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Development of an automated estimator of life-cycle carbon emissions for residential buildings: A case study in Nanjing, China

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ABSTRACT

Residential buildings consume a significant portion of energy and resources during the whole life-cycle phase and meanwhile discharge an enormous amount of carbon dioxide emissions, which has directly led to the aggravation of the greenhouse effect and become a great threat to the environment and human beings. To reduce the life-cycle carbon emissions from residential buildings, researchers have made many efforts to estimate the emissions accurately. Although several building-level carbon emission databases and related calculation systems have been set up in developed countries, there unluckily remains a vacancy in China. To fill in this gap, this study develops an automated estimator of life-cycle carbon emission for residential buildings entitled “Carbon Emission Estimator for Residential Buildings (CEERB)” in China. The development process was based on the life-cycle assessment (LCA) theory, standardized carbon emission calculation method, and collection and compilation of numerous carbon emission coefficients available in China. The database for storing carbon emission coefficients is based on the SQLite 3.0, and the user interface is designed with Qt 4.7. Followed by the establishment of the CEERB system, it has been exemplified in a masonry concrete residential building in Nanjing (China), demonstrating its applicability and capability in estimating the life-cycle carbon emissions of residential buildings. The results indicate that: (1) the life-cycle carbon emissions of this project were 1.7 million kg and the annual emissions per square meters were 19 kg/m^2/year; (2) the O&M phase contributed the most (63%) to carbon emissions, followed by the material production (32%); (3) regarding to material embodied emissions, concrete reached roughly 44% of total material emissions, followed by the steel (20%); (4) during the construction phase, the superstructure project accounted for the most emissions (78%), primarily by tower cranes and hoist; (5) during the operation phase, electricity contributes 88.3% of emissions, followed by natural gas of 8%. Discussion and implicated policies, such as annual emission profile and impact of using recycled materials, have also been elaborated at the end of the study. Based on the proposed estimator CEERB, contractors can be more efficient and convenient to evaluate carbon emissions at the early stage of a project and make appropriate carbon management plans to reduce emissions when facing stricter environment policies in the future.

1. Introduction

Carbon dioxide emissions, as the primary component of greenhouse gases, have been emitted in unprecedented speed in past decades. In 2012, the amount of carbon dioxide in the air had increased to 393.1×10^{-6}, 41% higher than the level before the industrial revolution (WMO, 2013). The greenhouse effect caused by carbon emission makes an ever enormous impacts to the environment, including global warming, the rising of sea level, the infestation of insects, desertification, the decrease in agriculture production and the imbalance of the ecosystem, also generating a severe impact on the survival and development of human beings. The building sector is responsible for 30% of the total carbon emissions in the world (IPCC, 2014) and 40% of carbon emissions in China (Eduard, Ganesh & Joule, 2015). Residential buildings, as one of the main products of the construction industry, are well known as the primary sources of carbon emissions. For instance, in 2005, the carbon emissions of residential buildings in the United States

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(US) accounted for roughly 21% in its total carbon emissions (Kenisarin & Mahkamov, 2016), and 25% in the United Kingdom (UK) (Chandel, Sharma & Marwaha, 2016). On average, the electricity consumption per capita in residential sector generated 1710.3 million metric ton of CO_2 in the European Union (EU) (Chandel, et al., 2016).

China, as the largest carbon emitter and the second largest economy in the world, has proposed a series of policies and made many efforts to control the carbon emissions of buildings. For instance, the *2014–2015 Action Plan for Energy Conservation, Emissions Reduction and Low Carbon Development* committed to cutting carbon dioxide emissions per unit of GDP by 4 percent in 2014 and 3.5 percent in 2016 (NDRC, 2014b). The government also pledged in the *National Plan to Address Climate Change (2013–2020)* that carbon emissions per unit of GDP is to be reduced by 40%–50% by 2020 from the 2005 level (NDRC, 2014b). As a result, during 2010–2014, the national energy consumption per unit of GDP has dropped by 13.4%, equivalent to the saving of 600 million tons of standard coal and 1.4 billion tons of carbon dioxide (NDRC, 2015). The above indicator was also 33.8% lower than the 2005 level (Wei, 2015). At the 2015 United Nations Climate Change Conference held in Paris, China's government has officially determined its long-term actions by 2030 including the followings. 1) Achieve the peaking of carbon dioxide emissions around 2030 and making best efforts to peak early; 2) lower carbon dioxide emissions per unit of GDP by 60%–65% from the 2005 level; 3) increase the share of non-fossil fuels in primary energy consumption to around 20%; and 4) increase the forest stock volume by around 4.5 billion cubic meters on the 2005 level (Wei, 2015). In the meanwhile, several national standards have been carried out to reduce emissions from various phases of buildings, such as *Green Building Evaluation Standard* (PRCMC, 2006), *Standard for measuring, accounting and reporting of carbon emission from buildings* (CADRG, 2014), and so on.

However, some shortfalls in the carbon emission assessment still existed in China, such as the fragmentation of carbon emission database, unclear boundaries and phases, and poorly updated and maintained. This paper aims to develop an automated estimator that can accurately calculate carbon emissions in the whole lifecycle of a building based on China's actual conditions. The study is structured as follows. First, it defines the research boundary of the objective and also the life-cycle process, establishes the calculation method of life-cycle carbon emission of a residential building, and collects various kinds of carbon emission coefficients. Then, this paper develops an automated carbon emission estimator that realizes two primary functions: database management including edit, query, and update carbon emission coefficients and the calculation of life-cycle carbon emissions. Finally, this study estimates the life-cycle carbon emissions of a residential building in Nanjing, China to testify the reliability of this estimator and further proposes suggestions to seek low or even zero carbon emission targets for buildings.

2. Literature review

Commonly used methods for measuring a buildings' carbon emission include direct energy consumption statistics on the production line (Zhang, Wu, & Le, 2012), inter-industrial linkages statistics method (Wang et al., 2013), input-output method (Su & Ang, 2013), monitoring the carbon emission by equipment directly (Tirol Padre et al., 2014), and carbon emissions coefficient method (CECM) (Li, Chen, Hui, Zhang & Li, 2013). Among them, the CECM is widely accepted and easy to use for all different phases of a building. The accuracy of the method mainly depends on the reliability of available carbon coefficients, the quantity of used materials and consumed energy.

Based on the CECM, a series of databases and tools for measurement and evaluation related to carbon emissions have been developed in several developed countries. One example is Building for Environmental Economic Sustainability (BEES) (Lippiatt, 1998), which is an online evaluation tool developed by US National Institute of Standards and Technology (NIST) in 1997, based on the Standard Reference Data (Lemmon, Huber & McLinden, 2012). The BEES measures the environmental performance of building products by using the Life Cycle Assessment (LCA) approach specified in the ISO 14040 standards and Multi-Attribute Decision Analysis of the American Society for Testing and Materials (ASTM) standards. The environmental performance indexes of BEES include 12 indexes, such as global warming (mainly carbon dioxide emissions), acidification, and indoor air quality. According to the US life-cycle inventory database, the Athena Sustainable Materials Institute, a non-for-profit organization in Canada, have also developed four environmental impact estimators, including Impact Estimator for Buildings, Impact Estimator for Highways, EcoCalculator for Commercial Assemblies and Residential Assemblies. Among them, Impact Estimator series are to-be-installed software, while EcoCalculator series are structured Excel spreadsheets (Means & Guggemos, 2015). Inventory of Carbon and Energy (ICE) is another popular database developed by the Sustainable Energy Research Team of the University of Bath in the UK (Hammond, Jones, Lowrie, & Tse, 2008). ICE provides energy consumption and embodied carbon of building materials based on the references collected from public resources like journal articles, LCA reports, books, conference papers. In the open-access part of ICE, there are 247 cited references, among which only 107 references were published in recent ten years, and almost none was published in last five years. Therefore, the coefficients may not reflect the latest status of current production and construction technologies. There are other kinds of carbon emission-related database or tools, such as the Economic Input-Output Life Cycle Assessment (EIO-LCA) developed by Carnegie Mellon University (Trappey et al., 2013), US Life Cycle Inventory Database developed by National Renewable Energy Laboratory (NREL) (Sander & Murthy, 2010), and Publicly Available Specification (PAS) 2050 established by British Standards Institute (PAS, 2008). However, these databases or tools are primarily developed by using the data collected from designated developed countries, so the application of these estimators in other countries might be challenging. Meanwhile, these estimators are designed for universal goods and services but not specifically for buildings, so the application for building materials may need additional conversions that are repetitive and time-consuming.

In China, although a great number of scholars and organizations have carried out studies on carbon emissions of buildings, little is known for the carbon emission-related database or tools for buildings specifically. Now, the most popular open-access carbon emission database in China is Chinese Life Cycle Database (CLCD) (Yue, You & Darling, 2014), in which data were derived from industrial statistics and technical literature delivered nationally, including more than 500 types of life-cycle data for energy, raw materials, and transportation. CLCD can provide data for LCA analysis of products and evaluation of energy conservation and emission reduction in China. eBalance is a software developed based on CLCD, and it can analyse the life-cycle environmental impact of buildings, as well as its uncertainty and sensitivity. However, CLCD has several limitations in estimating the life-cycle carbon emission of a building. First, the basic data in the database is relatively old with few frequent update. Second, it only provides the coefficients of primary energy sources for general use but does not link the energy sources to the construction process and building materials. Last, the majority of data in the CLCD are not open access. Therefore, a database that enables emissions calculation from the