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Models and method for estimation and comparison of direct emissions in building construction in Australia and a case study

Malindu Sandanayake [a], Guomin Zhang [a,*], Sujeeva Setunge [a], Chun-Qing Li [a], Jun Fang [b]

[a] School of Civil, Environmental and Chemical Engineering, RMIT University, GPO Box 2476, Melbourne, VIC 3001, Australia
[b] School of Civil Engineering and Architecture, Wuhan University of Technology, Wuhan 430070, China

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ABSTRACT

Building construction incurs direct emissions from equipment operation and transportation. These emissions at a collective level seem to be high, which alerts contractors who are keen to explore reduction possibilities for emissions. Understanding emission contributions at the activity and equipment level are important to achieve this target. However, none of the past studies have conducted an in-depth analysis to identify direct emissions reduction prospects at the construction stage. This study aims to develop models and method to enable the estimation and analysis of emissions at project, activity and equipment levels in a building construction. A framework is then established to provide a systematic procedure to aid the decision making for reducing direct emissions at the construction stage. A case study of foundation construction in a commercial building is presented to validate and demonstrate the functions of the framework developed. The results show a GHG emission distribution of 77.13%, 13.53% and 9.34% for materials, equipment usage and transportation respectively at the project level. CO and NO_x were the governing non-GHG emissions recorded. In-depth equipment level analysis concludes the importance of considering emission rates to compare and identify critical equipment for emission reduction. Activity level analysis ushers the identification of activities with significant emissions from transportation and equipment.

1. Introduction

The present world is moving towards achieving sustainability [1], and this trend encourages the global communities to explore all possibilities to reduce energy use and minimise environmental emissions. Many countries have stipulated emission standards and reduction policies such as carbon taxes to control emissions, the importance of which was asserted by several studies [1,2]. While the carbon tax policy has not been successfully implemented in Australia so far due to various reasons [3], a political debate of reintroducing this policy pervades which may affect the building and construction sector significantly in the foreseeable future. This is beyond question as buildings are responsible for two-fifth of resource consumption and environmental emissions of the world [4].

Buildings consume energy and produce emissions throughout the life cycle starting from the material acquisition stage, through the construction stage and the use stage to the end of life stage [5]. Most of the emission studies on buildings concentrated on the material and the use stages of the buildings and largely neglected the construction and the end of life stages [6–11]. Contractors who are conscientious of environmental sustainability acknowledge the importance of considering emissions at the construction stage to explore emission reduction opportunities [12]. Even though the estimation of emissions at the construction stage is regarded as highly important, several issues retard research progress in this area [4]. Lack of reliable inventories in LCA software and complex modelling issues are the predominant reasons that compel many researchers to neglect the emissions at the construction stage.

The few studies attempting to explore the emissions at the construction stage acknowledged the importance of considering these emissions at an aggregate level [4,13–16]. Some of these studies highlighted the importance of exploring direct emissions such as emissions from equipment usage and transportation [17], while others emphasised the significance of indirect emissions such as embodied emissions from materials [18]. However these studies only considered emission distributions at project level by using case studies which takes into account all the emissions in the defined scope of one project. Merely a conclusion on emission reduction by concentrating on direct emissions or use of recycled materials

* Corresponding author.
E-mail address: kevin.zhang@rmit.edu.au (G. Zhang).

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at project level will not offer enough information to contractors who seek to reduce their carbon footprints. Moreover, for a specific construction project where the choice of materials is limited, reducing direct emissions seems to be imperative for contractors. Thus a method to enable in depth analysis is essential to thoroughly investigate direct emissions at the construction stage and to identify the feasible emission reduction opportunities. An in-depth analysis scrutinises emission pattern at activity and equipment level to obtain a thorough understanding on the emission reduction opportunities. A typical activity at the construction stage of a building involves direct emissions from equipment usage and transportation and indirect emissions from materials and electricity usage [14,19]. Activity level analysis will identify activities with significant emissions from equipment usage and transportation. Subsequently, an in-depth analysis on equipment and transportation can be carried out to provide insights to contractors to reduce emissions.

Thus the objective of the paper is to present models and method of emission estimation which helps solicit direct emission reduction possibilities at the construction stage of a building. A framework is then developed to carry out an in-depth direct emissions analysis at the construction stage of a building. A case study of foundation construction is used to show the implementation and test the validity of the framework.

2. Review of past research studies

Several studies have attempted to estimate and highlight the significance of emissions at the construction stage of a building. Guggemos et al. compared emissions on steel and concrete office building construction using a case study [4]. Yan et al. [21] estimated emissions from manufacture and transportation of building materials, energy consumption from construction equipment and processing resources and disposal of construction waste. The results indicated that 82–87% of the total emissions at the construction stage are from materials, which encourages the use of recycled materials to minimise the emissions at the construction stage. On the other hand, some studies suggested emission reduction possibilities at the construction stage by adopting various construction methods. Mao et al. in their study compared the emissions in conventional and pre-fabrication construction methods [14] and concluded that the use of prefabricated components can achieve up to 15% of emission reduction at the construction stage. However, none of the above studies have observed the significance of carrying out an in-depth direct emission analysis at the construction stage of a building.

Three types of models including input-output model, process based model and hybrid model were used to estimate emissions [13,14,22–26,28,29]. On measuring CO_2 emissions of a life cycle of a residential building, Seo and Hwang adopted a matrix based model to estimate emissions from building materials [28]. Crawford developed a combined matrix and algebraic model to estimate embodied emissions from construction materials [29]. Several other studies used algebraic models to calculate embodied emissions from construction materials [13,14,21]. Some of these models considered construction waste using waste factors while others incorporated losses during transportation and installation separately. The focus of most of these models was to estimate on-site environmental impacts due to material usage.

Due to partial combustion of fuel, almost every equipment and transportation vehicle accounts for both greenhouse gas (GHG) emissions and non-GHG emissions such as carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter (PM) and sulphur dioxides (SO_2) [31]. Most of the studies used fuel based mathematical models to calculate emissions from construction equipment [14,21,32]. However, studies showed that non-GHG emissions are dependent on not only fuel consumption but also vehicle characteristics [33]. Thus, this complication led to most of the studies to concentrate only on GHG emissions from construction equipment. A more accurate model to calculate non-GHG emissions from construction equipment would be to consider machine characteristics such as power, age and efficiency of the machine [12,20,34,35]. Two types of models were developed to calculate emissions from transportation. One type used the amount of fuel consumed by transportation vehicles while the other type used the weight of materials and the distance travelled to calculate emissions [14,16,21]. It is worth noting that the fuel based models are ideal for GHG emissions calculation while distance based models are suitable for non-GHG emissions calculation due to transportation [36]. The review on models signifies that the models developed by previous emission studies are only able to calculate project level emissions while complications occur in estimating emissions at each machine, vehicle and activity.

It is evident that the previous emission studies have been mainly focused on the project level emissions estimation. Direct emissions have been seldom given enough significance. Moreover, none of the studies have given enough consideration on conducting an in-depth analysis to identify the insights of direct emissions at the construction stage of a building. More often than not in construction projects where construction materials and methods are pre-defined, effective resource planning and selection seems to be the only option to enable emission reduction at the construction stage. Under such circumstances, it is important to conduct an in-depth equipment and activity level emission analysis to scrutinize more areas of improvement to reduce emissions at the construction stage. Therefore, the study observes the requirement of developing models and a framework that would enable a systematic procedure to identify the significant emission sources and options to minimise them.

3. Method for emission estimation

Estimation of both direct and indirect emissions at project level is essential for understanding the significance of direct emissions before considering an in-depth analysis [22]. Therefore, four models have been identified to estimate emissions at project level of the construction stage of a building. They include fuel based emission models for GHG emission evaluation and time or distance based emission models for non-GHG emissions evaluation. The non-GHG models consider emission substances such as CO, NO_x, PM and SO_2 which are generated from combustion during equipment usage and material transportation and further investigated on their short term impacts on the environment.

3.1. Embodied emissions from materials

Embodied emissions from materials are estimated from the following equation.

$$E_m = \sum Q_m \times e_m \quad (1)$$

Where, E_m is the embodied emission of material m used in the construction in $kgCO_2$-eq, Q_m is the amount of m^{th} material used in kgs and e_m is the emission factor for m^{th} material in $kgCO_2$-eq/kg. The emission factor is obtained from the inventory of Carbon and Energy (ICE) database published by the University of Bath [37]. ICE database is chosen because it is one of the most comprehensive databases available to obtain emission factors for construction materials.