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A multivariable regression tool for embodied carbon footprint prediction in housing habitat

Syed Shujaa Safdar Gardezi [a], [*], Nasir Shafiq [a], Noor Amila Wan Abdullah Zawawi [a], Muhd Faris Khamidi [b], Syed Ahmad Farhan [a]

[a] Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, 32610, Bandar Seri Iskandar, Tronoh, Perak, Malaysia
[b] Department of Built Environment, University of Reading Malaysia, Menara Kotaraya, 80000, Johor Bahru, Johor, Malaysia

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ABSTRACT

A novel embodied carbon prediction tool has been developed for conventionally constructed housing units. Single and double storey terraced, semi-detached and detached housing projects were evaluated by adoption of partial life cycle assessment (LCA) framework. The statistical technique of multivariable regression analysis was merged with LCA and building information modeling (BIM) for prediction of such environmental issue in housing sector. The assessment was limited to pre-use phase with LCA boundary of "cradle to site". The criteria and requirements for a statistically consistent and efficient prediction tool were successfully satisfied with an acceptable average prediction error of less than ±5%. Based on very basic explanatory variables, the tool also helped to manage the barrier of huge data requirements for such environmental studies. The study is expected to act as a milestone and help the researchers and industry professionals for quick, effective and sustainable environmental assessment, decision making and solutions.

1. Introduction

The housing sector holds a very pivotal role in providing basic living needs and this role becomes more crucial with an increase in population and rapid urbanization in any country. The activities undertaken to develop this sector are not eco-friendly and generate huge amounts of greenhouse gas (GHG) and CO_2 emissions (Gardezi, Shafiq, Zawawi, & Farhan, 2014). Population growth and rapid urbanization is not only increasing the demand of housing units but also causing an increase in carbon footprint. However, at this moment, no standardized tool to baseline the carbon footprint for typical housing units is available. The quantification of environmental effects from the residential building, especially houses/dwellings, has been a keen area of interest in Malaysia for the environment researchers like many other countries in the recent past. The emissions from a housing sector can broadly be divided into embodied and operational emissions. This study focused on the embodied part of carbon footprint. According to Farhan, Shafiq, Azizli, Umar, and Gardezi (2014), much of the attention has been paid to the operational carbon and embodied carbon footprint seemed to be disregarded. Densley Tingley and Davison (2012) also reported that the issue of embodied energy or carbon is often neglected/ignored whereas embodied carbon footprint can make a significant contribution to the whole life carbon of a building. According to Blengini (2009) and Thormark (2002), it accounted for 29%–40% of the energy used for manufacturing and transporting the building materials. Embodied energy represents the energy used for producing building materials (from the extraction of the raw materials to the manufacture of the final product, including transportation) and their implementations in the building (Rossi, Marique, Glaumann, & Reiter, 2012).

Different researchers have developed and proposed new tools and methods to quantify and assess the embodied carbon footprint of buildings in recent years. Densley Tingley and Davison (2012) adopted LCA methodology to investigate the environmental effects of reused construction materials in design for deconstruction. The outcome resulted in development of tool "Sakura" to help in calculating the embodied carbon based parts of the building structure, life-span of building components, lives of reused building components and lifecycle stages of the building. Rossi et al. (2012) developed a basic LCA tool to assess the embodied carbon footprint

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[*] Corresponding author.

E-mail addresses: engineershujaa@gmail.com (S.S.S. Gardezi), nasirshafiq@petronas.com.my (N. Shafiq), amilawa@petronas.com.my (N.A.W.A. Zawawi), m.f.khamidi@reading.edu.my (M.F. Khamidi), syfarisk@gmail.com (S.A. Farhan).

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of residential buildings located in different climatic conditions in three European towns with main focus on the structure and the materials of the buildings. Steel-framed and masonry houses were evaluated in a comparative analysis. Memarzadeh and Golparvar-Fard (2012) proposed a new carbon footprint monitoring tool to benchmark, monitor, and visualize expected and released embodied carbon footprint at a construction work site by adopting n-dimensional augmented reality (DnAR) models in a common 3D environment. Moncaster and Symons (2013) presented a design decision tool to calculate the whole-life embodied carbon and energy of buildings called the ECEB. The main aim was to develop an empirical approach for early environmental related design decision for UK buildings. The lack of data was observed to be the main barrier to obtain such results wherein the construction and manufacturing industries were proposed to develop pertinent data. Iddon and Firth (2013) developed a Building Information Model (BIM) tool to simultaneously estimate embodied and operational carbons for a typical four-bedroom detached house. Similarly Basbagill, Flager, Lepech, and Fischer (2013) proposed a decision support tool to assess the influence of decisions on the embodied carbon footprint. The tool incorporated BIM, LCA, energy simulation, maintenance, repair and replacement (MRR) scheduling and sensitivity analysis software and helped to forecast decisions that crucially influenced the embodied impact of the building. However, development of new tools and methods is always required to improve the efficiency and ease of conducting estimations, projections, assessments and monitoring of the embodied carbon of buildings (Farhan et al., 2014).

The current research also focused on the development of new tool for embodied carbon footprint assessment and predictions. Life cycle assessment (LCA) methodology was used to evaluate the environmental effects. However, LCA was merged with of multivariable regression to develop a novel tool for prediction/forecasting of carbon footprint. Different housing units from the tropical Malaysian climate with conventional construction were selected and a statistical tool was developed. It successfully qualified the requirements for a statistically consistent and efficient prediction tool with an average forecasting error of almost ±5%. The usage of this tool has been observed to save a considerable time and also manage the barrier of non-availability of huge data for carbon footprint estimates in early design designs as it is based upon very basis explanatory variable for assessments. The methodology for development and evaluations along with results has been elaborated in respective sections.

2. Methodology

The Life cycle assessment (LCA) approach was adopted in the study to conduct a partial assessment, from cradle to site. According to ISO 14040:2006, LCA is a technique for assessing the environmental performance of a product, process or activity from ‘cradle to grave’, i.e. from extraction of raw materials to final disposal. However, the scope (including the system boundary and level of detail) depends on the subject and the intended use of the study. The depth and the breadth can differ considerably depending on the goal and a particular LCA can be restrained to a specific stage or process according to the defined scope (ISO, 2006). LCA is a very helpful tool which not only provides an account of materials and energy involved but also enables to measure associated environmental impacts in a product or system Asif, Muneer, and Kelley (2007). Similarly, Alting (1995) and Azapagic (1999) also defined LCA as management tool which not only quantifies but also enables to assess the environmental burdens and their potential effects throughout the life cycle. The ability of LCA to measure the environmental impact of a product throughout its life cycle makes them a unique holistic tool for assessing the environmental and resource consequences of choices made in product development and it was one of the main reasons for such adoption. Different researchers adopted LCA to assess the environmental burdens of different buildings as well as housing projects in the past, Table 1:

LCA is a powerful set of tools for quantifying, evaluating, comparing, and improving goods and services in terms of their potential environmental impacts (Rebitzer et al., 2004). The system boundaries of the current study have been limited to pre/use phase. According to Blengini (2009), the pre-use consists of the manufacturing and transportation of building materials, as well as the erection of the building envelope. Therefore, in order to complete the model, inventory data relevant to the most important building materials were included. These construction materials were categorized in to subsystems (Table 2):

2.1. Pre-use phase

The physical construction/execution of projects is also termed as pre-use phase. In this phase, different activities are undertaken which result in actual physical construction of a facility that has been envisaged in planning and design (P & D) phase. In other words “execution is the implementation of a design envisioned”. As the project moves to the execution phase, it requires the necessary resources to carry out the project. The materials are the basic elements in any type of construction activity. The construction sector consumes a handsome amount of construction materials while completing any construction project and ultimately not only depleting the natural resources but also increasing the content contribution of CO_2 from construction sector. Likewise, the transportation of these materials for incorporation in construction works also consumed fossil fuels and results in carbon footprint addition. Therefore, the footprint of materials in this phase is the summation of carbon footprint from materials and the transportation from the manufacturing to the construction site. Mathematically

$$CO_{2\ \text{exe}} = CO_{2\ \text{mat}} + CO_{2\ \text{tran.}} \tag{1}$$

2.2. Materials

A fair quantity of natural resources is consumed by buildings in form of construction materials and energy during their life cycle. Building materials are one of the prime sources of these GHG emissions from the construction sector (Gardezi, Shafiq, Zawawi, et al., 2014). These materials have to go through certain processes during their life cycle to be used for specific purposes. Besides the valuable contribution of housing sector in betterment of human life, the building materials used also make a significant contribution in embodied CO_2 emissions through their life cycle. Each of this construction material has to go through the extraction, manufacturing and transportation/dispatch process for their final consumption. During these processes of their life cycle, these construction materials consume a fair amount of energy in terms of electricity or fuels and make a significant contribute in CO_2 emissions through their embodied CO_2 emissions i.e. CO_2 emissions produced from extraction to their final consumption (Nasir Shafiq et al., 2015).

2.3. Transportation of materials

The quantification of such emission was based on the weight of each material, type of vehicle and travelling distance. A carrier vehicle with a standard load carrying capacity (6 tons) normally