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Variations in embodied energy and carbon emission intensities of construction materials

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ABSTRACT

Identification of parameter variation allows us to conduct more detailed life cycle assessment (LCA) of energy and carbon emission material over their lifecycle. Previous research studies have demonstrated that hybrid LCA (HLCA) can generally overcome the problems of incompleteness and accuracy of embodied energy (EE) and carbon (EC) emission assessment. Unfortunately, the current interpretation and quantification procedure has not been extensively and empirically studied in a qualitative manner, especially in hybridising between the process LCA and I-O LCA. To determine this weakness, this study empirically demonstrates the changes in EE and EC intensities caused by variations to key parameters in material production. Using Australia and Malaysia as a case study, the results are compared with previous hybrid models to identify key parameters and issues. The parameters considered in this study are technological changes, energy tariffs, primary energy factors, disaggregation constant, emission factors, and material price fluctuation. It was found that changes in technological efficiency, energy tariffs and material prices caused significant variations in the model. Finally, the comparison of hybrid models revealed that non-energy intensive materials greatly influence the variations due to high indirect energy and carbon emission in upstream boundary of material production, and as such, any decision related to these materials should be considered carefully.

Introduction

Overview of hybrid life cycle assessment

Life cycle assessment (LCA) is used to quantify environmental impact for a product's entire life cycle, including raw material extraction, material or product manufacturing, construction, operation and maintenance, and demolition. This can be classified as either a top-down or bottom-up approach. The traditional LCA or process LCA, known as bottom-up approach, is considered most accurate in embodied energy and carbon assessment. However, it fails to include the upstream boundary of material production. The embodied energy and carbon embodied in upstream boundary are those inputs used further upstream in supplying goods and services to the main life cycle stages (Crawford, 2004). There are four steps to conduct hybrid LCA: (1) derive an I-O LCA model; (2) extract the most important pathway for the evaluated sector (e.g. plastic products and structural metal products sector); (3) derive specific data for the evaluated sector or components; and (4) substitute the case-specific LCA data into the I-O model (Treloar et al., 2000).

More than 90% of energy and carbon emissions emanate from the upstream boundary of the supply chain in product manufacturing (Nässén et al., 2007). Due to the complexity of upstream inventory analysis in terms of time and labour consumption, the traditional LCA often uses processed data available within commercial databases such as Ecoinvent, GaBi, SimaPro, Athena and etc. Contrary to the process LCA, the top-down approach based on Input–Output (I-O) data (I-O LCA) includes a wider system boundary of the entire economic supply chain. However, I-O LCA inherits uncertainty, data aggregation, homogeneity assumption, age of data and capital equipment (Crawford, 2004).

Recently, the hybrid LCA has been developed as an effective method for assessing EE and EC emissions for the whole supply chain of materials or products while maintaining the accuracy of process data (Acquaye, 2010; Crawford, 2004; Lee and Ma, 2013; Suh and Huppes, 2005; Treloar, 1998; Wan Omar et al., 2012). The hybrid LCA can be defined as a combination of physical and monetary units or the integration of a process and I-O data. The flow of materials in process LCA and I-O LCA are expressed in physical (e.g. MJ, GJ, MJ/kg, and GJ/m^2) and monetary quantities (e.g. RM$, RM$/RM$, MJ/RM$, and GJ/RM$) (Acquaye, 2010). The I-O LCA provides a top-down linear microeconomic approach to explain the industrial structure in which the sectoral monetary transaction data are used in an inter-industry model to

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account the complex interdependencies of industries (Lenzen et al., 2003).

Although, the hybrid LCA is widely used to overcome the limitations of process approach, it still depends on the I-O data, which consists of highly aggregated industry sectors such as building construction that can cause variations to the hybrid LCA inventory (Dixit et al., 2013). Variations to energy and carbon emissions over the life cycle of building materials are known as uncertainties. These are due to stochastic variation and a lack of knowledge of precise parameter values (Gustavsson and Sathre, 2006). Generally, hybrid LCA has five types of uncertainty: data inventory, system cut-off error, sector or product aggregation, and temporal and geographic uncertainty (Williams et al., 2009). Data uncertainty occurs in input due to inadequate parameters and data. Cut-off and truncation errors in the hybrid LCA can lead to a high level of uncertainty in inventory data (Lee and Ma, 2013). Cut-off error occurs when the definition of *system boundary* is inconsistent whereas truncation occurs between process and I-O inventory. Previous studies have been proposed to improve hybrid models by reducing uncertainty between process and I-O data, but further improvement is also needed when integrating process and I-O data.

The iterative nature of hybrid LCA means more detailed assessment needs to be conducted to attain more reliable data. Previous studies proposed methodologies to identify uncertainty and variability in life cycle inventory (LCI) analysis (Heijungs, 1996; Huijbregts et al., 2003; Williams et al., 2009). For example, Heijungs (1996) outlined operational and generic methods for identifying key issues for further analysis in detailed LCI. *Key issues* were defined as the areas where product or process improvement leads to highest environmental improvement, as depicted in Fig. 1. Small changes that have large consequences (hot-spots) are crucial to the subsequent details of LCI, and are further identified as (Heijungs, 1996):

- Areas that represent highly sensitive parameters where small changes have great impact and must be accurately known prior to drawing conclusions; and
- Areas that represent highly sensitive parameters whereas small changes have great impact and might be affected by alternative product or process design.

The uncertainty and variation level in hybridising EE and EC assessment can be summarised, and is illustrated in Fig. 2. With regard to the whole life cycle of a building, the uncertainty and variation can occur vertically and horizontally. Vertical uncertainty arises due to parameter variation in the upstream boundary of the supply chain, while horizontal variability occurs due to human decisions and management methods over the entire life of a building, and can be easily measured through standard rating or certification system such as Green Star, LEED, CASBEE, and etc. However, vertical uncertainties involved in upstream system boundary due to parameter variation are difficult to measure, and there is a lack of simple methods for checking I-O data (Crawford, 2004). The only available approach was firstly introduced by Crawford (2004) to evaluate the applicability of I-O hybrid LCA to variety of buildings and building products but solely focusing on the final results of hybrid LCA inventory data.

Hybrid LCA limitations

Hybrid LCA approach can be classified into three categories: (1) tiered hybrid model; (2) I-O hybrid model; and (3) integrated hybrid model (Suh and Huppes, 2005; Suh et al., 2003). These models were developed to overcome limitation of process approach by combining I-O approach using a monetary unit. However, variations in direct and indirect energy between energy and non-energy intensive materials draw a variety of results. For instance, converting a monetary unit of materials with high indirect energy in an upstream boundary could increase EE and EC intensities of materials due to price fluctuations (Wan Omar et al., 2013). Therefore, using a highly aggregated industry sector such as building construction (e.g. residential and non-residential building sector in I-O tables) with a high level of indirect energy tends to cause more variation in the hybrid model (Dixit et al., 2013).

Using an inappropriate system boundary could lead to truncation error and variation in LCI data. Dixit et al. (2013) identified variation in system boundary definition as a key parameter that can cause problems in EE and EC results. Hence, the hybrid LCA needs to be improved by including more process data and the disaggregation of aggregated industry sectors. For instance, in the Malaysian I-O tables, electricity and gas are aggregated together even though they are two different sectors. Further disaggregation of the current Australian I-O models, with the use of commodity details, may be useful in reducing the inherent errors associated with I-O data (Crawford, 2004). Despite limitation of I-O LCA, Lenzen (2000) pointed out that the errors associated with I-O LCA are often significantly lower than the truncation error of a typical process LCA.

Previous studies have sought to hybridise process and I-O data to increase reliability, completeness and accuracy of model. These studies (Acquaye, 2010; Crawford, 2004; Crawford and Treloar, 2003; Crawford et al., 2010) calculated the EE of the entire building using data from a highly aggregated industry sector (such as residential construction) that does not differentiate between a low and a high-cost, a horizontal and a high rise structure, or a modular and a custom-designed structure (Dixit et al., 2013). Further, cut-off errors occur in hybrid models, and lack of truncation criteria between the process and I-O inventory may lead to a high level of uncertainty in the hybrid model (Lee and Ma, 2013). To overcome these limitations, process LCA plays an important role in determining the precision of hybrid data,

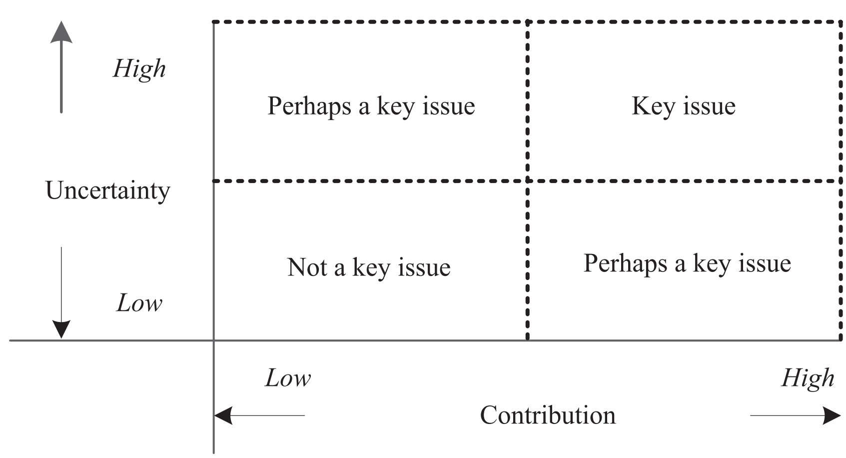

Fig. 1. Key issues of uncertainty and contribution of inputs in evaluation of life cycle inventory analysis results (Heijungs, 1996).