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# Life cycle carbon dioxide emissions simulation and environmental cost analysis for building construction

Jui-Sheng Chou*, Kuan-Chih Yeh

*Department of Civil and Construction Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan*

A R T I C L E I N F O

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A B S T R A C T

The construction industry causes a number of complex environmental effects, particularly carbon dioxide emissions. In the past decade, decision makers in the construction industry have focused on economic costs rather than environmental habitat concerns. However, in recent years, companies have slowly realized the importance of the environmental effects of building life cycles, in addition to maximizing profit. Therefore, this study developed a carbon dioxide emissions evaluation system and an environmental cost calculation method. The simulations considered the consumption of fossil fuel, electricity, and water. A systematic approach was proposed for optimizing the balance of the carbon dioxide emissions and environmental cost during building life cycle. Particularly, this study demonstrated a simplified metric for converting carbon dioxide emissions into environmental costs. The proposed method can guide engineers and architects in evaluating the primary environmental risk for a building life cycle and selecting an appropriate construction method.



## 1. Introduction

The building and construction sector is one of the seven dominant sectors that contribute most to global greenhouse gas (GHG) emissions (IPCC, 2007). The building sector consumes approximately 40% of the total energy used, thus contributing up to 30% of total GHG emissions annually. The United Nations Environment Programme (UNEP) declared that GHG emissions will more than double in the next 20 years unless actions mitigating the emissions are undertaken (UNEP, 2009). Therefore, environmental problems related to GHG emissions in the building sector should be investigated further.

Because of the prosperous development of industries worldwide, the demand for energy (*i.e.*, coal and oil) is continually rising. These developments have resulted in increased GHG emissions such as carbon dioxide ($CO_2$), methane ($CH_4$), and chlorofluorocarbons temperatures, and effects of global warming. The activities of the construction industry cause multiple and complex environmental impacts on the environment. The GHG with the greatest effect on global warming is $CO_2$ (Gaussin et al., 2013; Jing et al., 2014), comprising approximately 82.9% of all GHG emissions (Todd et al., 2001). In addition, the Environmental Protection Agency (EPA) has also confirmed that, of the various gases in the atmosphere, $CO_2$ is the primary contributor to global warming (EPA, 1997).

To accurately assess the environmental load of a building, the building's life cycle must be examined thoroughly, including the environmental load factors for construction material production, construction, occupation and renovation, and demolition (Blengini, 2009; Guggemos and Horvath, 2005; Gustavsson et al., 2010). Numerous studies have focused on the development of advanced technologies, policies, and measures to reduce GHG emissions at the operation stage (Sentman et al., 2008; Su and Zhang, 2010; Zhang et al., 2011). In addition, several studies have investigated the environmental effects and GHG emissions produced in the construction phase (Cole, 1998; González and García Navarro, 2006).

Prefabrication and cast-in-place construction methods are used widely in reinforced concrete structures. The cast-in-place construction method is a conventional method performed on site. By contrast, prefabrication is a manufacturing process generally conducted at a specialized facility and in which various materials are joined to form a component part of the final installation.

* Corresponding author. Tel.: +886 2 2737 6321; fax: +886 2 2737 6606.
*E-mail address:* jschou@mail.ntust.edu.tw (J.-S. Chou).

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Prefabrication is the transferring of on-site construction activities from field to an off-site production facility (Tatum and Vanegas, 1986).

To the best of the authors' knowledge, no previous study has proposed a method for simulating the $CO_2$ emissions of a building during its life cycle as an environmental cost. Therefore, this study proposed a method to simulate the $CO_2$ emissions of a building during its life cycle as an environmental cost to provide a quantitative value for assessing the global environmental load contributed by the construction industry. Prefabrication and cast-in-place construction methods were used to demonstrate the applicability of the proposed method. Monte Carlo simulation (MCS) was used to calculate the probability distribution of $CO_2$ emissions in the complete life cycles of the prefabrication and cast-in-place construction methods. Monetary concepts were then used to convert environmental loads into tangible costs.

The primary contribution of this study is to guide engineers and architects in evaluating the primary environmental risk to a building life cycle and selecting a construction method. The research process used in this study is detailed below. The related literature on resource and energy consumption was reviewed to develop formulas for estimating the consumption of water resources, electricity, and fuel. The formulas were then modified to incorporate life cycle concepts. The above process was used as the foundation for comparing the $CO_2$ emissions of buildings constructed using the prefabrication and cast-in-place construction method. Regarding the uncertainty characteristics of variables, the variable distribution types in the estimation formulas were defined, and the environmental loads were simulated to construct curves for the cumulative probability distribution of $CO_2$ emissions for each phase of the construction life cycle under desired confidence levels. Finally, $CO_2$ emissions were converted into environmental costs by using the standard concepts of carbon taxes and trading. To supplement conventional cost estimates, engineers and architects can present $CO_2$ emissions in monetary units when analyzing, comparing, and selecting construction costs.

## 2. Literature review

The background of the environmental loading index, $CO_2$ emissions estimation models, and application of the life cycle concept are presented in the following subsections.

### 2.1. Environmental loading index

The environment can be defined as any influence on a unique life form (Miller, 2007; Zhang et al., 2014), and environmental load factors refer to human-caused influences such as GHGs (e.g., $CO_2$), which exert an environmental load (Todd et al., 2001). Global studies have identified numerous environmental load factors in the construction industry.

For example, Junnila and Horvath (2003) quantitatively assessed five pollutants emitted throughout the life cycle of a five-floor cast-in-place office building with a total floor area of 15,600 $m^2$ in southern Finland (Junnila and Horvath, 2003). The total emissions of the pollutants, namely $CO_2$, sulfur dioxide ($SO_2$), butatrienylidene ($H_2C_4$), phosphate ($PO_4$), and lead (Pb), were 48,000, 130, 24, 16, and 0.15 tons, respectively. The study found that $CO_2$ emissions were 370 times higher than $SO_2$ emissions and 320,000 times higher than Pb emissions. Therefore, the environmental impact of $CO_2$ emissions is immense and cannot be ignored.

Sihabuddin and Ariaratnam (2009) assessed the environmental load factors of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides ($NO_x$), $CO_2$, and $SO_2$ emissions produced by underground engineering construction machines (Sihabuddin and Ariaratnam, 2009). Their analysis revealed that horizontal directional drilling machines used to dig underground tunnels (diameter, 300 mm; length, 152 m) generated environmental load factor emissions of 0.112 (HC), 0.574 (CO), 1.539 ($NO_x$), 65.7 ($CO_2$), and 0.205 kg ($SO_2$). Of these, $CO_2$ emissions comprised 98.7% of environmental load factor emissions.

Dimoudi and Tompa (2008) further investigated $CO_2$ and $SO_2$ emissions in terms of environmental loads of construction materials used in two scaled reinforced concrete office buildings in Athens, Greece (Dimoudi and Tompa, 2008). Separate analyses were performed for the roof, internal/external walls, beam-columns, and internal structures. The construction materials of the building in Case 2 were generally similar to those used in Case 1. The $CO_2$ emissions in both cases were 252 times the $SO_2$ emissions.

Yan et al. (2010) developed a calculation method and defined four sources of GHGs emitted by buildings in Hong Kong (Yan et al., 2010). Their case study examined three GHGs: $CO_2$, $CH_4$, and nitrous oxide ($N_2O$). Of the GHG emissions, 98.6–9 9.2% were emitted by the manufacture and transportation of building materials and the operation of construction equipment. The results indicated that concrete and reinforcement steel comprised 93.99–95.11% of the GHGs emitted by all building materials.

Thus, many studies have shown that the amount of $CO_2$ emitted over the life cycle of buildings and construction machines is higher than that of other environmental load factors. The greenhouse gas with the largest effect on global warming is $CO_2$ (Gaussin et al., 2013; Jing et al., 2014), which is also the primary contributor to global warming (EPA, 1997). Reducing $CO_2$ emissions greatly benefits the environment and the sustainable development of construction technology. In accordance with the key-point management approach, $CO_2$ emissions were selected as the primary indicator of environmental load.

### 2.2. $CO_2$ emissions estimation models

In process-oriented estimation models, decomposition flow diagrams are used to measure the environmental effects of resource and energy inputs in construction or material production processes. By assessing the amount of $CO_2$ emissions from the production of building materials, construction, and human activities, process-oriented estimation models can be used to categorize the environmental load factors of a product life cycle (from product manufacturing and use to disposal) systematically and comprehensively (Chen et al., 2001; Kuo and Chen, 2009; Weisser, 2007). However, because information accessibility, time efficiency, and costs are difficult to quantify, a simplified data collection process is required. This simplified process should enable the use of estimation formulas established in extant data as a reference when making estimations.

Previous studies have typically expressed the results obtained using estimation formulas as single values or deterministic values. However, $CO_2$ emissions estimation is characterized by uncertainty resulting from other factors that affect or change them during the emission process. Therefore, using probability for estimation is more appropriate than using single values during the initial planning phase of a project, which is characterized by high uncertainty. The probability distribution results can compensate for the insufficiency of single value estimations, which do not consider potential uncertainties, thereby increasing the reliability and accuracy of the estimation results for assessment targets (Chou, 2011; Sonnemann et al., 2003). Therefore, in this study, a probabilistic simulation was performed to estimate $CO_2$ emissions in terms of consumption of fuel, electricity, and water resources during the building life cycle.