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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%–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%–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.

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.

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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 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 modeling 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 modeling 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 modeling. 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 modeling 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 modeling 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