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Technique for quantification of embodied carbon footprint of construction projects using probabilistic emission factor estimators

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ABSTRACT

Buildings consume a significant proportion of the world's resources, mostly in the form of materials usage. In addition, with the ongoing efforts focusing on reducing the operational energy consumption of buildings, the embodied emissions of buildings are expected to increase in proportion in the future. With the increasing focus placed on the embodied emissions of buildings, organizations in the construction industry will face requirements to report information regarding the embodied emissions of buildings. However, in order to obtain the embodied emission of buildings, tremendous efforts have to be placed as the process is data intensive. In order to overcome this challenge, a streamlined technique is proposed to minimize the efforts required by practitioner to obtain the embodied carbon footprint. The proposed technique comprises a probabilistic model of emission factor estimators used to estimate the required embodied emissions. Based on the four projects presented as case study for the proposed technique, the practitioner would be required to manually match the appropriate emission factors to the activity data for between 12 and 21% of the data points. This is in contrast to the current traditional technique, which requires the manual matching of 100% of data points. The resultant deviation of the computed embodied carbon footprint from the proposed technique and the current technique was between −0.25% and +3.65%.

1. Introduction

1.1. *Background*

According to the United Nations Environment Programme, buildings consume about 40% of the world's resources, mostly in the form of materials usage (UNEP, 2007). A large myriad of materials is used which include concrete, cement based products, timber, stones, ceramic tiles, glass, metals like steel, aluminum and copper, paint and coating and various types of plastics such as PVC, acrylic and PET. Large amounts of resources and energy are required when producing and recycling these materials. Each material has to be extracted, processed and finally transported to its place of use. More than 30 billion tons of various materials are used in buildings each year (Rincón, 2011). Correspondingly, in 2010 buildings accounted for 32% of total global final energy use and 19% of energy-related greenhouse gas (GHG) emissions. This energy use and related emissions is expected to double or potentially even triple by mid-century (Lucon et al., 2014).

Mitigating the release of GHGs into the atmosphere has been a growing issue in the area of sustainability. Therefore, to limit the use of resources and environmental degradation, the concept of ‘green building’ is proposed to reduce the environmental impact of buildings throughout their life cycle. At present, materials selection in building design are based almost solely on materials and products that had been labeled or certified green in accordance with criteria set out in the respective schemes prevalent in the countries of origin or exported to. Such schemes include the Singapore Green Building Product Certification Scheme (SGBC, 2014) developed by the Singapore Green Building Council, Singapore Green Labeling Scheme (SEC, 2014) by the Singapore Environment Council and China Energy Conservation Program (CECP, 1998). Malaysia has SIRIM Certified Eco-labeling scheme (SIRIM, 1997) and IBU Environmental Product Declaration (IBU, 2004). Other commonly encountered and well-known schemes include the Good Environmental Choice Australia (GECA, 2002), Blue Angel in Germany (Blue Angel, 1978) and Energy Star (Energy Star, 1992) and Design for the Environment in the United States (EPA, 1992).

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The usage of energy is closely linked to the release of greenhouse gases as approximately 80% of the global primary energy supply is derived from carbon-based fossil fuel (International Energy Agency, 2013). Energy and pollutant emissions such as carbon dioxide (CO_2) may be regarded as being 'embodied' within materials. That is to say, embodied energy of primary production can be viewed as quantity of energy required to extract, process, manufacture and transport the materials that constitute the building (Koskela, 1992; Lee et al., 2011; Bribián et al., 2011; Sahagun and Moncaster, 2012). Gonzalez and Navarro (González and Navarro, 2006) asserted that building materials possessing high embodied energy could possibly result in higher carbon dioxide emissions in comparison to materials possessing low embodied energy. Recently, under the EU Framework Program Horizon 2020, researchers carried out work to study the behavior of eco-building materials and the ecological significance of the low-carbon materials (Torgal, 2014). It was shown that in the assessment of the ecological performance of building materials, the structure or constitution of energy consumption and the methodology for evaluation are the main factors to be taken into consideration (Lee et al., 2011; Bribián et al., 2011). Various studies show that, for buildings, embodied carbon footprint is 37–43% of a 60 year life cycle carbon emissions in the UK (Eaton and Amaton, 1998), 11–50% of a 60 year life cycle in the USA and Canada (Engin and Frances, 2009), 45% of 50 years life cycle in Sweden (Thormark, 2002), and 60% of 50 year life cycle in Israel (Huberman and Pearlmutter, 2008). This shows that the traditional views to ignore embodied energy and the associated carbon emissions are not appropriate (Langston and Langston, 2008; Holtzhausen, 2007). This is particularly true due to the emerging trends towards "zero energy" buildings in which renewable energy coupled with low-energy consumption measures resulting in close to zero energy consumption derived from fossil fuels. As buildings become more energy efficient over time, the level of the energy consumption of the building is set to decrease in the foreseeable future. This will result in rising significance placed on the embodied energy and the associated carbon emissions of buildings (Plank, 2008; Nabel et al., 2008; Sartori and Hestnes, 2007; Optis and Wild, 2010; Ibn-Mohammed et al., 2013).

1.2. Life-cycle assessment for environmental evaluation of buildings

Life-cycle assessment (LCA) method have been used for environmental evaluation of product development processes in other industries for a long time (Cole and Rousseau, 1992; Jönsson, 1998; Suzuki and Oka, 1998), although application to the building construction sector has only been adopted for the last 10 years (Singh et al., 2011; Buyle et al., 2013). LCA is a tool for systematically analyzing environmental performance of products or processes over their entire life cycle, including raw material extraction, manufacturing, use, and end-of-life (EOL) disposal and recycling (Silvestre et al., 2014). Hence, LCA is often considered the most suitable approach to the evaluation of environmental impacts.

Efforts have been made to apply the LCA to the assessment and design of green buildings. Design of green buildings is achieved by reducing its operating energy through active and passive technologies. Abanda et al. (2013) presented a comprehensive set of 25 models for computing the embodied energy, GHG emissions and cost associated to construction activities. Multi-criteria evaluation models have also been established to evaluate material choices of buildings especially when conflicting objectives exist (Akadiri et al., 2013). Approaches in reducing buildings' operating energy could include changing the source of energy (e.g. from coal to natural gas), improving efficiency in equipment that utilize energy, and using green-materials that are also high performance. However, reduction in operating energy may sometimes be accompanied by an increase in embodied emissions of the building due to the energy intensive materials used to achieve energy saving (Ramesh et al., 2010). Generally, as the operating energy decreases, the embodied emission as a proportion of the building's life cycle emissions increases. Thormark (2002) reported that embodied energy and its share in the life cycle energy for low energy building is higher than conventional ones. At present, the application of LCA to the green buildings can be divided into three aspects: (1) the quantitative evaluation of energy consumption and environmental emission, which can provide guidance for the ecological design and rehabilitation; (2) comparison between more than two kinds of materials by considering some performance requirements to give advice when selecting building materials; (3) analysis on the total energy consumption and emission of the building itself throughout the life cycle.

1.3. Challenges

1.3.1. Rising requirement for quantification of embodied emissions

With the increasing focus placed on the embodied emissions of buildings, organizations in the construction industry will face requirements to report information regarding the embodied emissions of buildings. For example, Singapore's latest version of the green building scheme Green Mark 4.0 (BCA, 2012a, 2012b) has started to include the carbon footprint as one of the assessment criteria, which requires the measurement of the embodied carbon footprint attributed to the materials used in construction for residential and non-residential buildings.

Organizations in the construction industry embarking on carbon footprint studies, however, face major hurdles in the process of measuring the embodied carbon footprint for building projects. Langston and Langston (2008) suggested that, while measuring operating energy is less complicated, determining embodied energy is more complex and time consuming. This is due to the time consuming process of the data collection and data processing efforts to collate the bill-of-materials (BOM) of the buildings and convert them into their corresponding embodied emissions.

1.3.2. Practical challenges in data collection

Various surveys conducted on LCA practitioners have similarly highlighted that data collection phase is the biggest challenge commonly faced when conducting life cycle studies. Cooper and Fava (2006) state that approximately two-thirds of LCA practitioners cited that the inventory data collection process is the most time-consuming and costly part of LCA. Subsequent surveys done by Teixeira and Pax (2011) also presented similar results on the challenges of conducting LCA. Previous studies have proposed carbon footprint streamlining methods applied in other context such as data grouping suggested by Rugrungruang et al. (2010) can be done on electronic products (Rugrungruang et al., 2010) and algorithmic approach by Ng et al. (2012) to streamline carbon footprint quantification for metal stamping production operations. Predictive emission factors in combination with structured data and uncertainty analysis were also developed to deal with tremendous data requirements for simultaneous multi-product carbon footprinting (Meinrenken et al., 2012). Yeo et al. (2013) have established a method combining activity data screening, emission estimation and cut-off criteria for fast approximation of carbon footprint results.

Issues arising from the process of data collection must first be understood in order to streamline the process of deriving the embodied carbon footprint for buildings. One of the largest challenges associated to data collection, is the availability of timely and complete data (Reap et al., 2008). The size and complexity of dataset often compounds the issue. Tremendous practical challenges exist due to the decentralized nature of the activity data