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Embodied energy consumption of building construction engineering: Case study in E-town, Beijing

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ABSTRACT

Presented in this paper is a detailed embodied energy consumption evaluation framework for building construction engineering. The building construction engineering comprises nine sub-projects, which are *Structure and outside decoration engineering*, *Primary decoration engineering*, *Electrical engineering*, *Water supply and drainage engineering*, *HVAC engineering*, *Civil engineering*, *Municipal electrical engineering*, *Municipal water supply and drainage engineering* and *Gardening engineering*. Our study chooses the construction engineering of a cluster of landmark commercial buildings in E-town, Beijing (Beijing Economic-Technological Development Area, BDA) as a case. As far as we know, this study is the first attempt to account the embodied energy consumption for building construction engineering based on the most exhaustive first-hand project data with about 1000 input items in the Bill of Quantities (BOQ). The embodied energy consumption of construction engineering is quantified as 7.15E+14 J. *Structure and outside decoration engineering* contributes more than half of the total embodied energy consumption, followed by *Primary decoration engineering*'s 23% and *Electrical engineering*'s 3%, respectively. As for the input items, the sum of the embodied energy consumption by steel, cement, lime and metal products is more than 3/4 of the total embodied energy consumption.

1. Introduction

According to Energy Information Administration (EIA), building-related energy consumption (5.3 million tons of standard coal) accounts for about 29% of the global energy consumption in 2007 (17.9 million tons of standard coal) [1], while the proportions for many developed countries are even larger [2,3]. In China, about 1/4 of the total energy consumption is due to building construction in 2007 [4–7].

The earliest building energy consumption accounting only considered the direct energy consumption in the construction and operation process of buildings. Along with the introduction of the life cycle concept, some researchers began to consider the indirect energy consumption which occurred during the building materials' production [8], in which some major indirect energy consumption caused by some key inputs were traced, such as energy consumed by the electricity generation and iron and steel smelting. Most of the existing studies employed the process analysis method to investigate the indirect energy consumption of buildings [8–21]. For instance, the energy consumption of an eight-story wood-frame apartment building in Sweden and a six-story building in the campus of the University of Michigan was measured [14,18], and the energy consumption of some building materials was analyzed [8]. These efforts have contributed significantly to the development of the energy consumption assessment for buildings. However, several limitations, especially the truncation errors, are also observed in the process based studies [22].

In recognition of the limitations of the process analysis, some researchers tried to assess the energy consumption of buildings on the basis of input–output analysis, under which all buildings in the same country or region are analyzed as an economic sector. Nässén et al. used input–output analysis to evaluate the direct and indirect energy consumption of Swedish construction industry and compared the accounting results of the top-down and bottom-up methods [23]. A linear mathematical model similar to input–output analysis was established by Ziębik et al. to calculate the coefficients of cumulative energy consumption in complex buildings [24]. Although providing a complete economy

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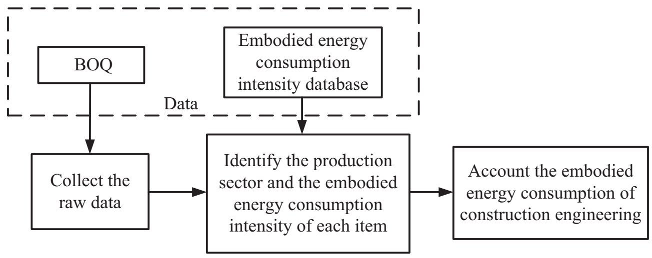

Fig. 1. Accounting procedure for energy consumption of construction engineering.

modeling can avoid the truncation error of process analysis, the input–output analysis tends to be applied to macro analysis, i.e., it is not applicable for specific building's energy consumption accounting.

Regarding the advantages and disadvantages above, Bullard et al. [22] suggested a hybrid method by combining the process and input–output analyses to evaluate energy consumption required by the target product, and it was also applied to calculate environmentally important input paths of a variety of goods and service [25,26]. Later it was employed to calculate the embodied carbon emissions [27,28]. Goggins et al. used the process based hybrid method to assess the embodied energy of reinforced concrete in Ireland and discussed the application of input–output based hybrid method [29]. On the basis of systems method, a low-carbon building evaluation framework was developed by Chen and co-workers to assess the carbon emissions of an individual building, in which the life cycle procedure of buildings is divided into nine stages [30,31]. Then this framework was applied to access the carbon emissions, as well as the energy consumption of *Structure and outside decoration engineering* of case buildings [32]. This method was also applied to assess the nonrenewable energy cost and greenhouse gas emissions of a constructed wetland, a 1.5 MW solar power tower plant, a wind farm in Guangxi, and a corn-ethanol production [33–36].

The aim of this paper is to quantify the embodied energy consumption of building construction engineering in terms of two major engineering projects, five secondary engineering projects, and nine tertiary engineering projects of six commercial buildings in E-town, Beijing (Beijing Economic-Technological Development Area, BDA), supported by the hybrid method as a combination of process and input–output analyses with a detailed embodied energy consumption accounting procedure.

2. Method and date sources

2.1. Procedure for energy consumption accounting

The accounting procedure for embodied energy consumption based on the hybrid method is shown in Fig. 1. It can be operated by the following three steps:

(a) Collect the raw project data from the Bill of Quantities (BOQ)

The embodied energy consumption accounting of building construction engineering is highly data-sensitive. To enhance the maneuverability of the procedure, the accounting in this study is based on the first-hand project data in the BOQ. Prepared in accordance with requirements and regulations of construction engineering, BOQ quantifies the work of all the inputs of construction engineering as documenting the quantity and price of each item [37]. The inputs are usually listed in the BOQ in terms of three categories as labor, material and machinery, and the tables corresponding to each sub-project are divided into six columns, as number, item, unit, quantity, price, and economic cost, respectively (a blank sample table shown in Supplemental Table S1).

(b) Identify the corresponding productive sector and the embodied energy intensity of each input

To calculate the embodied energy consumption of the construction engineering, each item should be given its productive sector and corresponding embodied energy intensity based on the existing intensity database (see more information in Section 2.2). Embodied energy intensity, an economic measure of energy consumed per unit of GDP (J/$, etc.), is usually calculated through the economic input–output table. The embodied energy intensity of each input item can be adopted in the existing database with reference to its corresponding economic sector. With the corresponding intensity and economic cost, the embodied energy consumption of each item can be achieved. In order to simplify the calculating process, the various building materials from the same sub-project and economic sector are combined and calculated as a whole after totaling their economic cost, with the blank sample tables shown in Supplemental Table S2 and S3.

(c) Obtain the embodied energy consumption of each sub-project

With the processed data provided in the step (b), the embodied energy consumption of each sub-project's sector is given by multiplying each sector's economic cost by its corresponding embodied energy intensity. Then the embodied energy consumption of each sub-project can be obtained by totaling the embodied energy consumption of each sector:

$$E = \sum_{i=1}^{n} E_i = \sum_{i=1}^{n} (\varepsilon_i \times I_i)$$

where I_i is economic cost of sector i in the BOQ, ε_i is corresponding embodied energy intensity of sector i, E_i is embodied energy consumption of sector i, and E is the embodied energy consumption of each sub-project.

After summing the embodied energy consumption of each sub-project, the embodied energy consumption of the construction engineering can be given.

2.2. Database

The embodied energy consumption accounting requires a proper energy intensity database covering economic products, especially these in the building construction engineering. Focusing on the macro-scale economy simulation, the input–output analysis method can avoid truncation errors and is recommended to account target products' energy intensity. A number of energy consumption databases based on the input–output analysis for various economy systems at global, national and regional scales have been established by individual researchers [38,39]. At the global scale, Chen and Chen carried out a network modeling for the global economy and calculated the embodied resources and emissions for 112 nations and regions [40]. At the national scale, Zhou presented two databases: one included 151 goods in 1992 based on Material products system, and the other covered 42 economic sectors in 2002 based on System of national account [41]. Later the Chinese databases were updated to 2005 and 2007 with 42 and 135 economic sectors involved, respectively [42,43]. At the regional scale, databases on Beijing 2007 and Macao since 1999 were provided by Guo et al. and Li et al. [44,45]. Considering of the fact that the case buildings are constructed around 2007 and almost all materials for the construction engineering are produced in China, the database on the Chinese economy 2007 presented by Chen and Chen [42]