Energy and Buildings 85 (2014) 400–409

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

An assessment framework for analyzing the embodied carbon impacts of residential buildings in China

Xiaodong Li[a,*], Fan Yang[a], Yimin Zhu[b], Yuanxue Gao[a]

[a] *Department of Construction Management, School of Civil Engineering, Tsinghua University, Beijing, China*
[b] *Department of Construction Management, Louisiana State University, Baton Rouge, LA 70803, United States*

ARTICLE INFO

Article history:
Received 7 June 2014
Received in revised form
22 September 2014
Accepted 27 September 2014
Available online 13 October 2014

Keywords:
Embodied carbon impact
Carbon footprint
Residential building
Design and construction
Engineering quota

ABSTRACT

To improve the integrity and accuracy of methods for quantifying the embodied carbon impacts of residential buildings during early design stages, an assessment framework was developed in this study to analyze the embodied carbon impacts of buildings to support decision making in China. During the development of this framework, the carbon emission characteristics of pre-occupancy stages were modeled based on the work breakdown structure (WBS). Then, the bill of quantities (BOQ) and the engineering quota were used along with the established carbon footprint factor database (CFFD) to calculate the carbon footprints (CFs) of the buildings. The embodied carbon impacts of three types of residential buildings in China were assessed as a case study to demonstrate the applicability of the proposed framework. The results showed that construction processes related to reinforced concrete, metal structures, and masonry materials are responsible for the majority of the CFs of residential buildings. Thus, enhancing the environmental performance of cement production and increasing the recycling rate of steel scraps in steel production are significant factors in reducing the total CFs of residential buildings in China. Furthermore, these results indicate that the proposed framework can effectively quantify the embodied carbon impacts of residential buildings at the design stage.

1. Introduction

In 2014, the Working Group III in the Intergovernmental Panel on Climate Change (IPCC) released its fifth assessment report [1], and noted that in 2010 the building sector accounted for approximately 32% of global final energy consumption and 30% of energy-related CO_2 emissions. Consequently, China, which has the largest construction industry in the world, was automatically considered as one of the top contributors to carbon emissions. Previously, scientific investigations comparing carbon emissions from different industries in China indicated that embodied carbon emissions from the building sector accounted for 29.79% of the total carbon emissions produced in 2007 [2]. In addition, a recent study reported that the energy consumption of a building in its pre-occupancy stage, including the manufacturing and construction stages in this study, accounted for 25% of its life-cycle energy consumption [3]. Given the significant share of carbon emissions of the Chinese building industry, we believe that creating a method that accurately analyzes the carbon emissions of construction products is the first step in solving the above-mentioned carbon emission problem.

From a life-cycle perspective, greenhouse gas (GHG) emissions from the operation stage typically account for a dominant share of the life-cycle carbon emissions of a residential building. Therefore, numerous studies have focused on the carbon emissions from buildings during their operation phase. Gajewski et al. assessed the carbon emissions while heating in selected European countries [4]. Tettey et al. discussed the effects of different insulation materials on operational CO_2 emissions of a multi-storey residential building [5]. However, the focus of these researches is on minimizing the final energy use or the purchased energy in the operation phase, while the energy use of the other phases is often neglected [6]. Moreover, because most carbon emissions result from human activities during a building's operation period, the operational carbon emissions are relatively easy to calculate from monthly utility bills [7] or using advanced energy simulation tools [8]. Compared with the process of calculating the operational carbon emissions, determining the embodied carbon impacts of construction products is difficult. This is because the sources of the embodied carbon emissions include numerous manufacturing and service activities, which makes it

---

[*] Corresponding author. Tel.: +86 010 62784957; fax: +86 139 11750029.
E-mail address: eastdawn@tsinghua.edu.cn (X. Li).

http://dx.doi.org/10.1016/j.enbuild.2014.09.051
0378-7788/

difficult to completely define the system boundary of constituent products and to reflect the specific characteristics of production processes.

Generally, embodied carbon impact assessments of the pre-occupancy stages are included in research related to the life-cycle carbon emissions of buildings. Since 1998 [9], many researchers have focused on analyzing carbon emissions during the life cycle of buildings. In addition, this number is still increasing because of the development of LCA theory. Kim et al. proposed a life-cycle CO_2 ($LCCO_2$) analysis model based on the life-cycle cost (LCC) theory for analyzing the life-cycle cost-carbon effect of buildings [10]. Fesanghary et al. developed a multi-objective optimization model to minimize the LCC and carbon emissions of the buildings [11]. In most of these studies, the life cycle of buildings is divided into four or five stages. Carbon emissions of each stage are estimated as a whole based on the energy and resource consumptions of each stage. Consequently, in such studies, the carbon emissions are analyzed without details regarding the sub-processes of each stage.

In recent years, some achievements have been made in the assessment of the embodied carbon impacts of buildings. Lee et al. put forward an LCA CO_2 assessment method for concrete in the construction industry of South Korea [12]. Besides researches solely focused on the building materials, the assessment of the carbon emissions during construction process is another important research area. Yan et al. established the calculation method of GHG emissions during building construction in Hong Kong [13]. Baek et al. proposed a carbon emission assessment tool for building construction based on the average quantity of materials consumed per unit area [14]. In particular, bill of quantities (BOQ) was used to systematically investigate building materials in building construction. This paper provides a reference for inventory analysis in this study. However, those studies have several limitations, which require further investigation of the embodied carbon impacts of buildings in a more cautious manner. The limitations include:

- Few assessment tools provided reliable data conversion mechanisms and coefficients for facilitating the embodied carbon assessment based on the bidding documents. In contrast to factory-fabricated products, construction products are deliverables that contribute to realizing the objectives of a project. Different construction methods and objectives make it difficult to obtain the embodied carbon impacts of specific projects in a simple or convenient manner. Moreover, it is difficult to extract reliable material and energy consumption data for the embodied carbon assessment at the early design stage.
- Sources of embodied carbon emissions include numerous manufacturing and construction activities. However, few researches have been conducted regarding systematic investigations of the involved unit processes. In addition, large-scale construction is a mix of several human activities rather than a single activity and is characterized by multiple processes involving many stakeholders. Consequently, it is important to understand how to appropriately break down projects, define carbon emission responsibilities among stakeholders, and perform comparisons between different projects and activities that are highly significant for reducing carbon emissions.
- LCA studies are highly dependent on data [15]. The temporal implications of the data used in LCA studies can be significant. For example, data concerning obsolete processes that represent out-of-date technologies or manufacturing processes may fail to reflect the actual conditions of more recent technologies with lower energy consumption and emissions. Similarly, spatial differences in data are also responsible for variations in LCA results. Construction in different countries varies not only in terms of geographic and climatic characteristics but also in terms of the raw material quality, production processes, transportation distances, energy tariffs, and other factors [16]. All of these differences reduce the reproducibility of specific data between locations. Therefore, the aforementioned discussion suggests that the direct application of foreign data [17] for assessing the embodied carbon impacts of buildings in China is impractical.

Our research group proposed a raw idea of assessing the carbon footprint of building construction. However, the carbon footprint analysis was conducted on base of the classification of on-site and off-site carbon emissions. Moreover, as a research dedicated to the conference, it was brief and immature, and did not provide the detail about the elements of the framework [18]. Consequently, a well-rounded and well-developed calculation approach for analyzing the embodied carbon emissions of buildings in China is still being developed. In this study, the authors discuss an assessment framework for analyzing embodied carbon emissions during pre-occupancy stages to support decision making for different stakeholders during the early design stages of buildings in China. This assessment framework was developed based on the work breakdown structure (WBS) to organize construction activities and the associated materials. While performing this assessment, bills of quantities (BOQ) and engineering quotas were used together with an established carbon footprint factor database (CFFD) to calculate the carbon footprints (CFs) of the buildings. In addition, the embodied carbon impacts of three types of residential buildings in China were assessed as a case study to demonstrate the applicability of the proposed framework and to provide findings regarding the major factors that contribute to the carbon footprints of residential buildings.

2. Work breakdown and scope definition

2.1. Work breakdown

In this study, the concept of a work breakdown structure (WBS) in building construction is applied to organize building components and construction activities to track associated embodied carbon emissions during the pre-occupancy stage of a construction project. The WBS concept is used because a complex construction process can be viewed as a collection of dynamic and interdependent work items, such as earthworks, foundations, concrete, masonry, metals and finishes, from the systems perspective. Each work item can be further broken down into an ordered set of unit processes with spatial, temporal and technical requirements that are specified in the construction documents of a project [19]. Generally, at the unit process level, the specific equipment and materials that are required by a particular process are clearly identified. Thus, the carbon emissions that are generated from this process can be properly accounted for. Therefore, using WBS, the carbon emissions that are associated with building processes can be comprehensively investigated and traced upstream to facilitate the process data integration and to reflect specific building information.

In this study, the *Code of valuation with bill quantity of construction work* (CVBQCW, GB 50500-2013) [20], which is now a mandatory standard for bidding and is commonly used in preparing construction documents in China, was used to decompose a construction process into work items and smaller unit processes to facilitate the collection of materials and equipment data from the construction documents of real projects [18]. The code contains the permanent and temporary work items that support the construction of a typical building. This classification provides a uniform and consistent basis for breaking down various building projects, which allows comparative studies between different building projects to be performed.