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Stochastic analysis of embodied emissions of building construction: A comparative case study in China

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ABSTRACT

Owing to the extensive building projects that are currently underway in China, evaluation of the embodied emissions in the building construction phase is crucial for reducing the carbon footprint. Previous studies have focused on the quantity of emissions, whereas the present study focuses on the issue of uncertainty in building emission assessment. In this context, a semi-quantitative approach was adopted, and the probabilistic distributions of the quantities and emissions of building materials and energy were assessed based on data quality indicators. Further, a case study was conducted to compare the deterministic and stochastic emissions. The results showed that the sample mean of the stochastic results (5891.97 tCO_{2e}) was consistent with that of the conventional method, while the relevant standard deviation was estimated as 248.90 tCO_{2e} owing to the uncertainty of input parameters. In addition, scenario analyses were conducted, including the system boundary, potential reduction of material consumption and emission, and adoption of local production and low-carbon energy to quantify the scenario uncertainty, and the transformation coefficients and temporal correlation to quantify the model uncertainty. The relevant analyses revealed the key factors (e.g. system boundary, steel, concrete, and masonry works, local production, and applicable period of the data) in reducing the embodied emissions and corresponding uncertainties. Overall, the present study can facilitate comprehensive assessment of the uncertainties in building embodied emissions, thereby contributing to low-carbon policy-making in the building industry.

1. Introduction

Greenhouse gas emissions (which are usually measured as carbon dioxide equivalent emissions) have emerged as an international concern because of their potential effect on global warming [1,2]. The building sector is considered as one of the main sources of such emissions worldwide [3], with the building operation phase accounting for a major part of the emissions in developed countries [4]. As a developing country with a large population, China is facing a great opportunity to develop its economy and accelerate urbanization [5]. This situation has resulted in a drastic increase in construction works [6] and subsequent carbon emissions [7]. Consequently, the building production phase has accounted for more than 60% of the annual emissions of the building sector, as indicated by previous studies [8]. In this context, embodied emissions of building construction are also crucial for fulfilling China's target of low-carbon development.

Two main techniques have been applied for carbon emission calculations, namely input–output analysis and the process-based method [9,10]. On the one hand, input–output analysis combines environmental issues with economic flows, makes it possible to track the carbon footprint from the entire supply chain, and is usually applied either in macro-level studies of the building sector [8,11] or for evaluating upstream emissions of individual building life-cycles [12–14]. On the other hand, the process-based method facilitates the investigation of the particulars of detailed emissions in each process, and it has been widely used in case studies of building emissions. For example, Gustavsson et al. [15] analyzed the life-cycle emissions of a wood-framed apartment building. Luo et al. [16] employed the project data of 78 office buildings in China in their discussion on embodied emissions. Sandanayake et al. [17] conducted an in-depth investigation of direct emissions of foundation construction works. Hong et al. [18] measured the

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embodied emissions during the building construction phase by considering the supplementary emissions of related human activities. Mao et al. [19] and Dong et al. [20] conducted comparative studies of embodied emissions of off-site precast and conventional on-site construction methods. Overall, these previous studies have provided not only useful knowledge about methods for calculating embodied emissions, but also insights into the magnitude of emissions related to building construction through case buildings.

In addition to calculating the quantity of building embodied emissions, conducting uncertainty analysis is equally important, owing to its crucial influence on decision-making. Extant researches have proposed various explanations and strategies for handling uncertainties in life-cycle assessment (LCA), as summarized in Table 1. In general, parameter uncertainty, model uncertainty, and scenario (choice, assumption) uncertainty are the three fundamental sources of uncertainty; among these, parameter uncertainty seems to be the most critical in research related to building emissions [28,29] owing to the large amount of data involved in the calculations.

Despite the importance of uncertainty of the assessed results in LCA [30,31], studies on this issue are relatively rare. Cellura et al. [24], Kang et al. [32], and Su et al. [33] investigated the embodied emissions of building materials using statistical distribution and scenario analysis. Huijberts et al. [27] evaluated the three abovementioned sources of uncertainty in the environmental assessment of a Dutch dwelling. Acquaye et al. [31] employed a hybrid input–output method to analyze the embodied emissions of Irish apartment buildings based on statistical parameters collected from related institutes. Wang and Shen [29] recommended a hybrid data quality indicator and statistical method for uncertainty analysis of the building embodied energy. Chou et al. [34] and Hong et al. [28] adopted Monte Carlo simulation (MCS) to analyze the emissions during the building construction phase. Overall, although numerous researchers have proposed various methods and conducted case studies on the quantities of building emissions, studies on the relevant uncertainties are rare, especially for buildings in China, which is witnessing extensive construction works.

Statistical methods and data quality indicator (DQI) are regarded as two useful approaches for uncertainty analysis in LCA studies [28–30]. Statistical approaches use fitted probabilistic distributions of data samples to characterize the studied variables. Although this type of method can provide accurate outcomes [35], it requires a sufficiently large number of data samples, which leads to high implementation costs. On the other hand, DQI is a semi-quantitative method that can be adopted to estimate the degree of data uncertainty based on metadata (indicators) and expert judgments either qualitatively or quantitatively [36]. DQI is appropriate for LCA studies facing the problem of data scarcity, as in the case of China's building sector. At present, no authoritative database for the emission factors of building products is available in China, making it nearly impossible to perform pure statistical analysis. On the other hand, despite the recognized uncertainty, engineering quantities are always given as fixed values for a specific project, measured by bills of quantities or building information modeling. Hence, DQI might be a better approach for the uncertainty assessment of building emissions given the current circumstances in China.

By considering the lack of uncertainty analysis in building emission assessment, the present study aims to achieve the following: (1) propose a DQI-based stochastic method to quantify the parameter uncertainty of emissions during the building construction phase, and (2) adopt scenario analysis to determine the model and scenario uncertainty. Accordingly, the remainder of the paper is organized as follows. Section 2 describes the research scope, stochastic analysis procedure, outcome evaluation indicators, data and information collection, and scenario decisions. Section 3 presents and discusses the results of a case study; in addition, it describes a scenario analysis conducted to identify the key factors in embodied emissions and the relevant uncertainty. Finally, Section 4 concludes the paper by summarizing the limitations of the present study and briefly exploring future prospects.

2. Methodology

2.1. Research scope

Building embodied emissions are categorized into material production, off-site transportation, and construction works. The process-based approach is adopted because it offers the advantage of detailed component analysis; the fundamental concept for calculations can be explained as "Emission = Quantity × Coefficient". For material production, the quantity and coefficient represent the consumption and relevant emission factors of materials, respectively. For off-site transportation, the quantity represents the freight in terms of ton-kilometer (weight multiplied by distance), and the coefficient represents the emission per unit freight (usually by road or railway). For construction works, the quantity can be expressed as the on-site energy consumption by machinery, temporary lighting, and office work; the relevant coefficient denotes the energy-related emission factors. Hence, the embodied emissions can be expressed as

$$EC = \sum_{i=1}^{n} \left(m_i \times ef_{m,i}\right) + \sum_{i=1}^{n} \left(m_i \times d_i \times ef_{t,i}\right) + \sum_{j=1}^{m} \left(e_j \times ef_{e,j}\right) \quad (1)$$

where n and m represent the total number of material types and sources of energy consumption, respectively; m_i, d_i, and $ef_{m,i}$ represent the quantity, transport distance, and emission factor of material i, respectively; e_j represents the energy used in the construction of source j; and $ef_{t,i}$ and $ef_{e,j}$ represent the corresponding emission factors of transportation and energy, respectively.

A combination of deterministic and stochastic results was employed to quantify the parameter uncertainty, and three aspects were evaluated for the determination of key processes: contribution to the embodied emissions, coefficients of variation (*CV*) of emissions from the studied process, and effects on the output uncertainty. Furthermore, scenario analyses implemented by resampling various scenarios were performed to assess the scenario and model uncertainty. The fundamental framework of the present study is shown in Fig. 1.

2.2. DQI-based stochastic analysis

DQI is a semi-quantitative approach for evaluating parameter uncertainty, which consists of a set of descriptive indicators indicating the quality of original data. The DQI-based stochastic method combines both qualitative evaluations of the data quality by expert judgments and quantitative calculations by mathematical simulations.

2.2.1. Data quality indicators

The selection of indicators is critical to DQI-based analysis. Previously, researchers employed various indicators in relevant LCA studies [25,28,29], including rule of inclusion/exclusion, supplier independence, reliability of source, completeness of data (or data representativeness), temporal correlation, geographical correlation, and technological correlation. For building emission assessment, the relevant data have the following characteristics: (1) the data sources for emission factors (e.g. relevant reports, researchers, and enterprises) and engineering quantities (e.g. project final accounts, construction budget, and bidding documents) are complicated owing to the multiplicity of the involved