wall with an insulating layer inside. It consists of four major parts: the concrete-made inner and outer slabs, an insulating layer, and several connecting pieces. Note that with the rapid development of prefabrication technology in China, fiber reinforced plastic (FRP) is selected as the primary material instead of the reinforced steel bar in the production of connecting pieces, which further reduces thermal conductivity and eliminates the thermal bridge in the joint part of building components, thereby enhancing the thermal effectiveness of prefabricated walls. The second scenario assumes that the target building is constructed with the traditional construction method by following the local ordinance guidance on the energy conservation of buildings. Such an assumption is consistent with the current building construction practice in China, which further differentiates the basic attributes of existing buildings against the brick-concrete structure. In this situation, the aerated concrete block is identified as the primary material used for non-bearing external walls. This type of material is presented as lightweight and high-strength with better duration and thermal insulation compared to traditional clay bricks. Furthermore, the third scenario provides insights on target buildings with the brick-concrete structure, which is the primary structural frame in the existing buildings in China. In fact, the structure of most existing buildings in China is brick-concrete dominant, a result of the tradeoff between cost and quality in the construction field, which causes a longstanding challenge in reducing the operational energy use of existing buildings. The fourth scenario is designed to examine the operational energy performance of the buildings built in compliance with the minimum requirements of the mandatory design standard endorsed by the local government. This scenario aims to provide a baseline for verifying the effectiveness of operational energy consumption of buildings under different scenarios. The software DesignBuilder is used to simulate the operational energy consumption under four scenarios.

Table 1 Basic profile of different scenarios

	Basic Feature
Scenario 1	Buildings constructed with prefabricated techniques
Scenario 2	Traditional buildings constructed under the guidance of the ordinance on energy conservation of buildings
Scenario 3	Traditional buildings with brick-concrete structural frame
Scenario 4	Baseline Buildings meeting the minimum requirement of the mandatory design standard

2.5 Data consolidation

Three categories of data sources were collected in this study: monetary transactions in the latest I–O table, sectoral direct energy consumption data, and case-specific process-based data. The most recent I–O table (2012) compiled by the Chinese National Bureau of Statistics with 139 sectors was adopted. The sectoral energy input data were derived from the Chinese Energy Statistical Yearbook 2013. Given the difference in the level of sector aggregation in these two data sources, the direct energy use data were further disaggregated to match the sectoral classification in the I–O table. Disaggregation was conducted based on the strategy where energy consumption among sub-sectors was proportional to their economic output. The basic building parameters and process-based inventory data were collected from a group of documents through a field survey on the construction site, including construction drawings, bill of quantities, accounting receipts, and secondary data from upstream suppliers. The process-based energy intensity data were obtained from the China Building Material Academy [26] and the Chinese Life Cycle Database developed by Sichuan University. The basic profile of target buildings includes information on location, building type, structure, gross floor area, height, and prefabrication techniques adopted in each building.

3. Case study

This study investigated two typical prefabricated buildings located in Chengdu and Shenzhen to explore their energy consumption behaviors. Chengdu (30.67N, 104.06E) is the provincial capital of Sichuan, which is located in the Hot Summer and Cold Winter Climate Zone and influenced by the humid subtropical climate with moderate rainfall concentrated mainly on the warmer months. The daily average temperature is 5.6 °C in winter and 25.2 °C in summer. Shenzhen (22.62N, 114.07E) is the Special Economic Zone in China with a monsoon-influenced and humid subtropical climate. This climate is a typical winter-warm and summer-hot zone in China, with the daily average temperature at 15.4 °C in winter and 28.9 °C in summer. Both buildings under investigation are semi-prefabricated. The prefabricated components adopted in these two cases include precast façade, staircase, slab, and balcony. Table 2 summarizes the basic profiles of sample buildings. Evidently, these two buildings are both residential buildings with the same frame-shear structure. More specifically, two types of precast façade are adopted in the case buildings. One is prefabricated with 160-mm thickness, and it is installed as a basic formwork combined with cast-in-situ concrete. This type of façade reduces time and cost intensity by reducing the frequency of formwork installation but provides less support in bearing the structural load of buildings. Similarly, the floor slab is also semi-prefabricated with laminated technology. Half of the slab (80 mm) is produced at the offsite factory, and the remaining part is built with cast-in-situ concrete. Such manipulation reduces overdependence on formworks, alleviates workforce demand for building construction, and improves onsite construction efficiency. The other one is manufactured at the offsite factory with a thickness of 310 mm, assembled directly with connecting pieces. This type of prefabrication is adopted as one of the major structural components in building construction.

Table 2 Basic profile of building cases

		Project A	Project B
Geographic information	Location	Chengdu	Shenzhen
	Temperature		

	Climate		
Building information	Building Type	Residential	Residential
	Structure	Frame shear structure	Frame shear structure
	Gross floor area (m2)	6890	216200
	Basement	1 floor	2 floors
	Height	11 floors	26-28 floors
Prefabrication techniques	Construction method	Semi-prefabrication	Semi-prefabrication
	Volume of prefabrication (m3)	1250	7850
	Prefabrication rate (% by volume)	59	10
	Precast facade	✓	✓
	Semi-precast slab	✓	✓
	Precast balcony	✓	
	Precast staircase	✓	✓

The primary factors influencing the operational energy performance are the U-value and the air tightness, whose interactions directly determine the thermal and air infiltration performances of buildings. Table 3 summarizes the basic thermal parameters and the reported values of air tightness under the four scenarios. The simulation is performed daily for a year using the parameters provided in Table 3.

Table 3 Thermal parameters and air tightness under four scenarios

Scenario	Region	U-value (W/m2·K)	Air tightness (m3/m2·h)	Features
1	Shenzhen Chengdu	0.738 0.738	8 6	● A two-plate sandwich wall with an insulating layer inside ● Uses FRP as the connector
2	Shenzhen Chengdu	0.678 0.678	8 6	● Using 200 mm aerated concrete blocks as the major materials for thermal insulation ● Uses cement mortar for plastering surface
3	Shenzhen Chengdu	2.226 2.226	10 8	● Using clay bricks as the major materials for thermal insulation ● Using cement mortar for plastering surface
4	Shenzhen	0.800	8	● Refers to “Design standard for energy conservation of residential buildings in Shenzhen”
	Chengdu	1.000	6	● Refers to “Design standard for energy conservation of residential buildings in Sichuan Province”

Table 4 lists the delivered quantity of materials used and their corresponding embodied energy consumption in each building project. No obvious difference was observed between the prefabricated and the traditional buildings regarding the amount of the main building materials. Steel and concrete were still dominant in both physical quantity and energy contribution.

Table 4 Embodied energy use of primary building materials

	Physical quantity	Embodied energy (GJ)

	Energy intensity	Project A	Project B	Project A	Project B
Concrete	1.6 GJ/m3	4348.9 m3	100587.3 m3	6958.2	160939.6
Steel	29 GJ/t	331.8t	11380.1t	9622.5	330023.6
Cement	5.5 GJ/t	612.3t	13930.9t	3367.8	76620.2
Aluminum	180 GJ/t	48.6t	175.5t	8746.2	31598.0
Block	2 GJ/t	334.3t	51935.0t	668.6	103869.9
Sand	0.6 GJ/t	1202.9t	41792.8t	721.7	25075.7
Ceramic	15.4 GJ/t	322.5t	13628.4t	4966.5	209876.6
Paint	60.2 GJ/t	29.9t	595.5t	1797.3	35851.0
Glass	16 GJ/t	21.4t	128.8t	342.4	2061.5

4. Results analysis

4.1 Embodied phase

Table 5 shows the embodied energy intensities of two target building projects. The system boundary extension in the hybrid analysis allows an accurate assessment of the results by considering the energy inputs in the higher order upstream production process. To further illustrate the difference among the reported value derived from different assessment methods, this study used process-based and hybrid models to simulate the embodied energy consumption of two case buildings. Table 5 shows that the embodied energy intensities were 6.11 GJ/m2 and 5.04 GJ/m2 in Projects A and B, which were 13.1% and 11.0% higher than the results obtained from the process-based model. This finding is mainly attributed to the following: apart from the traditional primary production process, the hybrid model also quantified the energy consumption from the higher order upstream process, thereby providing a complete system boundary in the building embodied energy assessment.

Table 5 Embodied energy intensity of two building projects

	Process-based	I-O based	Hybrid	Percentage change
Project A	5.40	2.19	6.11	13.1%
Project B	4.51	1.60	5.04	11.8%

Moreover, the value of the embodied energy intensity of prefabricated buildings requires further validation by comparing the results obtained from previous research. On the one hand, this comparative analysis can validate the reliability of the final results, indicating the feasibility of the adopted method. On the other hand, the comparison result can provide robust evidence on the environmental benefits during the embodied phase of prefabricated buildings. Therefore, selecting appropriate buildings with comparable features is essential. The selection criteria for the subsequent comparison include the following:

(1) The target buildings should be built in China. A consistent geographical location

provides similar levels of economic development, construction productivity, and energy efficiency, which largely ensure the comparability of the chosen cases.

(2) The selected buildings should be constructed with a similar building type, structural system, and other profiles that may cause the materials used to change.
(3) This study assumes that the effect of variations induced by the onsite construction management skill is negligibly minimal on the total embodied energy use because the direct onsite energy consumption of buildings only accounts for a slight proportion in the total life cycle energy use of buildings [[27], [28], [29]].
(4) To alleviate the effect of methodological diversity on the energy consumption assessment, this study also employed the process-based hybrid model to modify the energy intensity in the original article.

Table 6 Building profile of selected buildings

	Project 1	Project 2	Project 3	Project 4	Project 5	Project 6
Source	[30]	[31]	[32]	[32]	[33]	[27]
Location	Beijing	Beijing	Henan	Henan	Guangdong	Guangdong
Building type	Residential	Residential	Residential	Residential	Residential	Residential + commercial
Assessment model	Process-based	Process-based	Process-based	Process-based	Process-based	Process-based
Energy intensity (GJ/m2)	4.49	5.96	5.05	4.01	5.11	5.13
Structure	Frame-shear wall	Reinforced concrete frame	Reinforced concrete frame	Frame-shear wall	Reinforced concrete frame	Reinforced concrete frame
Gross floor area (m2)	7000	26717	5240	12375	20105	11508

Fig. 1 suggests that the prefabricated buildings failed to possess obvious superiority over the traditional buildings. The process-based results of Projects A and B were 5.40 and 4.51 GJ/m2, respectively, which were nearly equal to the selected comparison buildings ranging from 4.49 GJ/m2 to 5.74 GJ/m2. Moreover, considering the infinite energy interactions through the upstream production process, the energy intensities modified by the hybrid model were approximately 10% higher than the results obtained from the process-based model. This finding revealed that the arbitrary determination of the system boundary by disregarding the energy use embodied in the higher-order upstream services may underestimate energy consumption. In summary, the results of the comparative analysis indicated that the energy reduction potential of prefabricated buildings during the embodied phase is less evident.

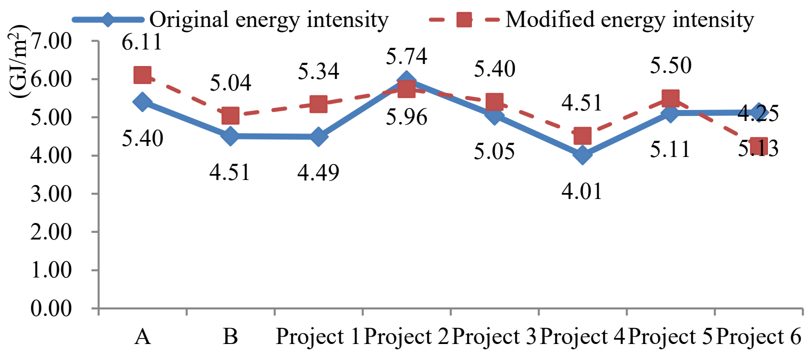
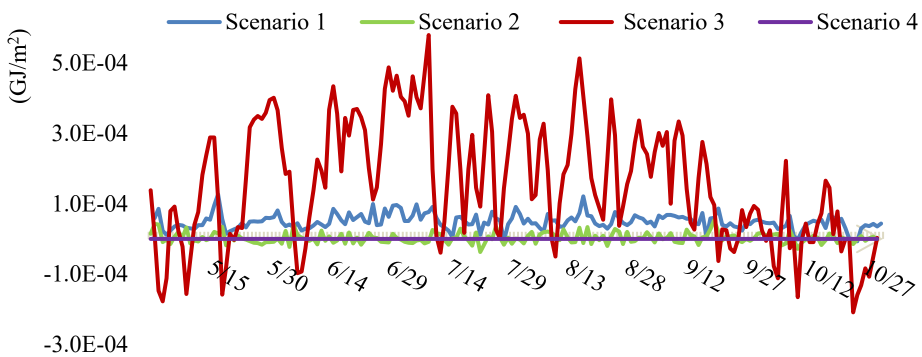


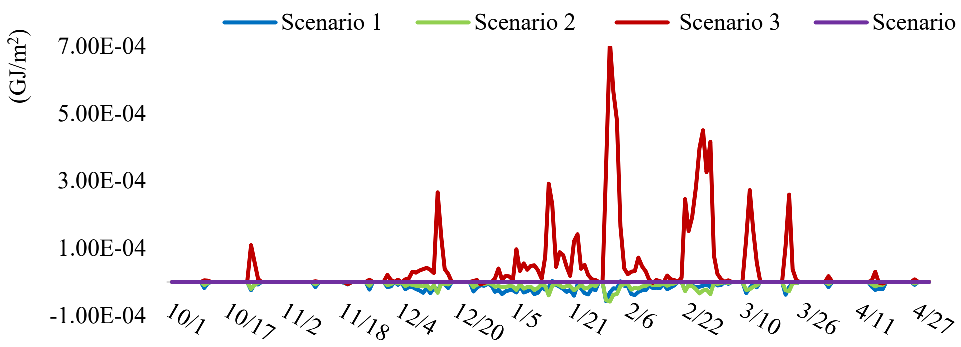
Fig. 1. Comparative analysis results

4.2 Operation phase

The estimated heating and cooling loads were used as the primary factors to represent operational energy performance under different scenarios. Fig. 2, Fig. 3 show the relative changes in the operational energy intensities of the two case buildings in the cooling and heating seasons compared with the baseline scenario. The building assumed to be constructed under the brick-concrete structure (Scenario 3) consumed more energy compared with other scenarios, performing an average of 10.2% and 19.6% higher than the baseline scenario in Shenzhen and Chengdu, respectively. The energy consumption trend for Scenarios 1 and 2 was similar, which was also quite close to the baseline scenario. Such similarity implied the energy efficiency of the new buildings both met the requirements of the local standards for energy conservation. More specifically, the case building in Shenzhen was less obvious in the energy saving in the first scenario. Although it consumed the lowest energy in the heating season, such environmental benefit was still negligibly small when compared with the building constructed with the traditional construction method (Scenario 2).

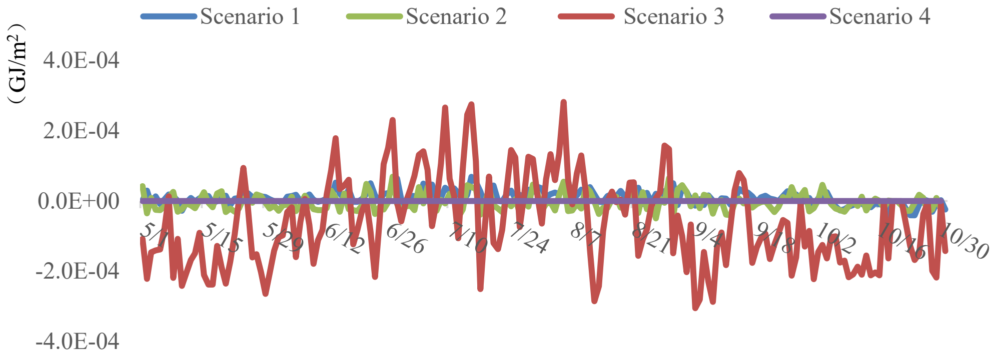


Cooling season

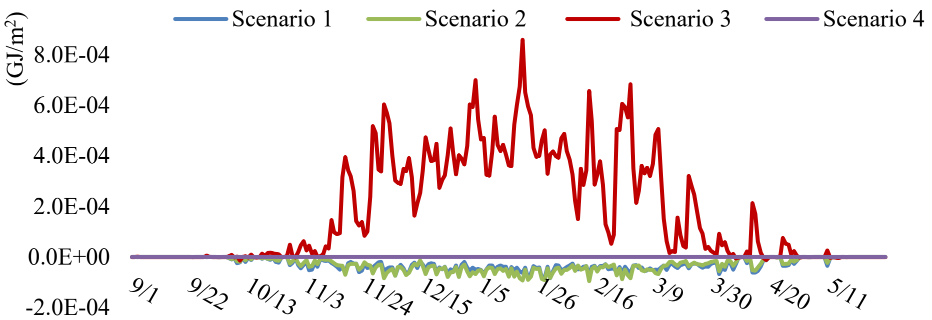


Heating season

Fig. 2. Annual operational energy performance of the Shenzhen case under different scenarios.



Cooling season



Heating season

Fig. 3. Annual operational energy performance of the Chengdu case under different scenarios.

In the case of Chengdu, Scenario 3 notably has the lowest energy consumption in the cooling season, during which the operational energy intensities were 9.1% and 7.5% less than in Scenarios 1 and 2, respectively. This finding is mainly explained by the following: although the cooling energy requirements were relatively large in the hottest months (e.g., July and August), the operational energy consumption was still small during the transition seasons (e.g., May, June, September, and October) given the moderate temperature and comfortable environment in this period in Chengdu. More specifically, the cooling load requirements can be further offset using natural ventilation during the building operational phase. The lower value of air tightness in the building with brick-concrete structure (Scenario 3) can increase the heat transfer efficiency between indoor and outdoor environments, consequently improving the natural ventilation performance and in turn reducing the operational energy consumption in the transition season. Similar to the case building in Shenzhen, the sample prefabricated building in Chengdu consumed less operational energy during the heating season. However, such environmental advantage is also not obvious in the total heating and cooling energy requirements.

Table 7 summarizes the annual-based operational energy consumption under difference scenarios. All the energy sources were categorized into the energy for heating, cooling, and the use of lighting and other appliances. Other operating energy requirements were excluded assuming the same consumption behavior of these two case buildings. Apparently, the annual operational energy consumption of the target building in Shenzhen is higher than the target building in Chengdu. This finding is mainly contributed by the difference in the climate features between these two places.

Table 7 Annual operational energy consumption under different scenarios

Region	Scenario	Cooling MJ/m2	Heating MJ/m2	Use of lighting and appliances MJ/m2	Total operational energy use MJ/m2
Shenzhen	Scenario 1	184.1	7.6	213.6	405.3
	Scenario 2	179.4	7.9	209.9	397.2
	Scenario 3	195.4	13.7	211.5	420.6
	Scenario 4	179.1	8.7	211.4	399.2
Chengdu	Scenario 1	81.1	23.0	210.2	314.4
	Scenario 2	79.7	22.8	207.0	309.5
	Scenario 3	73.7	54.4	208.4	336.5
	Scenario 4	80.1	27.0	209.8	316.9

4.3 Life cycle energy analysis

The life cycle energy consumption of the target prefabricated buildings can be calculated by assuming that the life span of buildings in China is 50 years (See Fig. 4). The overall energy use patterns were divided into seven categories, they are: material production, transportation, services, cooling, heating, lighting and appliances, and others (energy supplied by other economic sectors). It can be observed that the embodied energy use of the prefabricated building in Chengdu was similar to the case in Shenzhen whereas the operational energy consumption represented a huge difference between these two target buildings, with the values of 15.5 GJ/m2 and 20.5 GJ/m2, respectively. The overall life cycle energy intensity of buildings was 21.6 GJ/m2 in Chengdu and 25.5 GJ/m2 in Shenzhen. This variation was primarily caused by the energy-intensive cooling process in Shenzhen owing to its relatively higher average temperature in summer. Form a life-cycle perspective, material production, cooling, and the use of lighting and other appliances were three biggest contributors to the overall energy consumption of buildings.

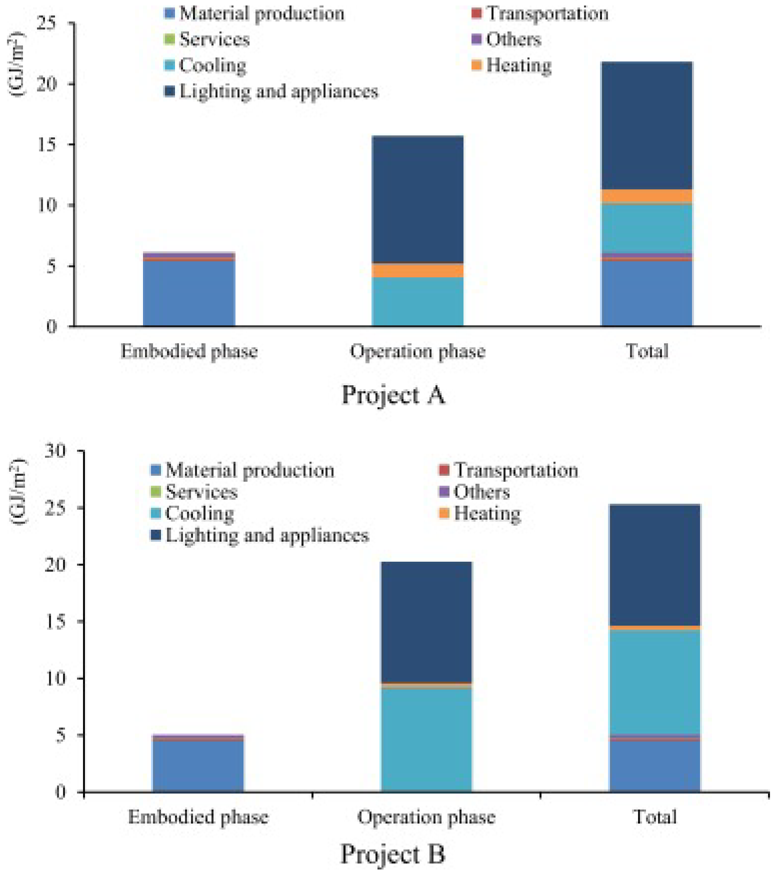


Fig. 4. Life-cycle energy performance of the target prefabricated buildings.

To further explore the life cycle environmental benefits of prefabricated buildings, a comparative analysis was conducted by reviewing previous research based on the similar climate, temperature, and structure conditions. Table 8 lists the basic profile of comparison buildings, and Fig. 5 shows the comparative results. The life cycle energy intensities of the two case buildings were smaller than the selected traditional buildings, except for that in Zaragoza, Spain. The line in Fig. 5 represents the ratio of the embodied energy use to the annual operational energy use. Buildings labelled with a higher ratio but less amount of life cycle energy consumption indicate their green features and superiorities in energy conservation. It can be found that the investigated prefabricated buildings represent a higher ratio in comparison to other counterparts, indicating that buildings can reduce life-cycle energy use by adopting prefabrication techniques. The factory-based production is a primary cause for this superiority. For instance, the external wall of the prefabricated building is made of concrete, which is manufactured under a controlled condition using mass production technology. Such production-related features provide higher quality and integrity of building components but may also increase energy use during the building embodied phase. These additional energy inputs in the manufacturing process will enhance thermal performance in return during the building operational phase, which will continuously reduce the required cooling and heating loads in the daily operations. This pay-back process is capable of trading off the energy increment or even gaining environmental benefits from a life-cycle perspective.

Table 8 Basic profile of comparison buildings

	Source	Location	Climate	Lowest (°C)	Highest (°C)	Building type	Structure
A	Present study	Chengdu, China	Subtropical	5.6	25.2	Residential	Frame shear
B	Present study	Shenzhen, China	Subtropical	15.4	28.9	Residential	Frame shear
[1]	[34]	Zaragoza, Spain	Subtropical	6.1	24	Residential	Concrete brick
[2]	[35]	Semarang, Indonesia	Tropical	26.5	28	Residential	Concrete brick
[3]	[36]	Turin, Italy	Temperate	1.4	23.6	Residential	Concrete brick
[4]	[37]	Belgian	Temperate	5.1	21.9	Residential	Concrete brick (Terraced)
[5]	[37]	Belgian	Temperate	5.1	21.9	Residential	Concrete brick (Sime-detached)
[6]	[37]	Belgian	Temperate	5.1	21.9	Residential	Concrete brick (Detached)
[7]	[37]	Belgian	Temperate	5.1	21.9	Residential	Concrete brick (No-compact)
[8]	[38]	Belgian	Temperate	5.1	21.9	Residential	Steel framed
[9]	[38]	Belgian	Temperate	5.1	21.9	Residential	Masonry frame

Table 9. Summary of relevant policies and standards in China

Area	Province	No. of polices	No. of standards
Northeast	Heilongjiang, Jilin, Liaoning	5	6
Bohai Economic Rim	Beijing, Tianjin, Hebei, Shandong	19	5
Yangtze River Delta	Shanghai, Jiangsu, Zhejiang	36	8
Southern coast	Guangdong, Fujian, Hainan	17	5
Central	Shanxi, Henan, Anhui, Hubei, Hunan, Jiangxi	22	4
Northwest	Xinjiang, Qinghai, Ningxia, Gansu, Shaanxi, Inner Mongolia	6	1
Southwest	Sichuan, Chongqing, Yunnan, Guangxi, Guizhou	9	1

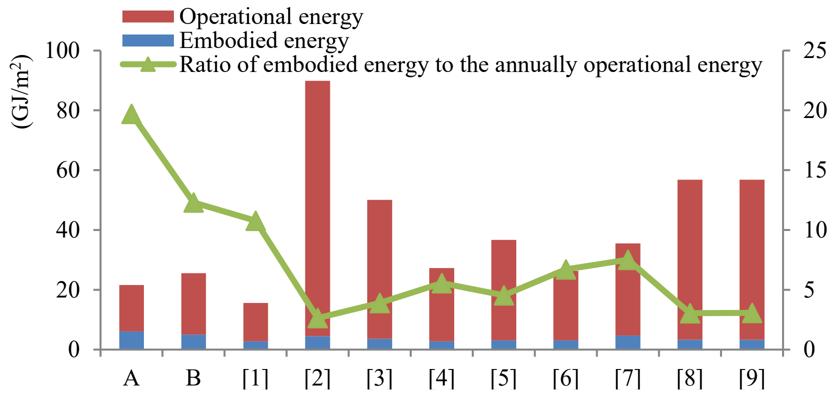


Fig. 5. Results of the comparative analysis.

5. Discussions and policy implications

This study provides a holistic understanding of the life-cycle energy use of prefabricated buildings in China. For different life cycle stages, the energy consumption behaviors of prefabricated buildings represent a number of distinctive features. In the building embodied phase, no significant difference exists between the precast construction and traditional construction methods. The embodied energy intensities of all types of buildings investigated are in the same range of value. By further examining the full process of precast construction, this finding is primarily attributed to the following reasons. First, although the prefabrication process provides a controlled condition for component replication in the offsite plant (which may minimize waste generation), the manufacturing process itself requires other resource inputs, such as using additional connecting pieces and steel bars to facilitate onsite installation and to enhance the structural integrity of prefabricated buildings. Second, the envelope of prefabricated buildings is more energy-intensive than the counterparts. Substituting reinforced concrete for bricks in traditional buildings increases energy intensity in the prefabricated façade and form.

During the operation phase, prefabricated buildings are even more energy-consuming than buildings with a brick-concrete structure in the cooling season in some cases. This finding relates primarily to the fact that a relatively moderate temperature exists in Chengdu, which leads to a higher frequency of natural ventilation during summer, thus reducing the required cooling load. However, such discrepancy may be even larger than the simulated value due to the uncertainty of the occupants' behavior. In fact, the living habit in the context of China tends to prioritize the use of natural ventilation when such manipulation can satisfy the indoor thermal comfort of people. Unfortunately, precisely simulating the occupant's behavior is difficult. This unpredictability may exaggerate the difference of the operational energy intensity between prefabricated and traditional buildings. From a spatial perspective, as a typical hot-summer and cold-winter zone in China, Chengdu has a higher required heating load in winter in comparison to Shenzhen, which is located in the hot-summer and warm-winter zone. Given the energy-efficient features of prefabricated buildings in the heating season, promoting the development of precast construction in this area is highly necessary, especially from a life-cycle energy conservation perspective. Moreover, Shenzhen is identified as a major supplier for the prefabrication sector in the surrounding regions. The relevant regulations, facilities, and services through the entire supply chain of the prefabricated housing production are more mature than in other places in China. To further explore the current development status of the precast construction at the regional level, this study comprehensively reviewed regional policies and standards associated with the industrialization in building construction (see Table 9). Extra emphases and efforts were placed on developing innovative construction technologies by the local government in the Yangtze River Delta, Bohai Economic Rim, southern coast, and central part of China. In contrast, the regulations relevant to the precast construction were still rare in the north and west of China. For example, the practice of applying prefabrication technology in the construction industry in Sichuan province still lags behind due to lack of mandatory policies and applicable standards. The findings of this study provide solid evidence and concrete foundation for the significance of prefabricated techniques in the building energy conservation, particularly for regions with a relatively colder climate. Therefore, establishing a mature construction market with a highly evolved industrialization is quite urgent and necessary in these regions, which can significantly achieve an efficient life-cycle energy reduction and management of buildings.

6. Conclusions

Considering the rapid urbanization in China, industrialization in building construction has been regarded as a key national strategy in the construction sector. The central government ambitiously desires to further improve construction productivity, building quality, labor efficiency, and project schedule by adopting prefabrication techniques in China. Therefore, an in-depth investigation of life cycle environmental benefits of prefabricated buildings is critically important. This study employs a hybrid assessment method to explore the life-cycle energy saving potential of prefabricated buildings. By conducting scenario and comparative analyses, the energy consumption features and energy reduction potential are identified. The findings of this study are as follows:

(1) The embodied energy intensities calculated by the hybrid model were 6.11 GJ/m2 and 5.04 GJ/m2 in the target prefabricated buildings, which were 13.1% and 11.0% higher, respectively, than the results obtained from the process-based model due to an extended consideration of energy use embodied in the upstream supply chain. These energy intensities were in-line with the selected comparison buildings built under traditional construction methods.

(2) During the operation phase, the results of scenario analysis indicated that the energy consumption trend was quite similar between the prefabricated and traditional buildings. Given the difference in the local climate, the annual energy consumption of the target building in Shenzhen was higher than the building in Chengdu. Such variation was primarily caused by the energy-intensive cooling process of buildings in Shenzhen due to a relatively higher average temperature in summer.

(3) The results of the comparative analysis indicated that the life-cycle energy intensities of the two case buildings were smaller than the selected comparison buildings constructed with the traditional method with the similar climate. The ratio of the embodied energy use to the annual operational energy consumption among comparison buildings implied the superiority in energy conservation by adopting prefabrication in the construction industry.

(4) The examination of policies and standards associated with the precast construction at the regional level explored that the Yangtze River Delta, Bohai Economic Rim, southern coast, and central part of China were on the frontier of industrialization in building construction; whereas the north and west of China still lag behind in terms of the mandatory policies and applicable standards.

The findings of this study provide robust evidence for the life cycle energy performance of prefabricated buildings in the Chinese context. The size of case studies for comparative and empirical analyses is not large enough to capture all types of prefabricated buildings in China. More building cases with diverse construction features and locations are expected in the future research to conduct a thorough investigation of prefabrication techniques in different contexts.

Acknowledgements

The authors wish to express their sincere gratitude to Chongqing Social Science

Planning Project (No. 2017BS30), National Key R&D Program of China (No. 2016YFC0701807, No. 2016YFC070160106, and No. 2016YFC070200504) and the Fundamental Research Funds for the Central Universities (No. 0204005201043) for funding this research. Appreciation is also due to all members of the research team for their invaluable contributions.

References

[1] GOSC , National Plan on New Urbanization 2014–2020, in: G.O.o.t.S.C.o.t.P.s.R.o. China (Ed.), 2014 Beijing, China .

[2] M.o.H.a.U.-R.D.o.t.P.s.R.o.C. MOHURD , Plan on Green Building, National Devel- opment and Reform Commission, Beijing, China, 2013 .

[3] W. Pan , A.G. Gibb , A.R. Dainty , Strategies for integrating the use of off-site pro- duction technologies in house building, J. Constr. Eng. Manage. 138 (11) (2012) 1331–1340 .

[4] V.W. Tam , C.M. Tam , S. Zeng , W.C. Ng , Towards adoption of prefabrication in construction, Build. Environ. 42 (10) (2007) 3642–3654 .

[5] L. Jaillon , C.S. Poon , The evolution of prefabricated residential building systems in Hong Kong: a review of the public and the private sector, Autom. Constr. 18 (3) (2009) 239–248 .

[6] H. Li , H. Guo , M. Skitmore , T. Huang , K. Chan , G. Chan , Rethinking prefabricated construction management using the VP-based IKEA model in Hong Kong, Con- str. Manage. Econ. 29 (3) (2011) 233–245 .

[7] W. Lu , G.Q. Huang , H. Li , Scenarios for applying RFID technology in construc- tion project management, Autom. Constr. 20 (2) (2011) 101–106 .

[8] W. Pan , A.G. Gibb , A.R. Dainty , Perspectives of UK housebuilders on the use of offsite modern methods of construction, Constr. Manage. Econ. 25 (2) (2007) 183–194 .

[9] C.Z. Li, J. Hong, C. Fan, X. Xu, G.Q. Shen, Schedule delay analysis of prefabri- cated housing production: a hybrid dynamic approach, J. Clean. Prod. (2017) . http://dx.doi.org/10.1016/j.jclepro.2017.09.066 .

[10] J. Hong , G.Q. Shen , Z. Li , B. Zhang , W. Zhang , Barriers to promoting prefabri- cated construction in China: a cost-benefit analysis, J. Clean. Prod. 172 (Suppl. C) (2018) 649–660 .

[11] C.Z. Li , G.Q. Shen , X. Xu , F. Xue , L. Sommer , L. Luo , Schedule risk model- ing in prefabrication housing production, J. Clean. Prod. 153 (Suppl. C) (2017) 692–706 .

[12] C. Mao , Q. Shen , L. Shen , L. Tang , Comparative study of greenhouse gas

emis- sions between off-site prefabrication and conventional construction methods: two case studies of residential projects, Energy Build. 66 (2013) 165–176 .

[13] L. Aye , T. Ngo , R. Crawford , R. Gammampila , P. Mendis , Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules, Energy Build. 47 (2012) 159–168 .

[14] J. Hong , G.Q. Shen , C. Mao , Z. Li , K. Li , Life-cycle energy analysis of prefab- ricated building components: an input-output-based hybrid model, J. Clean. Prod. 112 (2016) 2198–2207 .

[15] X. Zhang , F. Wang , Assessment of embodied carbon emissions for building con- struction in China: comparative case studies using alternative methods, Energy Build. 130 (Suppl. C) (2016) 330–340 .

[16] C.W. Bullard , P.S. Penner , D.A. Pilati , Net energy analysis: handbook for com- bining process and input-output analysis, Resour. Energy 1 (3) (1978) 267–313 .

[17] Y. Chang , R.J. Ries , Q. Man , Y. Wang , Disaggregated IO LCA model for build- ing product chain energy quantification: a case from China, Energy Build. 72 (2014) 212–221 .

[18] J. Guan , Z. Zhang , C. Chu , Quantification of building embodied energy in China using an input-output-based hybrid LCA model, Energy Build. 110 (Suppl. C) (2016) 443–452 .

[19] S. Joshi , Product environmental life-cycle assessment using input-output tech- niques, J. Ind. Ecol. 3 (2–3) (1999) 95–120 .

[20] S. Suh , M. Lenzen , G.J. Treloar , H. Hondo , A. Horvath , G. Huppes , O. Jol- liet , U. Klann , W. Krewitt , Y. Moriguchi ,System boundary selection in life-cy- cle inventories using hybrid approaches, Environ. Sci. Technol. 38 (3) (2004) 657–664 .

[21] G. Rebitzer , T. Ekvall , R. Frischknecht , D. Hunkeler , G. Norris , T. Rydberg , W.-P. Schmidt , S. Suh , B.P. Weidema , D.W. Pennington , Life cycle assessment: part 1: framework, goal and scope definition, inventory analysis, and applica- tions, Environ. Int. 30 (5) (2004) 701–720 .

[22] M.M. Bilec , A Hybrid Life Cycle Assessment Model for Construction Processess, University of Pittsburgh, 2007 .

[23] J. Hong , X. Zhang , Q. Shen , W. Zhang , Y. Feng , A multi-regional based hybrid method for assessing life cycle energy use of buildings: a case study, J. Clean. Prod. 148 (2017) 760–772 .

[24] H.V. Rowley , S. Lundie , G.M. Peters , A hybrid life cycle assessment model for comparison with conventional methodologies in Australia, Int. J. Life Cycle As- sess. 14 (6) (2009) 508–516 .

[25] G.J. Treloar , P.E. Love , G.D. Holt , Using national input/output data for embodied energy analysis of individual residential buildings, Constr. Manage. Econ.

19 (1) (2001) 49–61 .
[26] P. Zhao , J.-F. Tong , J.-R. Ma , The research on the system of the building material environment load index and evaluation, China Build. Mater. Sci. Technol. 13 (2004) 1–7 .
[27] J. Hong , G.Q. Shen , Y. Feng , W.S.-T. Lau , C. Mao , Greenhouse gas emissions dur- ing the construction phase of a building: a case study in China, J. Clean. Prod. 103 (2015) 249–259 .
[28] Z. Liu , Y. Geng , S. Lindner , H. Zhao , T. Fujita , D. Guan , Embodied energy use in China's industrial sectors, Energy Policy 49 (2012) 751–758 .
[29] C. Scheuer , G.A. Keoleian , P. Reppe , Life cycle energy and environmental per- formance of a new university building: modeling challenges and design impli- cations, Energy Build. 35 (10) (2003) 1049–1064 .
[30] D. Gu , Y. Zhu , L. Gu , Life cycle assessment for China building environment im- pacts, J. Tsinghua Univ. 46 (12) (2006) 1953 .
[31] P. Zhong , Study of Building Life-cycle Energy Use and Relevant Environmental Impacts, Sichuan University, 2005 (in Chinese) .
[32] S. Li , H. Li , Quantitative calculatoin of construction initial energy use in resi- dential building, J. Huazhong Univ. Sci. Technol. (Urban Sci. Ed.) 22 (4) (2005) 54–57 . [33] J. Hong , G.Q. Shen , Y. Feng , Life cycle assessment of green buildings: a case study in China, in: ICCREM 2013@ sConstruction and operation in the context of sustainability, ASCE (2013) 209–220 .
[34] I. Zabalza Bribián , A. Aranda Usón , S. Scarpellini , Life cycle assessment in build- ings: state-of-the-art and simplified LCA methodology as a complement for building certification, Build. Environ. 44 (12) (2009) 2510–2520 .
[35] A. Utama , S.H. Gheewala , Life cycle energy of single landed houses in Indone- sia, Energy Build. 40 (10) (2008) 1911–1916 .
[36] G.A. Blengini , Life cycle of buildings, demolition and recycling potential: a case study in Turin, Italy, Build. Environ. 44 (2) (2009) 319–330 .
[37] G. Verbeeck , H. Hens , Life cycle inventory of buildings: a contribution analysis, Build. Environ. 45 (4) (2010) 964–967 .
[38] B. Rossi , A.-F. Marique , M. Glaumann , S. Reiter , Life-cycle assessment of resi- dential buildings in three different European locations, basic tool, Build. Envi- ron. 51 (2012) 395–401 .