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Analysis of embodied carbon in the building life cycle considering the temporal perspectives of emissions: A case study in China

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ABSTRACT

The building sector contributes substantially to worldwide greenhouse gas emissions, and efforts to meet emission reduction targets have been gaining importance. Accordingly, the present study investigates the importance of building embodied emissions to the entire life cycle and potential approaches for low-carbon development in China. Life-cycle assessment was proposed for the analysis of building emissions, dividing the life cycle into production, construction, operation, and disposal phases. The temporal perspectives of emissions were considered, including the potential improvements to energy efficiency and the weighted average impacts for delayed emissions in the operation and disposal phases. A case study of a residential building in a cold region was analyzed, and scenario analyses were conducted. The results indicated that the relative contribution of embodied emissions (10551 tCO_{2e}) considering the temporal perspectives could be twice that of conventional calculations. Further discussion revealed that the payback time of constructing a new building could be 45 years compared to the current regional average buildings. Hence, with respect to the high costs and technical limits of passive houses, renovating old buildings with energy saving measures might be the most appropriate approach for implementing the short-term low-carbon development target. Overall, the present study is helpful to better understand the importance of embodied emissions and for policy-making in the regional building sector.

1. Introduction

The greenhouse effect has been regarded as the most significant challenge to the relationship between humanity and nature owing to its serious consequences of global temperature increase and sea level rise [1,2]. Greenhouse gas emissions originating from human activities (especially, carbon dioxide [3]) have been reported to be the most likely reason for climate change [1]. As a result, people all around the world are making efforts on the issue of energy conservation and carbon reduction [4,5]. As indicated by previous studies, the building sector contributes approximately 36% of total emissions worldwide [6], and it is considered to have more potential and lower costs in the near future for reducing emissions compared to other sectors [7,8]. In this context, research on the life-cycle emissions of buildings has recently been highlighted [9].

Life-cycle assessment (LCA) has been recommended for analyzing the various environmental impacts from a comprehensive view [10], and two main approaches—the process-based method and input–output analysis—are widely used in the LCA of building emissions [11]. Input–output analysis combines economic input–output tables and relevant environmental data to convert monetary values into carbon emissions, consequently capturing the carbon footprint from the entire supply-chain [12,13]. However, this method applies the average emission coefficient of a sector, which makes it inaccurate for assessing a detailed industrial process [14]. In this context, process-based LCA is more popular in the research relevant to emissions from individual buildings. For example, many researchers have analyzed the life-cycle emissions of residential buildings [15–18]; Wang et al. [5] and Cheung et al. [19], for example investigated the life-cycle emission reduction of public buildings based on case studies. Peng [20] and Zhao et al. [21] estimated the emissions from each life-cycle stage based on building information modeling. Chau et al. [22] and Islam et al. [23] summarized the various concepts and equations for calculation of building emissions. These studies have provided good knowledge for process-level emission assessment. Nevertheless, concerns about the truncation error and possible underestimation of emissions by process-based methods have been raised owing to the subjective definition of the system boundary of the calculations [24,25]. Hence, a combi-

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nation of process-based and input–output methods, i.e., a hybrid method, might be a more efficient approach [26,27]. For Example, Suh and Lippiatt [28] proposed a framework for hybrid life-cycle inventory databases; Stephan and Crawford [29,30] investigated the life-cycle energy and emissions of residential buildings based on input–output–based hybrid analysis; Dixit [31] proposed an improved hybrid method for analyzing the embodied energy of building materials.

Typically, a building life cycle is divided into several processes—materials manufacturing, transportation, building construction, operation, maintenance, and demolition [32,33]—of which the operational emissions are regarded as the largest contributor to the life-cycle impacts [34,35]. However, the importance of building embodied emissions has been emphasized in recent studies [36–39]. On the one hand, for new buildings, the application of energy efficiency techniques could significantly decrease operational emissions; accordingly, embodied emissions are crucial to realizing low-carbon buildings [40]. On the other hand, construction-related emissions are considerable for developing countries such as China, which is conducting extensive construction work every year [41].

Furthermore, the temporal perspectives of carbon emissions should also be noted. First, the construction of new buildings generates a significant amount of greenhouse gas emissions in a very short time horizon. This sudden increase of emissions can raise the level of carbon concentration in the atmosphere in a short time, which might lead to irreversible climate change, making the benefits of future energy efficiency useless [7,14]. Second, the LCA of building emissions based on current technology might overestimate operational emissions owing to potential future improvements in energy efficiency; therefore, the contribution of embodied emissions might have been underestimated [42,43]. Finally, emissions in early life-cycle stages are present in the atmosphere for a longer time during the assessment period, and accordingly weighted average impacts have been suggested for the delayed emissions from the operation and disposal phases [44,45].

However, despite the recognized temporal perspectives of life-cycle emissions as summarized above, limited studies have accounted for these effects in their case studies of building emissions. Säynäjoki et al. [7] and Heinonen et al. [42] compared the life-cycle emissions of a residential area with different building energy efficiencies. Oldfield [46] investigated the importance of embodied emissions to the life-cycle impacts of buildings, and discussed the influences of increasing energy efficiency. Jones [47] indicated that future improvement in electricity generation could benefit the reduction of building operational emissions. With consideration of this knowledge gap, the present study aims to (1) apply hybrid LCA and scenario analyses to compare building life-cycle emissions with respect to the temporal perspectives, (2) investigate the importance of embodied emissions in the building life cycle, and (3) propose suggestions for low-carbon development. Accordingly, the remainder of the paper is organized as follows. Section 2 introduces the research scope and the hybrid method for emission assessment. Section 3 presents the information of the case study and scenario decisions. Section 4 analyzes the life-cycle emissions in different scenarios based on a case study building and discusses the importance of embodied emissions from a comprehensive view. Section 5 concludes the study, identifies its limitations, and suggests prospects for future research.

2. Methodology

2.1. Research scope

The total emissions from buildings can be divided into operational emissions and embodied emissions [48]. Operational

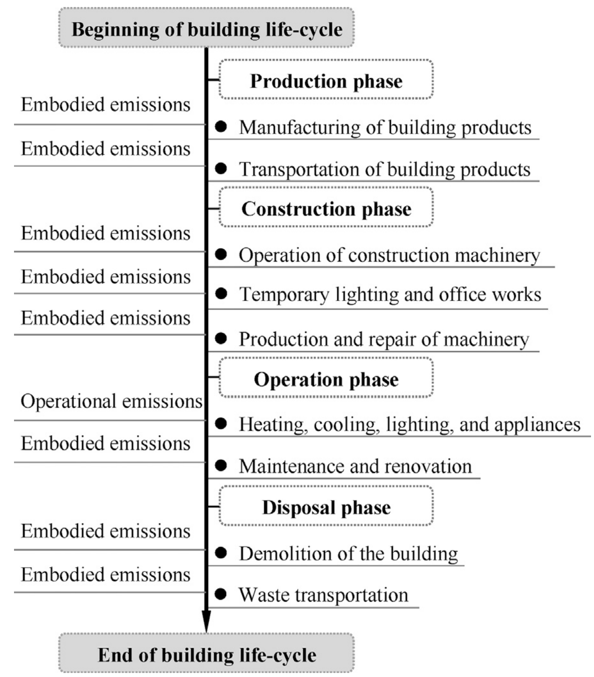

Fig. 1. Scope and system boundary of building life-cycle emissions.

emissions refer to the energy-related emissions for daily running of buildings such as powering heating, cooling, lighting, and appliances [49]. In contrast, embodied emissions are the total emissions from the processes of manufacturing building products, transportation, building construction, maintenance, renovation, and demolition [50]. The scope and system boundary of the life-cycle emission sources are illustrated in Fig. 1.

Both the process-based method and input–output analysis were applied for emission assessment in order to achieve comprehensive results. The fundamental outcome of the process-based method can be interpreted as the product of engineering quantities (or energy consumption) and emission factors, whereas input–output analysis applies a coefficient matrix between environmental impacts and economic flows [51,52] to calculate emissions based on the Leontief quantity model [53]:

$$\mathbf{EF}^{IO} = \varepsilon \cdot (\mathbf{I\text{-}A})^{-1} \quad (1)$$

where $\mathbf{EF}^{IO}$ is the total (both direct and supply chain) emission intensity for the unit economic cost of sectoral products, $\boldsymbol{\varepsilon}$ is a row vector containing the sectoral direct emission coefficients, and $(\mathbf{I\text{-}A})^{-1}$ represents the Leontief inverse square matrix. Furthermore, the input-output method for emission assessment can be expressed as "Emission = Cost × Intensity", where "Intensity" represents the sectoral emission intensity, and "Cost" represents the consumption of products in monetary values. More detailed information is presented in previous studies [14,26,52].

The process-based method incorporates energy consumption data to assess the operational emissions; however, embodied emissions are sourced from various processes throughout the life cycle, and it is nearly impossible to characterize each single activity owing to information scarcity and high costs. In this context, emissions from the key processes are calculated based on process-level data, and the others are estimated by input–output analysis according to the monetary values as suggested by previous studies [10,26]. It should be noted that the proposed hybrid method was process-based; input–output analysis was applied to estimate the emission factors of products and activities, for which no process-level data was available. Previous researchers have also proposed other hybrid methods [54]. These methods could assess