Review on building life cycle assessment from the perspective of structural design

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ABSTRACT
The resource-related, environmental and ecological problems raised by building construction activities have drawn a wide range of concerns among researches, especially in China. Those problems have become prominent. In last decade, the building life cycle emissions and energy efficiency have been researched widely. Most of the studies focus on the assessment models and emission analysis based on the available project data and statistical data. Few of them study the emissions from the view of structure design, which can reduce the building emission at source. This review summarizes and examines different models proposed for the building life cycle assessment, focusing on the model scopes, assumptions, and their applications from the view of structure design. A great attention is given to the data used in the current studies. Finally, a variety of future research directions of building life cycle assessment are discussed.

1. Introduction
In 2016, only considering the housing construction in China, the yearly construction area has reached 12.642 billion m², and the completed area has reached 4.224 billion m² (National Bureau of Statistics 2017). In the next few decades, the scale of construction will maintain the same, due to the acceleration of urbanization and large-scale urban construction. The resource-related, environmental and ecological problems behind the large-scale construction have become more prominent. In China, construction activities account for about 40% of total carbon emissions, among which structural engineering accounts for the largest proportion.

In China, the post-evaluation of engineering design is an indispensable mean for the continuous improvement and optimization of technological progress and design. The current adopted evaluation methods are qualitative, rather than quantitative. In the past, it was generally believed that the structural efficiency was reflected by its cost performance. In recent years, with the concept of green structural design being gradually accepted, green can be also considered as one of structural evaluation standards. Currently, “Assessment standard for green building (DB11/T 825–2015)” (Beijing Municipal Commission of Housing and Urban-rural Development 2015) is adopted in China. From the view of structure design, the evaluation is conducted by examining two major items: material saving and design optimization. Due to lack of research data, it is difficult to quantify the examination work, and the evaluation may not be objective. Through the study of carbon emission during the whole life cycle, the emission reduction will be quantified, and structure evaluation can become more scientific if advantages and disadvantages of adopting different structures designs can be assessed. In addition, the introduction of quantitative emission indicators to the evaluation method can also help promote the application of green high-performance materials, structural systems and technics in China’s engineering application field.

In last decade, building life cycle assessment (LCA) has been researched widely. Among them, only Gan et al. (2017a); (2017b)) considered the emissions from the view of structure design. This study aims to give a review on the building life cycle assessment, focusing on the scopes, assumptions and application of different models. A great attention is given to the data used in the current studies.

The contributions of this paper are as follows:

✓ This paper provides a systematic summary of emission estimation methods at each stage and their considerations related to the actual practice.
✓ This paper categorizes current studies into three types and points out the research trends of LCA problems.
✓ This paper points out some problems in the data adopted by the current studies, especially for purchased energies in China.
✓ This paper identifies some research gaps in current studies and highlights some research directions for future studies, especially in the structural design aspects.
2. Related definitions

2.1. Scope of the research

Life cycle can be split into five stages, including (1) material manufacture; (2) material transportation; (3) onsite construction; (4) operation and maintenance; and (5) building disposal.

Stages (1)–(3) are called materialization stage. Stage building disposal considers the procedure of (5a) building demolition; (5b) waste transportation; and (5 c) waste recycling and reuse. Most of the current studies set their research scope as from “cradle” to “grave”, i.e., from (1) to (5), expect for (5 c). Very few research studies the whole life cycle of the building, i.e., from “cradle” to “cradle”. Cycle “cradle” to “cradle” considers the procedure of turning the construction waste into construction material by recycling treatment.

2.2. Measurement indicators

The measurement indicators listed below are commonly used in the recent studies to evaluate the influences from the building on the environment during their entire lives:

(1) **Carbon dioxide**

Materials and energies consumed at each stage are converted to the carbon emissions by carbon dioxide emission factors, then summed up together to obtain the life cycle carbon emission (LCCE). The unit is t CO₂/m².

(2) **Carbon dioxide equivalent (greenhouse gases)**

Other than CO₂, CH₄ and N₂O are also considered. These gases have significant environmental influences compared with others emitted from the building industry. Global Warming Potential (GWP), raised by Intergovernmental Panel on Climate Change (IPCC), is adopted to convert the amount of CH₄ and N₂O to CO₂, which has an equivalent environmental impact. Thus, the summation is also called carbon dioxide equivalent. The unit is t CO₂e/m².

(3) **Energy/heat**

Similar as carbon dioxide and carbon dioxide equivalent, standard coal and heat can also be treated as an environmental impact measure. The calculation model is called Life Cycle Energy (LCE). Standard coal and heat can also be converted to the carbon dioxide equivalent by emission factors. The units are tce and GJ.

Among the above-mentioned indicators, the carbon dioxide equivalent considers the gases which have less emission amount but greater impact on the environment, compared to carbon dioxide. It considers a more comprehensive range, thus is most widely used in the current researches. In the remaining sections, the term “emission” is used to represent the environmental impact measured by the above-mentioned indicators.

2.3. Life cycle assessment models (methodologies)

The models in the current studies are derived from the life cycle assessment to fit their studied problems. Those models can be categorized into three groups: (1) processed method; (2) input–output (I-O) method; and (3) Hybrid method.

The processed method summaries the emissions from materials and energies at each life cycle stage; while the I-O method considers the conversion from the monetary value on the supply chain to emissions during the life cycle. The precision and application of these two methods mainly depend on the input data, including the usage of materials and energies from processed method, monetary value from I-O method and their corresponding emission factors. Table 1 shows the comparison between the processed method and I-O method.

Regarding the processed method, the input data refers to the amount of materials and energies consumed at each life cycle stage and their corresponding convert factors, named as emission factors. For real projects, a common problem is missing data. The usage of structural materials, such as reinforced concrete and steel can be easily accessed from the bill of quantities (BOQ). BOQ can provide the types and quantities of materials with a guaranteed accuracy in form of an exhaustive list. However, it finds difficulties in collecting data on other materials. Here, we take the auxiliary materials used at the stage of onsite construction as an example. The auxiliary materials normally refer to the formwork and scaffolding materials. They are consumables but can be reused with limited times within a project or across projects. Thus, the usage of auxiliary materials for a single project is difficult to

| Table 1. The comparison between the processed method and input-output method. |
|---------------------------------------------------------------|
| **Formulation** | **Processed method** | **Input-output method** |
| Quantity × EF | Monterey × EF |
| Input data | The usage amount of materials and energy | Monetary values on the supply chain |
| Pros | Data reliability | Data availability |
| Cons | Data availability | Data reliability |

EF represents the emission factors corresponding to the listed methods.
obtained. This problem makes the processed method have limited calculation boundaries, and leads to an underestimation of the emissions. For the emission factors used in the processed method, they are determined based on the material manufactory or energy generation technics, thus they are relatively stable.

For the I-O method, the data adopted is the capital input. These values are easy to access and normally quite in details. Compared to processed method, the input-output method considers a more comprehensive range, but the monetary value is fluctuating, which will induce more calculation errors.

The hybrid method is proposed by taking the advantages from the processed method and the I-O method. The ways of hybridization are various based on different concerns of studies. Here, we take the hybrid method proposed by Zhang and Wang (2017a) as an example. For those materials and energies whose usage data can be easily obtained from BOQ, the emissions are calculated by the processed method model, whereas for whose usage data are not clearly stated, I-O method is then applied.

3. Scope of the current research (assumptions and considerations)

Currently, the building-related emission has been researched widely. It includes, but not limited to, BIM information management system (Wang, Zhao, and Liu 2016; Ou, Li, and Li 2016), the life cycle emission for the building heating and cooling systems (Li, Wang, and Guo 2014a, 2015), the recycled concrete emissions (Wang et al. 2015; Xiao, Li, and Ding 2016; Gan, Cheng, and Lo 2016; Ding, Xiao, and Tam 2016; Serres, Braymand, and Feugeas 2016), and the building emission during the lifetime.

Based on the data sources, research can be categorized into two groups, national statistical data-based research and case study-based research. In China, the national statistical data can be accessed from the statistical yearbooks published by National Bureau of Statistics (NBS). The commonly used ones include China Statistical Yearbook, China Energy Statistical Yearbook, China Statistical Yearbook on Construction and Yearbook of China Transportation and Communications. The case study-related data can be obtained from the bill of quantities (BOQ) where the types and quantities of materials are provided by an exhaustive list. If not specified, research in the following text refers to the case study-based research.

In this section, the assumptions and methods proposed by previous studies are summarized. Given the scopes of various research as shown in Table 2, most of the preceding methods considers the entire life cycle or the stages whose summed-up emissions taking up most of the whole. For example, You et al. (2011) and Chen, Cui, and Zhang (2016) set the research scope as the entire life cycle, which also includes (5 c) waste recycling and reuse and (5d) waste treatment. Few papers consider only one specific stage. Kang et al. (2015) focus on the emissions from the stage of material manufactory; Wu, Lai, and Sun (2016) only study the emissions at the stage of onsite construction; Qi et al. (2014) and Jiang (2016) only consider the emissions at the stage of building operation and maintenance.

3.1. Material manufactory stage

Material manufactory stage considers the procedures of raw material extraction and transportation and material manufactory. Emissions are induced mainly from the energy consumption and chemical reaction through these industrial processes.

Very few researches focus on the emission calculation of a single building. Given the BOQ, emissions from all listed materials are calculated (Guggemos and Horvath 2005; Zhang, Lin, and Peng 2014; Chen, Cui, and Zhang 2016; Jia 2016; Zhang and Wang 2016b, 2017a). Most researches consider emissions from main structural materials, including reinforced concrete, cement, rebar and structural steel, and main envelope materials, such as timber, aluminum, glass, bricks/ blocks, aggregates, sands, and ceramics. The criterion for selecting main materials is consistent in all types of researches (i.e., national statistical data-based research and case study-based research). The criterion is to select the materials which contributes the most to both aspect of whole building material content and carbon emissions.

Table 3 summaries main building materials studied in the recent researches. Most of the researches are case study-based. The selected materials from real projects varies. It is a common phenomenon that some of the building material names are not consistent throughout the researches. Thus, materials are categorized as follows:

1. Mao et al. (2013), Han, Zhang, and Fu (2014), She, Zhang, and Qi (2014), Li and Liu (2015), Kang et al. (2015), Zhang and Wang (2015), Xu, Xu, and Li (2016), Li and Bao (2016), Jia (2016), Su and Zhang (2016), and Gan et al. (2017a, 2017b) considered ready-mixed concrete as one of the main structural materials, while others mentioned that cement was selected as the main structural material. Cement is the major component of the concrete; thus, ready-mixed concrete and cement are treated as the same category (presented in the first column in Table 3).
2. Rebar is one of the main structural materials for the reinforced concrete structures, for example, the reinforced concrete office building studied by She, Zhang, and Qi (2014); while for the steel structures, both structural steel and rebar are
| References | Material manufactory | Material transportation | Onsite construction | Building operation | Demolition | Waste transportation | Waste recycling & reuse | Waste treatment |
|------------|----------------------|-------------------------|---------------------|-------------------|------------|---------------------|------------------------|---------------|
| Scheuer, Keoleian, and Reppe (2003) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| Guggemos and Horvath (2005) | ✓ | ✓ | ✓ | ✓ | × | ✓ | × | × |
| You et al. (2011) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| Scheuer, Keoleian, and Reppe (2003) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| Guggemos and Horvath (2005) | ✓ | ✓ | ✓ | ✓ | × | ✓ | × | × |
| You et al. (2011) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | × | × |
| Zhang, Wu, and Le (2012) | ✓ | ✓ | × | × | × | ✓ | ✓ | × |
| Aye et al. (2012) | ✓ | ✓ | ✓ | ✓ | × | ✓ | × | × |
| Mao et al. (2013) | ✓ | ✓ | ✓ | ✓ | × | ✓ | × | × |
| Zhang, Wu, and Le (2012) | ✓ | ✓ | × | × | × | ✓ | ✓ | × |
| Aye et al. (2012) | ✓ | ✓ | ✓ | ✓ | × | ✓ | × | × |
| Mao et al. (2013) | ✓ | ✓ | ✓ | ✓ | × | ✓ | × | × |
| Zhang, Wu, and Le (2012) | ✓ | ✓ | × | × | × | ✓ | × | × |
| Aye et al. (2012) | ✓ | ✓ | ✓ | ✓ | × | ✓ | × | × |
| Mao et al. (2013) | ✓ | ✓ | ✓ | ✓ | × | ✓ | × | × |
| Zhang, Lin, and Peng (2014a) | ✓ | × | ✓ | ✓ | × | × | × | × |
| Zhang, Lin, and Peng (2014b) | ✓ | ✓ | × | ✓ | × | × | × | × |

1 Emissions at the material transportation stage were considered at the stage of material manufactory.
2 Stage of recycling and reuse was not considered in the case study.
3 The transportation from material/structural element production factory to building construction site and structural element production factory/construction site to waste treatment site were also considered at the stage of material transportation.
4 Emissions at material transportation stage are considered at the stage of building construction.
5 No formulation was proposed.
6 Emissions were calculated by BELES. BELES handled waste transportation and treatment at the stage of material manufactory; thus there is no need to calculated emissions during the building disposal separately.
Table 2. (Continued).

| References                  | Material manufacture | Material transportation | Onsite construction | Building operation | Demolition | Waste transportation | Waste recycling & reuse | Waste treatment |
|-----------------------------|----------------------|-------------------------|---------------------|--------------------|------------|---------------------|------------------------|------------------|
| Han, Zhang, and Fu (2014)   | ✓                    | ✓                       | ✓                   | ✓                  |            | ✓                   | ✓                      | ✓                |
| Wang, Zhang, and Wang (2014)| ×                    | ×                       | ✓                   | ✓                  | ✓          | ×                   | ✓                      | ×                |
| She, Zhang, and Qi (2014)   | ×                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |
| Qi et al. (2014)            | ×                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |
| Lin et al. (2015)           | ✓                    | ×                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |
| Li and Liu (2015)           | ✓                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |
| Kang et al. (2015)          | ✓                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |
| Zhang and Wang (2015)       | ✓                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |
| Xu, Xu, and Li (2016)       | ✓                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |
| Liu et al. (2016)           | ✓                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |
| Xiao and Yang (2016)        | ✓                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |
| Wu, Lai, and Sun (2016)     | ×                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |
| Li and Bao (2016)           | ✓                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |
| Chen, Cui, and Zhang (2016) | ✓                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |
| Jia (2016)                  | ✓                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |
| Luo, Liu, and Liu (2016)    | ✓                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |
| Zhang and Wang (2016a)      | ✓                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |
| Zhang and Wang (2016b)      | ✓                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |
| Jiang (2016)                | ✓                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |
| Zhang and Wang (2016c)      | ✓                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |
| Su and Zhang (2016)         | ✓                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |
| Zhang and Wang (2016d)      | ✓                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |
| Wu, Peng, and Lin (2017)    | ✓                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |
| Gan et al. (2017a)          | ✓                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                   | ✓                      | ×                |

7 Emissions at the stage of building disposal in the case study were not calculated by the proposed formulation, but by roughly estimation.

8 Recycling ratio was considered at the stage of material manufactory.

9 Emissions induced by the maintenance procedure at building operation stage were included in the emissions at material manufactory and transportation stage.

10 Emissions was estimated proportionally to the emissions at the materialization stage.

(Continued)
Table 2. (Continued).

| References                  | Material manufacture | Material transportation | Onsite construction | Building operation | Demolition | Waste transportation | Waste recycling & reuse | Waste treatment |
|-----------------------------|----------------------|-------------------------|---------------------|--------------------|------------|----------------------|------------------------|-----------------|
| Gan et al. (2017b)          | ✓                    | ✓                       | ×                   | ×                  |            |                       | ✓                      | ×               |
| Jin et al. (2017)           |                      |                         |                     |                    |            |                      |                        |                 |
| Zhang and Wang (2017c)      | ✓                    | ✓                       | ✓                   | ×                  |            |                      | ×                      | ×               |
| Zhang and Wang (2017b)      | ✓                    | ✓                       | ✓                   | ✓                  | ✓          | ✓                    | ✓                      | ×               |

5. Emissions at the material transportation stage were considered at the stage of material manufacture.
6. Stage of recycling and reuse was not considered in the case study.
7. The transportation from material/structural element production factory to building construction site and structural element production factor/construction site to waste treatment site were also considered at the stage of material transportation.
8. Emissions at material transportation stage are considered at the stage of building construction.
9. No formulation was proposed.
10. No formulation was proposed. Emissions were calculated by BELES. BELES handled waste transportation and treatment at the stage of material manufacture, thus there is no need to calculated emissions during the building disposal separately.
11. Emissions at the stage of building disposal in the case study were not calculated by the proposed formulation, but by roughly estimation.
12. Recycling ratio was considered at the stage of material manufacture.
13. Emissions induced by the maintenance procedure at building operation stage were included in the emissions at material manufacture and transportation stage.
14. Emissions was estimated proportionally to the emissions at the materialization stage.
considered as the main structural materials, like the residential building considered by Xu, Xu, and Li (2016); thus, structural steel and rebar are put together in Table 3.

(3) The materials used for building partition walls are generally decided by the architects. In the previous studies, bricks and blocks are the most commonly used materials, and are considered together.

In Table 3, a “✓” in a column of a particular row means that the material listed in that column is considered by the study listed in the specific row; and no “✓” means that that material is not considered. Other than the materials listed in Table 3, some studies also consider mortar (Zhang and Wang 2015, 2017c), PVC pipes (Li and Liu 2015), copper (Han, Zhang, and Fu 2014; Jia 2016), roofing (Jia 2016; Zhang and Wang 2017a). Compared to the main structural materials, the usage amount of these materials is relatively small, so as the emission. The data accuracy may not be guaranteed. Thus, some studies do not consider the emission from these materials or consider it by roughly estimation. “Counts” means that the number of times a certain material considered in the previous studies. Here, we take ceramics as an example. In total, 4 studies consider ceramics as one of the emission sources in the stage of material manufactory, including Han, Zhang, and Fu (2014), She, Zhang, and Qi (2014), Liu et al. (2016) and Xiao and Yang (2016). Regarding “Counts”, we can conclude that the reinforced concrete, rebar/structural steel, glass, and partition wall materials are the most used materials in the stage of material manufactory. This conclusion is consistent with the actual situation: (1) the reinforced concrete, rebar and structural steel are the structural materials; (2) glass is the major component of curtain wall and windows; (3) bricks and blocks are the most common materials used for partition walls.

Guggemos and Horvath (2005) pointed out that in addition to the building main materials, auxiliary materials (i.e., formwork and scaffolding materials) should also be considered. Those materials can be reused, but with limited time which is presented by turnover frequency. Therefore, the consumption amount of those materials during the building construction cannot be neglected and considered in the stage of material manufactory. The auxiliary materials used for a real project is estimation by \( m_i/f_i \), where \( m_i \) is the usage amount of material \( i \) and \( f_i \) is the turnover frequency \( f_i \) of material \( i \). Zhang (2014) summarized that the turnover frequency for timber and steel are 10 ~ 20 and 50 ~ 100 times respectively according to the engineering experiences. For a certain material, the turnover frequency interval is large. The material quantity calculated by the lower bound value is twice of that obtained from the upper bound value. Thus, a guidance on how to take a reasonable turnover frequency value from the interval should be provided.

### 3.2. Structural system-related considerations

Some current researches focus on the emissions from buildings of specific structural systems. Special considerations on steel structures and reinforced concrete structures are introduced in this section.

| References | Ready-mixed concrete/ cement | rebar/ structural steel | Timber | Glass | Aluminum | Bricks/ Blocks | Aggregates | Sands | Ceramics |
|------------|-------------------------------|------------------------|--------|-------|----------|--------------|-----------|-------|----------|
| Zhang and Zhang (2010) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| You et al. (2011) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Mao et al. (2013) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Li et al. (2013) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Han, Zhang, and Fu (2014) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| She, Zhang, and Qi (2014) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Lin et al. (2015) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Li and Liu (2015) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Kang et al. (2015) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Zhang and Wang (2015) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Xu, Xu, and Li (2016) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Liu et al. (2016) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Xiao and Yang (2016) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Li and Bao (2016) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Jia (2016) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Luo, Liu, and Liu (2016) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Zhang and Wang (2016a) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Su and Zhang (2016) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Wu, Peng, and Lin (2017) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Gan et al. (2017a); Gan et al. (2017b) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Zhang and Wang (2017b) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Zhang and Wang (2017c) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Counts | 22 | 22 | 7 | 12 | 7 | 12 | 5 | 7 | 4 |

Structural steel refers to the steel plate and shaped steel.
3.3. Steel structure-related considerations

The considerations related to the steel structures are as follows:

1. Fireproof paint and anticorrosive paint (Xu, Xu, and Li 2016; Su and Zhang 2016):

As chemical productions, the production procedure of paint materials will introduce non-negatable greenhouse gases. The amount of fireproof paint and anticorrosive paint needed in the steel structure is tremendous, so as the emissions.

2. Steel manufactory processes (Su and Zhang 2016; Gan et al. 2017a, 2017b):

Two main steel production routes refer to the blast furnace-basic oxygen furnace (BF-BOF) and the electric arc furnace (EAF). These two routes differ in the usage of recycled steel scrap. The major raw materials of BF-BOF are pig iron and coke; while recycled steel scrap is the main raw materials for EAF. BF-BOF also utilizes recycled steel scrap but taking up a low percentage. As summarized by Gan et al. (2017a) from the previous researches, the emission factors are $2.09 \pm 0.15$ kg CO$_2$/kg for BF-BOF and $1.54 \pm 0.23$ kg CO$_2$/kg for EAF. To produce steel of same weight, EAF saves 26% of emissions compared to those from BF-BOF.

3. Steel finishing procedures (Mao et al. 2013; Su and Zhang 2016; Gan et al. 2017a, 2017b):

For rebar, it will be transported to the construction site directly from the steel manufactory; while other steel productions, like steel slab, will be transported to the processing factory rather than reaching the construction site. These steel products will be processed and reformed to the required structural elements. During finishing procedures, considerable amount of emissions is induced by fuel combustion and electricity consumption.

3.4. Reinforced concrete structure-related considerations

The major considerations related to the reinforced concrete structures are concrete grades and supplementary cementitious materials.

Li and Liu (2015) mentioned that in the case study the concrete with various strength grades is used, but they consider a same emission factor for the concrete with different strength grades. Regarding the emission factors for the concrete (without supplementary cementitious materials) provided by Gan et al. (2017a), the emission factors for the concrete grade C30, C60 and C70 are $295 \pm 30$ kg CO$_2$/m$^3$, $402 \pm 27$ kg CO$_2$/m$^3$ and $471 \pm 27$ kg CO$_2$/m$^3$ respectively. For the concrete of unit volume, emissions from concrete C70 is 1.5 times those from concrete C30, 1.17 times those from 1.17.

Gan et al. (2015) reported that the embodied carbon in concrete may be affected by its composition, i.e., the application of supplementary cementitious materials, such as fly ash (FA) and ground granulated blast-furnace slag (GBFS). Here, we take concrete C30 as an example. The emission factors for 100% cement, 65% cement plus 35% FA, and 25% cement plus 75% GGBS are $295 \pm 30$ kg CO$_2$/m$^3$, $200 \pm 19$ kg CO$_2$/m$^3$ and $108 \pm 9$ kg CO$_2$/m$^3$. It is obvious that the emissions from concrete can be highly reduced by the use of supplementary cementitious materials.

In all, the emission differences induced by concrete grades and supplementary cementitious materials cannot be ignored, that is, the calculation for the concrete with various grades and compositions cannot be simplified.

3.5. Building material transportation stage

Emissions at the stage of material transportation mainly comes from the fuel combustion by the transportation tools. Given the material weight/volume and its transportation distance, the emissions at the material transportation can be calculated by $Q_{\text{TRANS}} = \sum m_i \cdot D_i \cdot \varepsilon_{\text{trans}}$, where $m_i$ is the weight/volume of material $i$, $D_i$ is the transportation distance of material $i$, $\varepsilon_{\text{trans}}$ is the emission from transporting materials of unit weight unit distance. For the emissions at this stage, the current studies differ from each other in various assumptions and considerations.

Some studies consider trucks, trains and ships as the major transportation tool (Mao et al. 2013; Zhang and Wang 2016a), while others only consider trucks (Li et al. 2013; She, Zhang, and Qi 2014; Li and Liu 2015; Liu et al. 2016). This is because that locally supply is suggested to reduce costs. This assumption is supported by Zhang and Wang (2016a). They studied annual carbon emission from the trucks, trains and ships to transport construction materials in China from 2005 to 2012. The results show that the annual carbon emission from trains and ships take about 7.04% and 32.91% in 2005 and dropped to 2.08% and 11.38% in 2012; while the percentage of annual carbon emission from trucks increased from 60.05% in 2005 to 86.65% in 2012.

Assumptions considered by the previous researches at the material transportation stage are as follows:

1. [Processed method] Zhang and Wang (2015) consider the emissions from the returning trip from the construction site after unloading materials (empty trucks). They assumed that the emissions from the returning trip is about 2/3 of the emissions from the going trip (i.e., from the material manufactory to the construction site). Thus, the emissions factors
adopted in the research is 5/3 times the actual emission factor (in the unit of per kilometer per kilograms);

(2) Input-output method] Zhang and Wang (2017a) assumes that the material transportation cost is about 5% of the material manufactory cost. The transportation cost is then converted to the emissions at the material transportation stage.

Additional considerations introduced by the previous researches are as follows:

(1) For the structures with prefabricated components, the transportation distances include the distances from material manufactory to prefabricated factory and the prefabricated factory to construction site;

(2) For steel structures, the transportation distances include the distances from steel manufactory to the processing factory and processing factory to the construction site;

3.6. Onsite construction stage

The emissions at the construction stage is mainly transferred from the energy consumption by onsite machinery operation, temporary lighting and power supply. The energies include gasoline, diesel, gas, coal, fuel and electricity.

The most commonly used methods are stated as follows:

(1) Subproject-based method

The construction project can be divided into several subprojects. The emissions from each sub-project can be easily estimated given the energy consumption provided by Unified National Construction Engineering Foundation Costs Quota and Unified National Construction Machinery Costs Quota (both in Chinese). The emissions from temporary lighting and power supply can be obtained from the electricity consumed (Wang, Zhao, and Wang 2014; She, Zhang, and Qi 2014; Li and Liu 2015; Zhang and Wang 2015; Liu et al. 2016). This method is most commonly used for processed method.

(2) Cost-based method

Given the bill of quantities (cost), emissions during the construction stage can be calculated, similar as the calculation of the project total cost. The only difference is that the unit cost for each item in the project cost calculation is substituted by the emission factor (Wu, Lai, and Sun 2016). This method is only used in input-output method.

(3) Estimation method

Chen, Cui, and Zhang (2016) use an estimation model (Emission = X + 1.99) which is based on the total floor number (X) of the building to roughly estimate emissions (in kg/m²) during the construction stage.

It should be noted that the emission differences brought by regional power grids in China are considered by Mao et al. (2013), Li and Liu (2015), Chen, Cui, and Zhang (2016) and Zhang and Wang (2016b). The importance of considering regional power grids in China is illustrated later in Section 5.2.

3.7. Building operation stage

The emissions from building operation stage mainly come from two activities, building operation and building maintenance.

Building operation mainly considers lighting, heating and ventilation. Emissions are generated by the consumed energies including electricity, gas, natural gas etc. She, Zhang, and Qi (2014) point out that the energies consumption (emissions) during building operation highly depends on the comfort level requirements and usage schedules of citizens, and climatic conditions. Simulation software is the most common measure adopted by the current studies. It is used to simulate the building operation state during a year. Multiplying to the design life of the building, the total consumption for the building operation is then achieved. Common software includes DeST-H, DeST-C, PBEC2008, Energy plus, e-QUEST, Green building studio and Ecotec.

Regarding building maintenance, emissions mainly come from the material manufactory, transportation and installation of the replaced components. The considered procedure is the same as the materialization stage, therefore, it is also called re-materialization stage (She, Zhang, and Qi 2014). The emissions at the re-materialization stage is calculated by $E^M = \begin{cases} \frac{T^B}{t_i} - 1 & \text{if } T^B/t_i \text{ is an integer} \\ \lfloor T^B/t_i \rfloor & \text{if } T^B/t_i \text{ is not an integer} \end{cases}$, where $E^M$ is the emission during the materialization stage, $T^B$ is the building design life, and $t_i$ is the service life of the material $i$. $T^B/t_i - 1$ or $\lfloor T^B/t_i \rfloor$ represents the number of times that material $i$ has to be replaced. Current studies focus on the replacement emissions from the envelope materials tabulated in Table 4.

Some studies estimate the emissions from re-materialization stage with the reference to those from the materialization stage. For example, Han, Zhang, and Fu (2014) assumed that the emission amount from the maintenance is about 1% of those released by the building structure. In addition, Li and Liu (2015) pointed out that the data for estimating emission from re-
materialization stage is difficult to collect, therefore the emission can be excluded from the calculation boundary, whereas Zhang and Wang (2017a) mentioned that the emission is relatively insignificant compared to those from other stages and can be ignored.

3.8. Building disposal

4. Building demolition and waste transportation

Currently, very rare research studies the emission from building disposal stage. The emission is normally calculated by roughly estimation. For those studies considering the emission from building disposal stage, only (5a) building demolition and (5b) waste transportation are considered and their corresponding emissions are estimation with assumptions as follows:

Given a project,

(1) Based on the energy consumption during the building construction stage

It is assumed that the energy consumption during the building demolition is about 90% of those in building construction stage, so as the mission released. This method is adopted by Li et al. (2013), She, Zhang, and Qi (2014) and Liu et al. (2016). The waste transportation distance is assumed to be 5 km. Regarding the assumption related to the waste, Li et al. (2013) and She, Zhang, and Qi (2014) use the weight/volume same as the one used the material transportation stage, whereas Liu et al. (2016) consider a loss rate of 0.2.

(2) Based on the energy consumption during the materialization stage

Given the research results from Zhong (2005) and Ge et al. (2005), the emission from building demolition stage is about 10.1% and 7.8% of that from the materialization stage. Li and Liu (2015) consider a ratio of 8.95% (i.e., the average value of 10.1% and 7.8%) for estimation, while Jia (2016) uses 10%.

(3) Based on the energy consumption in each subproject

Similar as the building construction stage, demolition stage can also be divided into several subprojects, including removal of elements, ground leveling, crane handling. The emission from each subproject is first estimated based on its emission factor, then summed up to get the total emission from the building demolition (Zhang and Wang 2017a). The emission factors adopted are 7.8 kgCO₂/m² for removal of elements, 0.62 kgCO₂/m² for ground leveling, and 2.85 kgCO₂ /m² for crane handling, obtained by Zhang and Wang (2015).

(4) Estimation model

Chen, Cui, and Zhang (2016) and Wu, Peng, and Lin (2017) use ‘Emission = 0.06X + 2.01’ to estimate the emission (in kg/m²) at the disposal stage, where X is the total floor number of the building.

The above-mentioned methods are applied to the building cases. From the perspective aspect of national building sector, the waste transportation emission can
be estimated based on the building area demolished, denoted by \( A^D \), and the building area under construction, represented by \( A^C \), i.e., \( 0.055t/m^2 \times A^D + 1.3t/m^2 \times A^C \). It should be noted that this emission also includes the construction waste.

### 4.1. Waste recycling and reuse

Currently, few researches consider a negative emission from recycling and reuse of the demolition waste at the material manufactory stage. None of the studies proposes a mathematical model specific for waste recycling and reuse. 

\[ M = (1 + \varphi_1) \times Q_M \times C_M \times (1 - s), \]

proposed by Zhang, Wu, and Le (2012), is commonly used to consider the negative emission impact from waste recycling and reuse at the material manufactory stage. In the equation, \( \varphi_1 \) is the loss ratio due to technological limits, \( Q_M \) is the material weight, \( C_M \) is the material emission factor, and \( s \) is the recycling ratio. \((1 + \varphi_1) \times (1 - s) \times Q_M\) represents the actual amount of the material considered at the material manufactory stage. The weight of materials which can be recycled and reused are directly subtract from the total amount. This may result in underestimation of the material emissions. The reasons are as follows: First, there exist losses during the process of building demolition and waste recycling and reuse. The weight of waste, both nonrecyclable and recyclable, should be smaller than that of the materials composed the building. Second, in the recycling process, energies and additional materials will be consumed, which will lead to more emissions. Here, we take the concrete as an example. Concrete structural elements turn into blocks after demolition. Those blocks have to go through separation, crushing, separation again, and sieving to get recycled concrete aggregates. Through these processes, the production of very small fragments and ashes, which are nonrecyclable components, is inevitable. There must exist some material losses. Therefore, without any supplementary materials, m kg concrete cannot get m kg recycle concrete aggregates through recycling procedure.

Table 5 tabulates the recyclable materials and their corresponding recycling ratio considered in the previous studies. In the table, “not specific” means that the material is considered in the research, but its recycling ratio is not given. “N/A” refers that the material is considered as nonrecyclable. From the table, we can find that structural steel/rebar, aluminum and copper are the most common recyclable materials considered by the current studies. It can also be observed that for a specific material, the recycle ratio proposed in the literatures are quite different. For example, Li and Liu (2015) treat 85% aluminum to be recycled, while Jia (2016) and Wu, Peng, and Lin (2017) only consider 40% and 20.20% respectively. In addition, some data are derived from case studies in the developed countries. Those data cannot describe the current development state in China.

Regarding the above-mentioned phenomena, the actual recycling and reuse ratios for the building materials, which fit the condition of current recycling state, need to be identified. An integrated model for material manufactory and recycling should be proposed to analyze the negative emission impact of recycling materials.

### 5. Trend of the current research

Based on the objectives of the current research, the research can be categorized into three:

I. Single-case study

Based on the project information, emissions during the life cycle are calculated and analyzed. Normally, the single-case study aims to verify the life cycle assessment models. The studies of this type include Shang and Zhang (2010), Han, Zhang, and Fu (2014), and She,
Zhang, and Qi (2014).

II. Multiple-case study

Similar as single-case study, the life cycle emissions for each project are calculated based on its engineering data. Then, the emission differences among selected cases are compared and analyzed.

Studies of this type aim to figure out the emission characteristics of a specific property type/structural system, and/or compare the emission differences from different property types/structural systems. For example, Kang et al. (2015) conducted surveys on 3048 buildings, constructed in the year of 2009 ~ 2013, in Suwon City, Korea. They pointed out that the emissions from reinforced concrete structures take up about 97.49% of emissions from all buildings, thus the emission characteristics of reinforced concrete structure is further studied. Luo, Liu, and Liu (2016) analyzed the emissions from 78 office buildings and proposed emission prediction models on the basis of building height and material usage, respectively. Wu, Peng, and Lin (2017) selected 26 buildings located in various temperature zones in China. The emission characteristics of residential buildings versus commercial buildings, and green buildings versus nongreen buildings are analyzed and the relationship between emissions and structure/building height is studied. Similar studies include Mao et al. (2013) and Zhang and Wang (2016b).

III. National statistical data-based study

Given the national statistical data, the emission factors of the building materials and energies are obtained and applied to the case studies; and the emission trends of building sector can be analyzed. For example, the emission trends of the residential building emissions from 1990 to 2010 in Beijing are studied by Xiao and Yang (2016). The emissions of different regions, in China are calculated according to the regional statistical data provided by Chia Statistical Yearbook (Zhang and Wang 2017b). According to the regional economic development and urbanization reflected by emission data, the emission permit allocation method is proposed. Similar studies include Zhang and Wang (2016a); Zhang and Wang (2016c)), Jiang (2016), and Zhang and Wang (2017a).

For the studies of type I, the objectives are to evaluate the emission conditions for the specific case and verify the proposed life cycle emission model. All the considerations at each stage should be detailed enough to describe the real project case. Those studies normally require a very detailed material and energy usage list. Studies of type II involve the calculation and analysis of emissions for several building projects. They only consider the materials and energies which contributes the most to emissions. For the stage of building construction and building operation, assumptions are proposed to simplify the scenarios. Given adequate samples, statistical analysis is conducted as follows: (1) identify key materials and energies and evaluate their impacts by sensitivity analysis; (2) conduct parameter analysis on building structural systems, building height, property type, construction method (i.e., traditional method or prefabricated method) and building location (i.e., whether and energy structure); propose emission prediction model based on parameters. Studies of type III analyze the emission trends during a certain period.

The research findings of type I studies, i.e., relatively precise emission models, provide the foundation of conducting the research of type II. The findings from type II studies, such as key parameters identification, can provide guidance on collecting real project data and help with the real project database.

6. Discussions

The fitness of models can be affected by the following aspects: (1) the definition of research boundary; (2) assumptions (always related to the boundary); (3) the data accuracy/quality. Here, data refers to the usage amount and emission coefficient of building materials and purchased energies. In this section, how the current research considers the above-mentioned aspects are summarized.

6.1. Emissions during building life cycle

Table 6 summarizes the proportions of emissions at the life cycle stages given by the current research. Given a project, it is obvious that building operation contributes the most, more than 80% and the material manufactory ranks the second, taking up around 15%.

| Table 7. Emission coefficients for purchased electricity in different regions in China (2006 ~ 2011). |
| --- | --- | --- |
| Regional grid | Carbon emission coefficient (tCO₂/MWh) | Greenhouse gases emission coefficient (tCO₂/MWh) |
| | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
| North | 1.0942 | 1.0697 | 1.1067 | 1.0574 | 1.0908 | 1.1282 | 1.0996 | 1.0749 | 1.1121 | 1.0625 | 1.0959 | 1.1335 |
| Northeast | 1.1942 | 1.1389 | 1.1545 | 1.1096 | 1.0760 | 1.1367 | 1.2001 | 1.1444 | 1.1601 | 1.1150 | 1.0812 | 1.1422 |
| East | 0.8614 | 0.8364 | 0.8128 | 0.7976 | 0.7736 | 0.7843 | 0.8565 | 0.8404 | 0.8167 | 0.8014 | 0.7772 | 0.7881 |
| Central | 0.7834 | 0.7645 | 0.6804 | 0.6460 | 0.6660 | 0.7030 | 0.7873 | 0.7682 | 0.6837 | 0.6491 | 0.6692 | 0.7063 |
| Northwest | 0.8409 | 0.8612 | 0.8417 | 0.8186 | 0.8136 | 0.8119 | 0.8450 | 0.8654 | 0.8458 | 0.8226 | 0.8175 | 0.8159 |
| South | 0.7517 | 0.7373 | 0.6525 | 0.6561 | 0.6661 | 0.6694 | 0.7553 | 0.7409 | 0.6556 | 0.6683 | 0.6692 | 0.6725 |
Here, the emissions from building operation consider the summation of the all emissions during its design life, i.e., 50 years. However, the production cycle for material manufactory is much shorter; thus, the emissions are more concentrated than those from building operation. Zhang and Wang (2016a) studied the annual emissions at each stage for the China building sector and brought quite different results: Material manufactory takes up 72.89% out of all life cycle emissions, ranking the first; building operation counts for 24.37%, ranking the second. The large proportion of annual emissions from material manufactory implies massive construction volumes conducted in China in recent years. In addition, considering the promotion and the development of green buildings, the annual emissions from building operation will continue to decline, resulting that the emissions from material manufactory become more and more significant.

Emissions from the stage of material manufactory are directly calculated by multiplying the material usage amount and its corresponding emission coefficient. From the point of view of the structural design, the selection of material types highly depends on the building function and the structure system. The building function affects the choice of the structure system to a certain extent, whereas the structure system determines the material usage of each type. The usage amount and emission coefficient depend on the material type. Here, we take the concrete, which is the major material in the structure design, as an example. As mentioned in Section “Reinforced concrete structure-related considerations”, different emission coefficients should be applied to the concrete with various strengths. Concrete with higher strength has a larger carbon intensity, i.e., a larger coefficient value. Given the structure design concept, material usage can be reduced by the adoption of higher strength materials and the recycling ratio can be enhanced, comparing with the scenarios using relatively low strength. There exist trade-offs among carbon intensity, material usage and recycling ratio. To make a smart material selection, a comprehensive model integrating the emissions at material manufactory and waste recycling and reuse is required to further understand the “actual” emissions from materials. Nowadays, under the premise of meeting all requirements by the codes and specifications, engineers always choose materials to achieve the most cost-effective design. The above-mentioned integrated model can help engineers to propose a both cost-effective and sustainable design. In addition, a problem observed in most developed cities in China is that the tremendous amount of construction waste. It has been far beyond the city treatment capacity. The integrated model is expected to enhance the recycling and reuse ratio of the major materials used by a certain building at this design stage. As a consequence, it can help to relieve the environmental burden induced by the construction waste, reduce the need of virgin materials, thus achieve building sustainability.

Regarding the stage of building disposal, there exists a lack of information. A survey or questionnaire on relevant industrial companies should be conducted to understand the current situation. The form of demolition adopted depends on the structure system and the structure height, so do the structure material and the manner of building construction. Thus, it is suggested to calculate the emission based on structural systems.

6.2. Data-related findings

Zhang, Lin, and Peng (2014) pointed out that the data accuracy is guaranteed by its currency and relevance. Here, currency indicates that the adopted data should fit (or can represent) the current state of social productivity development. As the development of social productivity and technologies, the carbon emissions from unit products varies. Therefore, the emission factors should be updated from time to time. The relevance in LCA problems mainly implies that the data used should be extracted from the condition of the studied location.

One of the most important considerations from regional differences refers to the different energy structure composition in different regions. Various emission coefficients for energy supplies will lead to different material manufactory emissions supplied. For those regions that clear energy is the dominant energy supply, it is obvious that less emissions will be generated by material manufactory.

Table 7 shows the emission coefficients for purchased electricity in different regions in China from 2006 to 2011(Song et al. 2013). Considering a certain region, changes at different degrees can be observed in both carbon and greenhouse gases emission coefficients over time. Here, we take the grid of northeast China as an example. The carbon emission coefficient in 2006 is 0.8614 tCO₂/MWh and reduces to 0.7834 tCO₂/MWh in 2011, decreased by 8.95% in 5 years. Similar trend can be found in the greenhouse gases emission coefficients.

It is worth noting that different countries have different levels of technological development, and the emission factors corresponding to different building materials and energy sources are quite different. Therefore, the emission coefficients adopted in the case studies in China should be consistent with the national conditions and the characteristics of the region where the building is located.

Currently, there are some misunderstandings in the application of data issued by the National
Development and Reform Commission of China. Two sets of data related to carbon emission are “China Regional Grid Baseline Emission Coefficient” and “the Average Carbon Emission Coefficient for China’s Regional Grids in 2011 and 2012”. “China Regional Grid Baseline Emission Coefficient” is released to develop “clean development mechanism” (CMD) projects and greenhouse gas resource reduction projects. Marginal emission (OM) coefficient is proposed by only considering the emissions from fossil fuel power stations, not involving hydroelectric power station, wind power stations, solar power stations, and nuclear power stations. In addition, as the baseline parameter to conservatively estimate the emission reduction, OM value is the lowest value in the confidence interval. Song et al. (2013) pointed out that the use of OM coefficient may lead to overestimation of emissions for the regions where the renewable energies are the dominated energy sources; and underestimation for the regions where fossil fuel power stations are the major energy suppliers. Therefore, it is not suggested to use “China Regional Grid Baseline Emission Coefficient” for emission estimation of electricity in LCA problems. Though data “the Average Carbon Emission Coefficient for China’s Regional Grids in 2011 and 2012” can be used to calculate the emissions from electricity, it is outdated.

Emissions calculations at all stages of the life cycle will ultimately be attributed to emissions from the consumption of energies, including electricity, fuel, natural gas, etc. Electricity is recognized as the most consumed energy source during the building entire life. In order to ensure its accuracy, updated emission coefficients which consider different energy structures in various regions should be proposed.

7. Conclusion

In recent years, building LCA has been researched widely. Most studies focus on the definitions of building life cycle, LCA formulations, methods comparison, and proposing qualitative emission reduction strategies. They applied the proposed formulations and models to some specific/selected projects and draw conclusion from the related results. The aspects stated as below can be enhanced.

(1) Sample size (i.e., the number of projects considered)

In China, the sample size of selected projects may not be large enough to represent the entire industry, thus the calculated emission may not be able to describe the emission state from building sector of China.

(2) Data accuracy (in terms of currency and relevance)

Most research were conducted on the data sourced from developed countries. For those developed counties, the period of intensively construction has been passed. They are now in the state of building maintenance and restore. Therefore, the research focus may be totally different. The developed counties mainly focus on the stage of building operation and maintenance, whereas the developing countries like China should pay more attention on the stage of material manufactory.

As discussed in Section 3.1, the emission factors reflect the development states. The material manufactory technics, construction and disposal manners, and recycling and reuse levels are very different in and outside China. Thus, the actual emissions cannot be obtained with the adoption of emission factors from previous research. This may also affect the conclusion drawn from data analysis. Another issue is that the material usage may also be influenced by the structure safety level designed by national codes, design methods, and the type of structure materials. These influencing factors are region-oriented. In all, the current emission-related data do not fit for China conditions. Some conclusions and/or emission reduction strategies proposed drawn from those quantitative researches may not be able to guide China at all.

To conclude, future study directions listed below are recommended, especially in China:

(1) Regional energy emission factors corresponding to various regional energy structures.

Different methods for generating power lead to various emissions. Thus, for a certain region, proportions of wind power, solar power, and nuclear energy power in the purchased energy will result in different energy emission factors.

(2) Emission factors of concrete at different strength grades.

The emission factors of concrete highly depend on the usage ratio of cement and supplementary cementitious materials. Great diversity can be observed in this ratio throughout regions. The most commonly used ratio needs to be investigated.

(3) The turnover frequency of template for building construction

In the current research, the frequency is selected from a large interval. This may result in big differences in results and leads a totally different conclusion. For example, the importance of reducing the emission at the stage of building construction and the selection of the template materials may be affected.
(4) An integrated model for material manufactory and building disposal.

The actual emission cannot be estimated properly without the consideration of recycling and reuse of building materials (wastes). Steel has been recognized as a “green material” due to its high recycling and reuse rate. If its negative emission impact is not considered, reinforced concrete buildings will be defined as greener than steel structural buildings. Thus, a sound structure selection strategy might be misleading, and an integrated model is demanded.

(5) Prediction models for buildings with different functions and structure systems.

For a specific building, different structural designs cannot be compared at the design stage and the green building evaluation stage. Prediction models can be proposed to help with the comparison and selection of the most efficient structure design.

(6) Establishment of the building structure emission database.

A common phenomenon in China being observed is that the most of the projects’ engineering data are missing or not quality-guaranteed. It is necessary to establish a database to help collect valid data for research and green building evaluation system. The advantages of having this database system are as follows: First, this database can help ensure the quality of the engineering data, so as the emission estimation. Second, with enough samples (i.e., projects studied), a baseline which stand for the average current state of building emission can be defined. This baseline can be treated as the evaluation baseline. It can help study the emission characteristics of buildings with different parameter settings (i.e., different combinations of the building heights, locations, functions, structure systems, and main structural materials).

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