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Greenhouse Gas Emissions during the Construction Phase of a Building: A Case Study in China

J. K. Hong, Geoffrey Q. P. Shen, Y. Feng, William S. T. Lau, C. Mao

Abstract: Many studies have been conducted on the contributions of the construction industry to greenhouse gas (GHG) emissions. However, these studies focused on the embodied GHG emissions of buildings and were restricted by limited system boundaries due to a lack of detailed on and off-site process data, especially data for assembly and miscellaneous works as well as construction related human activities. This study therefore analyzed GHG emissions during the construction phase of a case study building on the basis of an extended system boundary in the context of China by utilizing detailed onsite process data. The results show that indirect emissions accounted for 97% of all GHG emissions. On-site electricity use and building materials production were the two greatest contributors to direct and indirect emissions respectively. Recombining the construction activities revealed that construction related human activities generated significant GHG emissions (385 tCO_2e), which have been ignored in previous research. The findings also reveal that although some materials used during the construction process are negligible in terms of weight, such as polyamide safety nets and aluminum (<0.1%), they have a considerable impact on GHG emissions (2-3%).

Keywords: Greenhouse Gas Emission, Extended System Boundary, Building Construction, Case Study.

1. Introduction

In 2012, global energy-related CO_2 emissions reached a historic high of 31.6 gigatonnes (IEA 2013). The construction industry, as the primary contributor of global greenhouse gas (GHG) emissions, plays a significant role in global warming. According to a report by the Intergovernmental Panel on Climate Change (IPCC), the building sector was responsible for 40% of the global energy consumption and contributed a quarter of the global total CO_2 emissions. In fact, global CO_2 emissions generated from buildings increased at an average of 2.7% per year from 1999 to 2004 (Metz et al., 2007). As estimated by the China Building Energy Model (CBEM) in 2007, energy use by the building sector accounted for 23% of the total society energy consumption at that time. Due to its multitude of activities and long term duration, the construction industry has a significant negative impact on environmental sustainability.

Many studies have attempted to quantify the GHG emissions that the construction industry is responsible for. Based on different research objectives and research scope, two approaches have generally been used: (1) macro-level based on the whole construction industrial chain; (2) micro-level based on specific project. At the macro level, previous studies mainly adopted an input-output (I-O) life cycle assessment (LCA) method to quantify the energy or GHG embodied in the whole construction industry within the system boundary of the whole economy. For instance: Jonas et al. (2007) evaluated the energy use and CO_2 emissions from the Swedish building sector through I-O LCA analysis; Chen et al. (2011) set up a low-carbon assessment framework for evaluating carbon emissions based on multi-scale I-O LCA analysis; and Acquaye and Duffy (2010) used I-O LCA to evaluate GHG emissions of the Irish construction sector. At the micro level, hybrid and process-based LCA methods are frequently used in the evaluation of GHG emissions from a certain building or construction project. Salazar and Meil (2009), by comparing life cycle carbon dioxide equivalent emissions of two typical residential houses namely wood frame and wood-intensive house, pointed out that greater wood use can benefit for energy and carbon neutral housing. Kim et al. (2012, 2013a, 2013b) conducted a series of studies on GHG emissions from road construction projects. They established the corresponding framework for estimation of greenhouse gas emissions and applied it in eighteen typical highway construction projects in the Republic of Korea. They also studied GHG emissions from onsite equipment usage in road construction, and summarized eight major GHG related activities on the basis of the emission estimates during the road construction process. By reviewing previous research, Yan et al. (2010) summarized four major emission sources on construction sites, namely building materials production and transportation, energy use of construction machines, energy use for processing resources, and disposal of construction waste. They concluded that GHG emissions embodied in the manufacturing of materials and the fuel used in construction equipment accounted for 88%-96% of total GHG emissions. This result was also consistent with the findings of Cass and Mukherjee (2011).

Recent research suggests that an increasing array of technologies is being applied to assess GHG emissions in the construction industry. Suvish et al. (2013) used the carbon footprint estimation tool (CFET) to evaluate a transportation construction project. Barandica et al. (2013) developed a management information system to in-depth analyze the GHG emissions from road projects in Spain. Wong et al. (2013)

applied virtual prototyping technology to predict onsite GHG emissions for a construction project. Tang et al. (2013) used interactive simulation based method to select appropriate construction management strategies in controlling GHG emissions from unexpected disruptive events. However, in spite of these theoretical developments, high-efficient technologies, and a variety of environmentally friendly policies applied in the building sector, reducing GHG emissions in the construction industry is proving hard to achieve.

Most studies analyzed the GHG impact of construction sites based on incomplete system boundaries, with only a few studies including onsite assembly works and construction related human activities. Also, although China made the largest contribution to the increase in global CO_2 emissions in 2012 (IEA 2013) and some authors have already conducted a series of related studies on GHG analysis in China, the analysis of GHG emissions from human activities during building construction phase is still scarce and lack of actual cases in China according to the restrictions of data availability and incomplete system boundary. Some other studies emphasizing life cycle GHG emissions in China have been reviewed. Xing et al. (2008) made a comparative analysis between buildings with steel and concrete structure in terms of life-cycle energy consumption and environmental emissions. As a result, compared to concrete-frame building steel-framed building only generated approximately half of CO_2 emissions per square meter. Wu et al. (2012) conducted a process-based LCA model to quantify the energy use and CO_2 emissions of an office building, and emphasized the importance of environmental impacts from building operational phase. Zhang et al. (2006) evaluated the global warming potential (GWP) of an office building by establishing a building environmental performance analysis system (BEPAS).

In general, three LCA models are commonly used to conduct GHG emission analysis namely process-based model, I-O analysis model, and hybrid model. However, although the I-O analysis has the advantages of a more complete system boundary, easy data collection, and low time and cost-consumption, the assumptions of the model such as the proportionality and homogeneity still lead to high uncertainties of the final results. Additionally, hybrid LCA model not only has the weaknesses in double counting due to the combination of process analysis and input-output analysis but also time and data intensive. Therefore, considering the availability of detailed process data and the accuracy of the final result required, this study used process-based LCA method to fill the knowledge gap identified above. More importantly, the traditional system boundary will be extended by considering onsite assembly works and construction related human activities in order to reduce uncertainties rising from incompleteness of the system boundary.

2. Methodology

Product carbon accounting is an extension of organizational carbon accounts, which considers life cycle emissions of a product. That is, it reveals all emissions of a product throughout the entire life cycle of the product from cradle to grave. This includes the emissions from all components that make up the product, including emissions from the extraction of all raw materials, the manufacturing of the product's components, the usage phase of the product, and the handling of the product at its end of life as well as the emissions from all necessary transportations. Due to uncertainty over a products future, the carbon accounting standard allows for accounting that stops at the factory gate by allowing the rest to be completed by the downstream manufacturers and/or users. This is also known as ex-factory or from-cradle-to-gate accounting.

The carbon footprint or carbon account of a building is a form of carbon impact accounting that takes account of the climate change impacts of a building. It thus consists of the carbon impacts of all materials that contribute to the construction of the building, as well as the impacts during the construction phase, the operation phase, and the end-of-life phase (demolition). It should be noted that the carbon impacts of the in-use and end-of-life stages are future impacts and that over the many decades of a building's life-span there will be many renovations. Therefore, the carbon impact account of a building during its in-use stage as a whole can only be estimated or projected. This is often accounted for on a yearly basis as an operational account, and there are carbon accounting protocols that cover the in-use stage alone. In fact, the actual use of a building, the building's architecture, and the occupants' behavior will affect operational energy use and GHG emissions. Therefore, as it is difficult to predict the operational performance and assign an advisable life-span for a specific building, this study only focused on the construction phase of the case study building.

The simplest expression of a carbon account is the product of activity data (AD) and emission factor (EF), shown as Equation (1) below.

$$Account = AD * EF \tag{1}$$

While carbon dioxide is the greenhouse gas (GHG) of greatest concern, there are numerous other GHGs. As the impacts of these other GHGs may vary, they are accounted for by a group of conversion coefficients to establish a bridge between the different gases. The global warming potential (GWP), which translates the emission of a specific gas to carbon dioxide equivalent (CO_2e), was used for this study. The Intergovernmental Panel on Climate Change (IPCC) has developed three sets of GWP to account for the impact of a particular GHG with the same amount of CO_2 according to a set time horizon (TH). In this context, GWP is the integral of the global warming effect of GHG compared with that of CO_2 in the same time interval. Three TH are commonly calculated, namely 20 years, 100 years, and 500 years. IPCC's First Assessment Report (1990) quoted an atmospheric life-span of CO_2 to be between 50 and 200 years. Therefore, it is common to use the IPCC 100 TH GWP. For methane, the conversion coefficient is 25 and for nitrous oxide is 298. See Equation (2).

$$CO_2e = AD * EF * GWP \tag{2}$$

The carbon account of an entity, whether it is an organization, a product, a building, or even a nation, is the summation of all relevant emission sources. Therefore, the final expression of a building's carbon footprint can be shown as Equation (3).

$$Account = \sum_{i=1}^{n}(CO_2e)_i = \sum_{i=1}^{n}(AD_i * EF_i * GWP_i) \tag{3}$$

The basic steps required in ISO14064 include describing the project, identifying the scope of the account for the project, identifying GHG emission sources for estimation, quantifying the emissions, and reporting the final results (ISO 14064). This study has defined 8 emission sources in terms of direct and indirect emissions, aimed at a detailed analysis of the GHG emissions from the construction process by comprehensively considering on and off-site construction related human activities. The study's evaluation framework is shown in Figure 1.

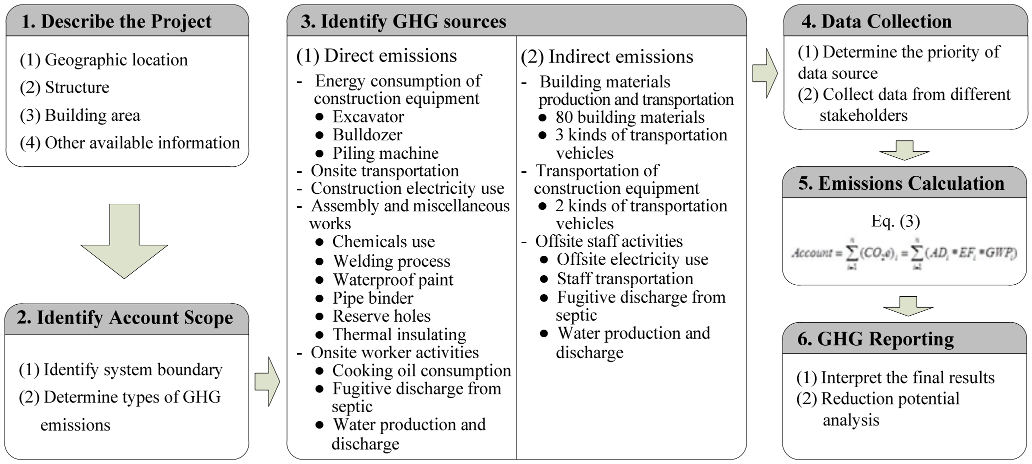

Figure 1: The framework of GHG emissions calculation

3. Case Study

3.1 Description of Project

The case study project is the podium of the Golden Valley Phase 2 residential complex in China's Guangzhou Province, which is a reinforced concrete framed building comprises by a club house and retail outlets, covering a building area of 11,508 m2 (the total area of the complex is 70,222 m2). The investigation period was from April 1, 2008 to August 31, 2010.

3.2 Scope of the Account

The scope of the account for this study covered the carbon impacts of all activities during the construction period of the building, including the direct emissions from fuel used in construction equipment and vehicles, onsite electricity use, assembly and miscellaneous works, and indirect emissions from the manufacture and transportation of building materials, transportation of construction equipment, and offsite construction related staff activities.

It should be noted that some construction activities, such as the use of waterproof paint and construction of thermal insulating, would create other GHGs. As previously mentioned, the purpose of a building carbon account is to reflect its climate impact and there is therefore no reason for the account to be consistent with all types of GHGs or other newly identified GHGs. In fact, the impact of such emissions would be very small.

3.3 Data Collection

In order to collect accurate process data on and off the construction site for the purposes of this study, the authors enlisted the help of and sought collaboration between client, contractor, supplier and other stakeholders. After interviews with the aforementioned and having conducted field investigations, process data was collected from multiple sources. Priority was allocated to different data sources so as to confirm the accuracy of the data. The data sources and their corresponding priority are shown in Table 1 below.

Table1: Data sources and the corresponding priorities

Data Source	Priority
Accounting receipt (e.g. electricity purchase bill/diesel purchase bill)	1
Stakeholder's report (e.g. material supply record)	2
Bill of quantity (BOQ)	3
Material use application record	4
Secondary data from the procurement agency	5

4. Quantification of GHG Emissions

For the activities that occurred during the construction period (April 1, 2008 to August 31, 2010), the quantification can follow the guidance of ISO 14064-1:2006 on direct and indirect emissions. The first step in this section is therefore the establishment of a calculation method for all emission sources related to Golden Valley Phase 2 within this specific period. Emission factors from Ecoinvent v2.0 software will be used to calculate the emissions from building materials production and transportation while the emission factors for direct fuels burning and energy use will be adjusted under the suggestion from IPCC guidelines.

4.1 Fuels Used by Construction Equipment and Vehicles

Statistical and scientific research by IPCC has revealed that machinery and equipment can emit different amounts of methane and nitrous oxide, which can be categorized in terms of stationary, mobile and off-road combustions (Eggleston et al., 2006). For the construction site, off-road combustion replaces stationary combustion as all machinery and equipment on site would not be permanent. Similarly, mobile emissions include the emissions from vehicles used on site. The emission factors for off-road combustion were developed using the default values suggested by the IPCC 2006 Guidelines. The default emission factors of CO_2, CH_4, N_2O are 74100, 4.15, and

28.6 kg/TJ for diesel oil respectively. Considering the heat value of diesel remains the same in China Statistical Yearbooks from 1986 to 2012, this study adopted the heat value of diesel suggested in the Appendix IV of China Energy Statistical Yearbook (2012), which is able to accurately reflect the diesel quality in context of China. The corrected emission factors for diesel oil are 3.16 kg CO_2/kg, 0.177 g CH_4/kg, and 1.220 g N_2O/kg (See Equation 4, 5, 6). The emission factors for mobile vehicle emissions can also be developed from the IPCC 2006 Guidelines, where the default emission factors of CO_2, CH_4, N_2O for diesel oil are 74100, 3.9 and 3.9 kg/TJ respectively. Similarly, they are equal to 3.16 kg CO_2/kg, 0.166 g CH_4/kg, and 0.166 g N_2O/kg.

Default EF_{CO2} = 74100 $kgCO_2/TJ_{diesel}$

Average heat value of diesel = 42652 kJ/kg_{diesel}

$$\text{Corrected } EF_{CO2} = 74{,}100\ kgCO_2/TJ \times 42652\ kJ/kg_{diesel} \times 10^{-9} = 3.16\ kgCO_2/kg_{diesel} \quad (4)$$

Similarly,

$$\text{Default } EF_{CH4} = 4.15\ kgCH_4/TJ \times 42652\ kJ/kg_{diesel} \times 10\text{-}9 = 0.000177\ kgCH_4/kg_{diesel} \quad (5)$$

$$\text{Default } EF_{N2O} = 28.6\ kgN_2O/TJ \times 42652\ kJ/kg_{diesel} \times 10^{-9} = 0.0012198\ kgN_2O/kg_{diesel} \quad (6)$$

4.2 Electricity Consumption

For purchased electricity, LCA studies for electricity production have been extensively studied in past years. In fact, the types of energy sources used to produce electricity as well as the system boundary considered in LCA analysis have a direct impact on the value of emission factor. Table 2 summarizes the emission factors for electricity generation resulting from previous research. It can be found that the value of emission factor is similar for a certain type of energy source in different geographic location and system boundary. A complete LCA analysis of electricity production should include fuel extraction, facility construction and demolition, facility operation and maintenance, residual products from fuel, network construction, operation, demolition, and transmission losses. This study employed EU emission factor data based on the complete system boundary to calculate the GHG emissions from electricity production. Moreover, given the target building is located in Guangdong province where the electricity supply depends on the mixed source of power (coal, oil, gas, hydro, and nuclear), the proportion of energy sources for electricity generation in China (Table 3) is used as the weighting factor to calculate the weighted average emission factor (Equation 7).

$$EF_{grid} = W_i \times EF_{co_2,i} \quad (7)$$

Where EF_{grid} is the weighted average emission factor of electricity production from cradle to grave, W_i represents the proportion of energy source i used for electricity production, $EF_{co_2,i}$ is the EU CO_2 emission factor of fossil fuel type i.

Therefore, the weighted emission factor for electricity production is 0.7898.

Table 2: Distribution of the amount of electricity among different generation method

Ref.	Region	Year	Scope	Sources	kg CO_2e/KWh
1	Hong Kong	2007	-	Average [a]	0.570
2	Australia	2003	Cradle to grave (Include facilities construction and demolition)	Coal	1.127
				Natural gas	0.512
3	Sweden	2005	Cradle to grave (Include facilities construction and demolition, network construction, operation, demolition, and transmission losses)	Average	0.006
				Coal	0.690
				Oil	0.550
				Hydro	0.005
				Nuclear	0.003
				Natural gas	0.410
				Wind	0.012
4	Thailand	2009	Cradle to grid	Thermal power	0.690
				Combined cycle power	0.540
5	Korea	1998	IPCC method (Include distribution loss)	Average	0.460
	Japan	1997	Japan method (Include distribution loss)	Average	0.380
	Europe	1994	CORINAIR method (Include distribution loss)	Average	0.440
6	Canada	2001	Cradle to grid (Include facilities construction)	Coal	1.050
				Oil	0.778
				Hydro	0.002
				Nuclear	0.015
				Natural gas	0.443
7	Europe		Cradle to grave	Coal	1.001
				Oil	0.840
				Hydro	0.004
				Nuclear	0.016
				Natural gas	0.469
				Wind	0.012

Reference: 1. EPD (2008); 2. May and Brennan (2003); 3. Vatenfall (2005); 4. Phumpradab et al. (2009); 5. Lee et al. (2004) ;6. Gagnon et al. (2002); 7. EURELECTRIC Renewables Action Plan (2011)

Table 3: Distribution of the amount of electricity among different generation method

Country	Total Production of Electricity (Million KWh)	Electricity Generation from Coal (%)	Electricity Generation from Oil (%)	Electricity Generation from Gas (%)	Electricity Generation from Hydro	Electricity Generation from Nuclear

					(%)	(%)
China	4208261	77.80	0.30	1.60	17.20	1.80

Source: China Energy Statistical Yearbook 2012

4.3 Assembly and Miscellaneous Works

In this study, the onsite assembly and miscellaneous works include chemicals use, welding processes, waterproof paint, pipe binders, holes reservation, and thermal insulation, which are actually involved with seven types of GHG emissions, namely CO_2, CH_4, N_2O, C_2H_2, HFCs, PFCs, SF_6. However, the purpose of a building carbon account is to reflect its climate impact and there is therefore no reason for the account to be inconsistent with all types of GHG, including those newly identified. In fact, GHG emissions such as HFCS, PFCS, SF_6 are rarely found in the building construction process. One of the direct emissions from a construction site is the combustion of acetylene during the welding process. The stoichiometric methodology is commonly used for developing the emission factor for acetylene. According to the chemical formula:

$$2C_2H_2 + 5O_2 \rightarrow 4CO_2 + 2H_2O \qquad (8)$$

The molecular weight of acetylene is 26 and that of carbon dioxide is 44. Therefore, one molecule of acetylene will form 4x44/2x26 = 3.3846 molecule of CO_2, which means the emission factor is 3.3846 kg CO_2e/kg for acetylene.

4.4 Building Materials Production

The quantification of GHG emissions from the manufacture of building materials is difficult, since there is a common lack of data in China. The College of Architecture and Environment of Sichuan University is currently developing a set of Chinese Life Cycle Database (CLCD) but until this is fully developed, using proxy data from LCA software remains the most feasible option. This study engaged proxy data that are available on international LCA software. The emission factor for each material was obtained from the Ecoinvent v2.0 software. Although most of these emission factor data have been developed for Switzerland and Europe, there are a few for global use.

4.5 Transportation

GHG emissions from the transportation of building materials and construction equipment were both considered in this study. The transportation emission factors in terms of tkm (ton-km) are used in the study, which were also extracted from Ecoinvent v2.0. The distances between the suppliers and the work site were obtained from Google Maps.

4.6 Workers and Staff Activities

Direct emissions from onsite human activities in this study include liquefied petroleum gas (LPG) consumption for onsite cooking, electricity consumption in the site office, and fresh water consumption. Indirect emissions include the emission impacts from the offsite office supporting the construction of the Podium, which includes the electricity consumed by the office, the emissions from gasoline used in company cars, and water consumed. The fugitive emission from septic refers to the impact from workers on site and staff working in the office. The quantification follows the national accounting method as described in the IPCC 2006 Guidelines Volume 5, Chapter 6.

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Table 4: The content of direct emission sources on construction site

Construction activity	Items	Quantity	Energy type	Emission Factor	Priority
Off-road combustions	Excavator	2 unit	Diesel	3.16 $kgCO_2/kg$ 0.177 gCH4/kg 1.220 gN_2O/kg	5
	Bulldozer	2 unit			5
	Piling machine	1 unit			5
Mobile Combustions	Vehicle	12 unit	Diesel	3.16 $kgCO_2/kg$ 0.166 gCH_4/kg 0.166 gN_2O/kg	5
Welding process	Combustion of acetylene	675 kg[a]	Acetylene	3.38 $kgCO_2/kg$	2
Construction electricity purchased	On-site electricity use	212462.2 kWh	Electricity	0.7898 $kgCO_2/kWh$	1
On-site worker activities	Cooking oil consumption	1216 kg	Liquefied petroleum gas	3.17 $kgCO_2/kg$ 0.0502 kgCH4/kg 0.005 kgN_2O/kg	1
	Fugitive discharge	380 kgBOD[b]	Methane	0.30 kgCH4/kgBOD	2
	Water production	10320 m3	Water	0.42 $kgCO_2/m3$	1

Table 5: The content of indirect emission sources

Construction activity	Items	Quantity	Emission Factor	Priority	Construction activity	Items	Quantity	Emission Factor	Priority
Building material production[c]	Tubular pile	11292.3 t	1.45 $kgCO_2/kg$	3	Building material production[c]	Wire entanglement	12.0 t	2.84 $kgCO_2/kg$	3
	Concrete	4443.5 m3	261 $kgCO_2/m3$	3		Formwork	46.0 t	644 $kgCO_2/m3$	3
	Talcum powder	617.7 t	1.25 $kgCO_2/kg$	3		UPVC pipe	7.8 t	3.23 $kgCO_2/kg$	3
	Steel	761 t	1.45 $kgCO_2/kg$	3		Marble	90.9 t	0.436 $kgCO_2/kg$	3
	U. F. foamed plastic	158.3 t	2.91 $kgCO_2/kg$	3		Gravel	6835.5 t	0.00241 $kgCO_2/kg$	3
	Polyamides safety net	26.4 t	9.27 $kgCO_2/kg$	3		Ceramic	14.6 t	0.78 $kgCO_2/kg$	3
	Cement	244.2	0.759 $kgCO_2/kg$	3		Mosaic	34.5 t	0.238 $kgCO_2/kg$	3
	Aluminum	29.6 t	5.9 $kgCO_2/kg$	3		Alcohol	9.7 t	0.828 $kgCO_2/kg$	3
	Stainless steel product	72.2 t	1.45 $kgCO_2/kg$	3	Transportation	Lorry 3.5-7.5t	28629 tkm	0.66 $kgCO_2/tkm$	5
	Glass	86.1 t	1.09 $kgCO_2/kg$	3		Lorry 7.5-16t	263275 tkm	0.292 $kgCO_2/tkm$	5
	Slag	176.6 t	0.443 $kgCO_2/kg$	3		Lorry 16-32t	1318493 tkm	0.168 $kgCO_2/tkm$	5
	Clay haydite	227.8 t	0.327 $kgCO_2/kg$	3		Lorry >32t	245160 tkm	0.117 $kgCO_2/tkm$	5
	Welding rod	3.1 t	20.5 $kgCO_2/kg$	3	Offsite activities	Off-site electricity use	133996.6 kWh	0.7898 $kgCO_2/kWh$	1
	Polyurethane	13.4 t	4.31 $kgCO_2/kg$	3		Staff transportation	8177 kg	2.99 $kgCO_2/kg$ 1.078 $kgCH_4/kg$ 0.345 kgN_2O/kg	1
	Perlite	45.6 t	0.995 $kgCO_2/kg$	3		Fugitive discharge	84 kgBOD[b]	0.30 kgCH4/kgBOD	2
	Timber plates	59.6 m3	583 $kgCO_2/m3$	3		Water production	3176 m3	0.42 $kgCO_2/m3$	1

*Note: **a.** The acetylene is carried in a solvent (acetone or DMF (Dimethyl-Formamide)). The solubility of acetylene is quoted as 227 g/l; **b.** The quantification will follow the national accounting method as described in IPCC 2006 Guidelines Volume 5 Chapter 6; **c.** This part only lists the materials accounting for more than 0.1%.*

The primary construction activities and their corresponding emission factors are listed in Table 4 and Table 5. According to the priority assigned to each item of data, the average priority of direct emissions and indirect emissions is 3.00 and 3.03 respectively, indicating that the data sources for this study were relatively reliable and acceptable.

5. Results and Discussions

5.1 Results Analysis

By applying corresponding emission factors and aforementioned equations, the final results of GHG emissions from the case study construction site can be calculated. Table 6 shows the total GHG emissions of the Podium of the Golden Valley Phase 2 and the corresponding percentage of direct and indirect emissions. The table clearly shows that direct emissions due to onsite construction (Scope 1) are relatively small at only 2.42% of the total GHG emissions, while indirect emissions (Scope 2) embedded in the production of building materials, transportation, and offsite human activities are considerably more at 97.58%. This vividly illustrates the value of exploring the large reduction potential existing in the upstream process of the construction phase. Further disaggregating of Scope 1 (Figure 2) reveals that construction electricity use is dominated by the conglomeration of many different emission sources on construction sites (79.56%), followed by emissions from construction machines such as excavators, bulldozers, and piling machines (10.60%), and the use of mobile vehicles such as lorries and dump trucks (3.50%). Onsite assembly and miscellaneous works, although generating some non-CO_2 GHGs, account for such a small amount of emissions that they can be ignored for all purposes.

Table 6: The result of total GHG emissions (kg)

	CO_2	CH_4	N_2O	CO_2 equivalent	Percentage
Scope 1	207641	115.40	1.34	210925	2.42%
Scope 2	8494385	34.16	2.82	8496079	97.58%
Total	8702026	149.57	4.16	8707004	100.00%

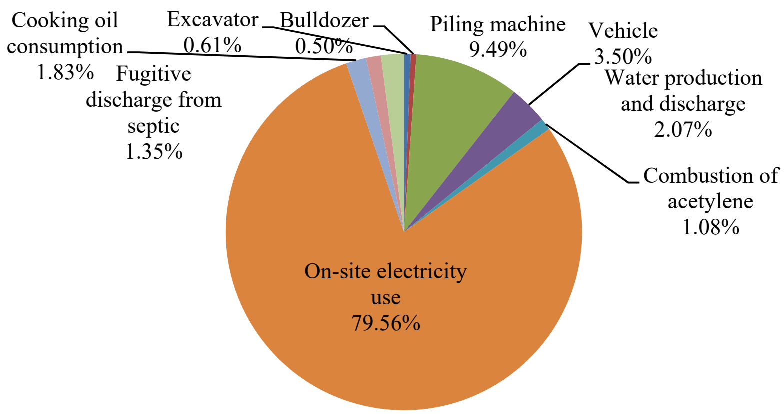

Figure 2: The distribution of direct GHG emissions

When considering the distribution of emission sources in Scope 2 (Figure 3), the building material production process discharged 8016.8t CO_2 equivalent, which accounted for approximately 95% of all emissions. If excluding the part of building material production in Scope 2, it can be seen that most GHG emissions are tied to the transportation of building materials (64.47%) and offsite construction related human activities (27.81%). Therefore, besides the strategy of choosing low-carbon building materials, selecting nearby building product suppliers and reducing the impact from human activities can also be regarded as the most efficient strategies to reduce GHG indirect emissions.

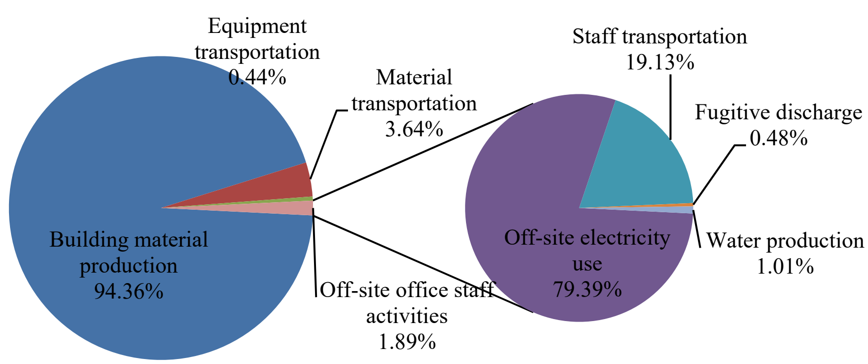

Figure 3: The distribution of indirect GHG emissions

Additionally, this study recombined all the items into three categories based on the interrelationship of each construction activity, namely: i) building material production and transportation; ii) on and offsite human activities; and iii) construction equipment use and transportation. It can be seen in Figure 4 that besides the huge emissions from building material production and transportation, human activities also influence GHG emissions in the construction phase and should be paid more attention from the research community. The importance of human activities has been ignored in most previous studies due to a lack of detailed process data, especially offsite data. Also, by close examination of the percentage of each specific emission source in the three categories, it can be seen that building material production, on and off-site electricity use, and equipment transportation are the three construction activities in each category that have the greatest potential for GHG emission reduction.

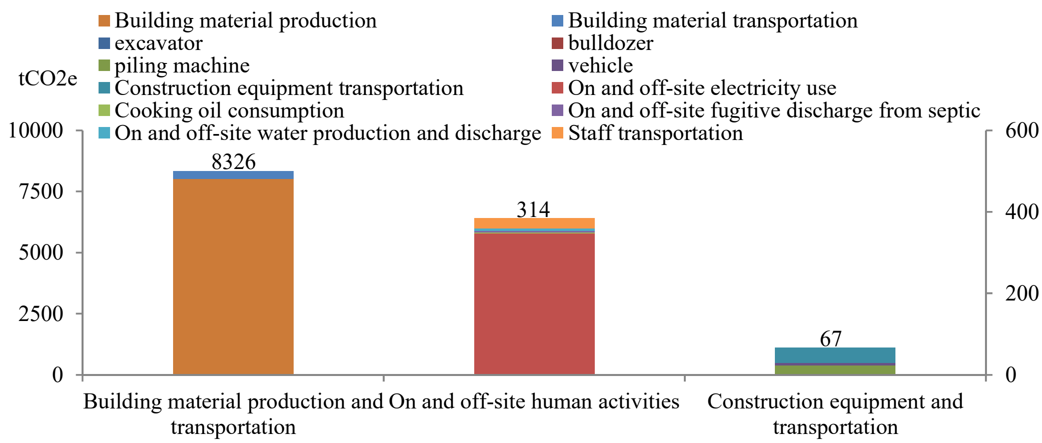

Figure 4: The amount of GHG emissions for recombined construction activities

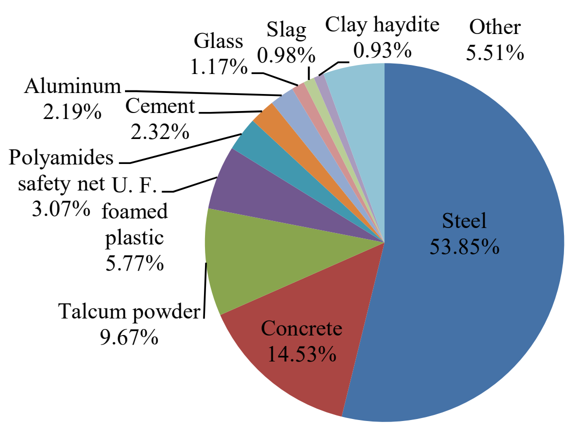

Figure 5: GHG emissions embodied in primary building materials

By ranking all the building materials according to their GHG emissions (See Figure 5), it is found that the top ten primary building materials accounted for 64.3% of total weight while discharging 86.6% of all carbon emissions. Steel and concrete, as the two most important and frequently used materials, were responsible for approximately 2/3 of total carbon emissions. Some other materials, such as polyamide safety nets and aluminum, although they only have a relatively small weight (<0.1%), release a significant quantity of GHG (2%-3%) during the construction phase. Therefore, selecting alternative building materials with low embodied carbon is an efficient approach to decrease GHG emissions during the building material production process.

According to the work conducted by Williams et al. (2012), the amounts of embodied GHG emissions represent 1/5 of total life cycle emissions. Sartori and Hestnes (2007) conducted a statistic study of 60 buildings and found that the embodied percentage is 2-38% for traditionally designed buildings, which implied an average of 20%. Therefore, this study made the assumption that the period of the construction phase and the operation phase are 2 years and 50 years respectively, and the ratio of the amount of carbon emissions between construction and operation is 1:4. Consequently, the carbon emissions intensity can be calculated, which is 0.38 tCO_2e/m^2 Yr during the construction process and 0.06 tCO_2e/m^2 Yr during the building usage stage. Moreover, it is necessary to verify the final results by comparing with other reports available in the previous literatures. Table 7 summarized the carbon emission intensity during building construction phase of 10 residential buildings, 7 office buildings, 3 commercial buildings, and 2 hotels. Considering the similarity of building type and structure, the result (757 kg CO_2e/m^2) obtained in this study is highly in-line with the emission intensity of office and commercial buildings with reinforced concrete structure in previous studies (121-803 CO_2e/m^2). In contrast, this value is more than the emission intensity of residential buildings (72-665 kg CO_2e/m^2) which is framed by masonry, wood or bricks. Especially for the case studied in Hong Kong (Yan et al. 2010) where shared almost the same geographic location, manufacturing technology, and building type, the GHG emission intensity is 520 kg CO_2e/m^2 which is consistent with the value concluded in this study, reflecting that the final results of this study are acceptable and reliable.

Table 7: GHG emissions of different types of building during construction phase

Reference	Country	Building type [b]	Floor area (m^2)	Structure	Method	$kgCO_2e/m^2$
Nässén, J et al. (2007)	Sweden	R	-		I-O analysis	72 98
Rossi et al. (2014)	Belgian	R	192 -	Masonry Steel	Process LCA	189 164
Konig and Cristofaro (2012)	Germany	R	970-7292	-	Process LCA	430 [c]
Brunklaus et al. (2010)	Sweden	R	-	Concrete, wood	Process LCA	400 180 350

Salazar and Meil (2009)	Canada	R	207	Standard	Process LCA	294
				Wood intensive		211
Blengini and Carlo (2010)	Italy	R	250	Reinforced concrete frame	Process LCA	770
						665
Oritiz et al, (2010)		R	125	Bricks based	Process LCA	246
			108			257
Blengini (2009)	Italy	R	6110	Concrete	Process LCA	308
ZabalzaBribián (2009)	Spain	R	222	Concrete	Process LCA	257
Blengini (2010)	Italy	R	250	Reinforced concrete	Process LCA	665
Suzuki and Oka (1998)	Japan	O	1857		I-O analysis	650
Williams et al. (2012)	UK	O		Reinforced concrete	Process LCA	467
Wallhagen et al. (2011)	Sweden	O	3537	Reinforced concrete	Process LCA	160
Scheuer et al. (2003)	USA	O	7300	Steel columns and girders	Process LCA	573
Xing et al. (2008)	China	O	46240	Steel	Process LCA	315
			34620	Concrete		606
Wu et al. (2012)	China	O	36500	Reinforced concrete	Process LCA	803
Dimoudi and Tompa (2008)	Greece	O	1891	Reinforced concrete		200
			400			289
Van Ooteghem and Xu (2012)		C	586	Hot-rolled steel	Process LCA	549
				Heavy timber structure		517
				Pre-engineered steel		355
				Steel-PREDOM		522
				Timber-PREDOM		451
Kua and Wong (2012)	Singapore	C	52094	Reinforced concrete	Process LCA	121
Yan et al. (2010)	Hong Kong	C	43210	Reinforced concrete	Process LCA	525
Filimonau et al. (2011)[a]	UK	H	3300		Process LCA	761
		H	2000		Process LCA	668

Note: a. This is an adjusted value based on the assumption that embodied GHG emissions account for 20% of the total GHG emissions.

b. "R" represents residential building, "O" represents office building, "C" represents commercial building, and "H" represents hotel.

c. This is an average value.

5.2 Sensitivity analysis

Considering the variation of data source priorities and parameter uncertainties, sensitivity analysis is conducted to enable to better understand the major sources or factors that influence the GHG emissions. In order to make in-depth analysis of the relative contributions of LCI input to the final results, six major GHG emission sources has been further disaggregated into thirty-five construction activities. Their sensitivity analysis result on the impacts of total emissions is shown in Figure 6.

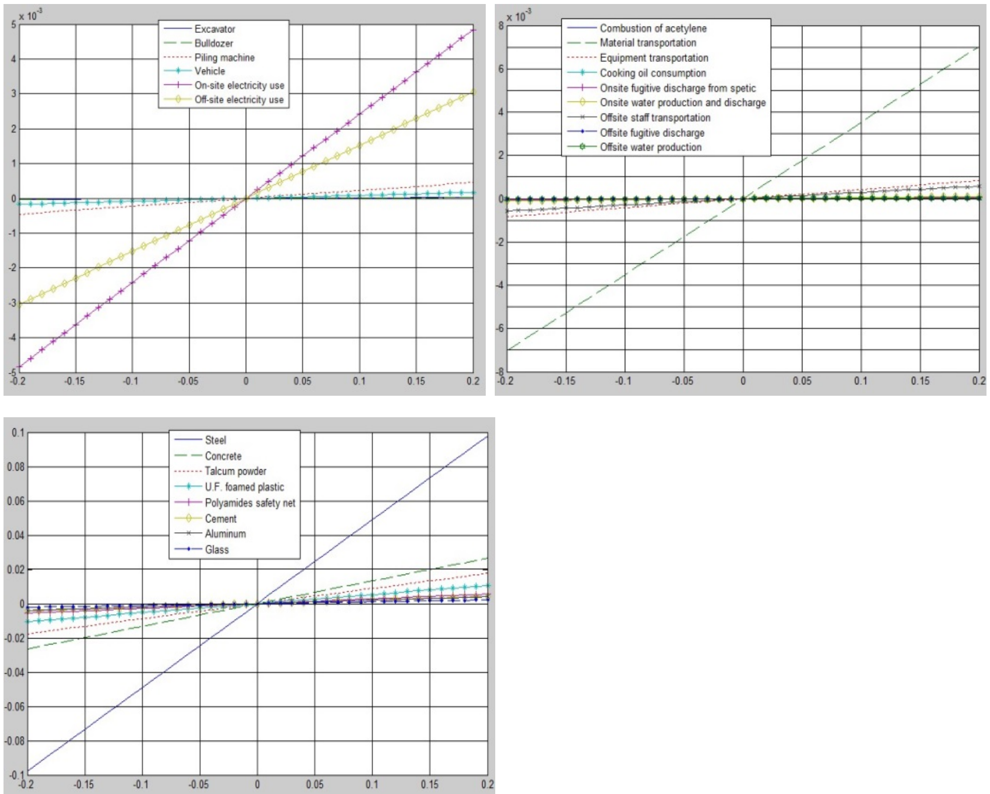

Figure 6: The results of sensitivity analysis

Note: The results of complete sensitivity analysis based on thirty-five construction activities, please refer to Appendix I.

It can be seen that building materials production, transportation, and electricity use have a higher influence on the final output. A 10% reduction in the emissions from building materials production can reduce the total GHG emissions by 9%. Additionally, the amounts of GHG emissions are also effected by workers and staff's activities. 10% increase or reduction will lead to 0.04% changes in the total emissions. The result of sensitivity analysis enhances the aforementioned discussions that building materials production and transportation contribute more significantly to total GHG emissions. Additionally, the management of construction related human activities still needs to be carefully concerned for decision makers in terms of their emission potential.

On the other hand, LCA results may vary with the selection of data sources. Therefore, in order to further examine the consistency among different data sources, this study employed EU emission factor data for all construction activities to analyze their significance to the overall CO_2 emissions. Table 8 shows the relative changes of the amount of GHG emissions according to different construction activities by using EU emission factor data.

Table 8: The relative changes of GHG emissions by using EU emission factor data

Construction activities	Energy sources	EU Emission factor [a] (kg CO_2e /kg)	Relative changes
On and off-site electricity use	Electricity	0.44 [b]	-46.79%
Construction equipment use	Diesel oil	3.15	-0.31%
Cooking oil consumption	LPG	3.23	1.89%
Staff transportation	Gasoline	3.06	2.30%
Total changes			-1.73%

Note: a. EU emission factor data come from EEA technical paper (Herold 2003)

b. The emission factor for electricity production in Europe comes from reference Lee et al. (2004)

The results show that the amount of GHG emissions from on and offsite electricity use reduces 46.79% due to the application of EU average emission factor. However, this may reflect the fact that the electricity production in China is thermal power dominant where the CO_2 emission factor is relatively high. In contrast, Europe generates electricity in a more clean and sustainable way where electricity production is mainly from hydropower and nuclear power. In the whole, the disparity generated from the use of EU data is not significant which only causes 1.73% changes to the total amount of GHG emissions.

5.3 Discussions

To sum up, building materials production contributes most in total GHG emissions where steel and concrete generate nearly 2/3 of all emissions. In fact, the production of these materials are closely related to the upstream processes such as steel processing and cement production, which are typical fossil energy oriented economic sectors. Therefore, materials selection in building construction directly determines the type of energy source and the amounts of GHG emissions. A large potential of energy and emission reduction lies in using the materials with low energy or carbon intensity and environment-friendly properties. For those secondary-processing building products, clean and renewable power should also be introduced in this process. The results of sensitivity analysis further confirm the environmental performance of each construction activity. Especially, the focus of concern in this study has widened to include measuring emissions from human activities on the basis of the extended system boundary and detailed process data. The results show that the importance of this GHG source is usually ignored in previous research. The construction related human activities still generated 314t CO_2e, which therefore should be paid more attentions in future. Meanwhile, compared with difficulties in material innovation and green technology application in building embodied phase, it is straightforward for decision makers to select advisable construction management strategies to control and reduce the relevant GHG emissions.

Through in-depth analysis of construction activities in an extended system boundary, this study revealed GHG emissions during the construction phase of a commercial building in China. However, during the data collection and GHG emissions quantification process, some problems have been identified that need to be addressed in future related research.

Firstly, the classification standard and unit of material used in the inventory of carbon emissions are not consistent with the functional unit of traditional bill of quantities for construction projects in China. It is therefore necessary to develop a conversion formula between the two systems to improve their compatibility and simplify the carbon emissions calculation process. As LCI data are distributed at different phases of the building's life cycle and held by different stakeholders, sub-databases should be formed in the design, procurement, and construction phases in order to establish a more consistent database. Secondly, as there is less opportunity to reduce emissions at the post-construction phase, it is more effective to conduct the analysis work at the early design stage. In terms of the data quality, some of the collected data were estimated from building drawings and construction budgets, such as the quantity of fuels used by onsite equipment and vehicles, whereas other data such as electricity and water use were measured by regular investigation and quantification. According to the criteria list in Table 1, the data sources in this study were basically reliable and acceptable. Due to a lack of local emission data in China, most of the emission factors used in this study were adopted from international sources with only a few selected from national or regional sources. Therefore, even though this study was conducted under an extended system boundary, the calculation model, input parameters, and assumptions used in this study still generated uncertainties during the calculation process.

6. Conclusions

Due to the damage it causes to the earth's ecosystem, GHG emissions have attracted a lot of attentions from the research community. As one of the primary contributors to global GHG emissions, the construction industry has been the focus of many recent studies. The focus of this study was the use of the carbon footprint method under the guidance of ISO 14064 to explore GHG emissions during the construction phase of a building in China. Under the framework of calculations established in this study, the quantity of GHG emissions on a case study construction site was evaluated.

Findings from the case study show that onsite electricity generated the most GHG direct emissions, and that indirect emissions such as emissions from building materials production and construction-supporting offsite human activities, were responsible for 97% of total emissions. Distinguished with previous research, the focus of concern in this study has widened to include the human activities on the basis of the extended system boundary and detailed process data. The results show that the importance of this GHG source is usually ignored in previous research. Additionally, the finding that in the construction phase of the case study 64.3% of the total building materials by weight discharged 86.6% of all carbon emissions, suggests that selecting alternative building materials with low embodied carbon or energy intensity and including a higher share of renewable energy are major challenges for future construction projects.

Based on the findings of this study, some suggestions aiming to explore high energy saving and emission reduction potential have been identified so that they can advance and contribute cleaner production of construction industrial activities in and outside of China. Firstly, for future research of this nature in China, a uniform and consistent conversion formula needs to be established between the inventory of GHG emissions and the traditional bill of quantities in order to improve the compatibility of the two systems. Secondly, raw materials, secondary-processing building products, construction techniques with low environmental damage are prior to apply in building construction phase. Emphasizes should be put on the selecting advisable construction management strategies in construction equipment use, human activities and transportation. Meanwhile, prefabrication components and materials are highly recommended to improve the environmental benefits on GHG emissions. Previous studies proved that the use of prefabrication technology at construction site has large potential to contribute significantly in sustainable development of the construction industry (Mao et al. 2013, Aye et al. 2012, Pons and Wadel 2011). Furthermore, due to the potential to significantly reduce GHG emissions at the design stage, clean production methods and technologies should be conducted as early as possible; perhaps even at the conception stage of a project.

Finally, although this study has its limitations in terms of some uncertainties over the sources and quality of the collected data, the results can nevertheless benefit to the related research of life cycle analysis of GHG emissions and be regarded as the data profile and solid reference foundation for future analysis of GHG emissions during the construction phase of buildings in China.

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Appendix I

Appendix I

Construction activities	Variation of total GHG emissions (%)
Fuels use of construction equipment and vehicles	**±0.0339**
· Excavator	±0.0015
· Bulldozer	±0.0012
· Piling machine	±0.0228
· Vehicle	±0.0084
Electricity use	**±0.3941**
· On-site electricity use	±0.2417
· Off-site electricity use	±0.1524
Assembly and Miscellaneous works	**±0.0026**
· Combustion of acetylene	±0.0026
Transportation	**±0.3941**
· Material transportation	±0.3520
· Equipment transportation	±0.0421
Workers and Staff activities	**±0.0439**
· Cooking oil consumption	±0.0044
· Onsite fugitive discharge from septic	±0.0032
· Onsite water production and discharge	±0.0050
· Offsite staff transportation	±0.0290
· Offsite fugitive discharge	±0.0007
· Offsite Water production	±0.0015
Building materials production	**±9.1314**
· Steel	±4.8954
· Concrete	±1.3243
· Talcum powder	±0.8795
· U. F. foamed plastic	±0.5259
· Polyamides safety net	±0.2789
· Cement	±0.2117
· Aluminum	±0.2002
· Glass	±0.1068
· Slag	±0.0891
· Clay haydite	±0.0848
· Welding rod	±0.0713
· Polyurethane	±0.0659
· Perlite	±0.0517
· Timber plates	±0.0396
· Wire entanglement	±0.0387
· Formwork	±0.0337
· UPVC pipe	±0.0284
· Marble	±0.0257
· Gravel	±0.0234
· Ceramic	±0.0130