Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: Two Case studies of residential projects

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Abstract

Greenhouse gas (GHG) emissions in the construction stage will be more relatively significant over time. Different construction methods influence GHG emissions in the construction phase. This study investigates the differences of GHG emissions between prefabrication and conventional construction methods. This study sets a calculation boundary and five emission sources for the semi-prefabricated construction process: embodied emissions of building materials, transportation of building materials, transportation of construction waste and soil, transportation of prefabricated components, operation of equipment, and construction techniques. A quantitative model is then established using a process-based method. A semi-prefabrication project and a conventional construction project in China are employed for preliminary examination of the differences in GHG emissions. Results show that the semi-prefabrication method produces less GHG emissions per square meter compared with the conventional construction, with the former producing 336 kg/m^2 and the latter generating 368 kg/m^2. The largest proportion of total GHG emissions comes from the embodied emissions of building materials, accounting for approximately 85%. Four elements that positively contribute to reduced emissions are the embodied GHG emissions of building materials, transportation of building materials, resource consumption of equipment and techniques, and transportation of waste and soil, accounting for 86.5%, 18.3%, 10.3%, and 0.2%, respectively, of reduced emissions; one a negative effect on reduced emissions is the transportation of prefabricated components, which offsets 15.3% of the total emissions reduction. Thus, adopting prefabricated construction methods contribute to significant environmental benefits on GHG emissions in this initial study.

Keywords: greenhouse gas, emissions, prefabrication, conventional construction, environmental impact

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1. Introduction

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) indicated that the building and construction sector is one of the seven dominant sectors that greatly contribute toward global greenhouse gas (GHG) emissions [1]. The building sector consumes approximately 40% of total energy used, thus contributing up to 30% of total GHG emissions annually. The United Nations Environment Programme (UNEP) declared that with the rapid increase in urbanization and the inefficiencies of existing building stock, GHG emissions will more than double in the next 20 years unless actions mitigating the emissions are taken [2]. Therefore, GHG emissions reduction in the building sector is a focus of research.

Most relevant studies in this domain evaluated GHG emissions during the entire life cycle of buildings or several individual phases of a life cycle. Approximately 80% of energy use and GHG emissions are generated during the operation stage of buildings (such as heating and cooling, ventilation, lighting, and appliances), whereas only 10% to 20% are from material manufacturing, construction, and demolition [3]. Numerous studies primarily concentrated on developing advanced technologies, policies, and measures to cut down GHG emissions in the operation stage [4-7] rather than in the construction stage. Guggemos et al. [8] pointed out that the environmental impact and GHG emissions from the construction phase cannot be ignored, even if this phase only accounts for 0.4% to 12% of the overwhelming impact from the operation stage. GHG emissions in construction is a small share of the entire life cycle at present, but the 80% to 90% of the life cycle of GHG emissions that occur during the operation has declined dramatically over time due to existing substantial energy saving codes or other policies, and thus, the relative contribution of construction stage emissions and impacts becomes more dominant and significant. Therefore, GHG emissions or impacts in the construction stage must be analyzed.

Several studies have focused on the environmental impacts and GHG emissions in the construction phase [8-11]. The literature has two common characteristics: (1) they are associated with conventional cast in situ construction methods, and (2) they concentrate on the scenario selection of building materials or structural systems to reduce GHG emissions. For example, Cole [9] examined the energy and GHG emissions associated with three alternatives, namely, wood, steel, and concrete structural systems, in the construction process to determine if significant differences occur between the structural material alternatives. Gonzalez et al. [10] indicated that carbon dioxide (CO_2) emissions can be reduced by as much as 30% in the construction phase through a careful selection of materials with low environmental impact. Guggemos et al. [8] emphasized the importance of the construction phase and designed a Construction Environment Decision-Support Tool. The tool helps decision-makers and designers optimize design, selection of materials, and construction scenarios according to estimated energy use, emissions, and waste generation rates in the construction phase. Yan et al. [11] established a quantitative model for GHG emissions in building construction. Their results indicated that the embodied emissions of materials is the main source of GHG, so adopting recycled materials can decrease GHG emissions in the construction phase.

Research on the aspect of reducing GHG emissions by alternative construction methods, such as off-site prefabrication instead of conventional methods, are limited. Although Lu et al. [12] conducted a comparative study on embodied energy use and GHG emissions in the life cycle among prefabricated steel, wood, and conventional concrete construction systems, the result of this study virtually suggested to reduce environmental impact via proper selection of materials in structural systems, rather than actual changes in construction methods or processes. Meanwhile, although several other studies consider prefabrication an effective and efficient approach to control environmental impact [13-15], rigorous calculation on the GHG emissions of prefabrication is lacking.

To fulfill this knowledge gap, this study aims to establish a calculation mode of GHG emissions for prefabrication, to investigate whether GHG emissions between prefabrication and conventional construction have significant differences, to determine the extent of the reduction of GHG emissions that can be achieved by prefabrication in comparison with conventional construction, and to demonstrate that prefabrication is also an effective way for GHG emissions reduction. This paper focuses on the discussion of the concrete structural system, because it is the dominant structural system for residential buildings in China. The objectives of this paper are the following: to define and delimit the process of prefabrication, the sources of GHG emissions, and the calculation boundary of GHG emissions; to establish a quantitative model to assess the total GHG emissions of prefabrication; and to compare the GHG emissions of prefabrication with those in conventional construction method based on the same structural system.

2. Overview of Off-site Prefabrication

Despite being one of the oldest industries, construction practice has had no remarkable innovation and improvement over the past 40 years. Furthermore, this industry is characterized as labor-intensive, wasteful, and inefficient because of its conventional on-site construction approach [16, 17]. As indicated in Egan's report [18], improving productivity and environmental performance in the construction industry requires the diffusion of new construction methods such as lean production and prefabrication. Prefabrication is an effective method already in practice. The United States National Research Council's 2009 report recommends prefabrication as an "opportunity for breakthrough achievement" to a modern construction industry [19]. With the requirement of environmental sustainability, off-site prefabrication provides a broad forward evolution compared with conventional construction methods.

Tatum [20] defined prefabrication as a manufacturing process generally conducted at a specialized facility, in which various materials are joined to form a component part of the final installation. Prefabrication is the transferring stage of on-site construction activities from field to an off-site production facility. Gibb [21] regarded off-site fabrication as a process that incorporates prefabrication and pre-assembly. The process involves the design and manufacture of units or modules, usually remote from the work site. It also includes their subsequent transport and installation to form the permanent structures at the work site. Although no single, widely accepted definition for prefabrication exists so far, numerous common threads are revealed from the definitions of previous literature. These threads represent a manufacturing process in the stage of construction, which is characterized by (1) off-site construction, (2) activities undertaken in a factory environment, (3) precast components built as types of pieces, units, or modules in the factory (e.g., floor slab, façades, staircases, beams, bathrooms, kitchens and so on), (4) transportation of prefabricated components to project sites, and (5) their assembly and installation to form an entire building. A prefabricated building is a product manufactured by the abovementioned process. The term "prefabrication" in the current study is labeled as possessing the features described above.

Building frame structural systems commonly used in prefabrication are light-gauge-pressed steel frame, precast concrete frame, and timber frame [21, 22]. The construction method of prefabrication is categorized as three types, namely, semi-prefabrication, comprehensive prefabrication, and volumetric modular building [15]. Semi-prefabrication is a construction method where some elements of the building are cast in situ on-site while the remainder adopts factory-built components or units. In comprehensive prefabrication, all building elements are independently manufactured in the factory and then fixed together on-site. Volumetric modular building refers to an entire building produced in a factory.

In China, Prefabricated Light Steel System (PLS) and Prefabricated Concrete System (PCS) are predominantly adopted from Japan's and Hong Kong's practice. In this study, the type of PCS by adopting semi-prefabrication construction method is concerned. This type is more available and acceptable in the Chinese construction market due to its higher cost efficiency compared with other systems. As the process of semi-prefabrication is significantly distinguished from conventional construction, the process will be defined in the succeeding sections of this paper.

3. Methodology

3.1 Selection of quantitative methods

Various evaluation tools are employed to assess the environmental impact of buildings, including energy use and GHG emissions. From previous studies, four methods are mainly used: statistical, process-based, input-output, and hybrid analyses [11, 12, 23].

Statistical analysis is an effective and speedy method based on comprehensive, consistent, thorough, and sufficiently detailed published statistics, which are difficult to collect in most countries. Therefore, this method is not available in most studies.

Process-based analysis is a bottom-up method developed to assess the environmental impact of goods and services according to their production process. Fay et al. [24] and Chen et al. [25] analyzed the energy use of all life cycle processes of buildings in Australia and Hong Kong, respectively. Yan et al. [11] calculated the GHG emissions in the building construction process. You et al. [26] established a life cycle model of carbon emissions , which integrated the main sources of each stage during the life cycle of buildings, to analyze carbon emissions.

Input–output analysis is a top-down method for assessing resource and pollution embodiments in goods and services on a macroeconomic scale, taking the entire economy as a system and involving any number of inputs from other industry sectors. This method is also widely adopted in numerous studies on GHG emissions of building sectors. Nassen et al. [27] used this method to assess energy use and carbon emissions in the production phase of buildings. Chen et al. [28] established a low-carbon building framework with detailed carbon emission account procedures based on a multi-scale input–output analysis.

A hybrid analysis combines the advantages of the abovementioned methods and attempts to incorporate their most useful features. Seo et al. [29] used a hybrid method to estimate CO_2 emissions in the life cycle of residential buildings, whereas input-output analysis was adopted to calculate CO_2 emissions in the manufacturing of buildings. They used a process-based method to analyze the remaining stages of buildings. Lu et al. [12] used an innovative hybrid assessment approach to evaluate embodied energy, whereby a large base of I-O data were obtained from the Australian National Accounts and process-specific data related to energy from the manufacture of building materials were obtained from the SimaPro Australian Database.

Prefabrication is still in its early stage in China. Economic input-output data, which should be collected from all potential transactions upstream through the supply chain of prefabrication or associated with the construction industry on the aspect of prefabrication, are currently unavailable in China. As an innovative attempt and a specific technology in the construction industry, the more applicable and reliable approach is to use the micro method to calculate GHG emissions [12]. Therefore, a process-based, micro-bottom-up method is adopted for this study. The process-based quantitative model can be addressed to define and limit the sources and scope of GHG emissions for calculation.

3.2 Scope of the study

3.2.1 GHG Emissions

According to the "2006 IPCC Guidelines for National Greenhouse Gas Inventories" [30], GHG include, but are not limited to, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), ozone (O_3), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). GHGs are mainly composed of CO_2, CH_4, and N_2O while the remainder are seldom emitted in this process [9]. Therefore, CO_2, CH_4, and N_2O are represented as GHG emissions in this study. Different GHGs vary in their environmental impact. Global

Warming Potential (GWP) value is commonly used to illustrate the climatic impact of different gases. Generally, CO_2 is adopted as the reference standard for GHG effects. By multiplying the individual gas emission factor by the respective gas GWP, the emissions of other GHGs such as CH_4, N_2O, and CO are converted to so-called CO_2 equivalents [31, 32]. The GWP values of CO_2, CH_4, and N_2O for 100 year time horizons are shown in Table 1. Thus, GHG emission factors (as equivalent CO_2) herein can be calculated by Formula (1),

$$\text{GHG Eemissions factor} = \sum_{c=1}^{c} F_c \times \text{GWPV}_c \qquad (1)$$

where F_c is a given gas c emissions factor per unit, and GWPV_c is the GWP value of gas c.

<Insert Table 1 here>

3.2.2 Calculation boundaries

Few studies have focused on the GHG emissions in the construction phase. The system boundary of the construction phase defined by researchers varies. For example, Yan et al. [11] summarized six sources of emissions in the construction phase from existing literature, namely, (1) manufacture of building materials, (2) transportation of building materials, (3) transportation of construction equipment, (4) energy consumption of construction equipment, (5) transportation of workers, and (6) disposal of construction waste. There is a different view on whether emissions from manufacturing building materials should be calculated in the construction phase. Guggemos et al. [8] proposed that the embodied GHG emissions of permanent building materials should be omitted in this calculation because they belong to an independent part of the materials manufacturing phase during the overall life cycle assessment (LCA). Nevertheless, construction processes and techniques used in semi-prefabrication are different from those in conventional construction methods. The way of handling materials and the amount of materials applied are different in the two types of construction methods. Therefore, including the embodied GHG emissions of building materials in the calculation is reasonable. Meanwhile, as the final quality and performance requirements of building products, requirements of energy consumption of the operation phase, and quantity of demolition are assumed to be similar during the comparison of this study, the GHG emissions of operation and demolition are not considered. In addition, Chinese construction projects observe the special situation where all workers live on-site in; thus, the transportation of workers is not included in this study. Therefore, we limit the calculation components to (1) embodied GHG emissions of materials (E_1), (2) GHG emissions of fuel combustion due to transportation associated with construction processes (E_2, E_3, E_4), and (3) GHG emissions of resource and energy consumption from the operation of equipment and construction techniques (E_5). The calculation boundary for the construction process of semi-prefabrication in this study is shown in Fig. 1. As to the conventional process, the calculation boundary is the same as that in the on-site section of semi-prefabrication.

<Insert Fig. 1 here >

3.2.3 Sources of GHG emissions

According to the calculation boundary shown in Fig. 1, GHG emissions of semi-prefabricated construction are derived from two parts: off-site prefabrication for building components and on-site construction for in situ cast and assembly. As to the conventional construction method, GHG emissions are solely from the in situ casting process. The following five sources should be calculated. Table 2 lists the related GHG emission sources for semi-prefabrication and conventional construction.

- E_1: Embodied GHG emissions of primary permanent building materials;
- E_2: GHG emissions from the fuel combustion of transportation for building materials, which may either be from a distribution center to the off-site prefabrication factory or from a distribution center to the project site;
- E_3: GHG emissions from fuel combustion of transportation for construction waste and soil from off-site prefabrication factory to landfill, or from project site to landfill;
- E_4: GHG emissions from fuel combustion of transportation for prefabricated components from off-site prefabrication factory to the project site;
- E_5: GHG emissions of resource and energy consumption from the operation of equipment and construction techniques, herein resources and energy, including diesel/oil, electricity, and water.

<Insert Table 2 here >

3.3 Quantitative model of GHG emissions

Based on the classification of emission sources above, the quantitative model for calculating GHG emissions during the construction stage of semi-prefabricated construction is composed of Formulas (2) to (7).

$$\mathrm{TGE} = \sum_{i=1}^{5} E_i \qquad (2)$$

where TGE is the total GHG emissions during the entire construction stage in tons CO_2-equivalent ($CO_{2\text{-e}}$), E_i is the ith GHG emission source during the process of construction, and i is from 1 to 5.

$$E_1 = \sum_{j=1}^{j} M_j \times f_j^b \times (1 + \varepsilon_j) \qquad (3)$$

where E_1 is the embodied GHG emissions of all building materials (in tons $CO_{2\text{-e}}$), M_j is the amount of building material j (in tons), f_j^b is the GHG emissions factor of building material j (in kg $CO_{2\text{-e}}$/kg), and ε_j is a factor for waste of building material j during the transportation of materials or erection of building. The waste factor value varies from the type of building materials; references [25] and [33] listed waste factors with related materials. The value of f_j^b may vary among different countries. However, data on GHG emission factors or CO_2 emissions factors of building materials are limited in China. Therefore, the factors in the calculation model in this study were collected from several international institutions and reports, such as "Embody Energy and CO_2 Coefficients for NZ Building Materials" from the Centre for Building Performance Research in New Zealand, and "The Inventory of Carbon and Energy" from the University of Bath [34-36]. Table 3 presents the related GHG emission factors (f_j^b) of six dominant materials for buildings collected for the current study.

<Insert Table 3 here >

$$E_2 = \sum_{k=1}^{k}\sum_{j=1}^{j} M_j \times L_j^m \times f_k^t /1000 \qquad (4)$$

where E_2 is the total GHG emissions from the fuel combustion of transportation of building materials j (in tons $CO_{2\text{-}e}$); L_j^m is the distance from a distribution center to the off-site prefabrication factory or from a distribution center to the project site (in km); and f_k^t is the GHG emissions factor of fuel combustion for transportation method k (in kg $CO_{2\text{-}e}$/ton km), such as vehicle, train, or ship. Table 4 lists the GHG emission factors (f_k^t) of different transportation methods.

<Insert Table 4 here >

$$E_3 = \sum_{s=1}^{s}\sum_{l=1}^{l}\sum_{k=1}^{k} W_s \times L_l^w \times f_k^t /1000 \qquad (5)$$

where E_3 is the GHG emissions from the fuel combustion of construction waste or soil of earthworks (in tons $CO_{2\text{-}e}$), W_s is the amount of construction waste or soil (in tons), L_l^w is is the distance between the off-site prefabrication factory and landfill or the distance between the project site and landfill (in km), and f_k^t is the GHG emission factor for transportation methods (in kg $CO_{2\text{-}e}$/ton km). Normally, transportation of waste, soil, and prefabricated components is done using heavy trucks. Thus, the 0.207 kg $CO_{2\text{-}e}$/ton km shown in Table 4 is used for f_k^t in Formulas (5) and (6).

$$E_4 = P \times L^p \times f_k^t /1{,}000 \qquad (6)$$

where E_4 is the GHG emission from the fuel combustion of transportation for prefabricated components from the off-site prefabrication factory to the project site (in tons $CO_{2\text{-}e}$), P is the total amount of all prefabricated components (in tons); and L^p is is the distance between the off-site prefabrication factory and the project site (in km).

$$E_5 = \sum_{r=1}^{r}\sum_{v=1}^{v} R_r \times f_n^v /1000 \qquad (7)$$

where E_5 is the total GHG emissions from the resource consumption of construction equipment and techniques (in tons $CO_{2\text{-}e}$); and R_r is the amount of resources or energy usage r of related requirements of construction techniques (in kWh, in L, or in m) during the entire construction phase, r = 1, 2, 3. Normally, construction equipment include cranes, concrete mixer trucks, concrete pumps, welders, fork lift trucks, elevators. The main resources of consumption are examined by three types, namely, diesel, electricity, and water. R_1 (in L), R_2 (in kWh), and R_3 (in m^3) denote the usage amount of the three types of construction equipment, respectively. f_1^v is the GHG emission factor of fuel combustion (in kg $CO_{2\text{-}e}$ /l), $f_2^v$is is the GHG emissions factor of electricity usage (in kg $CO_{2\text{-}e}$/kWh), and $f_3^v$is is the GHG emissions factor from fresh water processing (in kg$CO_{2\text{-}e}/m^3$). Table 5 lists the CO_2 emissions factor of electricity in different regional power grids of China in 2010 published by the Department of Climate Change under National Development and Reform Commission [39]. Values for f_3^v are unavailable in the existing literature of mainland China; thus, 0.4137 kg $CO_{2\text{-}e}/m^3$was used as referenced from EMSD/EPD [40]. Table 6 lists GHG emissions factors (f_n^v) of resources consumption of construction equipment.

<Insert Table 6 here >

4. Case study

This paper employed two types of cases to demonstrate the aforementioned process-based quantitative models for GHG emissions and to conduct a detailed calculation and a comparative study. These two types of cases are Project A using semi-prefabrication and Project B using conventional construction method. Project A is a public rental housing project, and it is the first pilot project using prefabrication in Shenzhen. Shenzhen is one of the first places where industrialized building bases are established in China. Project A is considered representative of the level of prefabrication application in China. Project B is a general residential project associated with conventional construction method in Shenzhen. The reasons for choosing these two projects for comparison are as follows: first, the two cases have similar crucial structural characteristic variable and profiles that affect the quality, performance, and amount of material used on the project (such as floor plan, room aspect ratio, foundation, basement, floor-to-floor height, and structure system), as shown in Table 7 , Fig. 2 and Fig. 3. Second, the management skills of the two contractors were at an undifferentiated level. Arguably, different management skills or construction technologies of contractors can affect the amount of materials used on project sites. In this study, the contractors of the two projects are Pengcheng Construction (Project A) and China Construction Third Engineering Bureau Co., Ltd. (Project B). They both won the "second star level" award by Shenzhen Government under the "Evaluation Standard for Green Construction in Shenzhen". This Standard is an effective tool for assessing construction activities in terms of the savings of resources (e.g., water, material, energy, and land) and environmental performance. The same award of green construction star can briefly indicate that these two contractors have undifferentiated management skills and construction technologies in the area of green construction. While it is quite normal to acknowledge the heterogeneity of contractors, we assumed that the influence of construction management skill has, if not impossible, a negligible impact on the amount of materials used in this study.

Therefore, the assumption is that the two projects are available for comparison to a certain extent according to the above similarities. To enhance comparability using a consistent basis, the size of Project B is adjusted to equal that of Project A. To provide a consistent calculation basis for comparison between these two projects, 216,000 m^2 is used to represent a unit of orders of magnitude.(216,000 m^2 is the size of Project A) .Data collection is described in detail in the succeeding sections of the paper.

<Insert Table 7 here >

4.1. Data collection

Two clusters of data are collected in this study: data from semi-prefabrication in Project A and data from conventional construction method in Project B (see Fig. 2 and Fig.3).

<Insert Fig. 2 here >

< Insert Fig. 3 here >

4.1.1. Data collection for the semi-prefabrication method

Project A consists of six residential buildings, each adopting a frame-shear wall structure and a construction floor area (CFA) of 216,000 m^2. The project duration for Project A is from July 2010 to June 2012. The entire construction phase was monitored through site investigation and regular examination of site reports provided by the surveyors and project manager. In 2011, this project achieved a Green Star Accreditation from the Ministry of Housing and Urban-Rural

Development of China. One of the contributions of this project is the adoption of off-site prefabricated components. The level of prefabrication was 10.5% by concrete volume. Three types of prefabricated components were involved, namely, precast façades, precast staircases, and precast corridor slabs (Fig. 4). The main structure and remainder parts were cast in situ. Project A was closely monitored to collect relevant GHG emissions data throughout the construction phase. Monitoring was implemented through the combined methods of site investigation, Bill of Quantities and project reports review, and interview with senior project managers, material suppliers, and prefabrication factories associated with the project.

<Insert Fig. 4 here >

For the main body of the buildings (e.g., wall, roof, slab, floor), six building materials were the focus: steel, cement, sand, glass, ready-mixed concrete, and aerated concrete brick (hereinafter referred to as "concrete" and "brick"). The actual quantities of building materials used in the construction of Project A are shown in Table 8. L_1^w represents the transportation distance of the materials from their place of origin to the off-site prefabrication factory, whereas L_2^w represents the distance from the place of origin to the Project A construction site (Table 8). All of the building materials were transported by road with a GHG emissions factor of 0.207 (in kg $CO_{2\text{-}e}$/ton km). Data on the total amount of resources used on diesel, electricity, and water were collected monthly from the project contractors (Table 9). The amount of waste from the off-site fabrication factories was reduced substantially. For example, concrete waste during the process in factory was minimal. Waste was non-existent because for Project A, the factories produced concrete, which enabled reuse of surplus concrete and steel. Data on the amount of on-site waste were not directly available, but could be evaluated by the waste factors presented in Table 3. The quantities of soil generated by earthworks were obtained from the Bill of Quantities (Table 10). Two prefabrication factories were employed in Project A, which were 45 and 95 km away from the project site. An average distance of 70 km by truck was used to transport the precast components to the project site.

4.1.2. Data collection for the conventional construction method

Project B, referenced from the monthly report of *Shenzhen Construction Engineering Price Information* [42], was selected as a comparable project using conventional construction methods. This project is similar to Project A in terms of structural frame, height, foundation, room aspect ratio and so on (See Table 7 and Fig. 4). However, the floor gross area of Project B is different from that of Project A. To maintain a similar comparison baseline, the floor area of Project B was adjusted to be the same with that of Project A. The adjusted project is called Project B_o. In Project B, the values of the used index *(a used index is the ratio of the total amount of a certain material divided by construction floor area*) of materials per m^2 are as follows: 57 kg/m^2 for steel, 0.495 m^3/m^2 (1.188 kg/m^2)for concrete, 404.46 kg/m^2 for sand, 68.15 kg/m^2 for cement, and 287.14 kg/m^2 for brick (see Table 8). The corresponding amount of use of each material for Project B_o is acquired by multiplying the 216,000 m^2 (the same CFA of Project A) with the unit used as index of each material in Project B. For example, multiplying the 216,000 m^2 with the used index of steel per m^2 (0.057 tons/m^2) and the used index of concrete per CFA (0.495 m^3/m^2) yielded the total weight of steel (12,312 tons) and concrete (106,920 m^3 by volume; 256,608 tons by weight) in Project B_o. The other adjusted amounts of building materials for Project B_o are listed in Table 8. Glass, however, was fixed and installed on site and had similar quantities in both projects.

As for diesel consumption, it is mainly attributed to the concrete delivery pump and excavator. The amount of diesel used (120,000 L) by most of the equipment, except for the concrete delivery pump, was the same in Project A and Project B_o. The concrete delivery pump used in this study was the HBT40c, which consumes 0.8 L to 1.2 L of diesel to deliver 1 m^3 of concrete. Thus, an average value (1.00 L/m^3) was adopted in multiplying the quantities of concrete in conventional Project B_o (106,920 m^3) to obtain the amount of diesel used by the concrete delivery pump (106,920 L). The total amount of diesel used was 226,920 L. The total consumption of water (356,400 m^3) and electricity (2,470,912 kWh) in Project B_o (Table 9) was estimated according to the *Calculation Handbook of Construction* [43] . The amount of construction waste in Project B_o was assessed through the material waste factors (Table 3) by multiplying the amount of related materials used.

The variables in Formulas (2) to (7) vary from project to project, as well as in Project A and Project B. In this study, the differences in GHG emissions between the prefabrication method and conventional construction were examined by referring to the similar Projects A and B. Therefore, greater concern was placed on variables whose changes are mainly due to the different processes or techniques of prefabrication, including amount of materials, amount of water and electricity consumption, and quality of prefabricated components. Meanwhile, variables whose changes are not because of prefabrication were assumed to have the same value in Project A and Project B: distance L_2^w from the place of origin to project site, the distance for disposal soil and on-site waste, and the amounts of soil. These data can be found in columns 6 and 7 in Table 8 and line 4 in Table 9. The assumption was used to compare emissions between the two projects under the same bases.

Additional data are shown in detail in Tables 8 to 10. The data were used to calculate the GHG emissions of semi-prefabrication (Project A) and conventional construction (Project B_o).

<Insert Table 8 here >

<Insert Table 9 here >

<Insert Table 10 here >

5. Results and discussion

5.1. Total GHG Emissions of Semi-prefabrication and Conventional Construction

Detailed GHG emissions from five resources (according to Formulas 2 to 7) are shown in Table 11. Total GHG emissions in the construction phase of semi-prefabrication and conventional construction methods are 72,791 and 75,205 tons $CO_{2\text{-e}}$ (equivalent to 336 and 348 kg/m^2), respectively. A reduction of 1.1 tons per 100 m^2 was seen in the project with semi-prefabrication, approximately 3.2% less than that emitted in the project with conventional construction. This reduction seems relatively small, and it is in line with other similar studies by Pons [44]. Pons conducted life cycle analysis of environmental impacts between three main industrialized technologies and a non-prefabricated one in school projects. Findings suggest that the emissions of prefabricated concrete technology were approximately 2% to 5% lower than those of non-prefabricated one [44]. Table 11 presents the results of the current and previous studies. The small reduction might be attributed to the lower level of prefabrication. Pons' studies [44] also implied that a higher degree of prefabrication could contribute to greater benefits on environmental impact, such as GHG emissions.

Column 9 in Table 11 presents the contribution proportion of each emissions source to the total GHG emissions reduction brought by the use of semi-prefabrication. A total of 86.5% of the GHG emissions reduction are due to embodied emissions of building materials (E_1); 10.3% are due to the resource consumption of construction equipment and techniques (E_5); and only 3.2% are due to the fuel combustion from all transportation activities (the sum of E_2, E_3, and E_4). In the current study, 18.3% are from the transportation of building materials (E_2), about 0.2% are from the transportation of waste and soil (E_3), but -15.3% are from the transportation of prefabricated components (E_2). This case is only observed in the prefabricated project, and it is considered a negative effect on emissions reduction. Columns 4 to 7 in Table 11 show that embodied emissions of building material are also the most dominant source of GHG emissions either in semi-prefabrication or conventional construction. Both account for 85.1% of total GHG emissions. The second largest contributor to total GHG emissions is E_2, accounting for 7.7% and 8.1% in semi-prefabrication and conventional construction, respectively.

From the perspective of the reduction of individual emissions sources when adopting semi-prefabrication, column 10 in Table 11 shows that sources of *E2* and *E5* significantly benefited from semi-prefabrication compared with other sources. In the case studies, a reduction of 7.3% of the emissions from the transportation of building materials, 7.1% of the emissions from the resource consumption of construction equipment and techniques, 3.3% of embodied emissions of building materials, and 0.2 % of the emissions from the transportation of soil and waste were noted when adopting semi-prefabrication.

<Insert Table 11 here >

5.2. Embodied GHG emissions of building materials (E_1)

As the largest contributor to total GHG emissions in both types of construction methods, embodied emissions of each material vary from its use amount. Embodied GHG emissions per 1,000 $m^2$of each building material are shown in Table 12 and Fig. 5. The six building materials of the semi-prefabrication project generate about 286 tons of embodied GHG emissions per 1,000 m^2, whereas the amount for conventional construction project is about 296 tons per 1,000 m^2. Specifically, the contribution percentages of each material in semi-prefabrication are 56% for concrete, 17% for brick, 16% for cement, 8% for steel, 2% for glass, and 1% for sand. The corresponding figures for conventional construction are 49%, 24%, 17%, 7%, 1.6%, and 1.4%, in that order.

<Insert Table 12 here>

<Insert Fig. 5 here >

A total of 2,414 tons in reduction of GHG emissions is contributed by the semi-prefabrication project. This amount yields approximately 3.3% in reduction compared with conventional construction in this study. Comparisons of the two methods show that the disparity in the use amount of building materials is significant, except for glass (See Table 8). The significant disparity is due to the differences between semi-prefabrication and the conventional construction in terms of construction techniques, processes, and design requirements. Consequently, the use amount and embodied GHG emissions of building materials are also different. The embodied GHG emissions of concrete and steel in semi-prefabrication project are about 4% and 7%, respectively, which are more than those of conventional construction (Fig.5). To determine the reason for the increased embodied emissions of steel in semi-prefabrication project, the senior technician and the designer of Project A were interviewed. According to them, the increased usage of steel is due to design requirements and standards, especially evident in the off-site production of components. Numerous joint parts of reinforcement bars are embedded into precast façades, staircases, and slabs. These joint parts are also called embedded parts, and are utilized for on-site assembly together with the main building structures. Analysis of the embedded parts explains the increase in embodied GHG emissions of steel during prefabrication. The increased GHG emission of concrete is due to the adoption of precast concrete for the external wall, instead of conventional brick. As observed during site surveys and interviews, more steel and concrete are used in semi-prefabrication. However, the project manager stated that off-site prefabrication can control the usage of materials via a lean production process characterized by standardized designs, precise sizes, and controllable processes that eliminate material wastes. For example, the usage of steel can be reduced by optimizing the design of reinforced joint links in components, thus minimizing the potential of embodied GHG emissions in semi-prefabrication.

Meanwhile, approximately 15%, 11%, and 11% of the embodied emissions reduction per

1,000 m^2 for brick, cement, and sand, respectively, are attributed to semi-prefabrication. Comparison with conventional construction processes is shown in Fig. 5. The significant reduction is due to the use of precast concrete components, which eliminated the need for on-site plastering of prefabricated façades, staircases, and slabs before decoration. Simultaneously, this semi-prefabrication project scarcely adopted bricks on external walls, which decreased the usage of brick, sand, and cement in semi-prefabrication relative to the usage in conventional construction. Therefore, further design optimization could reduce the total amount and embodied emissions of building materials. One alternative is the selection of reasonable and economically efficient proportions of concrete and bricks, such as on external walls. Moreover, Jaillon and Poon presented developments in this regard [13]. Building materials could be decreased to 20% when the precast level is up to 65%. This finding implies a lower environmental impact after prefabrication adoption. The higher the level of prefabrication, the lesser the amount of building materials needed, as well as embodied GHG emission. Therefore, projects that adopt prefabrication have a larger potential to reduce embodied GHG emissions from building materials.

5.3. GHG emissions during transportation (E_2,E_3, E_4)

<Insert Fig.6 here >

GHG emissions associated with transportation activities include three types: E_2, E_3, and E_4. GHG emissions of transportation for prefabricated components (E_4) only exist in off-site prefabrication. The total GHG emissions from the three transportation types are 7,664 and 7,740 tons for semi-prefabrication and conventional methods, respectively. As to the lower total GHG emission in semi-prefabrication, which involves one more type of transportation than conventional construction, inspection of the off-site factories yielded valuable observations. First, a part of E_3 is zero because most materials in the factory can be recycled without waste. Second, the distance from the distribution center of the materials to the off-site factories is very short. Such a short distance is because many prefabrication factories tend to build their factory near the original place of materials in China as this enhances their competitive ability and efficiency. Therefore, this factor not only decreases factory expenses, but also reduces GHG emissions from the fuel combustion of material transport. However, the reduction is only 3.2% from total emissions from all transportation activities as can be gleaned from Table 11 and Fig. 6. This rate is because emissions from the transport of prefabricated components (370 tons) accounts for 4.8% of the total GHG emissions of all transportation activities (7,664 tons). This value is equivalent to -15.3% of the total GHG emissions reduction (2,414 tons). Reduction amounts from *E2* and *E3* in semi-prefabrication were offset to an approximate 83% reduction by E_4. Furthermore, with a rise in the degree of prefabrication used, E_4 could be increased accordingly. Therefore, transportation of prefabricated components is a critical factor affecting the potential environmental benefits of prefabrication. The capacity of total GHG emission reduction can be upgraded into a higher level as long as E_4 is reduced. A potential way to reduce GHG emissions of transportation for prefabrication components is to select off-site factories that are near the projects and material distribution centers. Thus, the reduction of GHG emissions through prefabrication can only be achieved by minimizing transportation distance.

5.4. *GHG emissions from resource and energy consumption of construction equipment and techniques (E_5)*

The reduction in the amount of total GHG emission from diesel, water, and electricity consumption after adopting prefabrication is 249 tons. This value is 10.3% lower than that of conventional construction (Table 11). GHG emissions from the use of diesel, electricity, and water are reduced by -2%, 9%, and 8%, respectively. The increase in diesel use for concrete delivery pumps is associated with the increase in the amount of concrete during semi-prefabrication. Concrete work with on-site wet trades, in terms of GHG emissions from the use of electricity and water, are substantially lower because most concrete works are conducted off-site. To illustrate, in precast façades, the amount of water used in curing concrete can be controlled in an off-site factory because a precise template to cast concrete is available for each piece of the façade. The façade has fixed water and concrete without wet-trade works. A standardized factory-built process also simplifies the task of manufacturing components, as well as enables the effective coordination and integration of construction links and interfaces. This process results in the reduction of unnecessary waste from each link and interface. The frequency of use of concrete pouring vibrators, welders, and cranes are greatly decreased according to the site survey conducted in this study. For example, the number of cranes used during semi-prefabrication construction is half of those used in conventional construction methods.

6. Conclusions

The building construction process emits substantial quantities of GHG emissions. Various construction methods generate different amounts of GHG emissions in the construction stage. Prefabrication is an alternative construction method to conventional cast in-situ. Its construction technologies and processes are different from those of the conventional one, as well as its GHG emissions. This study focuses on semi-prefabrication method for concrete structure system. Specifically, this study identifies a calculation boundary and five GHG emission sources for semi-prefabrication. These include embodied GHG emission of building materials, transportation of building materials, transportation of construction waste and soil, transportation of prefabricated components, and the operation of equipment and construction techniques. In addition, this study introduces a quantitative process-based model to calculate and analyze the GHG emissions of projects using semi-prefabrication. A comparison of two cases that adopt semi-prefabrication and conventional modes is employed to illustrate the differences and characteristics of GHG emissions.

Results indicate that the project under semi-prefabrication reduced about 1.1 tons per 100 m^2 in GHG emissions compared with the project under conventional construction. The most positive contributor of GHG emissions reduction is the embodied emissions of building materials, accounting for 86.5%. The following contributors are the transportation of building materials, the resource consumption of construction equipment and techniques, and the transportation of waste and soil, accounting for 18.3 %, 10.3%, and 0.2%, respectively. On the other hand, the negative contributor is the transportation of prefabricated components, which offsets 15.3% of total emissions reduction and weakens the emissions reduction advantages of prefabrication. The key approaches to enhance GHG emissions reduction in semi-prefabrication are reducing the amount of embedded parts of steel by a design optimization of reinforced joint links of components, making reasonable and economically efficient proportions of concrete and brick on external walls, and selecting off-site factories that are near the projects or material distribution centers. These aspects will gain increased recognition by more governments and clients as the competition in the prefabrication market increases.

This study presents a method to examine GHG emissions in semi-prefabrication projects in the construction stage. Analysis on the characteristics and differences of GHG emissions between semi-prefabrication practice and conventional construction shows the different sources and factors related to emissions. Prefabrication practice induces less emission compared with conventional construction, although the reduction level is not significant. A limitation of this research is that the subjects of the study are focused on only one project for each construction method. Thus, a future study is planned to investigate more practical cases for multiple examination of the correlation between the level of prefabrication and that of emissions.

Acknowledgements

This study was financially supported by the Hong Kong Polytechnic University through Research Grant No. 5-ZJD7 ,the China Special Social Science Research Program of National Higher Education Institute Basic Research Fund under Grant No.CDJSK11040 , and the Fundamental Research Funds for the Central Universities in 2013of Chongqing University.The authors wish to express their sincere gratitude to Mr. Duan for his help in data collection. The authors would also like to acknowledge the editing by Dr. Paul W. Fox of an earlier draft of this paper.

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