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Life-cycle energy analysis of prefabricated building components: An input–output-based hybrid model

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ABSTRACT

As an effective strategy for improving the productivity of the construction industry, prefabricated construction has attracted concerns worldwide. This study investigated the life-cycle energy use of prefabricated components and the corresponding effect on the total embodied energy use for a number of real building projects. Result showed that the life-cycle energy use of prefabricated components ranged from 7.33 GJ/m^3 for precast staircase to 13.34 GJ/m^3 for precast form. The recycling process could achieve 16% to 24% energy reduction. This study also found that apart from reusability, energy savings are also obtained from waste reduction and high quality control, saving 4% to 14% of the total life-cycle energy consumption. All these advantages can be regarded as important environment friendly strategies provided by precast construction. The linear regression analysis indicated that the average increment in energy use was nearly linearly correlated with prefabrication rate. Precast facade and form are identified as energy-intensive components compared with the conventional construction method. Therefore, the challenge lies in improving the integrality and quality of the prefabrication technique while reducing its dependence on energy-intensive materials. Besides, attention should be focused on improving the maturity of the precast market to avoid additional energy consumption during prophase investigation.

Keywords:
Life-cycle energy analysis
Hybrid analysis
Precast construction
Prefabricated component

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1. Introduction

Construction-related environmental issues have attracted concerns worldwide. To date, a series of integrated strategies, technologies, and assessment methods has been implemented in the construction field to improve the life-cycle environmental performance of buildings. One of the effective solutions is prefabricated construction, which has become increasingly important in the entire construction industry. Prefabricated construction refers to the practice of producing construction components in a manufacturing factory, transporting complete or semi-complete components to construction sites, and finally assembling these components to construct buildings (Tam et al., 2007). Compared with conventional construction technologies, prefabrication provides controlled conditions for bad weather and for ensuring quality, facilitates the compression of project schedule by changing workflow sequencing, and reduces the waste of materials (Li et al., 2014). Thus, prefabricated construction does not only reduce waste, noise, dust, operation cost, labor demand, and resource depletion, but also improves the quality control process, as well as ensure the health and safety of workers (Jaillon and Poon, 2009; Li et al., 2011; Lu et al., 2011). Moreover, adopting green technologies facilitates the use of materials that can be easily reused and recycled during possible future demolitions, which establishes a positive public image for contractors (Wang et al., 2014). Meanwhile, China is experiencing a rapid development period in urbanization. Based on an average annual increase rate of 0.8%, the urbanization rate in China is expected to reach a historic high of 51.5% by the end of "The Twelfth Five-Year Plan." Therefore, promoting the incorporation of information technology construction into industrialization is a critical issue in the development of urbanization in China, which has been emphasized through a series of national guidance and policies, including the Report to the Eighteenth National Congress (CPC, 2012), National Plan on New Urbanization 2014-2020 (GOSC, 2014), and Plan on Green Building. Beijing (MOHURD, 2013). Consequently, a long-standing and considerable demand for prefabrication exists because of industrialization during rapid urbanization, which is bound to result in large energy demands. Therefore, examining the energy-saving potential of prefabricated construction is necessary.

Life-cycle assessment (LCA) has been extensively used as a comprehensive environmental effect assessment method to help alleviate energy-related damages caused by the construction industry. In general, previous LCA studies in the construction industry have focused on concerns in two directions: building materials and components (BMCs) and whole buildings (WBs). BMC-related studies have mainly focused on the life-cycle analysis of energy consumption and environmental emissions for certain building products (Azari-N and Kim, 2012; Kim, 2011; Kosareo and Ries, 2007; Lopez-Mesa et al., 2009; Su and Zhang, 2010). Meanwhile, studies relevant to WBs have focused on holistically understanding the relative environmental load of each life-cycle stage during the entire life span of buildings (Ding, 2007; Huberman and Pearlmutter, 2008; Scheuer et al., 2003; Treloar et al., 2000a; Verbeeck and Hens, 2010). However, studies have rarely focused on concerns regarding LCA of innovative construction methods such as prefabrication technology. Aye et al. analyzed the embodied energy use of prefabricated building modules using the hybrid LCA analysis method (Aye et al., 2012). They found that although prefabricated steel buildings resulted in a significant increase in embodied energy, their reusability of materials represented up to nearly 80% of the savings in embodied energy, which implied high energy-saving potential from this construction method. Mao et al. conducted a comparative analysis between prefabrication and conventional construction in terms of greenhouse gas emissions by adopting process-based LCA (Mao et al., 2013). They pointed out that semi-prefabrication could produce less greenhouse gas emissions compared with the conventional method.

Given the increasingly important status of prefabrication in future applications in the construction field, assessing energy improvements from adopting this innovative construction method has become critical. Despite the contribution of previous studies to the body of knowledge on the prefabrication research domain at the project level, a systematic analysis of the life-cycle energy performance of a certain type of prefabrication, particularly in the context of China, is nonexistent. Such adoption is a key concern among various stakeholders in the construction process and is expected to influence the delivery of prefabricated buildings significantly. However, given that prefabrication is still at the very beginning in China, the detailed process data for the construction phase especially associated with the supply chain of prefabrication are commonly unavailable. Therefore, this study employed hybrid LCA model to calculate the embodied energy consumption for such innovative and specific construction technology in the construction industry.

Consequently, to understand the environmental benefits of adopting prefabricated components in construction sites, we develop an input–output-based hybrid LCA analysis framework to facilitate the assessment of the life-cycle energy use of a certain type of prefabrication, as well as to validate the final results by applying them on eight real precast buildings. Moreover, the environmental benefit obtained from adopting prefabrication for a certain building is also investigated. The specific objectives for achieving this goal are

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outlined as follows:

(1) To conduct life-cycle energy analyses for six major types of prefabricated components adopted in the Chinese construction industry;

(2) To investigate energy savings resulting from the reusability, high quality, and waste reduction of prefabricated construction; and

(3) To identify the environmental benefits obtained from adopting prefabrication in real building projects.

2. Overview of LCA approaches

In general, the modelling frameworks used in LCA practice can be classified into two different groups: attributional and consequential LCA, where the computational process and research purpose are different (Commission, 2010). The selection of LCA modelling framework is to large extent dependent on the proposed application context and study goals. More specifically, the consequential LCA is a change-oriented computational model where the focus of concern is to measure the effects of the analyzed decision in the investigated system on other economy systems. It aims to predict the consequences of a specific decision based on a dynamic techno sphere with rebound effect rather than models actual process. The attributional life cycle model measures the potential environmental impacts in life cycle stages for a target product based on static techno sphere. This type of LCA utilizes observed, reality-based, and measurable data to quantify the environmental contributions from all relevant processes in the studied system for practical reasons. Both producer-specific inventory data and average data are the primary data sources for the attributional modelling. In summary, consequential LCA is more appropriate in measuring structural changes with large-scale consequences and impacts of the economy while the attributional LCA is prior in assessing micro-level changes of actual processes in the different life cycle stages. In fact, according to Monteiro and Freire (2012), attributional LCA is more preferred for the construction related studies. By employing both approaches to evaluate the environmental impact of an office building , Vieira and Horvath (2008) also argued that the effect of modelling selection is not significant on final results. Given that the purpose of this study is to quantify the energy flows embodied in the goods and services input for manufacturing different types of prefabricated components, the most appropriate modelling framework is attributional LCA.

The computational models in the attributional LCA mainly include process-based model, input-output (I-O) model, and hybrid model. Process-based analysis quantifies the detailed resource and energy consumption from direct input of the manufacturing process to the indirect input with significant environmental contributions in the upstream and downstream process of the supply chain. Although the case-specific process data to some extent improve the accuracy of the calculation result, this model is time and cost-intensive. In addition, the intuitive determination of system boundary is subject to truncation errors and thereby results in variations (Rowley et al., 2009).

I-O analysis measures the resource consumption and environmental impact with the aid of sectoral monetary transactions in the national or regional based input-output table, which takes all infinite sectoral interdependencies in the modern economy into consideration. It minimizes the time and cost intensity for data collection by using public available data. However, this model calculates the result based on a higher level of aggregation which may be invalid for a particular product due to lack of specificity. Moreover, it also suffers from the inherent computational problems including proportionality, homogeneity, and the outdated input-output data (Treloar et al., 2004).

To eliminate the truncation errors and guarantee the specificity in environmental assessment process, hybrid analysis has been developed to provide more accurate assessment of environmental loadings. In general, three models have been commonly used in previous literature: tiered hybrid, input-output (I-O) based hybrid, and integrated hybrid model. Tiered hybrid model was firstly proposed by (Bullard et al., 1978). The scientific basis of this model is to employ process-based data at important lower order upstream processes, usage phase, and downstream processes whilst supplement I-O data for indirect impacts with negligible contributions from higher order upstream process. Such manipulation to large extent maximizes the accuracy and reliability of calculated results. However, the direct integration of process and I-O model may probably result in double counting. It is therefore important to subtract the process-based flows from the I-O model to represent only the cut-off inventory. Although the application of I-O derived data improve the completeness of the system boundary in the upstream process, truncation errors may still arise in use and downstream phases due to the limitations in data availability for details processes. More importantly, the interface of system boundaries between process-based and I-O based model is flexible, which depends on the research purpose, accuracy requirement, and time restrictions.

I-O based hybrid model is a top-down method which aims to further modify or disaggregate the direct supply chain of the sector in the I-O table that the product being investigated belongs. It allows the incorporation of the case-specific process data into I-O direct coefficient matrix, which provides the analyst with access to detailed process information within complete system boundary. However, according to Joshi (1999) and Suh et al. (2004), as the basic produce for I-O based hybrid analysis, the disaggregation is restrained due to the overdependence of the detailed data of input and sale information for the new hypothetical sector. Treloar (1997) proposed I-O based hybrid approach in a different way by substituting the most energy intensive paths with the process-based inventory data. A number of studies have been conducted under this hybrid framework (Crawford, 2008; Crawford and Pullen, 2011; Lenzen and Treloar, 2002; Treloar et al., 2000b; Treloar et al., 2004).

Integrated hybrid model integrates the I-O model with matrix representation of the physical process flows of a particular product, which makes the computational framework consistent (Bilec, 2007). It incorporates the physical quantities of process-based data into the I-O model directly. However, because of its higher requirement in detailed data, it is time and cost intensive and more complicated to practical application.

In summary, tiered and I-O based hybrid model are more dependent on budget information because only monetary value can be modeled in the I-O analysis for further environmental effect assessment. The results obtained from these two approaches are in the higher level of aggregation because the computational process is based on the sectoral framework derived from I-O model. In contrast, integrated model is prioritized to incorporate physical unit and monetary transactions. According to Suh et al. (2004), it is difficult to determine the most suitable hybrid model intuitively in a certain application, which is to large extent based on the actual data availability and accuracy requirement. In this study, the material-related process data are available whereas the labor and other service inputs are rare due to reporting limitations and confidentialities in upstream suppliers. Therefore, to avoid the truncation errors and alleviate the constraint in detailed data collection in the upstream process, the I-O based hybrid model is employed to guarantee the system completeness and product specificity.

3. Methodology

3.1 Scope, system boundary, and functional unit

The objective of this study is to employ I-O based hybrid model to analyze the life cycle energy consumption of typical prefabricated components in China. Given the environmental benefit and large potential in future application, it is critically important to study energy improvements from adopting prefabrication in the construction sector. Prefabricated construction is defined as an off-site construction method to manufacture, transport, and assemble construction components for building construction. Since it is still in the early stage in China and characterized by its industrialized production process, several representative samples could be easily identified and further studied. Base on the information collected from field survey, six types of prefabricated components with typical structural and construction pattern are identified as the representatives in construction practice of China.

By combining process and I-O based model, the system boundary for the energy quantification covers the whole life cycle of the prefabricated components, including prefabrication manufacturing, transportation, on-site assembling, and recycling in the demolition phase. More importantly, energy use embodied in the additional processing during demolition phase that satisfies the quality and shape for the intended function of recycling materials has also been quantified.

The basic functional unit for the energy quantification is per cubic meter of energy consumption of the prefabricated component (GJ/m^3). Furthermore, to reflect the energy impact of adopting prefabricated components on real building projects, other function units have been also elaborated. The additional energy use embodied in the prefabrications adopted for each project has been quantified (GJ) and then was further divided by total gross floor area to represent the incremental energy consumption on a per square meter basis (GJ/m^2).

3.2. Input–output-based hybrid life-cycle energy analysis framework

3.2.1. Prefabrication manufacturing (E_H)

An input–output-based hybrid LCA method is proposed to explore energy use embodied in the prefabrication manufacturing process. According to Treloar (1997) and Crawford (2008), I-O based hybrid model was designed to substitute the process-based data for the most energy intensive paths that were extracted from the I-O analysis. Treloar et al. (2001) summarized the basic procedures for this hybrid model, including:

(1) Calculation of the initial total environmental burden of the product being studied by using I-O analysis;
(2) Disaggregation of the complex upstream process based on I-O analysis and determination of the key paths with significant environmental impact;
(3) Modification of key paths with both delivered quantity and energy intensity data derived from process-based inventory;
(4) Subtraction of the corresponding I-O value of the key paths represented in the process inventory from the initial total environmental impact calculated by I-O model;
(5) Integration of modified energy paths derived from process-based analysis into remaining unmodified I-O framework.

The above entire process can be expressed as a series of equations. The result of the total energy consumption derived from the I-O analysis can be expressed as:

$$E_{I-O} = F(I-A)^{-1}V \quad (1)$$

where E_{I-O} represents the total embodied energy consumption from the final demand $V=\left[v_i\right]_{n\times 1}$, $F=\left[f_i\right]_{1\times n}$ is a vector that shows the direct energy intensity of each sector, I is the identity matrix, and $A=\left[a_{ij}\right]_{n\times n}$ represents the inter-industry requirement coefficient matrix.

The algorithm for further disaggregating the I-O model and extracting the key paths from the upstream process has been discussed in more detail by Treloar (1997) (For more detailed illustrations please refer to the supporting information). Consequently, these key paths with significant environmental contributions need to be further modified by delivered quantity and energy intensity data derived from process-based inventory. In fact, case-specific process data should include the quantity and energy intensity information derived from process-based model relevant to basic materials. The modified value of basic materials can be expressed as follows:

$$E_P = \sum_{i}^{k} \varepsilon_i q_i \quad (2)$$

where ε_i is the embodied energy intensity for primary material i, and q_i is the delivered quantity of material i used in the production site, k represents the types of basic materials.

Given the fact that the I-O derived value for primary materials are mutually exclusive, and process-based embodied energy value is more accurate than the I-O derived data, it is therefore prossible to substitute the process-based inventory data for I-O derived value because the substitution at the path level may not result in the unwanted iterated effect on the rest of the I-O model by running the I-O analysis (Treloar et al., 2001). Furthermore, to avoid double counting, the I-O derived value of the primary materials should be subtracted from the initial total environmental impact. Then the reminder of I-O model represents only the part being insignificant and is thereby appropriate to add to the case-specific process data. The substitution process can be expressed as:

$$E_H = E_P + E_{I-O} - E_{I-O}^{P} \qquad (3)$$

where E_P is the process-based embodied energy value of basic materials, E_{I-O}^{P} is the I-O derived value of energy paths representing the basic materials. Consequently, E_H represents a holistic manner for comprehensively considering the product specificity and system completeness.

3.2.2. Transportation (E_T)

Transportation from an off-site factory to the construction site is an important process in precast construction. Unlike that in conventional building material transportation, prefabrication logistic requires a careful load–unload control process, as well as additional protection and fixation, to avoid possible damage during transportation. According to the interviews conducted in this study, a high-load truck is commonly used as the major vehicle type for transportation, particularly when considering the large volume and weight of prefabricated components. Secondary data based on literature review are collected to assess embodied energy use during the transportation process.

3.2.3. Assembly on the construction site (E_C)

Additional construction techniques and equipment have been used to facilitate on-site assembly works for prefabricated components, including relevant construction-machine use, horizontal and vertical transportation, and lifting works associated with the precast construction process. However, separating energy consumption related to precast construction from the total energy used in a construction site is difficult for researchers. Therefore, pure input–output analysis is performed to estimate direct energy use from on-site assembly works for prefabricated components.

3.2.4. Reuse and recycle in the demolition phase (E_R)

In general, a limited number of studies have focused on energy use during the demolition process (Chen et al., 2001; Kua and Wong, 2012; Wu et al., 2012), particularly in the context of China. Relevant studies are restricted not only by the variations in customer requirements, contractor preferences, and market regulations (Scheuer et al., 2003), but also by the limitations in the availability of public documents and building demolition data. Energy consumption associated with building end-of-life decommissioning is relatively small compared with the life-cycle energy use of a building. However, the energy-saving potential of recycling and reusing is considerable and cannot be ignored during the entire life cycle of a building. Therefore, an in-depth analysis of energy savings from reusing and recycling activities in the building demolition phase was conducted in this study.

According to the literature review (Gao et al., 2001; Tam and Tam, 2006; Thormark, 2006), material-recycling processes can be categorized into two types, namely, reusing and recycling materials (Table 1). Given the features of the materials and the attributes of the prefabricated components used in the present study, steel was recycled using mixed recycling methods, whereas concrete and aluminum were recycled as raw materials with suitable processing.

Table 1

Material recycling methods during the building demolition phase.

Recycling method	Definition	Materials included
Reuse	Reuse materials without further processing	Steel
Recycle	Recycle materials as raw materials with suitable processing	Steel, concrete, aluminum

Note: This table was established in the studies of Gao et al. (Gao et al., 2001) and Thormark, (Thormark, 2006).

Traditionally, the energy-saving potential from the recycling process can be expressed as follows:

$$E_R = \sum_{i}^{k} \varepsilon_i q_i (\alpha_i + \beta_i) \,,$$

where ε_i is the energy intensity of material i; q_i is the quantity of material used by i;

and α_i and β_i represent the reuse and recycle rates, respectively.

In terms of the complete life cycle (that is, from cradle to grave), recycled materials must be processed further to satisfy the quality, intensity, shape, and size requirements of an intended function. Therefore, additional energy consumption is required in material recycling processes, such as material disassembly and secondary processing. Therefore, considering additional energy use is necessary. The formula can be expressed as follows:

$$E_R^{'} = \sum_i^k \varepsilon_i q_i \alpha_i + q_i \beta_i (\varepsilon_i - \gamma_i),$$

where γ_i represents the energy intensity of the secondary processing.

Table 2

Recycle and reuse rates for primary building materials.

		Concrete		Steel		Aluminum	
		Recycle	Reuse	Recycle	Reuse	Recycle	Reuse
Thormark (2001)	Reference scenario	20%	1%	65%	0%	65%	0%
	Maximum recycle scenario	90%	1%	95%	0%	95%	0%
	Maximum reuse scenario	80%	10%	75%	20%	95%	0%
Zhang et al. (Zhang et al., 2006)	Average level	10%		90%		90%	
Present study		60%	1%	80%	10%	80%	0%

A number of works have discussed the recycle and reuse rates during the building demolition phase. Blengini indicated that over 99% of demolished materials were converted into recycled materials; only a few plastic and insulating materials ended up in landfills (Blengini, 2009). Zhang et al. discussed the reclaimable rate of several building materials in the context of China (Zhang et al., 2006). Table 2 shows the reuse and recycle rates of different types of primary building materials from previous studies. Based on the different scenarios presented by Thormark (Thormark, 2001) and Zhang et al. (Zhang et al., 2006), the recycle rate used in the present study is provided in the last row of the table. In addition, Gao et al. carefully estimated the entire process involved in the energy input for recycling materials, such as material disassembly and secondary processing (Gao et al., 2001). Thus, we employed their research findings as the energy input for recycling.

Although the quality of most materials decreases through recycling and during their life span, the problem of recycling frequency will not be discussed in this study because of the main objective and system boundary of this study.

The life-cycle energy intensity (MJ/m^3) of a prefabricated component can be expressed as follows:

$$E = E_H + E_T + E_C - E_R \, . \tag{4}$$

3.3. Data collection and processing

The latest available input–output table (2010) with 41 sectors published by the Chinese National Bureau of Statistics was adopted in this study (NBSC, 2011). Sectoral direct energy input data were obtained from the China Statistical Yearbook 2011 and the Chinese Energy Statistical Yearbook 2011. In general, the input–output table compiled by the National Bureau of Statistics is specific on detailed monetary flow data. The table reflects the economic network and linkage among different sectors. However, the direct energy input data were collected at an aggregate level, and thus, the availability of direct energy use data, which specifically matched sector classification, functioned as a constraint. Consequently, this study disaggregated energy consumption data to match the input–output table under the assumption that energy use among sub-sectors was proportional to their economic output; hence, all economic information could be retained.

In addition, because the process-based inventory data are measured in the physical quantity whilst the I-O model quantifies the environmental impact in the monetary flow, it is therefore necessary to collect price data for basic materials to keep the consistency between two modelling systems. The price information from China construction cost network and Chang et al. (2014) has been used as the representative price for primary building materials. In addition, the price used in suppliers documents is a comprehensive or retail price which contains the retailer's profit and other additional expenses such as the transportation fee. In contrast, the inter-sectoral purchase of products in the I-O model is measured based on basic cost (e.g. the direct purchase price). Therefore, the data assumption by Chang et al. (2014) that the basic cost of materials was equal to be 90% of the comprehensive prices has been adopted to address such inconsistency.

Finally, field survey was also conducted to collect data, including site investigation and face-to-face interview with clients, contractors, prefabrication suppliers, and other stakeholders involved in the target project. The qualitative data collected from field survey through case studies can serve as first-hand data as well as an effective method to understand energy difference between prefabricated and conventional construction. The investigated information of a target building project included building type, location, gross floor area, type and volume of the adopted prefabrication components, and prefabrication rate. All the

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investigated buildings were residential buildings.

4. Life-cycle energy analysis of prefabricated components

4.1. Result analysis

The aforementioned hybrid LCA was employed to combine the specific process-based data of primary materials with social average manufacturing data through input–output analysis. System boundary completeness and result accuracy were ensured by the hybrid LCA analysis to a large extent.

Given that detailed process data are critical for the next analysis, studying material energy intensity by considering the current production technology and supply chain in China is important. However, studies on the life cycle energy intensity of primary building materials are limited in China. In particular, authoritative and systematic data are lacking. The Chinese Life Cycle Database (CLCD) and eBalance 4.7 LCA software developed by Sichuan University has been reviewed. In addition, a number of cases that focused on the energy intensity of primary building materials were also collected in this study through literature review to identify the advisable energy intensity that would be used in the investigation (Table 3).

Table 3

Process-based energy intensities of primary materials collected from China.

	Unit	Li et al. (2013)	Zhang et al. (2009)	Gu et al. (2006)	Zhao et al. (2004)	Zhong (2005)	Yang (2009)	eBalance (2015)
Concrete	GJ/m^3	1.6			1.6	1.6	2.5	1.6
Cement	GJ/t	5.5	6.8	5.5	5.5	5.3	7.8	2.2
Steel	GJ/t	29-32.8	34.5	29	29	26.5	56.6	22
Glass	GJ/t	16	19.9	16	16	17.6	14.1	16
Aluminum	GJ/t	180		180	180	421.7		110
Polystyrene	GJ/t			117	117		90.3	83
Ceramic tiles	GJ/t	15.4		15.4	15.4	29.4		
Brick	GJ/t	2	2.1		1.2–2.0	2	2	4.0

As shown in Table 3, although the energy intensity for a certain type of material is fluctuant in some cases, the result remains similar. This condition demonstrates the reliability of different studies. A detailed analysis of these case studies further exhibits that local production technology, particularly the specific production technique selected for the manufacturing process, also has a direct effect on energy intensity value. Therefore, previous findings in context of China were considered. The energy intensities of different materials and the corresponding production techniques assumed in the current study are listed in Table 4. The China Building Material Academy compiled the energy intensities for several typical building materials based on statistical data collected from the building material management department and the National Bureau of Statistic of China. Thus, this compilation can be regarded as a major source and reference in investigating building-material energy intensity in China.

Table 4

Energy intensities and production techniques of major building materials.

Material	Unit	Features	Reference	Embodied energy intensity (GJ/unit)
Concrete	m^3	• C30	Shuai et al. (Shuai et al., 2009)	1.76
Cement	T	• Ordinary Portland cement 42.5 • Pre-calcining	Gong (2004)	3.18
Glass	m^2	• Float glass • 2 mm		0.12
Steel	T	• Cold-rolled primary steel	Gu et al. (Gu et al., 2006)	29
Polystyrene	T	• General purpose polystyrene • Average level		117
Aluminum	T	• Average level	Zhao et al. (Zhao et al., 2004)	180
Ceramic tiles	T	• Average level		15.4
Brick	T	• Clay brick • Average level		2.0

Given that the energy intensity of concrete increases with its strength, this study used 1.76 GJ/m^3 as the energy intensity of C30 concrete, the major type of concrete used in China (Shuai et al., 2009). The selected production technique and the type of cement produced influence the energy intensity of cement. A major type of cement, that is, ordinary Portland cement 42.5, which is produced through the pre-calcining process (PCP) with an energy intensity of 3.18 MJ/kg, has been selected in this study (Gong, 2004). Similarly, cold-rolled primary steel (the main type of steel used in the prefabrication process), float glasses that were 2 mm thick, and general purpose polystyrene were identified as the primary materials used in the prefabrication production process with corresponding energy intensities of 29, 0.12, and 117 MJ/kg, respectively.

Given the material inventory collected through field survey for the six types of prefabricated components, concrete and steel are the major materials used in prefabrication manufacturing (Table 5). Other materials, such as aluminum and polystyrene, are only adopted in constructing external walls for the pre-installation of windows and thermal insulation.

Table 5

Material inventory for the six major prefabricated components.

	Unit	PC	PCF	Slab	Balcony	Staircase	Panel
Concrete	m^3	0.9	0.98	0.84	0.84	0.84	0.84
Steel	kg	273	240	152	316	144	186
Glass	m^2	1.5	1.5				
Aluminum	kg	6.51	6.51				
Polystyrene	kg	4.28	4.28				
Ceramic tile	kg	100	100				

Note: The budget information of material inventory for prefabricated components has been collected through the bill of quantities and documents provided by clients through field survey. The prices information in section 3.3 has been used to transfer the monetary value into physical unit.

Based on the input–output-based hybrid LCA analysis, embodied energy use in different phases is provided in Table 6. The results show that the hybrid result of the manufacturing process ranges from 8.70 GJ/m^3 to 16.41 GJ/m^3, which is higher than that of the pure input–output analysis (5.84–9.83 GJ/m^3). This result indicates that the input–output-based hybrid analysis is crucial to guarantee the completeness and reliability of the final result. Embodied energy use in transportation and on-site construction process is negligibly small compared with those of other processes. The recycling process exhibits a large energy-saving potential. This process reduces over 50% of the total embodied energy consumption. Even if the additional energy input from the secondary processing is considered, the recycling process still exhibits a reduction potential ranging from 16% to 24%. Physically, substituting virgin products by reusing and recycling materials can reduce embodied energy consumption in the new product manufacturing process, which provides considerable environmental benefits. Thormark found similar results in terms of recycling potential (Thormark, 2006). He pointed out that energy savings from material recycling varied from 34% to 50% of total material energy use, which is consistent with the finding of the present study. The life-cycle energy use of the six major prefabricated components ranges from 7.33 GJ/m^3 for precast staircase to 13.34 GJ/m^3 for precast form. Prefabricated building envelope (precast form and facade) consumes more energy than other types of prefabricated components.

Table 6

Life-cycle energy use of the six major prefabricated components (GJ/m^3).

	PC	PCF	Slab	Balcony	Staircase	Panel
Manufacturing (Input–output analysis)						
• Initial pure input–output analysis ①	7.96	9.83	8.10	8.03	5.84	6.11
• Specific process-related input–output analysis ②	4.41	5.44	3.82	3.84	2.79	2.92
Subtotal ③=①−②	3.56	4.39	4.28	4.19	3.05	3.19
Manufacturing (Process analysis)						
• Specific process-based result ④	12.84	12.02	5.89	10.64	5.66	6.87
Manufacturing (Hybrid analysis ③+④)	16.39	16.41	10.17	14.83	8.70	10.06
Transportation* ⑤	0.18	0.19	0.15	0.16	0.15	0.16
On-site construction ⑥	0.40	0.49	0.40	0.40	0.29	0.31
Recycling ⑦	−9.03	−8.25	−4.87	−9.15	−4.66	−5.76
Recycling (Consider processing) ⑧	−3.96	−3.56	−1.76	−3.70	−1.66	−2.16
Life-cycle energy use (③+④+⑤+⑥+⑦)	7.94	8.84	5.85	6.24	4.48	4.77
Life-cycle energy use (Consider processing ③+④+⑤+⑥+⑧)	13.01	13.53	8.96	11.69	7.48	8.37

Note: The energy intensity of the transportation process is calculated under the assumption that the distance from the off-site factory to the construction site is 100 km.

4.2. Energy analysis between precast and conventional construction

Compared with conventional construction techniques, prefabrication construction provides controlled conditions for bad weather and for ensuring quality, as well as facilitates the compression of project schedules by changing workflow sequencing. These advantages significantly improve the performance of the entire construction industry. However, the environmental benefits of prefabrication construction and its superiority in terms of energy savings are rarely studied. Therefore, investigating the environmental improvement potential associated with the precast process is important.

Table 7 shows the differences in energy use between precast and conventional construction for six typical building components. A considerable energy increase was observed for precast facade and form because of the change in major materials in conventional construction. In China, blocks and bricks have been used extensively as the primary materials for non-structural external wall construction instead of reinforced concrete. Such materials cannot only satisfy the integrality and quality requirements of a building envelope but also provide cost savings. By contrast, reinforced concrete is the major building material used in precast slab, balcony, staircase, and air-conditioning panel for both construction methods. Based on the wastage rate from previous studies (Blengini, 2009; Lu and Yuan, 2013; Poon et al., 2001; Tam et al., 2007) (Table 8), the energy savings from waste reduction are from 0.32–0.81 GJ/m^3. Moreover, the improvement in quality control from adopting prefabrication provides energy reduction through easy maintenance. However, directly evaluating such energy savings based on uncertainties during the operation phase is difficult. Thus, this study

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indirectly calculated energy reduction according to the expenses incurred during the maintenance process, which were estimated based on the experience of the interviewees. The overall energy savings from waste reduction and ease of maintenance are significant for prefabrication and account for 4% to 14% of the total embodied energy consumption. The application of prefabricated components, except precast facade and form, has a positive effect on energy saving. Despite the energy savings from waste reduction and ease of maintenance, precast facade and form still consumed more energy than conventional construction because of the energy embodied in reinforced concrete for precast external walls, which ranged from 7.42–8.17 GJ/m^3 when the additional energy input embodied in secondary processing was considered. In summary, the net environmental gain from ease of maintenance and waste reduction is significant for precast slab, balcony, staircase, and air-conditioning panel, but still negligibly small for precast facade and form.

Table 7

Energy use differences between precast and conventional construction (GJ/m^3).

	PC	PCF	Slab	Balcony	Staircase	Panel
Life-cycle energy use	7.94	8.84	5.85	6.24	4.48	4.77
Life-cycle energy use (Consider processing)	13.01	13.53	8.96	11.69	7.48	8.37
Virgin construction materials	Block	Block	RC	RC	RC	RC
Energy use embodied in virgin materials	5.23	5.00	-*	-	-	-
Waste reduction potential by weight	10%	10%	7.8%	7.8%	7.8%	7.8%
Energy saving of waste reduction	0. 32	0. 32	0.44	0.81	0.42	0.52
Ease of maintenance	0.04	0.04	0.07	0.06	0.04	0.00
Incremental energy use by volume	2.35	3.48	−0.51	−0.87	−0.46	−0.52
Incremental energy use by volume (Consider processing)	7.42	8.17	−0.51	−0.87	−0.46	−0.52

Note: Based on the similarity of construction technologies and materials use, this study assumed that slab, balcony, staircase, and panel consumed the same embodied energy in conventional construction as in the prefabricated process.

Table 8

Waste rate of building materials.

	Conventional construction			Prefabrication
	Blengini (Blengini, 2009)	Poon et al. (Poon et al., 2001)	Tam et al. (Tam et al., 2007)	
Concrete	7%	3%–5%	4%–7%	0.5%–3.5%
Steel bar	7%	1%–8%	3%–8%	0.2%–4%
Timber	7%	5%–15%	4%–23%	0.6%–12%
Block/brick	10%	4%–8%	5%–8%	0.6%–4%

5. Effect on total embodied energy consumption of buildings

This section aims to analyze the effect of adopting prefabricated components on embodied energy consumption in real building projects. The basic profile of the investigated building projects includes building type, structure, gross floor area, types and volume of the adopted prefabricated component, and prefabrication rate (Table 9). This section shows that building type and structural characteristics are the same among the eight cases, which implies that the eight building projects are available for further comparison based on their similarities. Meanwhile, other building profiles that may affect the prefabrication rate and their embodied energy consumption, such as building size and the volume of prefabricated components, are distinguished among the eight cases. In general, the prefabrication rate describes the ratio of the adopted prefabrication volume to the total volume of the materials used in the whole building. As shown in Table 1, the size of the building project varies and ranges from 6890 m^2 to 38352 m^2 with prefabrication rates ranging from 15% to 59%. These diversities can further explore the energy effect from the changes in prefabrication rate, as well as the selection of prefabrication combination, on the total embodied energy consumption of each building. In this empirical analysis, the net energy saving is given by the difference between impact caused by prefabrication manufacturing, transportation, onsite construction, and second processing and avoided impacts due to the recycle process, substitution of virgin building materials, waste reduction, and ease of maintenance processes (Section 4.2).

Table 9

Profiles of the eight building projects.

		Sichuan			Shanghai		Shenzhen		
		P1	P2	P3	P4	P5	P6	P7	P8
Building basic information	Building type	R	R	R	R	R	R	R	R
	Structure	FSS	FSS	FSS	FSS	FSS	FSS	FSS	FSS
	Gross floor area (m^2)	7770	6890	38352	7039	9467	28522	13600	8000
Prefabrication techniques	Volume of prefabrication (m^3)	933	1250	2891	804	1089	1740	1483	1254
	Prefabrication rate (%)	41	59	20	44	40	15	25	36
	Precast facade	850	769	0	415	0	1296	795	557
	Precast form	0	0	0	0	811.2	0	0	0
	Semi-precast slab	0	400.5	2240	265	0	0	463	574
	Precast balcony	27.5	54.7	498	74	166.6	301	138	82
	Precast staircase	32.0	25.9	153.4	36	89	142	87	41
	Precast air-conditioning panel	23.5	0	0	7	21.8	0	0	0
Energy analysis	Average energy use per m^3 (GJ/m^3)	12.7	11.5	9.4	11.3	12.7	12.3	11.3	10.9
	Incremental energy use (GJ)	6256.1	5442.2	−1646.2	2859.6	6430.3	9289.1	5502.7	3750.0
	Average incremental energy use per m^2 (GJ/m^2)	0.81	0.79	−0.04	0.41	0.68	0.33	0.40	0.47

Note: Prefabrication rate reflects the level of prefabrication measured according to concrete volume.

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FSS represents frame shear structure.

According to Table 9, the average energy use of a prefabricated component is nearly similar in each case, in which the average is approximately 11 GJ/m^3. Compared with a building built using the conventional construction method, the prefabricated building has consumed more energy during the embodied phase, except Project 3 (P3). The incremental energy use for each case ranges from 2859 GJ to 9289 GJ, which is equal to 0.33 GJ/m^2 to 0.81 GJ/m^2. A close examination of P3 confirms that adopting semi-precast slab, precast balcony, staircase, and air-conditioning panel can achieve less embodied energy consumption, whereas using precast facade and form increases the embodied energy consumption of buildings.

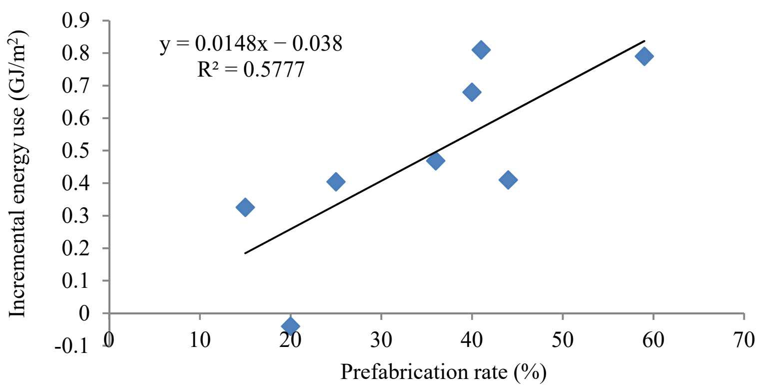

Fig. 1. Linear regression analysis between prefabrication rate and incremental energy use.

Linear regression analysis has been conducted to determine the relationship between prefabrication rate and incremental energy use from adopting the prefabrication approach. As shown in Fig. 1, average incremental energy use is nearly linearly correlated with prefabrication rate. With the improvement of prefabrication rate, incremental energy also increases, which implies that energy saving is negatively affected during the embodied phase of building prefabricated construction.

To further explore the effect of adopting the prefabrication approach on incremental energy use, scenario analysis is conducted to improve understanding on the sensitivity of prefabrication rate and prefabrication combination to incremental energy consumption. Four scenarios are organized, as shown in Table 10. Scenarios 1 and 2 focus on the effect of prefabrication rate, assuming that the rate is increased and reduced by 10% for each case, respectively. The other two scenarios investigate the effect of prefabrication combination to examine the effect of the change in the relative proportion of different prefabrication types. Scenario 3 is organized under the assumption that only precast facade and form are adopted with equal proportions of 50% each to measure the change in incremental energy use resulting from adopting the precast building envelope. Based on the preceding discussions, such type of prefabrication is identified as the major contributor to the increase in embodied energy. Scenario 4 aims to examine the energy-saving potential from the other four types of prefabricated components, assuming that the proportion of each type is equal to 25%. The result of the scenario analysis is provided in Fig. 2. An increase or reduction of 10% in the prefabrication rate leads to a relative change in incremental energy use from 24% to 65%. Precast building envelope, such as precast facade and form, is sensitive to incremental energy use. In Scenario 3, the relative change ranges from 16% to 160%. Meanwhile, the other types of prefabricated components are environment friendly because of the energy benefit obtained from high-quality control and waste reduction.

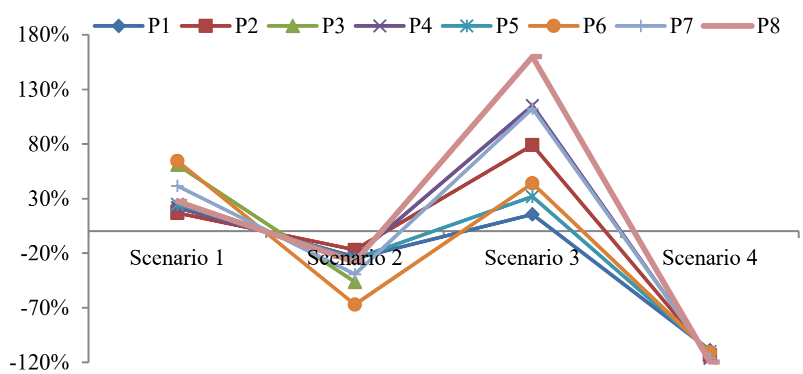

Fig. 2. Result of the scenario analysis.

6. Discussions

Compared with the results of the pure input–output analysis and the process-based model, the result of the input–output-based hybrid LCA model is more accurate because the system boundary is complete and specific process data are incorporated. In general, the result of the hybrid model is over 1.5 times that of the results of the pure input–output model and the process model in the present study, which further illustrates the importance of considering the

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truncation error and specific process data. During the recycling process, this study considers the energy input of secondary processing. The result indicates that disregarding such energy consumption may exaggerate the environmental benefits obtained from the recycling process to a certain extent. In fact, this study found that apart from reusability, energy savings are also obtained from waste reduction and high quality control. All these advantages can be regarded as important environment friendly strategies provided by precast construction. In the life-cycle energy analysis of prefabricated components, precast facade and form, which are designed for the external walls of buildings, are identified as energy-intensive components compared with the conventional construction method. The change in virgin material from block-concrete to reinforced concrete results in an increase in energy in the prefabricated building envelope. Therefore, the challenge in future research and construction practice lies in improving the integrality and quality of the prefabrication technique while reducing its dependence on energy-intensive materials. According to the result of the empirical study on real building projects, prefabrication rate and prefabrication combination are two major factors that affect the incremental energy use of a certain building. Therefore, considerable effort should be exerted on optimizing prefabricated component combination and seeking a balance between the prefabrication rate and embodied energy consumption of a building.

Although this study has assessed embodied energy use by considering the entire economic system, embodied energy consumption in relevant financial services and other real estate activities may still be underestimated. Prefabrication is a relatively new and innovative technology applied in the construction industry; thus, it must be elaborately designed and scheduled. This process is indispensable, which can be assumed as a premised step for prefabrication application, especially in China, which lacks the necessary practical experience and professional guidance. Additional services from professional consultants and designers in the upstream process also require extra energy input. Moreover, the immaturity of the prefabrication market leads to insufficient prefabrication facilities and factories. Therefore, additional energy consumption for building the preliminary market, such as constructing prefabrication facilities and off-site factories, should also be considered. Local governments should provide professional guidance, construct corresponding facilities, and attract experienced stakeholders and upstream prefabrication suppliers in the property market. These actions can effectively facilitate the implementation of prefabrication technologies during the pre-construction stage, which reduces additional energy consumption during prophase investigation.

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7. Conclusions

This study focuses on exploring the life-cycle energy use of prefabricated components and investigating its environmental effects on real building projects. The input–output-based hybrid LCA model is employed to guarantee the completeness of the system boundary and the accuracy of the final result. Therefore, the computational framework presented in this study can be used as a theoretical foundation for assessing prefabrication energy. Meanwhile, the results can help recognize the current development of the precast industry in China and its environmental effect on the country. The conclusions drawn from the study are as follows.

(1) Prefabrication manufacturing consumes over 90% of the total embodied energy consumption. The embodied energy use in the transportation and on-site construction processes are negligibly small compared with those in other processes. The recycling process exhibits high energy-saving potential. Even if the energy input from secondary processing is considered, the recycling process still presents a reduction potential ranging from 16% to 24%. The life-cycle energy use of prefabricated components ranges from 7.33 GJ/m^3 for precast staircase to 13.34 GJ/m^3 for precast form.

(2) The environmental benefits obtained from waste reduction and high quality control are identified in this study, and indicate savings ranging from 4% to 14% of the total life-cycle energy consumption. Precast facade and form are more energy intensive compared with the conventional construction method because of the material change from block-concrete to reinforced concrete.

(3) Prefabrication rate and prefabrication combination are identified as two major factors that affect the incremental energy use of a certain building. On the one hand, the average incremental energy use is nearly positively and linearly correlated with prefabrication rate. On the other hand, precast building envelope, such as precast facade and form, is sensitive to incremental energy use. By contrast, other types of prefabricated components are environment friendly because of the energy benefits obtained from high quality control and waste reduction.

(4) Attention should be focused on improving the maturity of the precast market, including issuing professional guidance, constructing relevant facilities and factories, and attracting experienced stakeholders and upstream prefabrication suppliers in the property market to avoid additional energy consumption during prophase investigation.

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