The case study of carbon emission in building construction process

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Abstract. Construction management in China has embraced a new practice encompassing the evaluation criteria of green construction. Thus, carbon dioxide (CO2) emissions produced during the construction period should not be overlooked anymore. A quota based CO2 emission calculation method was established. A commercial building and a school building, as two cases were studied. It’s shown that the unit CO2 emission for the two buildings’ construction process are 11.5 kgCO2/m2, and 11.6 kgCO2/m2, respectively. The CO2 emissions for earthwork, foundation work, masonry, concrete work, reinforcement work, formwork, decoration work and measurement work during construction were calculated. The results showed that foundation work and measurement work emitted the most CO2, contributing more than 50% CO2 emission, following by reinforcement work and concrete work. Formwork and masonry work emitted very little CO2. The CO2 emission of different machines were also studied, and the results show that the top 10 machines can take up about 90% of the total CO2 emission. Tower crane, electric welding machine, drilling rig, pile driver, truck, excavator and concrete pump are some of the most CO2 emission machines. These results could help construction managers identify low carbon construction methods and machines in order to maximize the carbon reduction opportunity during the construction stage.

1. Introduction

Human activities, particularly the carbon dioxide (CO2) emitted from fossil fuel combustion, has resulted in the warming of the earth at an alarming rate over the past century [1]. Climate change, leading to seriously deteriorated living environment, is considered as one of the most significant challenges to human in the future [2]. In order to mitigate the effects of climate change, many countries around the world have been making great efforts to reduce the CO2 emission [3].

Many studies concluded that the building industry is the main contributor to CO2 emission [4-6]. For instance, in the US, buildings contribute 43% of the national CO2 emission over the life cycle [7], and more than 50% in China [8]. Therefore, CO2 emission reduction in buildings has widely recognized as one of the most important and effective ways to eliminate the negative impact on climate change [9-10]. Although many policies have been proposed to promote the development of green buildings or building energy efficiency, main of them focused on operational energy and corresponding CO2 emission in buildings’ operation phase, such as energy consumption from air conditioner, lighting, heating. [11-12]. However, one should not ignore the CO2 emitted during the construction process, and some researchers have found that the environmental impacts associated with construction activities are underestimated [13-14]. For operation phase study, a long term of 50 years was always cited, whereas for construction
of a building, the period was around 2 years in general. When taking the year as the basis for comparison, the CO₂ emission from building construction would increase relative to operation phase.

Dispite that, construction process is complex as each project is composed of many activities. Dong and Ng introduced a method of substituting local data [15], but as construction process consists of hundreds or thousands of unit processes, collecting all the necessary site specific data would consume considerable time and cost which makes it impracticable [16]. So many researchers studied the CO₂ emission in building construction process from a macro-scope, which based on national statistical data, and did not rely on site data survey [17-18]. However, this macro-scope method usually cannot get the detail sources of CO₂ emission. Consequently, we established a quota based CO₂ emission calculation method in this study, which consists of a series information about construction activities. Furthermore, as many countries including China has the quota system, the construction data from the quota relatively can easily get.

Empirical evidence and case study are fundamental methods in the research of green buildings, building energy efficiency or CO₂ emission in buildings. Many scholars have conducted case studies on energy performance of various kinds of buildings in different countries and regions [19-22]. However, evidence of the status of CO₂ emission from building construction process, especially green building construction process, is still rare.

The aim of this work is to establish a method to quantitatively calculate the CO₂ emission of construction projects and each construction process, and examine the method by two cases studying. Two green building as cases are studied, and the CO₂ emission of different machines and different divisional works are carefully calculated and analysed, in order to contribute to building carbon emission reduction.

2. Method

2.1 Calculation of CO₂ emission of construction machines
Process-based analysis indicates that the operation of construction machine is the most pertinent carbon emission source from on-site work. In this study, the CO₂ emission of serious construction machine was researched. The energy related carbon emissions can be described as follows:

\[ CE_i = \sum_{j=1}^{3} M_j \times EF_j \]  

where \( CE_i \) is CO₂ emission of type \( i \) machine, \( M_j \) is the consumption of type \( j \) energy for type \( i \) machine per machine day (md, with 1 machine day = 8 machine hours), and \( EF_j \) is the emission factor for type \( j \) energy. There were 3 types of energy usually used, and they were diesel oil, gasoline and electricity, respectively. The emission factor of diesel oil, and gasoline in China were 3.1451 kgCO₂/kg, and 3.0425 kg CO₂/kg, respectively, which were calculated by equation (2) on the basis of the data of “the Study on Greenhouse Gas Inventory in China”(Table 1), promulgated by the Climate Change Division of the National Development and Reform Commission in 2005 [23]. The emission factor of electricity was 0.6101 kgCO₂/kWh, which refer to the average level of China in 2015, and published by the Department of Climate Change, National Development and Reform Commission (NDRC) of China [24].

The emission factors (EF) of diesel oil and gasoline were calculated according to equation (2) [25].

\[ EF_{\text{fossil based on weight}} = CC_m \times OF \times NCV_m \times \frac{44}{12} \]  

In equation (2), \( EF_{\text{fossil}} \) is the emission factor of diesel oil or gasoline in kgCO₂/kg fossil; \( CC_m \) is the carbon content for unit calorific value, tC/TJ; \( OF \) is the carbon oxidation rate, and a value of 98% is cited in this study; \( NCV_m \) is the net calorific value, i.e. the value for the unit energy consumption, TJ/10⁴t; when carbon is oxidized into CO₂, the molecular weight will change from 12 to 44, so there is a coefficient of \( \frac{44}{12} \) in the equation (2).

| Fossil name | \( CC_m \), tC/TJ | \( NCV_m \), TJ/10⁴t | \( EF_{\text{fossil}} \), kgCO₂/kg |
|-------------|------------------|---------------------|-------------------------------|
| diesel oil  | 20.2             | 433.30              | 3.1451                        |
| gasoline    | 18.9             | 448.00              | 3.0425                        |

Table 1 the CO₂ emission data of diesel oil and gasoline
2.2 Calculation of CO₂ emission of construction process basing on the construction quota

Some countries around the world including China have been applying a quota system to managing a construction project especially during the bidding and construction stages. The construction quota in China is published by the government with the information provided by contractors or consultants according to their historical records and experience. The general resource consumption which is recorded in the construction quota from the government is open to public and easy to collect.

As the carbon emissions of materials will always be considered by the manufacturing industry, this study will not be focusing on that part of carbon emissions. As the carbon emission arising from the labor, some researchers proposed that it should be estimated and added to the construction process. However, this study assumes that the extra carbon emissions of labor activities should be quite minimal and can therefore be ignored. Instead, the use of machines as a main source of energy consumption is accompanied to carbon emissions. Consequently, in this study, the resource consumption refers the machine consumption, and carbon emission refers to that causing by the energy consumption due to the application of machines.

The total CO₂ emission of construction process by all the machines is calculated according to equation (3):

\[ C_{ET} = \sum_{i=1}^{m} C_{Ei} \times M_{Ci} \quad (3) \]

Where \( C_{ET} \) is the total CO₂ emission of construction process, kgCO₂; \( C_{Ei} \) is CO₂ emission of the machine of type \( i \), kgCO₂/md; \( M_{Ci} \) is the consumption of machine \( i \), md; \( m \) is the amount of machine using in the construction process. The resource consumption, i.e. the consumption of various the machines is calculated according to the bill of quantities and the construction quota published by the government which reflects the general construction productivity level in the society. It can be calculated by equation (4):

\[ M_{Ci} = U_{MCi} \times q_i \quad (4) \]

In equation (4), \( M_{Ci} \) is the consumption of machine \( i \), md; \( U_{MCi} \) is the unit consumption of machine \( i \) per work quantity, and the unit of \( U_{MCi} \) is varied by work type, such as md/m³ earth for earthwork or md/t steel bar; \( q_i \) is the work quantities.

Some other researchers have also calculated carbon emission based on quota [19], but the method in detail is different. In the method stated above in this paper, to calculate the total CO₂ emission of construction process for a building, the CO₂ emission of various machines by one work day was calculated first by equation (1), which has not calculated in other researches [19, 20]. The CO₂ emission of a machine by one work day is a very important data, which can reflect the CO₂ emission ability of a given machine, and that would be calculated and discussed below.

3. Results and discussion

3.1 CO₂ emission of serious construction machine

In order to calculate the CO₂ emission of various machine, the machine worksheet was collected, and the energy types and consumption amount per machine day were investigated. Take crawler excavator with single bucket(CE) as an example, its energy type is diesel oil, and its energy consumption amount is 63.00 kg/md, so the CO₂ emission of CE is 198.14 kgCO₂/md calculated from eq. (1). Take track diesel pile driver for another example, its energy type is diesel oil and electricity, and the energy consumption was 56.9 kg/md for diesel oil, and 171.00 kwh/md for electricity, and consequently the CO₂ emission of track diesel pile driver was 283.28 kgCO₂/md calculated from eq. (1).

The 30 usually used construction machine and their corresponding CO₂ emission were summarized in this study (Table 2). The 8 high CO₂ emission machines were crawler dozer, crawler excavator with single bucket(CE), tyre loader bucker, track diesel pile driver, static pile driver, automobile drilling machine, concrete pump truck, and jack-up tower crane, whose CO₂ emission was more than 150 kgCO₂/md (Fig. 1). The 9 medium CO₂ emission machines were concrete shaking table, butt welder, crawler crane, truck crane, dump truck, watering car, slurry transport vehicle, electric multi-stage centrifugal water pump, and jack-up tower crane, whose CO₂ emission was between 50 - 150 kgCO₂/md (Fig. 1).
The CO₂ emission of other 13 machines were relatively low (<50 kgCO₂/md). The 13 low CO₂ emission machines included electric rammer, electric grouting machine, mortar mixer, concrete mixer, concrete flattener, concrete slitting machine, reinforcing steel cutting machine, steel straightening machine, woodworking circular saw, DC arc welding machine, electric single-barrel slow-speed winch, double cage construction elevator, and all of them use electricity. Because of the application of wind power generation and solar power generation, the carbon emissions of power generation in China are gradually decreasing, so the carbon emission of machinery using electricity as energy are relatively lower than those using diesel and gasoline.

According to the machine type, the 30 usually used construction machine was divided into 7 groups, including earthwork machinery, piling machinery, concrete and mortar machinery, processing machinery, welding machine, lifting and transportation machinery, pump machinery (Table 2, Fig. 1). The results show that the earthwork machinery and piling machinery are high CO₂ emission machine groups. Most of machines in these two groups had high CO₂ emission except electric rammer and electric grouting machine (Fig. 1). For the machines in the groups of welding machinery, lifting and transportation machinery, and pump machinery, 10 out of 12 machines had medium CO₂ emission, so the 3 groups were medium CO₂ emission machine groups (Fig. 1). All the machines in the processing machinery group had low CO₂ emission, so it can be seen that the processing machinery group was a low CO₂ emission group (Fig. 1). For the group of concrete and mortar machinery, it was heterogeneous. Some machines in the group had high CO₂ emission, such as concrete pump truck, some machine had medium CO₂ emission, such as concrete shaking table, whereas other machines in the group had low CO₂ emission, such as mortar mixer, concrete slitting machine, and etc. (Fig. 1).

Table 2 Energy consumption and carbon emission of various construction machine

| No. | Machine Type          | Machine Description                                      | Energy Parameter                      | Energy Consumption | CO₂ Emission (kgCO₂/md) |
|-----|-----------------------|-----------------------------------------------------------|---------------------------------------|--------------------|-------------------------|
| 1   | Crawler dozer         | Power = 105 kW                                           | Diesel oil                            | 60.80 kg/md        | 191.22                  |
| 2   | Crawler excavator     | Hydraulic pressure, Bucker capacity = 1 m³, Bucker capacity = 1 m³ | Diesel oil                            | 63.00 kg/md        | 198.14                  |
| 3   | Tyre loader           | Bucker capacity = 1 m³                                    | Diesel oil                            | 52.73 kg/md        | 165.84                  |
| 4   | Electric rammer       | Tamping energy = 250 N m                                   | Electricity                          | 16.60 kwh/md       | 10.13                   |
| 5   | Track diesel pile     | Impact mass = 3.5 t                                       | Diesel oil                            | 56.9 kg/md         | 283.28                  |
| 6   | Static pile driver    | Pressure = 2000 kN                                        | Diesel oil                            | 77.76 kg/md        | 244.56                  |
| 7   | Automobile drilling   | Bore diameter = 1000 mm                                   | Diesel oil                            | 48.80 kg/md        | 203.75                  |
| 8   | Electric grouting     | Capacity = 400L                                           | Electricity                          | 16.2 kwh/md        | 9.88                    |
| 9   | Mortar mixer          | Mixing capacity = 200L                                    | Electricity                          | 8.61 kwh/md        | 5.25                    |
| 10  | Concrete pump truck   | Transportation volume = 75 m³/h                            | Diesel oil                            | 83.87 kg/md        | 263.78                  |
| 11  | Concrete mixer        | Discharge capacity = 400L                                 | Electricity                          | 34.10 kwh/md       | 20.80                   |
| 12  | Concrete shaking table| Platform size = 2.4 m × 6.2 m                             | Electricity                          | 138.80 kwh/md      | 84.68                   |
| 13  | Concrete flattener    | Power = 5.5 kw                                            | Electricity                          | 23.14 kwh/md       | 14.12                   |
| 14  | Concrete slitting     | Power = 7.5 kw                                            | Electricity                          | 31.55 kwh/md       | 19.25                   |
|   | Equipment Description                                    | Specifications                  | Energy Consumption | Efficiency |
|---|---------------------------------------------------------|---------------------------------|--------------------|------------|
|15 | Reinforcing steel cutting machine                      | Diameter = 40mm                | Electricity 32.10 kwh/md | 19.58      |
|16 | Steel bender                                           | Diameter = 40mm                | Electricity 12.80 kwh/md | 7.81       |
|17 | Steel straightening machine                            | Diameter = 14 mm               | Electricity 11.9 kwh/md  | 7.26       |
|18 | Woodworking circular saw                               | diameter = 500mm               | Electricity 24.00 kwh/md | 14.64      |
|19 | Butt welder                                            | Capacity = 75 kVA              | Electricity 122.00 kwh/md | 74.43      |
|20 | DC arc welding machine                                 | Capacity = 20 kVA              | Electricity 72.46 kwh/md  | 44.21      |
|21 | Electric Single-barrel Slow-speed Winch                | Traction force = 3t             | Electricity 28.76 kwh/md | 17.55      |
|22 | Crawler crane                                          | Lifting quality = 15 t          | Diesel oil 29.52 kg/md  | 92.84      |
|23 | Jack-up tower crane                                    | Lifting moment=2500 kN·m        | Electricity 266.04 kwh/md | 162.31     |
|24 | Truck crane                                            | Lifting quality = 10 t          | Diesel oil 29.42 kg/md  | 92.53      |
|25 | Double cage construction elevator                      | Lifting quality = 2*1 t, Lifting height=100m | Electricity 81.86 kwh/md | 49.94      |
|26 | Dump truck                                             | Loading quality = 8 t           | Diesel oil 40.93 kg/md  | 128.73     |
|27 | Watering car                                           | Tank capacity = 4000 L          | gasoline 30.21 kg/md  | 91.91      |
|28 | Slurry Transport Vehicle                               | capacity = 4000L               | gasoline 31.57 kg/md  | 96.05      |
|29 | Electric multi-stage centrifugal water pump            | Outlet diameter=100mm, head of delivery<120m | Electricity 180.40 kwh/md | 110.06     |
|30 | Sludge pump                                            | Outlet diameter=100mm           | Electricity 234.60 kwh/md  | 143.13     |
3.2 Construction quota worksheet

Construction quota worksheets record the resource consumption quantities of construction activities for one unit of construction work. Table 3 is part of the construction quota worksheet for reinforcement works. Take quota of NO. 5-100 as an example, to manufacture and install 1t reinforcement would require a steel cutting machine, a steel bender to operate for 0.095, and 0.137 md (machine days), respectively.

Table 3 Part of the quota worksheet for reinforcement

| Quota code | activities                                      | Machine                                      | Unit Machine Consumption, md/t |
|------------|------------------------------------------------|----------------------------------------------|--------------------------------|
| 5-98       | Manufacture and Installation of Ribbed Steel Bars (above HRB400, diameter≤18mm) | Steel straightening machine (diameter = 40 mm) | 0.095                          |
|            |                                                 | Reinforcing steel cutting machine            | 0.105                          |
|            |                                                 | Steel bender                                 | 0.242                          |
|            |                                                 | DC arc welding machine (32kVA)               | 0.473                          |
|            |                                                 | Butt welder                                 | 0.095                          |
|            |                                                 | Electrode dryer (45×35×45cm)                | 0.047                          |
| 5-100      | Manufacture and Installation of Ribbed Steel Bars (above HRB400, diameter≤40mm) | Reinforcing steel cutting machine           | 0.095                          |
|            |                                                 | Steel bender (diameter = 40mm)              | 0.137                          |
3.3 Case study

Two cases were studied. The case 1 project is a 5 story commercial building in Nei Monggol, China, and its construction area is $1.1 \times 10^5$ m$^2$. The case 2 project is a $1.6 \times 10^4$ m$^2$, 3 story school building in Jiangsu, China. Some information of the 3 cases is listed in Table 4.

| Case | Location                  | Built year | Building type          | Structure type     | Number of floors | Height | Area            | Underground area, m$^2$ | Award            | CO$_2$ emission, kgCO$_2$ |
|------|---------------------------|------------|------------------------|--------------------|------------------|--------|-----------------|------------------------|-----------------|--------------------------|
| 1    | Baotou City, Nei Monggol  | 2016       | Commercial buildings    | Reinforced concrete frame | 5                | 23.8   | $1.1 \times 10^4$ | $1.9 \times 10^4$     | 1 star green building | $1.27 \times 10^6$ |
| 2    | Wuxi city, Jiangsu province | 2017      | School building        | Reinforced concrete frame | 3                | 14.2   | $1.6 \times 10^4$ | $3.7 \times 10^2$     | 2 star green building | $1.86 \times 10^5$ |

Based on the CO$_2$ emission calculation method illustrated in part 2, the CO$_2$ emission of the two cases are calculated, and listed in Table 4. The total CO$_2$ emission of the two projects are $1.27 \times 10^6$ kgCO$_2$, and $1.86 \times 10^5$ kgCO$_2$, respectively. The unit CO$_2$ emission of the two projects are 11.5 kgCO$_2$/m$^2$, and 11.6 kgCO$_2$/m$^2$, respectively. It showed that although the building type, the building area, and location of the two projected in this study are different, the unit CO$_2$ emission is much closer. Furthermore, this value of CO$_2$ emission intensity in this study is similar to other researches. Y. Fang et al. studied the CO$_2$ emission of a 4-story high teaching building and found the construction of the building had CO$_2$ emission intensity with a value of 3.53 kgCO$_2$eq/m$^2$ [19].

The construction process was divided into 8 divisional works, including earthwork, pile foundation work, masonry work, concrete works, reinforcement works, formwork, decoration work, and measurement work. The CO$_2$ emissions among the divisional works are shown in Fig 2. Pile foundation work and measurement work are the most CO$_2$ emission divisional works, which can contribute more than a half CO$_2$ emission in all. The following divisional works were reinforcement work and concrete work, which can contribute more than 10% CO$_2$ emission, respectively. Earth work and decoration work can contribute about 5% CO$_2$ emission, respectively. Lastly, masonry work and formwork emitted very little CO$_2$, namely less than 1%.

![Fig. 2 CO$_2$ emission of series construction process in case 1](image1)

![Fig. 2 CO$_2$ emission of series construction process in case 2](image2)
About 30 kinds of machines are needed during the construction process. The top 10 machines with most CO2 emission and their corresponding CO2 emission proportion in the two cases are shown in Fig. 3. These top 10 machines can take up about 90% of the total CO2 emission (Fig. 3). In case 1, the machine with most CO2 emission is tower crane, whereas no tower crane is used in case 2. The truck crane and crawler crane are used as the lifting machines in case 2, because this building has lower areas and height. In case 2, the electric welding machine emitted most CO2 (Fig. 3), because the case 2 project had more reinforcement works (Fig. 2). In fact, the construction of the case 1 building consumed 58.9 kg/m² steel bars, while the value of case 2 is 94.8 kg/m². The second CO2 emission machine in case 1 is long screw drill, and that in case 2 is diesel pile driver. These two machines are both used in pile founding work, but are not in the same pile type. For precast pile, the diesel pile driver was used, while for Cast-in-place pile, the drilling rig was used. Truck also had a high CO2 emission (11.89% for case 1 and 17.13% for case 2), because the transportation of earth, scaffolding, template, and so on all need truck. Furthermore, concrete pump truck also had a considerable CO2 emission (Fig. 3), because the construction of all the projects need concrete pumping.

4. Conclusion
This paper provides a framework for assessing the CO2 emissions from construction processes, and establishes a quantitative assessment model that considers the characteristics of each stage of construction. The assessment model was applied to two construction projects, and the CO2 emissions from the construction of two projects were determined. The principal findings of this study are summarized below.

A quota based method was established for calculating the CO2 emissions of each construction process and the overall construction project. The method can be used to calculate the CO2 emissions of any civil building. A commercial building and a school building are used as the example cases to outline the detailed calculations of carbon emissions for construction project. The unit carbon emissions are 11.5 kgCO2/m², and 11.6 kgCO2/m², respectively. The results of the calculation show that pile foundation work and measurement work emitted CO2 mostly, following by concrete work and reinforcement work, while the formwork and masonry work emitted very little CO2. Some machines have high CO2 emission nature, and/or are used frequently in construction process, leading to a high CO2 emission ratio in the case study, such as Tower crane, electric welding machine, drilling rig, pile driver, truck and so on. In fact, the top 10 machines can take up about 90% of the total CO2 emission. All these results give insight into the CO2 emission of the construction process, and provide valuable information on the reduction of CO2 emission during the construction stage.
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