Carbon emissions in the life cycle of urban building system in China—A case study of residential buildings

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ABSTRACT

Urban building system assumes significant environmental and ecological implications in terms of a contribution of emissions of CO₂ and other greenhouse gases. In order to understand the roles of urban building system in the global and regional climate changes, we set up an integrated model to analyze the carbon emissions of urban building system during its life cycle in this paper, which is called LCCE Model. The further analysis is made to examine the sources of CO₂ emissions and the life cycle characteristics of typical architectural structures as masonry-concrete and steel-concrete. We first identified four major sources of CO₂ emissions during the whole life cycle of urban building system, which are industrial process emissions, energy consumption emissions, fugitive emissions and land footprint emissions. Given an assumption of a building life cycle of 50 years, we took urban residential buildings as an example and calculated CO₂ emissions in the main five phases of an overall life cycle of a residential building system, including constructive materials preparation, building construction and reformation, building operation, building demolition as well as wastes treatment and recycling. A comparison was made to examine the differences of CO₂ emissions among buildings with two typical architectural structures as masonry-concrete and steel-concrete. The results show that the latter produces less CO₂ emission than the former per unit area. Specifically, the amount of CO₂ emission is 329.61 t for masonry-concrete buildings and 315.79 t for steel-concrete buildings per 100 m². Most emissions come from energy consumption and land footprint, accounting for 78–83% and 13–20% of the total emissions respectively.

According to our LCCE model, there is a great potential of reducing carbon emissions in urban building system. The key to reduce carbon emissions during the life cycle of urban buildings is directed to building wastes recycling, improvement of consumption patterns of energy and materials, preferential use of buildings with a moderate floor area ratio and effective utilization of natural energy and ecologically friendly building materials according to the characteristics of local urban development.

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1. Introduction

The global climate system is being affected by the emissions of greenhouse gases from human development, especially urbanization activities, of which the most significant is carbon dioxide (CO₂) (Prato, 2008). Many countries have set long-term goals for CO₂ emission reduction (IPCC, 2007). It is widely accepted that human settlements occupy a small proportion of landmass, while playing a significant role in the change of global carbon cycle (Potere and Schneider, 2007). Accurate analysis of urban carbon cycle and its interactions with other global or regional ecosystems is going to be crucial for predictions of future trajectories of atmospheric CO₂

concentrations and global climate change. Recent studies have focused on the carbon fluxes of different land type, such as forest (Churkina et al., 2003), grassland (Torssell et al., 2007) and cropland (West and Marland, 2002; Chakraborty et al., 2006), while neglecting carbon fluxes of urban areas or urbanization regions. As one of the main artificial constructions, urban buildings consume various natural resources, including energy, minerals and water, and release many kinds of pollutants or wastes back to the global/regional ecosystems. These inputs and outputs of mass and energy as a kind of metabolism result in global change presented by air pollution and huge amount of carbon emissions. According to data from the Worldwatch Institute, building sector annually consumes 40% of the stone, sand and gravel, 25% of the timber (Arena and Rosa, 2003). In the member nations of the European Union, buildings consume approximately 50% of the total energy use and contribute almost 50% of the CO₂ emissions released to the

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atmosphere through their life cycles (Dimoudi and Tompa, 2008; Pataki et al., 2009). Besides, compared to other sectors, there is the greatest potential of CO₂ emission reduction in the construction sector at a relative low expense, reaching 5.3–6.7 Gt CO₂ per year (IPCC, 2007), which makes the studies on CO₂ emission reduction from buildings be a hotspot for scientists, publics and policy makers. Although numerous studies have examined several individual phases of a life cycle of buildings, relatively few studies were focused on the carbon emissions over the entire life cycle of buildings. In particular, most studies paid a special attention to energy saving (Buchanan and Levine, 1999; Gustavsson and Sathre, 2006; Dodoo et al., 2009; Li and Colombier, 2009; Kneifel, 2010). Some studies being explicitly dedicated to constructive materials have been done during the recent several years (Seppälä et al., 2002; Nebel et al., 2006), while also neglecting the environmental or ecological performances of the entire building life cycle. The aim of this study is to set up an integrated model (LCCE model) to analyze CO₂ emissions over the life cycle of urban building system with two typical architectural structures as masonry-concrete and steel-concrete. The model is intended to serve as an assessment tool to help us identify major sources, fluxes and sinks of carbon cycle in urban building system or urbanizing areas and to improve the building planning, construction and management, finally promote sustainable transition of developmental pattern of urban building system towards a low-carbon one.

2. Methodology

2.1. LCA-based analyzing method for urban building system

The Life Cycle Assessment (LCA) methodology today represents the main tool used to estimate the positive or negative impacts on various environmental changes and alterations of ecosystems associated to urban building system. Usually, the LCA analysis is presented in the form of aggregation of environmental loads or impacts per unit of building activities, without considering their distributions in time and space (Tukker, 2000). Nowadays, the effective role of LCA methodology in the quantitative assessment of CO₂ emissions and its environmental and ecological impacts has also been recognized by relevant international organizations and researchers.

Carbon fluxes related to a life cycle of buildings can be estimated by using concepts and models developed in urban ecology. The concepts of urban metabolism (Wolman, 1965) and material flow analysis (MFA) or material and energy flow analysis (MEFA) methodology are introduced into this research to examine dynamic characteristics of CO₂ emissions of urban building system (Ulgiati and Brown, 1998; Warren-Rhodes and Koenig, 2001; Huang and Hsu, 2003). Based on these concepts and methodologies, we especially emphasize the three aspects of an overall process of carbon cycle of urban building system, which are sources, fluxes and sinks.

2.2. The definition of a building life cycle

In this article, we define a life cycle of 50 years for urban buildings in accordance with the prevailing design specifications in China, regardless of what the actual life span of a specific building is. From a perspective of building life cycle, the research period spans from the extraction of raw materials needed by buildings to their final demolition when all kinds of wastes are treated or recycled. There are generally five temporal phases including constructive materials preparation, building construction and reformation, building operation, building demolition as well as wastes treatment and recycling. All these phases have to be

considered in order to analyze the CO₂ emissions and environmental and ecological impacts in the life cycle of buildings.

2.3. Determination of main sources of CO₂ emissions

We consider four main sources of CO₂ emissions based on the guidance of IPCC report (IPCC, 2006): industrial process (extracting of raw materials and processing) emissions, energy consumption emissions, fugitive emissions and land footprint emissions.

2.3.1. Industrial process emissions (IE)

Industrial process emissions are caused by chemical reaction inherent to the production processes. For example, cement is made with limestone which releases CO₂ during its chemical decomposition. Its calculation is required to convert from material use amount to CO₂ emissions amount mainly based on chemical reaction equations.

2.3.2. Energy consumption emissions (EE)

This source includes the primary energy consumption and electricity consumption during the life cycle of a building. Primary energy consumption involves a relatively basic transformation from energy use to CO₂ emissions. Use of electricity is required to convert used megawatt hours into CO₂ emissions according to the parameters of CO₂ emissions associated with electricity production composition and efficiency of energy transformation.

2.3.3. Fugitive emissions (FE)

Biodegradable organic matter creates CO₂ emissions through respiration or combustion. Most of timber wastes in dumps are treated by combustion in China, which also contributes to the total amount of CO₂ emissions.

2.3.4. Land footprint emissions (LE)

Land footprint means natural land of ecosystems such as vegetational land or wetland occupied by and changed into other non-vegetational types of land use because of human activities. In this research, buildings and relevant wastes appropriate land which is originally vegetational areas or wetlands. CO₂ emissions from this source are a representative of change in types of land use from green land to built-up areas.

2.4. Connecting processes (fluxes) of building life cycle to their CO₂ emissions

From an ecosystem point of view, building processes like a kind of life metabolism can be demonstrated with fluxes of exchanges of materials and energy between building system and its surroundings. We present a conceptual model for the metabolism dynamics of a building system including three components, namely, inputs of constructive materials or energy, transformation and accumulation as a stock of construction materials or energy within the system and outputs of constructive wastes, all of which form a complete dynamic flux process of a building system in the five stages of its life cycle. Obviously, there is a close coupling relationship between building metabolism and CO₂ emissions, and a process-based analysis framework representing the relationships between materials and energy fluxes and their carbon emissions sources during the building's life cycle is indicated in Fig. 1.

2.4.1. Constructive materials preparation

The main feature of this phase is the intensive inputs of materials and energy. There are mainly six kinds of constructive materials used in a building system, which are cement, steel, timber, brick, gravel and sand. The CO₂ emissions mainly come from industrial process emissions and energy consumption

Fig. 1. Conceptual couplings between a building life cycle and CO₂ emissions.

emissions. The former refers to emissions coming from production of cement and steel, and so on, resulting from the decomposition of limestone or dolomite, and the latter means the emissions from the consumption of primary energy and electricity during the life cycle of all materials, including the process of raw materials extracting, transportation and production. The CO₂ emissions from land footprint occupied by factories and from wastes during processing were not included in this analysis because of data un-availability.

2.4.2. Building construction and reformation

In this phase, diverse materials are assembled into a complete building. Huge amount of constructive materials and energy are consumed in a short time to have a building constructed or reformed. On one hand, some construction wastes are generated in this process, which result in CO₂ emissions from wastes transportation to landfill. On the other hand, energy consumed in the process of constructive materials transportation, working lighting and building base, wall body and roof accounts for a large amount of CO₂ emissions.

2.4.3. Building operation

Generally speaking, the intensity of materials inputs and outputs are relative low in this phase. However, buildings last tens of years, also consuming huge amount of energy during their life cycle. In this phase, the consumption of food and other materials by residents is not taken into consideration in our study, and CO₂ emissions mainly come from energy consumption.

2.4.4. Building demolition

When buildings become out of use, manual or mechanical equipments are used for building demolition. Some wastes from demolition are recycled, while most of building wastes are transported to landfill. Therefore, CO₂ emissions mainly come from energy consumption during this period.

2.4.5. Wastes treatment and recycling

Most of building wastes are piled up in landfills. Some of them are biodegradable, which create CO₂ from fugitive emissions. Other non-degradable wastes occupy land for at least 10 years, which results in land footprint emissions. When taking the recycling of wastes into consideration, most of building wastes are not re-used in a building system, which means that the reduction of CO₂ emissions by recycling is relatively limited. The CO₂ emissions in this phase are determined by energy consumption, fugitive emissions of building wastes, land footprint emissions and the carbon abatement by wastes recycling.

3. Life cycle model of carbon emissions for urban building system (LCCE model)

3.1. Composition and structure of CO₂ emissions model for urban building system

Based on the analysis above, CO₂ emissions during the life cycle of urban buildings can be quantified by the formulas as follows:

$$TE = \sum_{i=1}^5 (IE_i + EE_i + FE_i + LE_i) \quad (1)$$

where TE is total amount of CO₂ emissions, and i is the i th phase of urban building life cycle, and i is from 1 to 5. We defined this basic model of analysis as the life cycle model of carbon emissions for urban building system, which was abbreviated to LCCE Model.

$$IE_i = \sum_{j=1}^n (M_{ij} \times F_j) \quad (2)$$

where IE_i is CO₂ emissions from industrial processes during the phase i , j is the j th type of constructive materials that may produce CO₂ emissions, M_{ij} is the use amount of the j th type of building materials during the phase i , and F_j is the conversion factor of CO₂ emissions for the j th type of building materials.

$$EE_i = \sum_{k=1}^n (M_{ik} \times F_k) \quad (3)$$

where EE_i is CO₂ emissions from energy consumption during the phase i , k is energy type, M_{ik} is the use amount of the k th type of energy during the phase i , and F_k is the conversion factor of CO₂ emissions for the k th type of energy.

$$FE_i = \sum_{l=1}^n (M_{il} \times F_l) \quad (4)$$

where FE_i is fugitive emissions during the phase i , l is the l th type of building wastes that are biodegradable, M_{il} is the generating amount of the l th type of building wastes during the phase i , F_l is the conversion factor of CO₂ emissions for the l th type of building wastes.

$$LE_i = \sum_{m=1}^n (A_{im} \times T \times F_m) \quad (5)$$

where LE_i is land footprint emissions during the phase i , m is the m th type of buildings and their wastes, A_{im} is the area that is appropriated by the m th type of buildings and their wastes during

the phase i , and T is the period of appropriation, F_m is the conversion factor of CO₂ emissions for vegetational land.

3.2. Conversion factors

3.2.1. Conversion factors for industrial process emissions (F_j)

Among the six main constructive materials of cement, steel, brick, timber, gravel and sand, the cement and steel produce CO₂ during the process of production. CO₂ is released during the production of cement due to the calcination reaction. Based on the related data on procedural techniques of constructive materials (Josa et al., 2004; Chen et al., 2007), for producing 1 t of cement, there is 0.75 t of clinker, which needs 0.9 t of limestone (CaCO₃), discharging 0.396 t of CO₂. Therefore, the conversion factor for cement is 0.396 t/t. For steel, 1 t of steel requires 0.367 t of limestone (CaCO₃) and 0.328 t of dolomite (CaMg(CO₃)₂), which discharges 0.319 t of CO₂ (Gielen and Moriguchi, 2002). In this way, the conversion factor for steel is 0.319 t/t.

3.2.2. Conversion factors for energy consumption emissions (F_k)

Coal, Oil and natural gas are mostly used primary energy. The conversion factors of CO₂ emissions vary with types, quality and combusting conditions of energy. To be simplified, the conversion factors of primary energy for CO₂ emissions in this research are taken from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006), as shown in Table 1.

Electricity is a type of secondary energy, being generated in power plants through energy conversion from primary energy. The CO₂ emissions factor is affected by the procedure and efficiency of electricity generation. In this study we use the conversion efficiency of 0.38 for thermal power based on the China Energy Statistical Yearbook (NBS, 2009a) and the composition of primary energy for electricity generation is shown in Table 2. According to the percentages of fossil energy and their conversion efficiency from heat energy into electricity, the CO₂ emissions factor for electricity is calculated to be about 0.798 kg/kwh.

3.2.3. Conversion factors for fugitive emissions (F_l)

Among the six kinds of constructive materials, except timber, most of them are non-degradable, such as cement, steel, sand, gravel and brick. When transported to landfills, timber may release CO₂ by respiration or combustion. The fugitive emissions factor for timber is about 1.467 t/t (IPCC, 2006).

3.2.4. Conversion factors for land footprint emissions (F_m)

Land footprint is caused by both buildings and their wastes. The land footprint is the summed area of the area occupied by buildings, infrastructures and the area required by wastes treatment. The former is land area occupied by building itself and relevant infrastructures, and the latter is determined by the total amount of wastes and required land area for treating a unit of

Table 1
Emission factors for primary energy.

Energy type	CO ₂ emissions factors	Unit
Coal ^{eq}	2.46	kg/kg
Oil	2.76	kg/l
Natural gas	2.09	kg/m ³

Note: a unit of Coal^{eq} is equal to 2.926×10^7 J.

Table 2
Composition of primary energy for electricity power production in 2008 in China.

Energy type	Coal	Oil	Natural gas	Water	Nuclear
Percentage (%)	80.87	11.93	4.13	2.73	0.34

wastes, which is about 0.067 m²/t (Li, 2009). In this study, we assume that the land occupied by buildings, infrastructures and their wastes is originally vegetational one, which generates as much as 73.66 kg/(a m²) of CO₂ (Chen and Su, 1998).

4. A case study of residential buildings

4.1. Estimation of material flows of residential building system

4.1.1. Site investigations and data collection

Urban residential buildings consist of different architectural structures which are made of various types of constructive materials. This analysis takes into account of six main constructive materials of cement, steel, brick, timber, gravel, sand and two types of dominate architectural structures of masonry-concrete and steel-concrete for survey. We investigated about 46 buildings in China, and the main items of building survey include their name, age, storey, architectural structure and area. For these sampling buildings, we obtained the necessary data on uses of constructive materials, land use and bill of quantities for building projects.

4.1.2. Estimation of material use per unit area of the investigated residential buildings

According to the survey data of sample buildings, we calculated the total amount of constructive materials used in different types of buildings, then calculated the use amounts of six main constructive materials per unit area, which mainly included materials used only by the main body of buildings (such as walls, foundation or substructure, roof, etc.). We also calculated the average use amount per unit area for each type of buildings of two typical architectural structures (see Table 3). Furthermore, we made an independent sample T -test between the two types of building structures, which indicated that the use amounts of cement, steel, brick gravel, timber and sand had significant differences between the two types of architectural structures (Hu et al., 2010).

4.1.3. Estimation of construction wastes per unit area for the investigated buildings

The amount of wastes generated is different in different periods of a building life cycle, mainly coming from the phases of materials preparation, building construction and reformation, and demolition. Construction wastes can be quantified by multiplying the quantity of constructive materials with their respective wastage

Table 3
Material use amount of residential buildings per unit area for different architectural structures (unit: t/100 m²).

Constructive materials	Architectural structure	
	Masonry-concrete	Steel-concrete
Cement	14.9 ± 0.1	24.6 ± 2.3
Steel	2.5 ± 0.4	5.9 ± 0.7
Timber	0.7 ± 0.1	0.8 ± 0.1
Brick	37.5 ± 8.7	8.2 ± 3.4
Gravel	36.9 ± 3.5	60.7 ± 5.5
Sand	44.5 ± 3.2	41.7 ± 2.9
Total	136.9 ± 16.8	141.9 ± 14.8

Source: Hu et al. (2010).

Table 4
Wastage rates and recycling rates for different kinds of constructive materials.

	Cement	Steel	Timber	Brick	Gravel	Sand
Wastage rate (%)	3	5	5	3	3	3
Recycling rate (%)	10	90	20	50	60	60

Table 5The generation of building wastes for typical architectural structures (unit: t/100m²).

Constructive materials	Architectural Structure							
	Masonry-concrete				Steel-concrete			
	UA	CW	RA	DW	UA	CW	RA	DW
Cement	14.9	0.44	1.45	13.01	24.6	0.74	2.39	21.47
Steel	2.5	0.12	2.14	0.24	5.9	0.30	5.04	0.56
Timber	0.7	0.03	0.13	0.54	0.8	0.04	0.15	0.61
Brick	37.5	1.12	18.19	18.19	8.2	0.25	3.98	3.97
Gravel	36.9	1.11	21.47	14.32	60.7	1.82	35.33	23.55
Sand	44.5	1.33	25.90	17.27	41.7	1.25	24.27	16.18
Total	136.9	4.15	69.28	63.47	141.9	4.40	71.16	66.34

Note: UA indicates use amount of different constructive materials, CW means generating amount of wastes from construction and reformation, RA indicates recycling amount of constructive wastes, DW means wastes from demolishing.

Fig. 2. Material flow chart of residential buildings for typical architectural structures (unit: t/100 m²).

rates (Zhang et al., 2006). As for demolition wastes, the re-use and recycling of materials should be excluded (Ma, 2004) (see Tables 4 and 5).

4.1.4. Material flows of residential building system

According to the results of analysis above, we established a building material flow chart. This flow chart described a complete dynamic material process of residential building system (Fig. 2.)

4.2. Estimation of energy flows of residential building system

4.2.1. Energy use in the phase of building materials preparation

Based on the data of energy consumption in relevant researches conducted in China and Europe (Josa et al., 2004; Chen et al., 2007; Gielen and Moriguchi, 2002; SFB, 2005; Koroneos and Dompros, 2007; Schuurmans et al., 2005), we got the energy use of different constructive materials (see Table 6). Then, the total energy use for 100 m² of residential buildings during this phase is shown in Table 7.

4.2.2. Energy use in the phase of buildings construction

The construction of buildings includes the transportation of constructive materials and the electricity amount required for

driving electronic instruments and lighting, as well as the diesel fuels used by heavy mechanical equipments at the construction sites.

According to the data of China Statistical Yearbook (NBS, 2009b), 60% of raw materials are transported by railways and 40% by roads in 2008, which cost 0.56 kg coal^{eq}/t and 9.125 kg coal^{eq}/t per 100 km respectively. The transportation distances for different constructive materials are listed in Tables 8 and 9.

The energy used in different procedures of construction varied from each other (Peng, 2002). In this study, energy uses for constructing a masonry-concrete building with 6 floors and a steel-concrete building with 10 floors were calculated as examples, see Tables 10 and 11.

4.2.3. Energy use in the phase of buildings operation

Contemporary typical buildings consume most of energy of their life cycles during the operation phase. The use of buildings covers all living activities that include all the energy consumed for heating, cooling, hot water preparation, lighting, cooking and equipment operation. Based on the report of Chinese Ministry of Housing and Urban-Rural Development, energy use for building operation in 2008 (Ding et al., 2009) is shown in Table 12.

4.2.4. Energy use in the phase of buildings demolition

As discussed in the Section 4.2.2, energy used in different procedures varied from each other. As shown in Table 13, we can get the use amount of energy in the phase of demolition and bill of quantities for building projects.

Table 6

Energy use of per unit constructive materials.

	Cement	Steel	Timber	Brick	Grave	Sand
Coal ^{eq} (kg/t)	119	490	49	28	1	1
Electricity (kwh/t)	140	144	71	12	50	50

Table 7Energy use of constructive materials for per 100 m² of buildings.

Constructive materials	Architectural structure					
	Masonry-concrete			Steel-concrete		
	UA (t)	FF (t coal ^{eq})	Electricity (kwh)	UA (t)	FF (t coal ^{eq})	Electricity (kwh)
Cement	14.9	1.77	2086	24.6	2.93	3444
Steel	2.5	1.23	360	5.9	2.89	850
Timber	0.7	0.03	50	0.8	0.04	57
Brick	37.5	1.05	450	8.2	0.23	98
Gravel	36.9	0.04	1845	60.7	0.06	3035
Sand	44.5	0.04	2225	41.7	0.04	2085
Total	136.9	4.16	7016	141.9	6.19	9569

Note: (1) UA has the same meaning as that in Table 5. (2) FF indicates fossil fuels. (3) t coal^{eq} means tons of coal equivalent, and a unit of Coal^{eq} is equal to 2.926×10^7 J as shown in Table 1.

Table 8

Average transportation distances of constructive materials (unit: km).

	Cement	Steel	Timber	Brick	Gravel	Sand
Distance (by rail)	446	1146	1409	458	458	458
Distance (by road)	171	171	171	171	171	171

Table 9Energy use for transportation of constructive materials (Unit: kg Coal^{eq}).

Building materials	Architectural structure							
	Masonry-concrete				Steel-concrete			
	UA	By train (kg)	By road (kg)	Total (kg)	UA	By train (kg)	By road (kg)	Total (kg)
Cement	14.9	22	93	115	24.6	37	154	191
Steel	2.5	10	16	26	5.9	23	37	60
Timber	0.7	3	4	7	0.8	4	5	9
Brick	37.5	58	234	292	8.2	13	51	64
Gravel	36.9	57	230	287	60.7	93	379	472
Sand	44.5	68	278	346	41.7	64	260	324
Total		218	855	1073		234	886	1120

Note: UA has the same meaning as that in Table 5.

Table 10

Average energy use for different construction procedures.

Procedures	Energy type	
	Fuels (l)	Electricity (kwh)
Field concrete (t)	–	44
Premixed concrete (t)	–	25
Excavation work (m ³)	3	–
Land leveling (m ²)	0.2	–
Fragmentation (m ²)	0.78	–
Lifting (t)	0.28	–
Lighting (m ²)	–	26

Note: “l” denotes a unit of volume “liter”, “kwh” indicates “kilowatt-hour”.

Table 11Average energy use for per 100 m² of constructed buildings.

Phases of procedures	Architectural structure					
	Masonry-concrete			Steel-concrete		
	BQ	FF (l)	Electricity (kwh)	BQ	FF (l)	Electricity (kwh)
Field concrete (t)	91.0	–	4004	30.4	–	1338
Premixed concrete (t)	5.2	–	130	96.7	–	2418
Excavation work (m ³)	66.7	200.1	–	100.0	300.0	–
Land leveling (m ²)	16.7	3.3	–	10.0	2.0	–
Lifting (t)	135.9	38.1	–	141.9	39.7	–
Lighting (m ²)	100	–	2600	100	–	2600
Total		241.5	6734		341.7	6356

Note: (1) BQ indicates the bill of quantities for building projects. (2) FF indicates fossil fuels.

After demolition, most constructive wastes are transported to landfills by garbage trucks. The distance for transportation of wastes is averagely 20 km (Li, 2009). According to the parameter above, we can get the use amount of energy in this phase, see Table 14.

4.2.5. Energy use in the phase of wastes treatment and recycling

Recycling can decrease landfills and partially compensate for the energy consumption of construction. As recycled products can be substituted for a part of raw materials, on the other hand, they are also responsible for the environmental and ecological impacts related to re-processing and transportation. Generally speaking, when recycled, building wastes can be substituted for the raw

Table 12Annual average energy use for per 100 m² of operating buildings.

	Other operational activities of buildings	Heating	Total
Coal ^{eq} (kg)	35	1240	1275
Fuels (l)	7.05	–	7.05
Natural gas (m ³)	125.76	–	125.76
Electricity (kwh)	1651	–	1651

Table 13Average energy use per 100 m² of demolished buildings.

Procedure of construction	Architectural structure			
	Masonry-concrete		Steel-concrete	
	BQ	FF (l)	BQ	FF (l)
Fragmentation (m ²)	100	78	100	78
Excavation work (m ³)	66.7	200.1	100	300
Land leveling (m ²)	16.7	3.3	10	2.0
Lifting (t)	135.9	38.1	141.9	39.7
Total		319.5		419.7

Note: (1) BQ indicates the bill of quantities for building projects. (2) FF indicates fossil fuels.

materials so as to save energy to a certain degree. Most of recycled bricks, gravel and sand may be used as building or roadbed materials, which means its percentage of energy saving becomes an equivalent to 100%. Recycled steels need to be melted and forged before re-using, which means that about 40% of the additional energy is needed to reproduce it. Therefore, the amount of energy saving for different kinds of materials is quantified by energy-saving ratio (ESR) in this study (Table 15).

4.2.6. Life cycle energy flows of residential building system

According to the analysis above, we presented an energy flows chart for residential building system shown in Fig. 3.

4.3. CO₂ emissions of residential building system

Based on the analyses of materials and energy flows of residential building system, the LCCE model discussed in Section 3.1 were used to calculate the CO₂ emission of residential buildings

for masonry-concrete and steel-concrete architectural structures, see Table 16.

5. Results and discussions

5.1. Characteristics of CO₂ emissions for residential buildings

5.1.1. Temporal characteristics

The amount of CO₂ emissions in the life cycle of residential buildings with masonry-concrete and steel-concrete structures is 329.61 t and 315.79 t per 100 m², respectively. During the life cycle of typical residential buildings, it was indicated that 85–90% of CO₂ emissions were created in the phase of building operation, 7–11% came from constructive materials preparation and 3% came from construction. Compared to the three phases above, building demolition generated fewer CO₂ emissions. Besides, the treatment and recycling of building wastes can reduce CO₂ emissions to some extent, which should be attached importance to. Based on the analysis before, the key to realize a goal of low-carbon urban residential buildings is to reduce the energy consumption and land footprint in the building operation phase (Fig. 4).

5.1.2. Characteristics of CO₂ emissions sources

Among the four sources of CO₂ emissions, 78–85% of CO₂ emissions resulted from energy consumption and 13–20% were caused by land footprint. The percentage for industrial process emissions was relatively low, which was 2–4%. And fugitive emissions were very few which could be neglected in the analysis. Most researches have pointed out the importance of carbon abatement by energy saving, while neglecting the potentials by reducing land footprint of urban building systems (Fig. 5).

5.2. Influencing factors of industrial process emissions and potentials of CO₂ reduction

In a building life cycle, industrial process emissions were mainly from cement and steel production. For the same building area of 100 m², the residential buildings with steel-concrete architectural structure created 4.93 t more CO₂ emissions than those with masonry-concrete architectural structure. As shown in Fig. 6, 83–85% of CO₂ emissions were from cement production because of the larger use amount and a relative high emission

Table 14

Average energy use for wastes transportation.

	CW (t)	DW (t)	TW (t)	Distance (km)	FF (kg coal ^{eq}) (by road)
Masonry-concrete	4.15	63.47	67.62	20	123
Steel-concrete	4.40	66.34	70.74	20	129

Note: CW, DW have the same meaning as that in Table 5, TW indicates the total amount of wastes, which is the sum of CW and DW.

Table 15

Average energy saving by wastes recycling.

Building materials	Architectural structure							
	Masonry-concrete				Steel-concrete			
	RA (t)	ESR (%)	FF (kg coal ^{eq})	Electricity (kwh)	RA (t)	ESR (%)	FF (kg coal ^{eq})	Electricity (kwh)
Cement	1.45	20	35	40.6	2.39	20	57	66.9
Steel	2.14	60	629	184.9	5.04	60	1482	435.5
Timber	0.13	10	1	0.9	0.15	10	1	1.1
Brick	18.19	100	509	218.3	3.98	100	111	47.8
Gravel	21.47	100	21	1073.5	35.33	100	35	1766.5
Sand	25.90	100	26	1295	24.27	100	24	1213.5
Total			1221	2813.2			1710	3531.3

Note: (1) RA indicates recycled amount of building wastes, ESR means energy-saving ratio for building materials. (2) FF indicates fossil fuels.

Fig. 3. Energy flow chart of residential buildings per 100 m² with different architectural structures.

factor. According to current technology of cement production, it is very hard to reduce emissions in this phase of production unless cutting down the use amount of cement and steel, or developing other new productive technologies which can substitute a new type of building materials with much less production emissions than the current type of cement products.

5.3. Emission characteristics of energy consumption and its potentials of CO₂ abatement

The amount of CO₂ coming from energy consumption was 257.25 t and 262.9 t per 100 m² for residential buildings with masonry-concrete and steel-concrete architectural structure respectively. steel-concrete residential buildings consumed more energy in the phase of constructive materials preparation, building construction and building demolition, while during the phase of wastes treatment and recycling, it saved more energy than that of masonry-concrete buildings mainly because more steel could be recycled.

Most energy was consumed in the operation phase, the amount of CO₂ emissions reaching 238.61 t per 100 m², which accounted

for 90% of the total amount. And almost 60% of energy was used for heating. When a residential building satisfied the China's state standard for energy saving, the patterns of living energy consumption might determine the total use amount of energy. Therefore, changing the consumption pattern to a level of high efficiency and energy saving was the key to decrease CO₂ emissions.

According to the analysis above, there are various kinds of practical ways to reduce CO₂ emissions in different phases of a building life cycle. Firstly, it is possible to reduce CO₂ emissions by changing the composition of energy consumption. From this aspect, it is shown that coal accounts for almost 60% of the total energy consumption, and the second is electricity, which is about 30% and only 10% is provided by natural gases or other energy. It is obvious that other clean primary energy (solar energy, wind and biomass etc.) are not efficiently used in the residential building system in China, but there is a great potential for better utilizing them. Besides, electricity also can be produced by cleaner primary energy such as solar or wind energy. Adjusting the use pattern of primary energy to produce electricity may help to decrease CO₂ emissions. For example, in China currently, the percentage of clean

Table 16
CO₂ emissions of a residential building system (unit: t/100 m²).

Phases of life cycle	Emission sources							
	IE		EE		FE		LE	
	MC	SC	MC	SC	MC	SC	MC	SC
Building materials preparation	6.68	11.62	15.83	22.86	–	–	ND	ND
Building construction & reformation	–	–	8.68	8.77	–	–	ND	ND
Building operation	–	–	236.81	236.81	–	–	61.51	36.83
Building demolishing	–	–	1.18	1.48	–	–	ND	ND
Waste treatment and recycling	–	–	–5.25	–7.02	0.83	0.95	3.34	3.49
Total	6.68	11.62	257.25	262.9	0.83	0.95	64.85	30.32

Note: MC indicates masonry-concrete, SC means steel-concrete. ND means that the original data were not available in our research.

Fig. 4. Temporal characteristics of CO₂ emissions for residential buildings.

Fig. 5. Characteristics of CO₂ emissions sources for two categories of architectural structures.

Fig. 6. Industrial process emissions for residential buildings.

primary energy in the total energy use is only 3%, while the average percentage in the world is 29% in 2008 (BP, 2009). If the local government invested more money on hydro-electricity and nuclear power or other alternative clean energy, it would be possible to improve the percentage of clean power up to 20%, which means 20.2 t of CO₂ emission reduction per 100 m² of

residential buildings. Secondly, even if the level of electricity production remained stable, if the efficiency of electricity production could be improved to 300 g coal^{eq}/kwh, which might be achieved by contemporary technology, the potential of CO₂ reduction would reach 10.8 t per 100 m² for residential buildings. Last but not least, from the aspect of energy consumption, the building design standard to save energy for 65% in residential buildings would be carried out in 2010 in China, which means energy consumption for heating may decrease up to 8.24 kg coal^{eq}/(m² a). For a 100 m² of residential building, the potential of CO₂ reduction can reach 26.1 t per 100 m² during its life cycle.

5.4. Potential of CO₂ reduction for constructive materials

5.4.1. Characteristics of CO₂ emissions of constructive materials

As the second largest contributor to CO₂ emissions, constructive materials are quite different from each other. In the phase of constructive materials preparation, for 100 m² of building area, buildings of steel-concrete architectural structure consume energy and bring about 22.9 t of CO₂ emissions per 100 m², while the amount for masonry-concrete architectural structure is about 12.8 t per 100 m² because more cement and steel are used in buildings of steel-concrete architectural structure. The contribution percentages of constructive materials to CO₂ emissions in masonry-concrete architectural structure buildings are 38% for cement, 21% for steel, 18% for brick, 12% for sand, 10% for gravel and 1% for timber, and the figures for steel-concrete architectural structure buildings are 43%, 34%, 3%, 8%, 11% and 1% respectively. To reduce emissions in this stage, we need focus on energy saving of cement and steel production (Fig. 7).

5.4.2. Building material and waste recycling in residential buildings

It is possible to save energy and reduce CO₂ emissions by the recycling of building wastes. As shown in Fig. 8, during the phase of wastes treatment and recycling, the reduction amount of CO₂ emissions is 5.2 t per 100 m² for buildings of masonry-concrete architectural structure and 7.0 t per 100 m² for buildings of steel-concrete architectural structure, which mainly result from the recycling of cement and steel.

Energy saving and emission reduction vary a lot because of different recycling rates and re-use pattern. In this study, we compared the EF (emissions factors, including industrial process emissions and energy consumption emissions: the ratio of CO₂ emission to use amount of each type of constructive materials), WRR (wastes recycling rates: the ratio of recycled wastes to total wastes of each constructive material) and ERP (emission reduction percentages: the ratio of CO₂ reduction amount to the total emissions of each type of constructive materials) among the six

Fig. 7. Composition of CO₂ emissions in the phase of constructive materials preparation.

Fig. 8. Characteristics of CO₂ emissions by recycling for different constructive materials.

kinds of constructive materials. From the aspect of EF (Fig. 8), 1 t steel results in the largest amount of CO₂ emissions, reaching as much as 1.64 t, which is followed by cement of 0.80 t, timber of 0.17 t, brick of 0.08 t, gravel of 0.04 t and sand of 0.04 t. As for the recycling rates, 90% of the steel wastes can be recycled, and the figure for brick, gravel and sand is above 50%. However, the recycling rates of cement and timber are relatively low. From the aspect of ERP, steel, brick, gravel and sand have relative high levels of emission reduction percentage which are about 50%, while the figures of cement and timber are low. Based on the three factors discussed above, there are various measures for us to reduce CO₂ emissions from constructive materials. Firstly, we need to decrease the emission factors by improving energy efficiency. For example, heat recovering technology is applied in many industrial sectors in China, including cement and steel, which could help improve energy efficiency; Secondly, effective management may help to improve the recycling rates of building wastes. Besides, it also could be very helpful to save more energy by employing the new technologies of re-use of building wastes.

5.5. Potentials of land footprint emissions reduction

5.5.1. Characteristics of land footprint emissions

Compared to the buildings with steel-concrete architectural structure, the buildings with masonry-concrete architectural structure could bring about more CO₂ emissions of 24 t per 100 m². As discussed above, land footprint emissions were a kind of emissions with a change of land use, which mainly came from building wastes and building itself. As shown in Fig. 9, the former constituted about 5–9% of the total emissions, while the latter accounted for 91–95%. The results of analysis indicated that the emissions resulted from land footprint by a building itself were one of the main sources, which had not been paid enough emphasis in the previous studies.

Fig. 9. Land footprint emissions for different categories of architectural structures.

Fig. 10. A quantitative relationship between land footprint emissions and building stories (BS).

5.5.2. Influences of building stories on land footprint CO₂ emissions

Generally speaking, for the sake of saving of land resources, it is a tendency to build more high-rise buildings. In China nowadays, a lot of flat houses and low-storey buildings have been replaced by the modern high-rise buildings in Beijing and other rapidly developing cities. According to the analysis above, we found out that land footprint emissions accounted for about 13–20% of the total emissions. In this study, buildings of steel-concrete architectural structure with 10 stories can reduce 24 t per 100 m² of CO₂ emissions in comparison to buildings of masonry-concrete architectural structure with 6 stories. How the stories of buildings influence the CO₂ emissions? We made an analysis of correlation between land footprint emissions and building stories, showing that there is a correlation coefficient of 0.99 for power function ($P < 0.01$). As shown in Fig. 10, the land footprint emissions of flat houses are 17 times of that of buildings with 20 stories, 9.2 times of that of buildings with 10 stories and 5.7 times of that of buildings with 6 stories. Furthermore, for a 100 m² area of flat house, the land footprint emissions can reach as much as 370 t of CO₂ emissions, which accounted for about 59% of the total emission amount in its life cycle, and was more than the sum coming from all other emission sources. It was clearly explained that the proper level of building stories is significant to reduce CO₂ emissions in the life cycle of residential buildings, but it is not meant that the higher for building stories, the better for a reduction of CO₂ emission.

5.5.3. Impacts of floor area ratios (FAR) of buildings on their total CO₂ emissions of a life cycle (TCE)

Floor area ratio (FAR) is an important indicator in urban architectural planning and management, which directly reflects the intensity of land use. Just as discussed above, we can raise FAR value by increasing building stories or changing designs of architectural structures which greatly helps reduce CO₂ emissions of residential buildings. In our analysis, there is a correlation coefficient of 0.97 for power function between FAR and TCE of buildings ($P < 0.01$). If we raise FAR value from 1.0 to 1.5, it can decrease 245.5 t of TCE per 100 m² in a building life cycle (Fig. 11). Nevertheless, it also should be pointed out that higher value of FAR indicates higher intensity of land use and greater ecological pressure on urban infrastructures and surrounding ecosystem processes, so a proper or moderate value of FAR is much better for building a sustainable urban building system. It is possible that a city may have higher FAR and lower carbon emission based on a limit of local ecosystem services, and this issue will be explored further in our future research.

Fig. 11. A quantitative relationship between total CO₂ emissions of a building life cycle (TCE) and its floor area ratio (FAR).

6. Conclusions

Urban building system is one of the biggest sources of CO₂ emissions. Our research introduces a newly developed carbon emissions model (LCCE model) to analyze CO₂ emissions of urban building system based on the principle of LCA. A case study from some typical residential buildings of different architectural structures in China was also employed to illustrate how the model help us understand and analyze CO₂ emissions in the different phases of a building life cycle and the differences between buildings with two different architectural structures.

It was shown that the CO₂ emissions during the life cycle of residential buildings mainly came from energy consumption and land footprint. Buildings of masonry-concrete architectural structure created more CO₂ emissions than the steel-concrete structure with the same area. The keys to reduce CO₂ emissions of urban building system are to promote the recycling of constructive materials, transformation of patterns of citizens' consumption and improvement of building floor area ratio in a proper extent.

Our research presents a useful analysis for helping understand the characteristics of carbon emissions of urban buildings, and how the architectural factors affect the carbon emissions of urban buildings as well as the possible potentials for the abatement of carbon emissions for urban buildings. The results from this study provide some references for improving and optimizing the planning and designs of urban building system.

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