Habitat International 57 (2016) 154–163

Contents lists available at ScienceDirect

Habitat International

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

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

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ARTICLE INFO

Article history:
Received 28 December 2015
Received in revised form
6 June 2016
Accepted 13 July 2016
Available online 1 August 2016

Keywords:
Carbon emission
Residential building
Life-cycle analysis
Integrated estimator
China
Case study

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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http://dx.doi.org/10.1016/j.habitatint.2016.07.003
0197-3975/

(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 life-cycle phases of a building is in urgent need.

In summary, three gaps have been identified from the literature. First, carbon coefficient database is essential for CECM to estimate building emissions, but is currently lacking in most of the countries including China. Second, most of existing databases and tools do not consider building characteristics, so it needs additional efforts to calculate the life-cycle emissions for a residential building. Third, existing database have been established for a relatively long term with the less frequent update, making the data out of date and the estimation inaccurate. Consequently, developing an automated emission estimator for residential buildings in China can assist the estimation of life-cycle carbon emissions and further help the contractors and the designers to evaluate actual carbon emissions and to optimize low carbon buildings.

3. Method

The study develops the estimator in three steps— investigation of carbon emission calculation, the collection of carbon coefficients, and the establishment of emission calculation database and estimator.

3.1. System boundary and calculation method

The measurement of carbon emissions is a key item in the life cycle assessment (LCA) which is defined from ISO 14040 standards as the compiling and evaluating of the inputs and outputs and the potential environmental impact of a product system during its lifetime. According to the goal and scope definition, inventory analysis and impact assessment in the LCA framework, this study needs to define the system boundary of objectives, including building spatial boundary and life cycle process boundary before calculating the carbon emissions. The space boundary is defined as the closed three-dimensional space constituted by the foundation bottom, the highest point and the building facade of a residential building, based on the Comprehensive Assessment System for Building Environment Efficiency (CASBEE) (Murakami, Iwamura, Ikaga & Endo, 2002). Regarding the process boundary, the life-cycle of a building is divided into five phases, namely material production phase, transportation phase (on-road), construction phase, O&M (O&M) phase, and demolition phase. Then, based on the CECM and LCA theory, the life-cycle carbon emission of a residential building can be calculated as:

$$E = E_1 + E_2 + E_3 + E_4 + E_5 \tag{1}$$

where E represents the life-cycle carbon emission of a residential building (unit: t), E_1, E_2..., E_5 respectively represent the carbon emission at material production phase, transportation phase, construction phase, O&M phase, and demolition phase (unit: ton).E_1 is discharged by burning fossil fuels and power consuming in the process of producing raw material, semi-finished and finished products, and is formulated as:

$$E_1 = \sum_{i=1}^{n} M_i \times f_{mat,i} \tag{2}$$

where M_i is the usage amount of material i (unit: depend on the type of material, e.g. ton or m^3), $f_{mat,i}$ represents the carbon emission coefficient of a material$i$. i is the kind of material.

E_2 is caused by energy consumption of different vehicles used to transfer the building material from factory to construction site, and it can be formulated as:

$$E_2 = \sum_{i=1,p=1}^{n} f_{tra,p} \times B_i \times L_i \tag{3}$$

where $f_{tra,p}$ represents the carbon emission coefficient of the type p transport vehicle (i.e. diesel-powered truck, electric locomotive), B_i refers to the total weight of material i (unit: ton). L_i represents the distance of moving material i from factory to construction site (unit: kilometer).E_3 is emitted by burning fossil fuels and power consuming of machinery and equipment in the construction process, and it can be calculated as:

$$E_3 = \sum_{j=1}^{n} f_{equ,j} \times X_j \times N_j \tag{4}$$

where $f_{equ,j}$ represents carbon emission coefficients of machinery and equipment$j$, X_j refers to the total workload of machinery and equipment j (unit: one-shift), N_j refers to the number of machinery and equipment$j$.E_4 indicates the energy consumption in operation and the material replacement, and it can be calculated as:

$$E_4 = \left(Q_1 \times f_{ele} + Q_2 \times f_{fos,g} + Q_3 \times f_{fos,l}\right) \times Y + \sum_{h=1}^{n} R_h \times f_{mat} \times C_h \tag{5}$$

where Y represents the lifespan of a building (unit: year). Q_1 represents annual average electricity consumption of the building (unit: kWh), f_{ele} represents the carbon emission coefficient of electricity; Q_2 represents annual average natural gas consumption (unit: m^3), $f_{fos,g}$ represents the carbon emission coefficient of natural gas; Q_3 represents annual average liquefied petroleum gas consumption of buildings (unit: kg), $f_{fos,l}$ represents carbon emission coefficients of liquefied petroleum gas; R_h represents the amount of building material h that needed to change (unit: ton or m^3)f_{mat} represents the carbon emission coefficient of building material h, C_h represents the renewal time of material h.

E_5 indicates the energy consumption of machinery and equipment in the demolition process, the energy consumption of vehicles for transferring construction waste to waste yard after demolition, and the energy consumption for material recycling, and it can be calculated as:

$$E_5 = \sum_{q=1}^{n} f_{equ,q} \times X_q \times N_q + \sum_{k=1}^{n} f_{tra,k} \times T_k \times D_k - \sum_{s=1}^{n} M_s \times w_s \times f_{rec,s} \tag{6}$$

where $f_{equ,q}$ represents the carbon emission coefficient of demolition machinery and equipment q, X_q represents the total workload of demolition machinery and equipment q, N_q represents the amount of demolition machinery and equipment q, $f_{tra,k}$ represents the carbon emission factor of transportation of material k, T_k represents the total weight of construction waste k(unit: t), D_k represents the distance between the construction site and landfill or reprocessing factory (unit: km), M_s represents the total weight of recyclable materials s(unit: t), w_s represents the recycling proportion of material s, $f_{rec,s}$ represents the carbon emission coefficient of recyclable material$s$.

3.2. The collection of carbon emissions factors

From formula (2) to formula (6), the required carbon emission coefficients can be classified into four categories, namely primary energy sources, building materials, transportation, and machinery. For the primary energy sources, a total of 19 sources are listed, and they include 13 types of fossil fuels (e.g. raw coal, gasoline, and diesel) and six types of electrical energy (i.e. supplied by north, northeast, east, central, northwest and south China area grid). For the building material category, it comprises of 63 kinds, namely 52 types of primary materials (e.g. cement, steel, concrete and mortar) and 11 types of accessible materials (e.g. lime, acrylic latex paint and cast iron). For the transportation category, 11 types are documented, including two highway transport (e.g. through gas trucks and diesel trucks), seven railway transport (e.g. through electric locomotives) and two waterway transport (e.g. through ships). Finally, 865 types of machinery and equipment (e.g. excavator diggers, bulldozers and gantry cranes) are used in the machinery category. The carbon emission factors above were collected from more than 50 construction and energy-related articles, various national statistical yearbooks and national standards, and so on. Due to this database is built with the focus on China's buildings, the majority of the referred sources were from China.

After collecting the above coefficients, it is necessary to process and to compile different sources of data into a single format. Since there are multiple sources of carbon emission factors and one coefficient may have two or more conflicting values of various sources, this study prioritized the coefficients in following principles. First, the collected data were used to the following rules: new rather than old references, and national data rather than international data. For instance, the value from the most recent experiment executed in China for the emissions of cement was used rather than a value from overseas. Second, for carbon emitters (e.g. building materials) that have different coefficients of various scales or categories, the general value rather than a particular value was accepted. For instance, cement has multiple types, such as Portland cement, white cement, high alumina cement, and so on, and this study used the coefficient of standard Portland cement. The reason is that although different types of cement may have various components and corresponding shares, the core composites of the cement are similar, and so are the carbon emissions. Third, although most of the carbon emission coefficients can be directly extracted from current carbon emission-related databases and publications, several factors must be calculated indirectly. For instance, there are three widely-accepted methods to produce copper in China, namely melting bath smelting, flash smelting, and blast furnace smelting. Since their carbon emission coefficients are measured as 10.01, 8.99 and 15.32 respectively (Zeng, Yang, Song, & Lv, 2012), and they were produced 42%, 35% and 23% of the total copper of China in 2007 (Deng, Li & Chen, 2006). The carbon emission coefficient of copper was determined as $10.01 \times 42\% + 8.99 \times 35\% + 15.32 \times 23\% = 10.87$. After summarizing all data sources, the carbon coefficients, their meanings, and the corresponding sources are shown in Appendix A.

3.3. The establishment of database and estimator

3.3.1. System development process

The process of database development comprises of 7 steps and is shown in Fig. 1. 1) User's requirements analysis, which includes data importing and exporting, querying and editing, calculating and updating for the carbon emission coefficients, as well as estimating the life-cycle carbon emissions based on the essential information of residential buildings. 2) Database design. After considering the data volume, flexibility of use and hardware requirement, SQLite 3.0 was chosen as the platform for this study. 3) Logical database design, which aims to arrange data into a series of logical relationships called the Entity–Relationship (E-R) model. 4) Physical database design. During this stage, a suitable data storage structure and the data access method were selected for the above logical data model. After compared popular interface programs currently, such as Windows Forms, Microsoft Foundation Class (MFC), and so on, the Qt 4.7 was chosen. 5) Implementation. After finishing the above works, a database was established by using data-oriented approach to store the data and to facilitate the life-cycle calculation process. 6) The last two steps are to test run the system, and to operate and to maintain the system in the use.

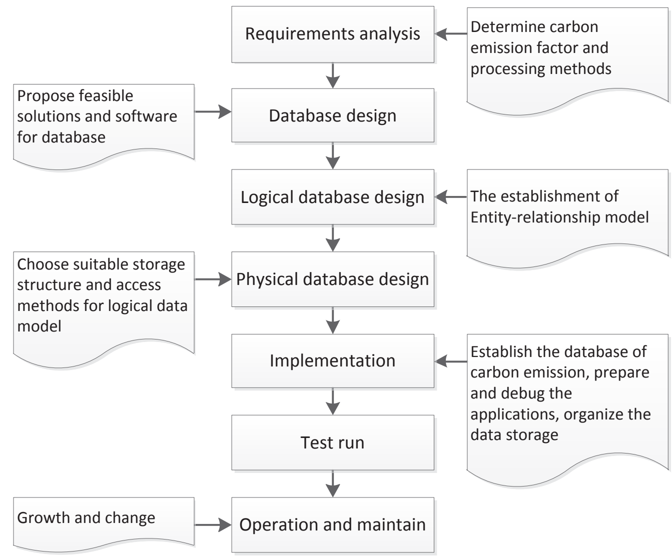

Fig. 1. System development process.

3.3.2. System architecture and interface design

The system architecture includes three levels— user interaction layer, request and calculation layer, and the database layer— as shown in Fig. 2. The characteristic of the first layer is to allow users to input the data and to inquire the output results. Fixed data such as the coefficients inventory was directly stored in and called from the database while calculation-dependent data were temporarily stored in the flash memory. The second layer is mainly for the carbon emission calculation. Different formulas were applied at various life-cycle phases. The database layer includes four types of factors— energy sources, building materials, transportation and machinery — in the format of their names, factors, sources, and years.

The primary functions of the interface of CEERB are shown in Fig. 3. Users can register a new account and log in the main interface with security assurance and individual needs. The main interface has four functions— data input, query, carbon emission calculation and software introduction. Users can carry out data query and calculation by clicking the “data input” button. The query is one of the essential functions of the database, from which users can obtain, edit and update all types of carbon emission coefficients, using keywords searching function with the help of inserted NLPIR Chinese word segmentation system (Zhou & Zhang, 2003). For any energy sources, each datum record includes name, unit, carbon emission coefficient, year, data source and other detailed information on that kind of energy. To aligning with five life-cycle phases described above, the estimation interface includes seven parts, namely basic information of the project, material

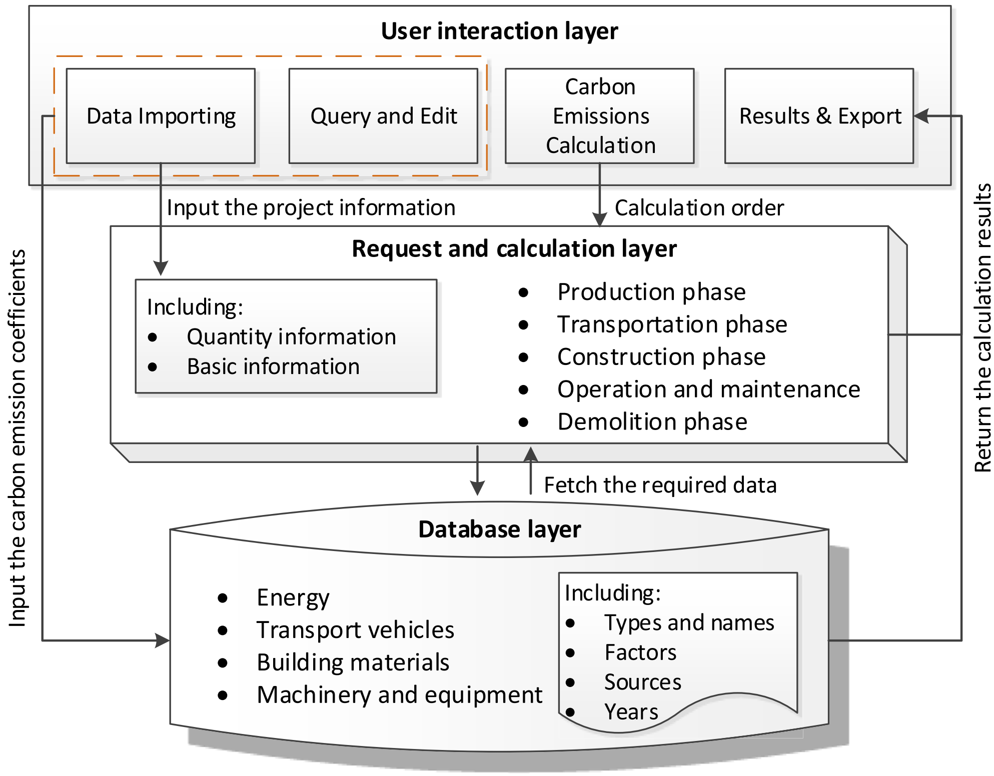

Fig. 2. System architecture.

production phase, transportation phase, construction phase, O&M phase, demolition, assessment results. Users need to fill in structural parameters of a residential building and then click "save" button to the next calculation step, namely 'material production phase' interface. In each step, the system will use individual calculation function to calculate carbon emissions in that step. Finally, after the completion of the whole calculation process, the life-cycle carbon emissions of the residential building will be shown in the resulting interface, and a pie chart will be generated automatically to visually show the proportion of carbon emissions in each life-cycle phase. Users can save and export the estimation results in PDF or Word format.

4. Case study and data collection

To test the applicability of the estimator, this study applied it to a four-storey masonry-concrete residential building in Luhe district of Nanjing. The overall floorage (above ground) of the building is 1838.7 m^2. The design service life of this building is 50 years, and it is built to host 16 households with a total of 40 residents. And the other detailed information is shown below in Table 1. The amount of building materials and machinery and equipment consumed in this project was exported from the Glodon, which is a widely used software in the quantity survey and cost estimation of construction projects in China. The transportation distance of building materials was acquired from Baidu online map, which is the most widely-used map search engine in China.

In addition to the real project data, several key assumptions were also made based on the context of the case. The consumed energy data were collected from various national agencies. For instance, the national average value of natural gas consumption (that is 19.7 m^3 per person in a year) was chosen as the amount of natural gas used in the O&M phase (DESNBS, 2008–2013). The electric consumption was assumed as 1503.0 kWh per person a year by referring to the urban residential electric consumption data in 2013, which was provided by the statistical bureau of Jiangsu province (BSJ, 2013). The data of fuel consumption of transport vehicles were collected from the *average index of road transport energy consumption in China* (Zhou, 2010), and that are 8.3 L per 100 ton per kilometer for gasoline and 6.3 L per 100 ton per kilometer for diesel.

During the O&M phase of 50 years, several temporary materials such as oil and latex paint are assumed to be replaced four times, while other durable materials are assumed to be replaced once, such as doors, windows, wall tiles, roofing waterproof and cast iron products. Moreover, according to China's construction productivity, the demolition is assumed to be completed primarily by construction workers with limited support from machines. Recyclable materials are assumed to include section steel, rebar and rolled products, while their recyclable factors are 0.8, 0.4 and 0.85, respectively (Li, 2007). Finally, all construction and demolition wastes of this project are assumed to be transported via diesel trucks to the nearest waste treatment center in Nanjing Chemical Industrial Park, which is 47.8 km away from the site.

5. Results and validation

After inputting all above data into the proposed estimator, the total carbon emissions and its components can be calculated, and the result is shown in Table 2. Over the whole life cycle of 50 years, the building contributed a total of 1.7 million kg carbon emissions, with annual emissions of 34,992.7 kg and the average emissions per square meter per year of 19.0 kg/m^2/year.

Among various types of emission sources, the energy usage during O&M phase emitted 61% of the total carbon emissions, followed by the embodied carbon of building materials that accounted

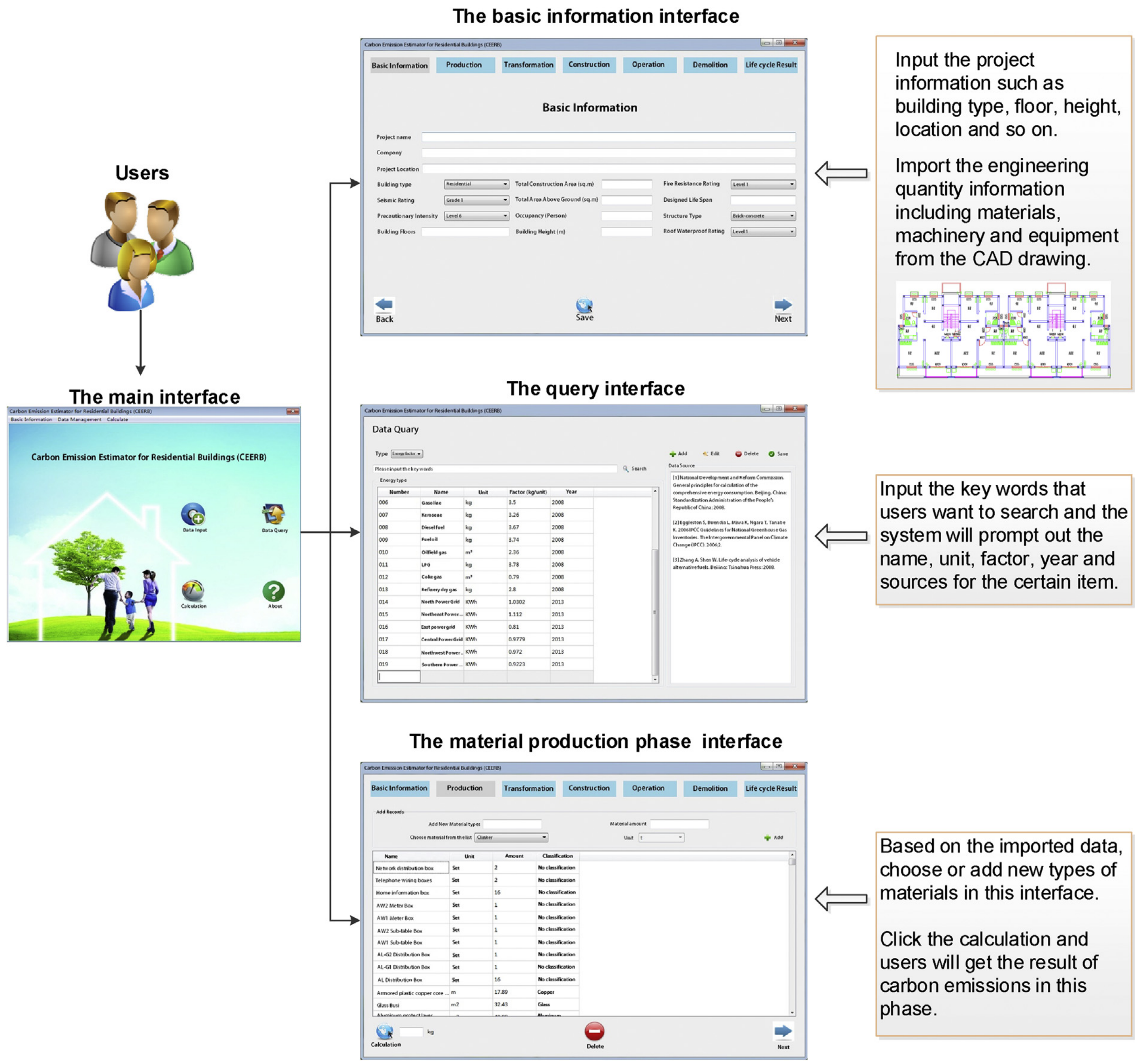

Fig. 3. The primary functions of the system interface.

Table 1
Project overview.

Title	The residential housing project of Zhuzhen Woodland (02#)				
Developer	Zhuzhen Government				
Location	Luhe district, Nanjing				
Building type	Multi-storey residential	Total construction area	1838.78 m^2	Ground floor area	358.43 m^2
Designed service life	50 years	Building height	14.40 m	Seismic intensity	7°
Building layers	4	Climate division	Hot summer and cold winter area	Structural types	Masonry-concrete

for roughly 34%. Transport vehicles and the machinery and equipment occupied 3% and 2%, respectively.

From the life-cycle perspective, this study discussed each of the phases as follows. The largest emitter was the O&M phase, which accounts for 63% of the 50-year building service life. Among it, electricity contributed to 19,479.4 kg carbon per year (equivalent to 88%), the proportion of natural gas was 8%, and the maintenance (primarily the embodied emissions from maintained materials) took up the rest of 3%. The carbon emissions of maintenance primarily came from the replacement of building consumable materials such as iron pipes (15,550.0 kg), paint (442.0 kg), wall and floor tiles (8369.8 kg), aluminium alloy window (3840.0 kg), PPR pipe (6899.4 kg), and so on.

The second largest contributor was the material production phase that provided 32% of the life-cycle emissions, where concrete-related emission (248,721.3 kg) and steel-related emission (111,687.3 kg) together accounted for 64.3% of the total material emissions. Besides concrete and steel, the hollow brick, cement mortar, and mixed mortar accounted for another 25.2% of total carbon emissions. In other words, the top five materials emitted almost 90% of the total emissions. Therefore, it is advisable for the contractors to use more environment-friendly building

Table 2
The Life-Cycle Carbon Emission of the Studied Building (Unit: kg).

Life cycle phases	Source of emissions*					Referred ranges**
	Energy	Embodied	Transport	Equipment	Total	
Production (E1)	N.A.	560,821.9	N.A.	N.A.	560,821.9 (32%)	10%–27% for a conventional commercial building [1]
Transportation (E2)	N.A.	N.A.	33,422.5	N.A.	33,422.5 (2%)	1–8% on average [2] 1–4% for local materials [3]
Construction (E3)	N.A.	N.A.	N.A.	23,725.1	23,725.1 (1%)	1.9% for a reinforced concrete framed building [4] 1% for a RC Structure Column building [8]
O&M (E4)	1,066,953.9	36,187.4	2156.6	1530.9	1,106,828.8 (63%)	15–40% for residential buildings [5] 80–90% for high-rise buildings [6]
Demolition (E5)	N.A.	N.A.	16,271.6	8567.4	24,839.0 (1%)	0.2% for a multi-storey building [7] 1.2% for a RC Structure Column building [8]
Total Emissions (E)	1,066,953.9 (61%)	597,009.3 (34%)	51,850.7 (3%)	33,823.3 (2%)	1,749,637.3 (100%)	

*Note: "Energy" means emissions from direct energy usage (i.e. natural gas, electricity); "Embodied" means emissions from embodied in building materials; "Transport" means the emissions from transport; "Equipment" means emissions from machinery and equipment, and "Total" means total emissions.
**Data Sources: [1] (Kotaji, Schuurmans & Edwards, 2003) [2] (Chau, Yik, Hui, Liu & Yu, 2007; Chen, Burnett & Chau, 2001; Yan, Shen, Fan, Wang & Zhang, 2010) [3] (Buyle, Braet & Audenaert, 2013; Ortiz, Bonnet, Bruno & Castells, 2009; Yung, Lam & Yu, 2013) [4] (Hong, Shen, Feng, Lau & Mao, 2015) [5] (Cole & Wong, 1996; Harris, 1999) [6] (Chau, et al., 2007; Ibn-Mohammed, Greenough, Taylor, Ozawa-Meida & Acquaye, 2013) [7] (Scheuer, Keoleian & Reppe, 2003) [8] (Roh, Tae & Shin, 2014).

materials that generate low carbon emissions during the production process.

The remaining emissions were allocated to three phases: transportation (2%), construction (1%), and demolition (1%), respectively. Regarding the transportation emissions, since all of the building materials came from factories nearby and the majority of transport vehicles were diesel and gasoline trucks, so the share of transportation emissions (2%) was in the low bound of the recommended range (1–4%). It is worth of mentioning that if a more stringent standard like the *Road transport primary or secondary energy consumption standard* (NBSC, 2008–2013) were adopted, the unit fuel consumption (liter per hundred ton per km) and corresponding carbon emission factors would drop. This adjustment would reduce the transportation emissions by 40.1% and 26.7% if standard Level 1 (higher efficient) and Level 2 (standard efficient) were applied, respectively. This reduction suggests that there is still a large room for saving emissions if the government enforce a stricter energy consumption policy for the transportation.

The construction phase accounted for 1% of the life-cycle carbon emissions, which were generated mainly by the energy consumption of machinery and equipment. During this stage, the superstructure project emitted most carbon emissions of 78%, followed by the substructure, mechanical and electrical (M&E), and finishing works. The study estimated more than 100 types of machinery and equipment that were used in this project. The detailed emissions by all kinds of machinery and equipment in three stages are shown in Fig. 4. Suggested emission reduction strategies include limiting the use of tower crane and hoist in the superstructure works, adopting more efficient AC welder in the M&E works. The demolition process accounted for 1% of life-cycle carbon emissions that were mainly due to two sources: machinery and equipment (34%) and waste transport vehicles (66%).

It is worth mentioning that when considering an expanded "construction" phase that is to sum up the emissions happening during the material production, transportation, and construction phases the total emissions accounted for almost 35% of the total emissions that generated at the beginning of the residential building. However, the remaining of 65% emissions was attributed to the long term of building operations. This result also echoes the finding of the past research that although the construction related emissions are not primarily sources for a building (Lu, Cui & Li, 2016), yet its impact could be quite significant since these emissions are released in such a short time.

The result of this paper has been compared to previous studies to show its validity (see the last column in Table 1). Although the context of referring studies may be different from this study regarding building types, climate zones, comfort requirements, local regulations, and different boundary settings (Chau, Leung & Ng, 2015), the share of carbon emissions in each phase over the life-cycle of a building falls within the reasonable range. Such a comparison can justify the accuracy of the result calculated from this proposed estimator.

6. Discussion

In addition to above results, two important issues have been further discussed as follows. One is the annual emission profile, and the other is the impact of using recycled materials.

6.1. Annual carbon emission time profile

Above results provide an understanding of carbon emissions of a building. However, the time distribution of these emissions is unknown. By knowing the time profile of carbon emissions is important because it can help identity the critical timing in which carbon reduces policies can be implemented. According to the life-cycle timeline of a residential building, this paper assumed that the material production lasts for six months at the beginning of the project, immediately followed by the transportation and construction that lasts for 12 months. Upon the completion of construction, O&M lasts for 50 years. At the end of the building's service life, there is the demolition phase that lasts for two months. The study also assumed that, within each stage, the intensity of machinery, equipment and energy use are evenly distributed. After these assumptions and calculation, the profile of annual carbon emissions of the project is shown in Fig. 5.

During the lifecycle phase, although the total amount of emissions from construction was small, the emission intensity per unit of time was very high. Within one year of construction, substructure construction emitted about 1700 kg CO_2 per month, and the superstructure project caused a spike of carbon emissions with 2300 kg per month. When the project approached the M&E and finishing works, the carbon emissions decreased gradually. O&M phase is a long period, where the emissions remained relative stable. Due to the aging of building materials, the building components are scheduled to have a full renovation at the 30th year, and

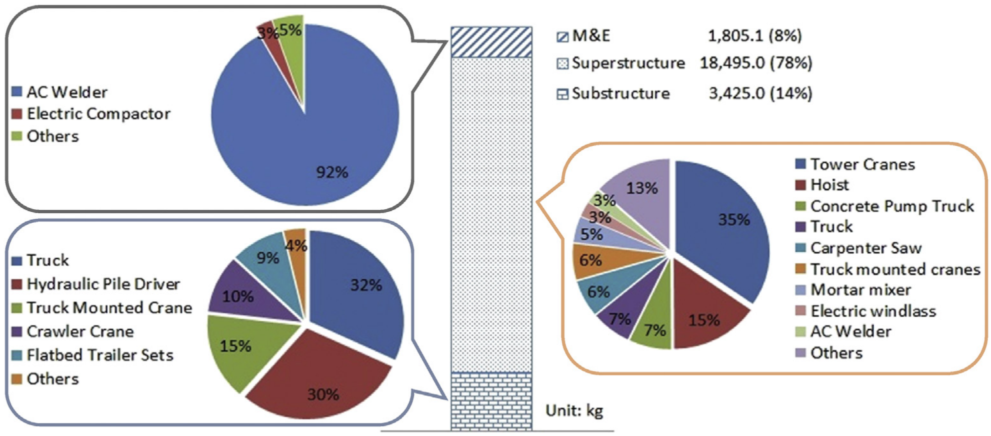

Fig. 4. Carbon emissions during the construction phase.

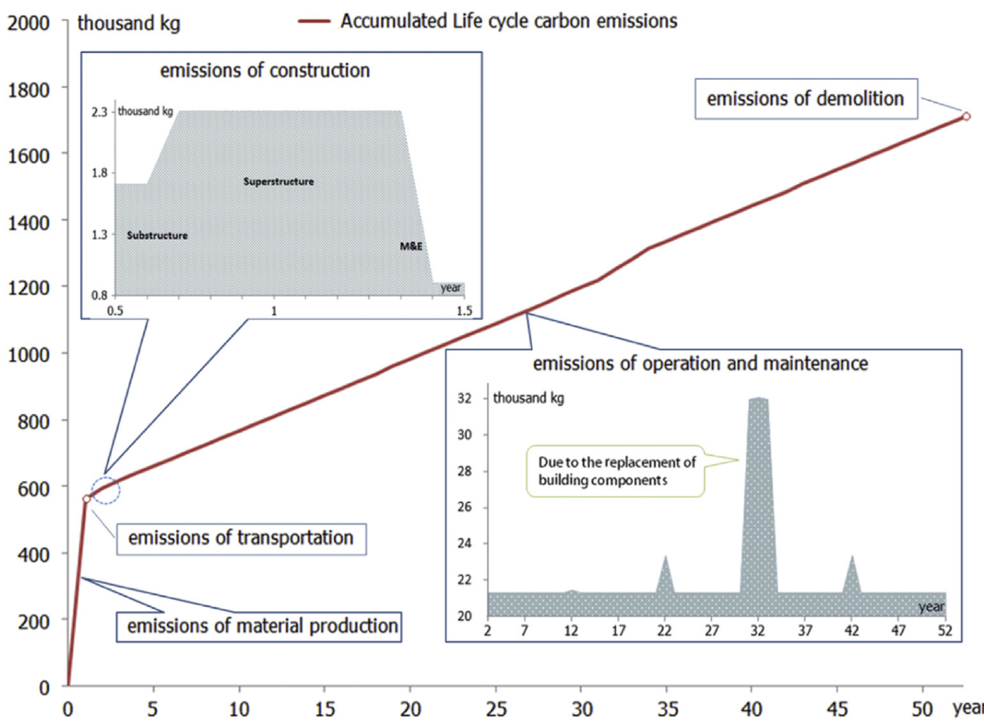

Fig. 5. The carbon emission timeline of the case building.

the carbon emissions could increase to 32,000 kg/year.

It is worth noting that the average life of residential buildings is 38 years in Japan, 44 years in the US, 64 years in Germany, and even 132 years in the UK (Kerckhove, 2012; Yozo Fujino, 2009). In contrast, the residential buildings in China usually last for less than 30 years. Many buildings have even been demolished within 10–20 years of service life, which is far less than the design lifespan of 50 years (Kerckhove, 2012) due to reasons such as the low construction quality, poor operational efficiency (Liu, Wang, Chen, & Shen, 2013), and the change of land use policy. As a result, such a short building lifespan can increase higher annual average emissions for a given building. That is to say, for the two same buildings, the short-life one will be considered with higher annual emissions than the long-life one. For instance, if the same studied building only lasted for 25 years, its annual emissions were 36,937.5 kg compared to the 34,992.7 kg in 50-years life span, an annual increase of 5.6%.

6.2. Emissions from building material recycling

Another key driving factor influencing carbon emissions is to recycle materials. When recycling the materials in the demolition process, two additional carbon emissions should be taken into account: 1) the emissions of the recycled building materials that are delivered to the recycling plant (E_t); 2) the emissions of secondary processing (E_s) that converts the recycle waste to new construction materials. Therefore, the recycled carbon emission (E_r) can be calculated as formula (7), where E_v denotes the carbon emissions using virgin material production.

$$E_r = E_v - E_t - E_s \tag{7}$$

After calculation, a sum of 38,016.9 kg carbon emissions can be mitigated as shown in Table 3. The majority of this recycling is from

Table 3
The mitigated carbon emissions due to recycled materials.

Recyclable materials	Initial amount[a]	Recycling rate[b]	Recycled volumes[a]	E_v (kg)	Et (kg)	Es (kg)	Er (kg)
Reinforced bar	55.91	0.4	22.35	40,007.2	123.8	12,002.2	27,881.3
Copper	0.42	0.9	0.38	4144.0	2.1	1243.2	2898.7
Section steel	1.44	0.8	1.15	2064.4	6.4	619.3	1438.7
Steel Pipe	4.59	0.85	3.90	6975.5	21.6	2092.7	4861.3
PVC	0.01	0.8	0.01	15.4	0.1	4.6	10.7
UPVC pipes	0.37	0.7	0.26	1210.0	1.4	363.0	845.6
Wood	24.89	0.75	18.67	195.1	55.8	58.5	80.8
Total reduced emissions (kg):							38,016.9

[a] Note: The unit for all materials is ton, except for wood which is measured by m^3.
[b] The source of recycling rate is collected from (Li, 2007).

the use of metal materials (i.e. copper, steel, reinforced bar), not only because they have occupied a higher amount in the case building, but also have high recycle rates. For instance, copper has the maximum recycling rate of 0.9. The reinforced bars have the largest recycling amount and the corresponding saving of carbon emissions of 27,881.3 kg.

Further, this study also performed the sensitivity analysis for reinforced bars. Compared with some developed countries, the recycled rate in China remained at a low level of 0.4 (Andersen, 2013). If increased the rate of reinforced bar to 0.9, the recycled carbon emissions will increase 1.25 times to 62,732.9 kg. Therefore, contractors should focus on improving the utilization rate of steel in the construction process to avoid unnecessary waste.

In addition to the steel, developed countries have already made enormous efforts to improve the utilization of all construction materials and wastes. For example, the Japanese government has established a comprehensive resource recycling system that improved the utilization of construction waste from 42% from 1995 to 97% in 2011 (Chen, 2014). South Korea and Germany has reached 95% of the waste recovery rate. Netherlands, Denmark are approximately 80%. The United States and Singapore are 75% and 70% respectively (Tam, 2008). In contrast, the overall recycling rate in China is still very low (about 5%) while it generated 15 million tons of construction waste each year (NDRC, 2014a). So legislating effective policies that can improve the recycling rate for the construction waste is also another key to mitigate carbon emissions from buildings.

7. Conclusion

This study established an automated estimator with a comprehensive database of life-cycle carbon emission for residential buildings in China. In particular, it 1) proposes a calculation method for life-cycle carbon emissions for a residential building; 2) collects and compiles the China's inventory of carbon emission factors in four types, including energy, transportation, building materials, and machinery and equipment; 3) establishes the automated estimator CEERB based on SQLite 3.0 and Qt 4.7; and 4) uses a four-storey residential building as a case to calculate its life-cycle carbon emissions and to verify the feasibility of the proposed estimator. The main conclusion can be summarized as follows.

During the life-cycle of a building project, the O&M phase contributed the most (63%) to the carbon emissions, followed by the material production (32%), transportation (2%), construction (1%) and demolition (1%). The construction related emissions —including building materials, transportation and construction process— generated as much as 35% of the life-cycle emissions in the beginning of the project (within 2 years), while the remaining 65% emissions were generated during the 50 years of building long-term operations and final demolition. During the material production phase, concrete occupied 44% of embodied emissions and followed by the steel of 20%; during the construction phase, the superstructure accounted for 78% of emissions primarily due to the use of tower cranes and hoist; and during the operation phase, the electricity contributed to 88.3% of emissions.

This research provides an automated tool—CEERB—with the carbon emission calculation method and embedded database that can help construction decision-makers quickly and accurately determine the total emissions for a residential project. For instance, contractors can use it to calculate emissions for given construction drawings and quantity take-offs. Designers can also use this tool to compare different plans and to select the one with low carbon emissions.

Although the proposed estimator is proved to be feasible and convenient in a real residential building, there are still rooms to be improved in the future. First, the database, particular the carbon emission coefficients, can be continuously updated and furnished with newly available data. Second, the energy consumption during the O&M phase is currently based on the average value at the provincial level. This value could be replaced by the actual consumption when the real data from the particular project is available. Third, the proposed CEERB can be further connected to Quantity Survey software or GIS software so that the whole calculation process can be made fully automated, and the data can be transferred seamlessly.

Acknowledgements

This research is jointly supported by National Natural Science Foundation of China (No. 71301024), Ministry of Education of the People's Republic of China (No. 20120092120019, No. 13YJC790067 and No. 15YJC790007), Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD), and the National University of Singapore (No. R-296-000-151-133).

Appendix A. A sample of collected carbon emission coefficients for building materials in China

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.habitatint.2016.07.003.

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