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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.

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 10–20% 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 and Horvath [8] pointed out that the environmental impact and GHG emissions from the construction phase cannot be ignored, even if this phase only accounts for 0.4–12% 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 80–90% 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,

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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 and Navaorro [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 and Horvath [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 et al. [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