Variations in embodied energy and carbon emission intensities of construction materials

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Parameter variations in Hybrid LCA of embodied energy and carbon emission intensities of construction materials in Australia and Malaysia

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.

Keywords: Variation; parameter; embodied energy; carbon emission; Australia; Malaysia; hybrid

1. Introduction

1.1 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).

More than 90% of energy and carbon emissions emanate from the upstream boundary of the supply chain in product manufacturing (Nässén, Holmberg, Wadeskog, and Nyman, 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 (HLCA) 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, Doh, and Panuwatwanich, 2012). The HLCA 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 account the complex interdependencies of industries (Lenzen, Murray, Korte, and Dey, 2003). There are four steps to conduct HLCA: (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, Love, Faniran, and Iyer-Raniga, 2000).

Although, the HLCA 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 HLCA inventory (Dixit, Culp, and Fernández-Solís, 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, HLCA has five types of uncertainty: data inventory, system cut-off error, sector or product aggregation, and temporal and geographic uncertainty (Williams, Weber, and Hawkins, 2009). Data uncertainty occurs in input due to inadequate parameters and data. Cut-off and truncation errors in the HLCA 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 HLCA 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, Gilijamse, Ragas, and Reijnders, 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 Figure 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 Figure 1. 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 HLCA to variety of buildings and building products but solely focusing on the final results of HLCA inventory data.

1.2 Hybrid LCA limitations

HLCA 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, Doh, and Panuwatwanich, 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 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 HLCA 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, Czerniakowski, and Fuller, 2010; Crawford and Treloar, 2003) 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). Furthermore, 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, and the proportion of the I-O inventory would be lower than for the process LCA (Lee and Ma, 2013).

1.3 Research objectives

Previous research studies demonstrated the changes of EE and EC intensities of materials and products over a certain period of time. The changes of EE and EC could be influenced by one or combination of the following factors: system boundaries, method of EE analysis, geographic location, primary and delivered energy, age of data sources, sources of data, completeness of data, and temporal representativeness (Dixit, Fernández-Solís, Lavy, and Culp, 2010). However, these factors have not been empirically studied to identify their relative contributions to the EE and EC intensities. Currently, there is limited research conducted to empirically investigate the impact of parameter variations in EE and EC intensities, particularly to study how this parameter can be incorporated into EE and EC analysis and to what extent this parameter influences the variations of EE and EE intensities. Therefore, the purpose of this paper is to identify factors and issues that have a strong influence on hybrid models resulting from material production, and to determine the different effects of parameters variation on hybrid model. Subsequently, comparisons were made between previous studies to determine key significant variation under which circumstances hybrid model have higher than other and further proposed methodology to reduce variation in HLCA model.

To overcome HLCA limitations, this paper demonstrates HLCA at material production levels first, then computing the EE and EC of the entire building or its components using actual quantity of materials, energy and construction equipment (process data). This model is more flexible, consistent, and capable of reducing uncertainty and variation in the hybrid model. As such, this approach would assist in generating EE and EC estimates specific to building design and types of building in agreement with, and providing contextual support to, previous studies (Dixit *et al.*, 2013).

2. Methodology and assumption

2.1 Deriving indirect EE and EC emission intensities of reference materials and products

Using I-O tables provided by the Australian Bureau of Statistic (ABS) and Malaysian Department of Statistics (DOE) enables the determination of uncertainty and variation due to geographical conditions. I-O tables are publicly published with a lag time of up to 5 years. Malaysian I-O tables are published every five years, whereas Australians I-O tables are updated every three years.

Indirect EE and EC intensities of reference materials was based on the latest available Australian and Malaysian I-O tables (produced in 2005 respectively). There are different aggregations apply to the energy supply sectors shown in the Australian and Malaysian I-O tables. For example, in the Australian I-O tables, data are available at division, subdivision, group and class levels, with each product or commodity being allocated to an I-O product group (Australian Bureau of Statistics, 2006). Meanwhile, the Malaysian I-O tables are classified according to division, group, class and item (Department of Statistic Malaysia, 2000). Energy tariffs, primary energy factors, disaggregation constants and emission factors were derived to convert monetary units in the supply chain into physical units that were then combined with process data.

2.2 Deriving hybrid EE and EC emission intensities of reference material and product

Hybridising EE and EC requires attention to two issues – namely the allocation of interface between I-O LCA and process LCA, and the potential for double counting (Alvarez-Gaitan, Peters, Rowley, Moore, and Short, 2013). Importantly, the HLCA needs to be improved by including more process data and disaggregation of the industry sector (Dixit *et al.*, 2013; Lee and Ma, 2013).

HLCA incorporates process data into I-O analysis during calculation of the hybrid energy intensity as show in Figure 2. Crawford (2005) explained that in calculating a building’s hybrid embodied energy and carbon intensities, the first step is to calculate the hybrid energy intensity of the most common basic materials. In this research, the hybrid embodied energy and carbon intensities of the basic material was determined by adding the difference between the I-O total energy intensity of sector n and input-output direct energy intensity of the path representing the basic material to the process energy intensity of the material. This I-O difference represents the energy intensity of the material unaccounted for by the process analysis as a result of truncation (or setting the system boundary). The embodied energy and carbon intensities of materials, as estimated using hybrid model, are given in Equation 1 and 2 below:

$$EI_m = EI_D + [(TEI - DEI) \times C_m] \tag{1}$$

$$ECO_{2-e}I_m = ECO_{2-e}I_D + [(TCO_{2-e}I - DCO_{2-e}I) \times C_m] \tag{2}$$

Where, EI_m is the energy intensity of a material using HLCA (MJ/kg); EI_D is the direct energy of a material from process LCA (MJ/kg); TEI is the total energy intensity of a material from I-O LCA (MJ/\$); DEI is direct energy intensity of a material from I-O LCA (MJ/\$); $ECO_{2\text{-}e}I_m$ is the carbon intensity of a material using HLCA (kg $CO_{2\text{-}e}$/kg); $ECO_{2\text{-}e}I_D$ is the direct carbon intensity of a material from process LCA (kg $CO_{2\text{-}e}$/kg); $TCO_{2\text{-}e}I$ is the total carbon intensity of a material from I-O LCA (kg $CO_{2\text{-}e}$/\$); $DCO_{2\text{-}e}I$ is the direct carbon intensity of a material from I-O LCA (kg $CO_{2\text{-}e}$/\$); and C_m is the material price (\$/kg).

The second step was to calculate the direct and total embodied energy intensities of material or product sector using Equation 2 and 3 below respectively by adding disaggregation constant.

$$DEI_n = \sum_{e=1}^{E} D_{RC} \times C_D \times T_e \times PEF \tag{2}$$

$$TEI_n = \sum_{e=1}^{E} T_{RC} \times C_D \times T_e \times PEF \tag{3}$$

Where, D_{RC} is direct requirement coefficient (\$/\$); T_{RC} is total requirement coefficient (\$/\$); C_D is disaggregation constant (dimensionless); T_e is average energy tariffs (GJ/\$); and PEF is primary energy factors (dimensionless).

To estimate direct and total carbon coefficient, national emission factor was employed to convert direct and total energy intensities to direct and total carbon intensities. Using disaggregation constant was essential to ensure individual emission factor can be assigned to its particular energy sector. Hence, the direct and total carbon intensities for a particular sector or product derived from I-O LCA was rewritten respectively as shown in Equation 4 and 5 respectively.

$$DCO_{2-e}I = \sum_{e}^{E} D_{RCe} \times T_e \times P.E.F_e \times C_e \times I_e \tag{4}$$

$$TCO_{2-e}I = \sum_{e}^{E} T_{RCe} \times T_e \times P.E.F_e \times C_e \times I_e \tag{5}$$

Where, $DCO_{2\text{-}e}I$ is the direct carbon intensity for a particular sector or product output (kg $CO_{2\text{-}e}$/\$); I_e is emission intensity of energy supply sector, e (kg $CO_{2\text{-}e}$/GJ); and $TCO_{2\text{-}e}I$ is the total carbon intensity for a particular sector or product output (kg $CO_{2\text{-}e}$/\$).

In order to identify total EE and EC intensities of a product (e.g. ready-mix concrete, precast concrete pipe, etc.) using HLCA, direct energy and carbon of the product were obtained from I-O LCA when process LCA was unavailable. The direct energy and carbon intensities of the product were derived from I-O LCA and were then multiplied by the product price. The total EE and EC of the product were formulated by summing all EE and EC intensities of materials with direct energy and carbon of the product as given in Equation 6 and 7 below.

$$EE_T = \sum_{m=1}^{M} (EI_m \times W \times Q_m) + DEI_{pdt} \times C_{pdt} \tag{6}$$

$$ECO_{2-e,T} = \sum_{m=1}^{M} (ECO_{2-e}I_m \times W \times Q_m) + DCO_{2-e}I_{pdt} \times C_{pdt} \tag{7}$$

Where, EE_T is the total EE of a product using HLCA (MJ/kg); W is the material wastage factor ; Q_m is the quantity of material in the product manufacturing (kg/unit); DEI_{pdt} is the direct energy intensity of a product using I-O LCA (MJ/\$); C_{pdt} is the total price of a product (\$/kg); $ECO_{2\text{-}e,T}$ is the total EC of a product using HLCA (MJ/kg); and $DCO_{2\text{-}e}I_{pdt}$ is the direct carbon intensity of a product using I-O LCA (kg $CO_{2\text{-}e}$/\$).

2.3 Evaluation methods

A variety of factors can affect the energy and carbon emission of building materials over its entire lifecycle. These factors can be classified into uncertainty and variability (Gustavsson and Sathre, 2006). Uncertainty occurs due to stochastic variation or lack of knowledge of precise parameter values, while variability is identified as human decisions and management methods. Uncertainty in LCI is categorised into parameter uncertainty, model uncertainty, and scenario uncertainty.

Parameter uncertainty occurs due to incomplete knowledge of true values of data, and management error in input values (Acquaye, 2010). Data uncertainty may arise due to data inaccuracy, lack of specific data, data gaps, and unrepresentative data (Huijbregts *et al.*, 2001). This uncertainty can be dealt with using techniques such as analytical propagation methods, stochastic models, fuzzy logic, and neural networks.

Model uncertainty arises due to unknown interactions between models. Simplification of aspects that cannot be modelled in EE and EC analysis such as temporal and spatial characteristic lost by aggregation, non-linear instead of linear model, or derivation of characteristic model, were identified as factors affecting the uncertainty in a model. This can be mitigated by re-sampling different model formulations (Huijbregts *et al.*, 2003), or using a combination of I-O LCA and process LCA (Williams *et al.*, 2009).

Scenario uncertainties arise due to choices relating to functional unit, system boundaries, weighting of factors and forecasting. Huijbregts *et al.* (2003) suggested scenario uncertainty could be quantified by re-sampling different decision scenarios. For example, results can be calculated for both a data set with high emission values and one with low emission values. This technique involves investigating what effects different sets of data, models and choices have on results (Acquaye, 2010). For example, in an analysis of parameter variations in embodied energy and carbon analysis of a building, the effects of high and low process embodied carbon intensities of building materials on the results can be measured.

A number of techniques were identified for dealing with uncertainty and variability in LCI. Uncertainty analysis can be conducted using two approaches – one based on calculating extreme values, the other on statistical methods (Heijungs, 1996). The first approach identifies lower and upper values of every parameter and combines them to determine the lower and upper values of the area. The second approach uses a statistical method to establish margins of uncertainty (margins of confidents). Uncertainty analysis can be categorised into four groups: parameter or scenario analysis; sampling methods; analytical methods; and non-traditional methods such as fuzzy logic (Acquaye, 2010). Parameter or scenario analysis involves investigation of the impact on results from different sets of data, models and choices. Meanwhile, sampling methods are undertaken by iterative calculation using statistical techniques such as Monte Carlo analysis. Analytical methods, on the other hand, are based on an explicit mathematical equation such as a first order approximation of Taylor expansion. Non-traditional statistical approaches involve more complicated mathematical models such as

Bayesian analysis, fuzzy logic, neural network, and non-parametric statistics. González, Adenso-Dı́az, and González-Torre (2002) incorporated fuzzy logic into LCA, whereas Shipworth (2002) conducted Bayesian analysis to model the embodied greenhouse gas emission of construction materials.

With regard to the complexity and lack of knowledge about uncertainty of data, evaluation of all uncertainty in LCI was considered too time-consuming to be applied to every life cycle impact assessment (LCIA). Due to the lack of transparency of detailed process data and lack of simple methods for I-O model evaluation, the HLCA evaluation in LCI was a difficult task. Crawford (2004) believed that it is necessary to focus on the evaluation of LCI data at a higher level. Therefore, parameter or scenario analysis was identified as a suitable evaluation method for this research into quantifying uncertainty in HLCA.

This research used coefficient of variation (CoV) to identify changes in every parameter and the calculation of extreme values (minimum and maximum values) to be incorporated into the hybrid model. Limiting the selection of lower and upper values of each parameter does not affect the results as sensitivity analysis is concerned with determining only minimum and maximum possible of EE and EC impacts (Basbagill, Flager, Lepech, and Fischer, 2013). Two important components were proposed in this research (as shown in Figure 4): (1) quantifying parameter variation in EE and EC inventory, and the identification of possible key parameters and issues by using coefficient of variation (CoV); and (2) identifying the solution by incorporating lower (minimum) and upper (maximum) values of each parameter into the HLCA model. All parameter variations were then combined to identify impacts upon the HLCA. Details of parameter variations are discussed in the following section.

3. Descriptions of parameters

3.1 Technological changes

Technological changes in production of building materials could affect the variation of energy consumption and carbon emission in a hybrid model. The production inducement effect was used to identify the amount of domestic production changes by an additional unit of final demand for a particular industry (Department of Statistic Malaysia, 2010). If an increase to a unit in the final demand led to an increase of material production in the specified industry, this also could affect an increase in broader range of industries. The Malaysian 2005 I-O tables showed an average inducement coefficient increase to 0.61 as compared to 0.47 in the year 2000 (Department of Statistic Malaysia, 2010). The manufacturing and construction sectors have the highest production inducement of 2.88 and 0.75, respectively. Therefore, different production technology and types of energy used in the process could result in large differences to the embodied energy and carbon figures. Baird, Alcorn, and Haslam (1997) demonstrated the changes in EE over a period of time and found that three quarter of EE intensities of materials and products drop an average of 41% whereas the remainder showed a rise averaging 46%. He further demonstrated the significant effect of changes in material manufacturing technology to the overall figure of a building, ranging from 32% to 56%. Therefore, to determine the impacts of technological changes on energy and carbon emissions, the direct technological coefficient was assumed to be decreased by up to 30% for selected product (commodity) sectors to represents 30% increase of technology efficiency in material production.

3.2 Energy tariffs

An average energy tariff is defined as being the average price paid for energy supplied by a given energy supply sector. Economic data on energy used were converted to physical quantities using national energy tariffs. Energy tariffs for each energy supply sector were derived from Australian and Malaysian energy balance supplied by the International Energy Agency (IEA) database, and I-O tables were provided by the Australia Bureau of Statistic (ABS) and the Department of Statistics, Malaysia (DOE). Detailed variations of energy tariffs are given in Table 1 and Table 2 for Australia and Malaysia respectively.

Variations to the energy tariff for the coal sector were found to be highest of all energy supply sectors, accounting for 42.11% and 33.47% for Australia and Malaysia, respectively. A large variation within the energy sector becomes a possible key parameter impacting on the HLCA model. An energy tariff for crude oil, natural gas, petroleum and coal products varies by 19.42%, 9.17% and 16.23% for Australia and 18.34%, 0%, and 14.04% for Malaysia, respectively. Due to dependency on fossil fuel for electricity generation, the variation of electricity energy tariff shows a similar trend with other energy sectors (fuel input) in electricity generation. In this study, each of the extreme parameter values (minimum and maximum values) for energy supply sectors were identified and further incorporated into the HLCA model.

3.3 Primary energy factor

The primary energy factor (PEF) is used to convert delivered energy (on-site energy) to the primary energy (fossil fuel). For example, the production of electricity and heat is the most important form of secondary energy produced worldwide; however, approximately 70% of total energy is lost in secondary energy production during its transformation (Price *et al.*, 2006). About 90% of residual energy lost is due to the transformation of coal into more refined products and the conversion of crude oil into petroleum products. The PEF for coal products for 10 regions generally ranged from 1.5 to 2.5, meaning that 1.5 to 2.5 times more energy was required to produce one unit of coal products than its primary energy sources. Meanwhile, PEF for petroleum products ranges between 1.05 to 1.2, which requires up to 20% more energy to transform crude oil and feedstock into petroleum products than in the products themselves.

PEFs for Australia and Malaysia were derived from energy balance databases for the period of 2005-2008 (as supplied by International Energy Agency (IEA), and are shown in Tables 3 and Table 4 respectively. The parameter variations for Australia's PEF were found to be 8.13% for the natural gas supply sector and 0.75% for the electricity energy supply sectors. The natural gas and coal products sector has a high PEF variation due to its own energy fuel use during the transformation processes (e.g. transformation of natural gas into LNG). Meanwhile, Malaysia's PEF were found to be 3.31% and 4.28% for the natural gas supply and electricity energy supply sectors, respectively. Malaysia's PEF for the electricity energy sector varied slightly in comparison with Australia due to differences in the efficiency of electricity generation. Efficiency in Australian and Malaysian electricity generation can vary between 25.98% to 26.44% and 22.90% to 25.23% due to loss in distribution and own use.

3.4 Disaggregation constant

A major problem associated with the validity of I-O LCA is the relatively high level of aggregation. The limitation of I-O LCA is the aggregation of many different materials and products into one sector in the national I-O tables (Acquaye, 2010; Mongelli, Suh, and Huppes, 2005). For example, disaggregation of the Australian I-O model can reduce inherent errors associated with I-O data (Crawford, 2004). The use of more aggregated I-O models could further lead to the variation of HLCA. If the I-O model is further aggregated into smaller sectors (e.g. 106 sectors down to 70 sectors), an evaluation of I-O data and HLCA should be performed. Errors associated with I-O LCA are often significantly lower than the truncation error of a typical process LCA but could lead to high variation when dealing with more aggregated sector in HLCA model.

Disaggregation constants were included in reference case for both Malaysia and Australia EE and EC intensities of materials and products to disaggregate individual energy supply sectors. Both countries have different aggregated energy supply sectors that would cause variations in EE and EC emission intensities. To determine a variation, disaggregation constants were further excluded from reference material and product, and energy supply sectors were combined into five aggregated energy supply sectors for Australia and four for Malaysia. Other disaggregation constants were also excluded from HLCA to quantify variation in EE and EC intensities of materials and products. Detailed disaggregated energy supply sectors for both Australia and Malaysia are shown in Table 5 and Table 6 respectively.

3.5 Emission factor

Emission factor was used to convert EE intensity of materials and products into EC intensity through a product's supply chain in I-O LCA (Acquaye, 2010). Variation of electricity emission occurs due to the energy fuel mix during electricity generation within a public thermal power plant (PTPP) (International Energy Agency, 2010). Different countries have different energy policies depending on fuel input into their electricity generation plants; for example, a country with a high share of non-fossil fuel use in their electricity generation has a low emission factor (e.g. solar, wind or nuclear energy sources).

As shown in Table 7, the electricity emission factor was greatly influenced by natural gas and coal. The emission factor for each energy supply sector was accounted for, and these emissions were then compared with those from previous studies. These factors were slightly higher due to inclusion of gross caloric value (GCV) in emission factor calculation. The GCV refers to fuel quality which is characterised in terms of its heating value, also known as *higher heating value*. The main fuel characteristic affecting plant efficiency and specific carbon emissions are moisture content and the carbon-to-hydrogen ratio of the fuel's combustible components. Fuel with similar caloric value but different carbon-to-hydrogen ratio produce different amounts of carbon emissions (International Energy Agency, 2010).

3.6 Price fluctuation

The economic flow within the industry sector's supply chain depends heavily upon price variations. For instance, I-O data are most commonly produced in the form of economic data, thus the price assumptions are required to relate I-O data to a physical quantity of energy and product quantities (Treloar, 1998). However, if the prices are overestimated particularly for the most important materials or buildings, the overall total figure may be grossly overestimated. Treloar (1998) demonstrated the increases in total energy intensities from 7% to 106% due to problems with product prices. Therefore, while problems in price variations occur at material level, it was noted that these variations may be further increased at building production level due to overestimated building prices. Using sensitivity analysis, Crawford (2011) identified 40% variation in EE of steel and concrete building.

Previous research proposed that HLCA model uses material and building prices to quantify total energy intensity (Crawford, 2004; Treloar, 1998). However, using building prices with highly aggregated sectors (e.g. residential building and other construction by Crawford (2004)) tends to greatly impact upon the total energy intensity of a building due to two levels of problems in price variations: (1) the use of material price to convert economic flow into physical energy and product quantity; and (2) the use of building price to fill the remaining sideways and downstream gaps. Using high variation of material and building prices to fill the gaps would significantly influence the variation of EE and EC intensities in HLCA model particularly for materials and products (building) with high indirect energy and carbon in upstream boundary of supply chain in material and product manufacturing.

In this research, a variation of price from reference material was based on percentage range of maximum price value with minimum price value over the period of 2005 to 2008. Australian building materials prices were obtained from *Australian Construction Handbook* (Rawlinson, 2008) to identify variation in material prices over that period of time using deflected prices from the producer price index. The price of building materials (e.g. reinforcement steel) varies up to 35% from the reference price (prices were compared with the Australian producer price index to validate the price variation). Malaysian building materials prices were acquired from Construction Industrial Development Board (CIDB) database, and showed the material price for ready-mixed concrete increased up to 42% over the period of 2005 to 2008. As an example, the price variations over the period of 2004 to 2009 for ready-mixed concrete, reinforcement steel and clay brick are illustrated in Figure 5.

4. Results and discussions

4.1 Reference of EE and EC intensities for materials and products

Reference EE and EC intensities of materials and products were calculated by using the extreme value (minimum value) of each parameter input to the HLCA model. Each parameter with single minimum value was incorporated to estimate minimum EE and EC intensities of materials and products. The analysis considered the effect of varying one parameter at a time and determined the changes of each parameter (maximum value) while keeping all other parameters constant.

The detailed proportion of EE and EC intensities of materials and products according to process LCA, I-O LCA and HLCA are shown in Figures 6 and Figure 7 for Australia, and Figures 8 and Figure 9 for Malaysia respectively. Using HLCA, Australia’s EE and EC intensities for reference materials such as cement (7.902 MJ/kg) , plasterboard (13.05 MJ/kg), reinforcement steel (49.39 MJ/kg) and concrete are higher for Malaysia compared with Australia. These slight differences are due to differences between direct and indirect energy and emission generated during material production. The more significant difference between Australian and Malaysian material intensities were clearly seen in clear float glass and aluminium virgin, which is due to substantial differences between direct and indirect energy and emission intensities occurring in upstream boundary of material production. Substantially more indirect energy is required in the upstream process of material production for clear float glass compared to energy intensive material such as cement and steel.

Small gaps between process LCA, I-O LCA or HLCA were found in cement, aggregate, concrete and clay bricks as shown in Figure 1to Figure 4. Crawford (2004) evaluated gaps between these LCA methods and identified the appropriateness of HLCA evaluation. Crawford (2004) believed the evaluation of HLCA is inappropriate if the gaps between the methods are small, and there is also close correlation between process LCA and I-O LCA between materials and products. The small gaps between these methods occur due to the following reasons: (1) simple product; and (2) large amount of process data available for that material or product.

Materials with high indirect energy proportion were seen in clear float glass, aluminium, fibre glass insulation, steel and structural steel for both the Australian and Malaysian case studies. Materials with greater indirect energy upstream are those that have great influence on the total energy intensity value. For instance, indirect energy intensity for clear float glass (75.844 MJ/kg) accounted for 83.49% of total energy intensity value. This indicated a great discrepancy in process LCA that can only be covered by I-O LCA in the upstream process of materials production. However, great dependency on I-O LCA reduces the accuracy and increases uncertainty in LCI due to truncation error associated with I-O LCA. Therefore, when high accuracy of data is required, process LCA plays an important role in LCEA. In this case, the energy or carbon emission intensity from I-O LCA would be lower than process LCA (Lee and Ma, 2013). Although detailed process LCA are preferred, the majority of material energy intensities have greater I-O values than process values, accounting for 71% in LCIA (Crawford, 2004).

4.2 Effect of parameter variations in HLCA

The variations of EE and EC due to parameter changes compared with the reference case at material and component production level for Australia and Malaysia is presented in Tables 8 and Table 9 respectively. Increase in energy tariff for the energy supply sector has a single significant effect on EE and EC intensities of materials in Australia and Malaysia. The variations of EE and EC intensities of materials were found to be higher in Australia compared to Malaysia, with results showing the variations of EE and EC intensities of materials were up to 62.94% and 91.09% and 15.53% and 17.95% for clear float gas in Australia and Malaysia, respectively. In particular, EE and EC intensities of clear float glass were increased from 90.84 MJ/kg to 148.02 MJ/kg and 9.56 kg CO_{2-e}/kg to 18.27 kg CO_{2-e}/kg for Australia and 42.52 MJ/kg to 49.12 MJ/kg and 3.03 kg CO_{2-e}/kg to 3.58 kg CO_{2-e}/kg for Malaysia. Meanwhile, maximum increase of energy tariffs for both Australia and Malaysia also led to high variation of EE and EC of aluminium virgin up to about 36.92% and 68.72% for Australia and 8.18%

and 2.21% for Malaysia. This was due to influence of indirect energy and carbon in the upstream boundary of the supply chain in material production.

High variations in energy tariffs were influenced by the highest energy tariff of coal compared with other energy supply sectors. Using such high variations to convert monetary values into energy terms has great impact on EE and EC intensities. The maximum increase of Australian coal energy tariff from 0.544GJ/A$ to 0.208 GJ/A$ led to a significant increase in the EE and EC intensities of building material and product with high indirect energy and carbon such as clear float glass, paint, plasterboard, fibre glass insulation, aluminium virgin and structural steel.

In Australian construction materials, the variations in energy tariffs further increased carbon emissions compared with its energy intensity due to high consumption of coal and electricity generation in material production, compared to Malaysia as previously shown in Table 1 and Table 2. Using high variations of energy tariffs to convert monetary into energy values contributes to a high proportion of indirect energy and carbon emissions in I-O LCA data. Using indirect energy and carbon to fill the gaps in process LCA data in turn led to the high variation in the HLCA model. This is also due to the truncation error inherent in the process LCA as identified by previous research (Crawford, 2004; Lee and Ma, 2013; Lenzen and Dey, 2000; Nässén *et al.*, 2007; Treloar, 1998).

A technological change due to energy efficiency in material production was found to have a single significant impact on EE and EC intensity values for both Australia and Malaysia respectively. Reducing the direct requirement coefficient (technological coefficient) by 30% would decrease the EE and EC intensity values by up to 17.36% and 13.56%, and this could be further reduced if more renewable energy is used to replace fossil fuel (e.g. solar, wind, geothermal, etc.). High indirect energy and carbon in EE and EC intensities in the production of materials such as clear float glass, plasterboard, fibre glass insulation and paint would further impact upon variation in the HLCA model (negative value) due to the substantial influence of energy and carbon in the upstream boundary in material production. For instance, a 30% increase in energy efficiency of concrete (30% reduction in the direct energy requirement for cement, aggregate and water) decreased the EE and EC intensities in Australia by 17.36% and 13.96% respectively and in Malaysia by 13.26% and 9.33% respectively.

Aside from the influence of technological changes in materials and products manufacturing, the difference in EE and EC intensity values was also affected by the complexity of the economic structure and system. For example in manufacturing industry, Gutowski (2007) related energy and carbon emission with the gross domestic product which is depending on the technological change in the domestic production (Intermediate production). This was supported by Lenzen and Treloar (2002), who analysed the data from Börjesson and Gustavsson (2000) using energy intensity obtained from I-O data, based on the prices in Australia. They concluded that the variation in energy intensity could rely on differences in production structures between Australia and Sweden and/or scope of the studies. Gustavsson and Sathre (2006) added that using I-O LCA (top-down economic technique) to compare the physical impact of using different construction materials may be effected by differences in overall economic structures. Nevertheless, derivation of I-O data for both Australia and Malaysia shows a similar influence from variations of energy tariffs and technological changes. While materials with high direct energy and carbon (e.g. cement, clay brick, and reinforcement steel) have less significant impact on the HLCA model, the energy tariff and technological change variations greatly impact upon materials and products with high indirect energy and carbon (e.g. clear float glass, plasterboard, fibre glass insulation, and paint).

Furthermore, Lenzen and Treloar (2002) demonstrated the major discrepancies between Australian and Swedish energy intensities that exist for softwood, mineral wool insulation, plasterboard and plastic. These variations are due to the plasterboard and plastic products requiring more energy in their immediate manufacturing in Sweden, while the remaining items are more energy-intensive in Australia. They also agreed that these variations were due either to differences between the Australian and Swedish production systems (e.g. input structure, economics of scale, etc.), or simply because of the complete different of production layers between two countries.

A single variation in PEF for both Australia and Malaysia has less impact on EE and EC intensities of materials and products. A maximum increase of PEF (particularly the natural gas and electricity supply sectors) has less a significant impact on the HLCA model. Using maximum PEF values between the periods of 2005 to 2008 showed the EE and EC intensities of materials values increase up to about 4.21% and 2.81% for Australia and 13.02% and 4.80% for Malaysia respectively. In particularly, the EE and EC intensities for clear float glass slightly increased from 79.74 MJ/kg to 83.0 MJ/kg and 8.30 kg CO_{2-e}/kg to 8.52 kg CO_{2-e}/kg. Meanwhile, EE and EC intensities for plasterboard also slightly increased from 19.16 MJ/kg to 21.66 MJ/kg and 1.50 kg CO_{2-e}/kg to 1.58 kg CO_{2-e}/kg. The influence of parameter variations on other energy intensive materials is less significant (e.g. cement, clay brick, steel virgin, etc.), compared to that on less energy-intensive materials such as clear float glass, plasterboard, or plastic product, which have a large proportion of indirect energy and carbon in upstream boundary of material production. Treloar (1998) derived PEF based on previous findings and further used by Pullen (2007) and Crawford (2004) to identify indirect energy and carbon intensities from I-O data. These PEF values were further included to identify HLCA variations. Using these PEF values only increased EE and EC intensities of materials by up to 1% to 2% in the HLCA model.

Using a disaggregation constant for aggregated energy supply sectors had less impact on the variation of EC intensities in the HLCA model. In general, disaggregation constants were used to enable individual emission factors to be assigned to their energy supply sector in order to convert energy requirements to carbon emission intensities. Without disaggregation constants, EE and EC intensity values for paint varied up to 4.06% (4.06% reduction) and less than 1% (less than 1% reduction) in Australia and 10.31% (10.31% reduction) and 12.6% (12.6% reduction) in Malaysia respectively. As shown in Table 8 and Table 9, overall EE and EC intensities of materials in the HLCA model slightly decreased from the reference case. Meanwhile, the variations of EE and EC intensities in Malaysia were higher compared with Australia due to aggregated energy supply sectors in Malaysian I-O tables such as electricity and gas supply (e.g. aggregated into electricity and gas supply as shown in Malaysian 2005 I-O tables). Therefore, with high energy consumption and carbon emission factors for electricity generation, using this disaggregated energy supply sector increased the variations of EE and EC intensities in HLCA model. Acquaye (2010) also demonstrated the variation of EC intensity up to 2.6 times when disaggregation constants are used to disaggregate energy and non-energy supply sector such as disaggregation of coal, peat, and crude oil (energy supply sector) from metal ore extraction sector (non-energy supply sector). On the other hand, EE intensities are overestimated more than 2.6 times compared to when disaggregation are employed.

Similar impact of parameter variations can be found on other EE and EC intensities of materials with high indirect energy and carbon in the upstream boundary of material production, but were excluded from this paper. Therefore, materials with high indirect energy and carbon have the largest influence on the HLCA model. Using aggregated industry sectors such as residential construction itself with high indirect energy and carbon in upstream boundary of building system to quantify the embodied energy and carbon of an entire building may also result in a significant variation of EE and EC intensities of a building (building is considered as a product). Using sensitivity analysis for energy data uncertainty, Crawford (2011) identified 40% variation of EE for steel and concrete building using HLCA. On the other hand, this variation arises due to the aggregated building sector used and price fluctuation of building in the HLCA model.

An increased material price also has a moderate impact on EE and EC intensities in the HLCA model. In Australia, the maximum increase in a material price has a significant influence on a variation in the HLCA model and can be seen in structural steel in Australia, which increased up to 32.8%, leading to the increase of EE and EC intensities of up to 13.6% (from 64.91 MJ/kg up to 73.74 MJ/kg) and 17.54% (from 6.51 kg CO_{2-e}/kg up to 7.65 kg CO_{2-e}/kg) respectively. Meanwhile, the prices for such materials as cement, ready-mixed concrete, and reinforcement steel were much higher in Malaysia compared with Australia. Further increases of Malaysian cement price of 67.05% led to the variation of EE and EC intensities in the HLCA model by up to 13.93% (from 9.01 MJ/kg to 10.26 MJ/kg) and 8.67% (from 1.01 kg CO_{2-e}/kg to 1.09 kg CO_{2-e}/kg) in the HLCA model. These variations were considered to be moderate when involving material level compared to the variation in the product level (i.e. the entire building itself), which tends to be more complex in its production (i.e. a building made up of numerous materials and components). This moderate variation in EE and EC intensities in HLCA was in the same agreement with Crawford (2004) who identified small gaps between HLCA normally exist in simple products and those requiring large amount of direct energy requirement.

The variation in the electricity emission factor was due to the fuel mix of fossil fuel in national energy policy, which has less impact on the HLCA values. The maximum increase of emission factor has slightly increased EE and EC intensities of material values by approximately less than 1%. Therefore, using disaggregation constant for aggregated energy supply sector so that individual emission factor can be used instead of average emission factor result in less variation in the HLCA model.

4.3 Whole-case combination of parameter changes

The analysis in the previous section considered the effect of varying one parameter at a time and determined the changes in HLCA resulting from changes to each parameter while maintaining all other parameters constant. In this section, the whole-case scenario is also considered for this research and can be defined as the accumulated changes of all parameters on HLCA variation as given in Tables 8 and Table 9.

While all the parameter variations, compared to the reference cases increased the EE and EC intensities of materials and products in the HLCA model, some parameter variations decreased EE and EC intensity values, which can be seen in both Australian and Malaysian material intensities. Increase of technological efficiency and excluded disaggregation constant reduced the variations of EE and EC intensities as shown in the Malaysian material intensities. For example, increase of 30% of concrete technology efficiency reduced 13.3% of EE intensity value in the HLCA model.

To determine the effects of combined parameter variations, particularly those that could most affect the EE and EC intensities in the HLCA model, this research varied parameters to make whole-case scenario for both Australia and Malaysia by accumulating previous changes. As shown in Table 8 and Table 9, all previous changes from references cases (can be positive or negative changes) were summed to quantify total variation of EE and EC intensities of materials and products. With the whole-case combination of parameters for the HLCA model, the impacts on EE and EC intensities were classified into two categories: (1) impact on the non-energy intensive materials such as plasterboard, fibre glass insulation, and structural steel; and (2) impact on the energy intensive materials such as cement, steel, and clay brick. A high variation in HLCA model was observed with the whole-case scenario when applied to the non-energy intensive material that has high indirect energy and carbon emission intensities in the upstream boundary of the supply chain. These include materials such as aggregates, clear float glass, structural steel, paints and fibre glass insulation (only selected materials were included in this paper). For example, for non-energy intensive materials such as clear float glass, the variation of all parameters significantly increased EE and EC intensity values from 90.84 MJ/kg to 143.38 MJ/kg and 9.562 kg $CO_{2\text{-}e}$/kg to 17.960 kg $CO_{2\text{-}e}$/kg, accounting for 58.03% and 88.13% of the increase in HLCA model for Australia. Meanwhile, the variations of all parameters have less significant impact on energy intensive materials such as cement and clay brick which were largely influenced by the variation in process LCA.

While some parameter variations decreased HLCA in comparison to the reference material (e.g. 30% increase in technological efficiency and excluded disaggregation constant), high EE and EC intensity variations in the HLCA model were predominantly influenced by the variations in technological changes (direct requirement coefficient), energy tariffs, and material prices.

These key parameter variations are significantly impacted upon by materials or products with a high level of indirect EE and EC, and are therefore considered a key issue in EE and EC methodology development. With regard to these variations, using highly aggregated industry sectors such as residential building to quantify specific types of building or modular or custom-designed structures would increase EE and EC intensity variations of buildings. These results are in agreement with and provide contextual support to previous studies (e.g. Dixit *et al.* (2013)).

5. Comparison with previous studies

This research compares the results from the HLCA model developed in this research with previous researches based on Australian, New Zealand and Malaysian I-O tables and the results are depicted in Figure 11. Selected building materials were classified into energy and non-energy intensive materials that have different impacts due to the parameter variations as mentioned in the previous sections. The comparison of EE and EC intensities of materials and products across models and countries found that energy intensive materials such as cement, clay brick and steel virgin are more consistent and show less uncertainty and variation. This is due to the high proportion of process data that reduces uncertainty in the upstream boundary (Lee and Ma, 2013). More process data can reduce uncertainty and increase reliability in EE and EC intensities. Meanwhile, non-energy intensive materials with high indirect energy such as clear float glass, plasterboard, fibre glass insulation, plastic product and structural steel vary significantly between the studied models. For example, EE intensities for clear float glass were 15.9 MJ/kg for New Zealand, 83.6 MJ/kg for Australia (Pullen, 2007), 174.22 MJ/kg for Australia (Crawford, 2011), 111.62 MJ/kg for Australia (Current study) and 46.28 MJ/kg for Malaysia. All of these EE intensity values indicated significant variations due to parameter variations as previously discussed.

Incorporating these materials into EE and EC assessment would significantly impact the whole life cycle of a building and its components. Consequently, using HLCA with highly aggregated industry sectors such as residential construction would have a great influence on the variations of a building's EE and EC. Baird *et al.* (1997) demonstrated the changes in EE over a period of time and found that three quarter of EE intensities of materials and products drop an average of 41% whereas the remainder showed a rise averaging 46%. He further demonstrated the significant effect of changes in material manufacturing technology to the overall figure of a building, ranging from 32% to 56%. Unfortunately, the influences of parameter variations were not considered in determining these changes.

6. Conclusion

This research was conducted to identify factors that contribute most significantly to the variation of embodied energy and carbon using the developed HLCA model, and to compare the results with those from previous studies. Currently, there are limited researches empirically conducted to quantify uncertainty and reliability of parameter variations in a HLCA model. A first approach was proposed by Dixit *et al.* (2010) relating to parameter variation in EE assessment. Previous research conducted by Crawford (2004) used gap and comparative analysis to evaluate completeness and accuracy of HLCA between various case studies. However, the research was focused only on the final HLCA results instead of the input data (input parameter) to the HLCA model.

The completeness and accuracy of EE and EC assessment using HLCA model depend upon many factors, and previous studies have proposed methodologies to improving uncertainty and reliability in the hybrid model (Dixit *et al.*, 2013; Lee and Ma, 2013). Unfortunately, these methodologies were not empirically investigated to identify the influence of parameter variation in EE an EC assessment. Therefore, this study empirically demonstrates the changes in embodied energy and carbon emission intensities caused by parameter variations in HLCA model and identify key parameters and issues toward the development of robust EE and EC assessment methodology.

In this research, parameter or scenario uncertainty was conducted to empirically investigate key parameters and issues that significantly contribute to significant variations in EE and EC assessment in both the Australian and Malaysian case studies. This study found that technological changes, maximum increase in energy tariffs and material price fluctuation were the key parameters and issues leading to significant variations in EE and EC intensity values. Other parameters such as maximum increase in PEF, emission factor and excluding disaggregation constant have slight impact upon EE and EC intensity variations.

When compared with previous studies, the significant variations in EE and EC between energy and non-energy intensive materials can be clearly seen due to the significant contribution of indirect energy in non-energy intensive material during production process. Building materials with high indirect energy in the upstream boundary have great influence on HLCA variation between studies. Therefore, any decision relating to these materials should be considered carefully. Thus one strategy to reduce uncertainty and increase reliability of HLCA data is by firstly calculating EE and EC intensities of materials and products and then computing EE and EC of the entire building by using actual quantity of material, labour, and equipment (process LCA). This in turn can reduce the high variations of EE and EC intensity values caused by high dependency on aggregated industry sectors in the I-O tables (e.g. residential and non-residential sector used in Malaysian I-O tables).

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List of Tables

Table 1

Australian average energy tariffs (ET) for energy supply sector for the period 2005-2008

ANZSIC 2006[a]	Disaggregated energy supply sector	Average energy tariffs, T_e (GJ/A$)				Stdev.	Avg.	CoV (%)	Max. of ET	Min. of ET
		2005	2006	2007	2008					
0601	Coal mining	0.5439	0.3325	0.2827	0.2085	0.14	0.34	42.11	0.544	0.208
0701	Oil extraction	0.0854	0.0656	0.0579	0.0581	0.01	0.07	19.42	0.085	0.058
0701	Gas extraction	0.0908	0.1107	0.1036	0.1114	0.01	0.10	9.17	0.111	0.091
1701	Petroleum products	0.0519	0.0525	0.0388	0.0400	0.01	0.05	16.23	0.053	0.039
1701	Coal products	0.0519	0.0525	0.0388	0.0400	0.01	0.05	16.23	0.053	0.039
2601	Electricity generation	0.0236	0.0485	0.0484	0.0526	0.01	0.04	30.71	0.053	0.024
2701	Gas supply	0.1666	0.1913	0.1939	0.2257	0.02	0.19	12.48	0.226	0.167

Note:
(a) Australian and New Zealand Standard Industrial Classification 2006

Table 2

Malaysian average energy tariffs (ET) for energy supply sector for the period 2005-2008

I-O Sector MSIC2000[a]	Disaggregated energy supply sector	Average energy tariffs, T_e (GJ/RM$)				Stdev.	Avg.	CoV (%)	Max. of ET	Min. of ET
		2005	2006	2007	2008					
11100	Crude oil	0.0295	0.0253	0.0244	0.0186	0.004	0.02	18.34	0.0295	0.0186
11200	Natural gas	0.0820	0.0820	0.0820	0.0820	0.000	0.08	0.00	0.0820	0.0820
10100	Coal mining	0.1397	0.1400	0.1118	0.0598	0.038	0.11	33.47	0.1400	0.0598
23100	Petroleum refinery	0.0156	0.0179	0.0135	0.0135	0.002	0.02	14.04	0.0179	0.0135
40100	Electricity supply	0.0144	0.0144	0.0135	0.0125	0.001	0.01	6.59	0.0144	0.0125
40200	Gas supply	0.0820	0.0820	0.0820	0.0820	0.000	0.08	0.00	0.0820	0.0820

Note:
(a) The Malaysia Standard Industrial Classification 2000

Table 3

Australian primary energy factor (PEF) for the energy supply sector for the period 2005-2008

ANZSIC 2006[a]	Disaggregated energy supply sector	Primary energy factor (PEF)				Stdev.	Avg.	CoV (%)	Max. of PEF	Min. of PEF
		2005	2006	2007	2008					
0601	Coal mining	1.00	1.00	1.00	1.00	0.00	1.00	0.00	1.00	1.00
0701	Oil extraction	1.00	1.00	1.00	1.00	0.00	1.00	0.02	1.00	1.00
0701	Gas extraction	2.03	2.13	1.89	1.77	0.16	1.95	8.13	2.13	1.77
1701	Petroleum products	1.09	1.08	1.08	1.08	0.01	1.08	0.65	1.09	1.08
1701	Coal products	1.48	1.57	1.60	1.68	0.08	1.58	5.27	1.68	1.48
2601	Electricity generation	3.80	3.78	3.81	3.85	0.03	3.81	0.75	3.85	3.78
2701	Gas supply	1.10	1.10	1.10	1.10	0.00	1.10	0.00	1.10	1.10

Note:
(a) Australian and New Zealand Standard Industrial Classification 2006

Table 4

Malaysian PEF for the energy supply sector for the period 2005-2008

I-O Sector MSIC2000[a]	Disaggregated energy supply sector	Primary energy factor (PEF)				Stdev.	Avg.	CoV (%)	Max. of PEF	Min. of PEF
		2005	2006	2007	2008					
11100	Crude oil	1.00	1.00	1.00	1.00	0.00	1.00	0.00	1.00	1.00
11200	Natural gas	1.62	1.62	1.64	1.74	0.05	1.66	3.31	1.74	1.62
10100	Coal mining	1.00	1.00	1.00	1.00	0.00	1.00	0.00	1.00	1.00
23100	Petroleum refinery	1.01	1.04	1.04	1.06	0.02	1.04	1.95	1.06	1.01
40100	Electricity supply	4.18	4.04	3.96	4.37	0.18	4.14	4.28	4.37	3.96
40200	Gas supply	1.14	1.10	1.08	1.08	0.03	1.10	2.49	1.14	1.08

Note:
(a) The Malaysia Standard Industrial Classification 2000

Table 5

Australian disaggregation constant for energy supply sectors for the period 2005-2008

ANZSIC 2006[a]	Disaggregated energy supply sectors	Disaggregation constant, C_d				Stdev.	Avg.	CoV (%)	Max. of C_d	Min. of C_d
		2005	2006	2007	2008					
0601	Black coal[b]	0.44	0.45	0.46	0.45	0.01	0.45	1.15	0.46	0.44
0601	Brown coal[c]	0.56	0.55	0.54	0.55	0.01	0.55	0.94	0.56	0.54
0701	Oil extraction	0.66	0.73	0.72	0.72	0.03	0.71	4.89	0.73	0.66
0701	Gas extraction	0.34	0.27	0.28	0.28	0.03	0.29	11.76	0.34	0.27
1701	Petroleum products	0.96	0.97	0.97	0.97	0.00	0.97	0.33	0.97	0.96
1701	Coal Products	0.04	0.03	0.03	0.03	0.00	0.03	10.07	0.04	0.03
2601	Electricity generation	1.00	1.00	1.00	1.00	0.00	1.00	0.00	1.00	1.00
2701	Gas supply	1.00	1.00	1.00	1.00	0.00	1.00	0.00	1.00	1.00

Note:
(a) Australian and New Zealand Standard Industrial Classification 2006
(b) Black coal - Sub-bituminous coal, bituminous coal and anthracite
(c) Brown coal - lignite

Table 6

Malaysian disaggregation constant for energy supply sectors for the period 2005-2008

I-O Sector MSIC2000[a]	Disaggregated energy supply sectors	Disaggregation constant, C_d				Stdev.	Avg.	CoV (%)	Max. of C_d	Min. of C_d
		2005	2006	2007	2008					
11100	Crude oil	0.72	0.74	0.75	0.79	0.03	0.75	3.96	0.79	0.72
11200	Natural gas	0.28	0.26	0.25	0.21	0.03	0.25	11.88	0.28	0.21
10100	Coal mining	1.00	1.00	1.00	1.00	0.00	1.00	0.00	1.00	1.00
23100	Petroleum refinery	1.00	1.00	1.00	1.00	0.00	1.00	0.00	1.00	1.00
40100	Electricity supply	0.86	0.83	0.83	0.84	0.01	0.84	1.72	0.86	0.83
40200	Gas supply	0.14	0.17	0.17	0.16	0.01	0.16	9.22	0.17	0.14

Note:
(a) The Malaysia Standard Industrial Classification 2000

Table 7

Emission factors for electricity generation sector during the period 2005-2008 based on emission emitted from the Malaysian power plant (based on gross caloric value)

Year	Emission emitted (kton $CO_{2\text{-}e}$/y)			Emission factor (kg $CO_{2\text{-}e}$/GJ)	
	Petroleum Product	Natural Gas	Coal and Coke	PTM[a] and GreenTech[b]	Current study
2005	1,786.36	45,752.98	21,393.20	214.35	244.66
2006	2,644.76	47,719.93	22,174.54	221.30	235.94
2007	1,914.95	47,947.69	28,904.79	218.89	237.88
2008	1,768.35	54,617.64	31,156.32	198.89	260.16
Stdev.	415.92	3,866.37	4,859.62	10.07	10.99
Average	2,028.61	49,009.56	25,907.21	213.36	244.66
CoV (%)	20.50	7.89	18.76	4.72	4.49
Max.	2,644.76	54,617.64	31,156.32	221.30	260.16
Min.	1,768.35	45,752.98	21,393.20	198.89	235.94

Note:
a) Malaysia Energy Centre (PTM)
b) GreenTech Malaysia

Table 8
Embodied energy and carbon emission and changes in due to parameter variations compared with the reference case at material and component production level for Australia

Building materials or components	Changed parameter	Embodied energy (MJ/kg)						Embodied carbon emission (kg $CO_{2\text{-}e}$/kg)					
		Process LCA	I-O LCA			HLCA	Change from ref. (%)	Process LCA	I-O LCA			HLCA	Change from ref. (%)
			Direct	Indirect	Total				Direct	Indirect	Total		
Ordinary Portland cement (OPC)	Reference material (Minimum case)	5.200	4.671	2.702	7.373	7.902	0.000	0.740	0.386	0.264	0.650	1.004	0.000
	30% increase in tech. efficiency	5.200	3.270	2.095	5.364	7.295	-8.333	0.740	0.271	0.208	0.478	0.948	-5.602
	Maximum increase in ET	5.200	6.843	4.397	11.240	9.597	17.659	0.740	0.666	0.499	1.165	1.239	23.375
	Maximum increase in PEF	5.200	4.872	2.868	7.740	8.068	2.047	0.740	0.399	0.274	0.674	1.014	1.031
	Without disaggregation constant	5.200	4.474	2.541	7.016	7.741	-2.084	0.740	0.382	0.261	0.643	1.001	-0.339
	Maximum increase in material price	5.200	5.294	3.063	8.357	8.263	4.366	0.740	0.438	0.299	0.737	1.039	3.510
	Maximum increase in EF for elec.	-	-	-	-	-	-	0.740	0.388	0.265	0.653	1.005	0.095
	Whole-case[a]					**8.981**	**13.654**					**1.226**	**22.071**
Concrete (35 MPa)	Reference material (Minimum case)	2.020	1.091	0.480	1.571	2.500	0.000	0.217	0.090	0.047	0.137	0.264	0.000
	30% increase in tech. efficiency	1.693	0.764	0.373	1.137	2.065	-17.375	0.190	0.063	0.037	0.100	0.227	-13.991
	Maximum increase in ET	2.528	1.599	0.778	2.377	3.305	32.229	0.282	0.156	0.088	0.243	0.370	40.357
	Maximum increase in PEF	2.067	1.138	0.510	1.648	2.577	3.082	0.220	0.093	0.048	0.142	0.268	1.838
	Without disaggregation constant	1.974	1.046	0.450	1.496	2.424	-3.012	0.216	0.089	0.046	0.135	0.262	-0.617
	Maximum increase in material price	2.168	1.239	0.546	1.785	2.714	8.579	0.229	0.103	0.053	0.156	0.282	7.088
	Maximum increase in EF for elec.	-	-	-	-	-	-	0.217	0.091	0.047	0.137	0.264	0.172
	Whole-case[a]					**3.087**	**23.503**					**0.355**	**34.848**
Clear float glass	Reference material (Minimum case)	15.000	87.419	64.736	152.156	79.736	0.000	0.910	8.896	7.385	16.281	8.295	0.000
	30% increase in tech. efficiency	15.000	61.194	53.208	114.402	68.208	-14.458	0.910	6.227	6.060	12.287	6.970	-15.977
	Maximum increase in ET	15.000	133.295	113.537	246.832	128.537	61.203	0.910	16.490	14.819	31.308	15.729	89.622
	Maximum increase in PEF	15.000	91.166	67.997	159.163	82.997	4.090	0.910	9.162	7.614	16.776	8.524	2.764
	Without disaggregation constant	15.000	83.822	61.690	145.512	76.690	-3.820	0.910	8.766	7.344	16.110	8.254	-0.488
	Maximum increase in material price	15.000	97.347	72.088	169.435	87.088	9.220	0.910	9.906	8.223	18.129	9.133	10.110
	Maximum increase in EF for elec.	-	-	-	-	-	-	0.910	8.936	7.417	16.353	8.327	0.388
	Whole-case[a]					**124.576**	**56.235**					**15.463**	**86.420**
Aluminium virgin	Reference material (Minimum case)	155.000	42.294	152.465	194.760	307.465	0.000	9.160	6.807	17.746	24.552	26.906	0.000
	30% increase in tech. efficiency	155.000	29.606	144.386	173.992	299.386	-2.628	9.160	4.765	16.689	21.453	25.849	-3.928
	Maximum increase in ET	155.000	74.687	259.436	334.123	414.436	34.791	9.160	14.109	34.849	48.959	44.009	63.568
	Maximum increase in PEF	155.000	43.832	160.974	204.807	315.974	2.768	9.160	6.965	18.343	25.308	27.503	2.221
	Without disaggregation constant	155.000	41.056	144.860	185.916	299.860	-2.474	9.160	6.777	17.915	24.692	27.075	0.630
	Maximum increase in material price	155.000	46.099	166.179	212.278	321.179	4.460	9.160	7.419	19.342	26.761	28.502	5.933
	Maximum increase in EF for elec.	-	-	-	-	-	-	9.160	6.850	17.824	24.674	26.984	0.291
	Whole-case[a]					**420.974**	**36.918**					**45.394**	**68.716**

Note:
a) Difference compared to reference case and previous accumulated changes.

Table 9
Embodied energy and carbon emission and changes in due to parameter variations compared with the reference case at material and component production level for Malaysia

Building materials or components	Changed parameter	Embodied energy (MJ/kg)						Embodied carbon emission (kg CO_{2-e}/kg)					
		Process LCA	I-O LCA			HLCA	Change from ref. (%)	Process LCA	I-O LCA			HLCA	Change from ref. (%)
			Direct	Indirect	Total				Direct	Indirect	Total		
Ordinary Portland cement (OPC)	Reference material (Minimum case)	5.200	1.024	3.807	4.831	9.007	0.000	0.740	0.106	0.265	0.372	1.005	0.000
	30% increase in tech. efficiency	5.200	0.717	2.744	3.461	7.944	-11.798	0.740	0.074	0.192	0.266	0.932	-7.313
	Maximum increase in ET	5.200	1.443	4.668	6.111	9.868	9.565	0.740	0.141	0.332	0.473	1.072	6.642
	Maximum increase in PEF	5.200	1.085	4.015	5.100	9.215	2.315	0.740	0.114	0.281	0.395	1.021	1.558
	Without disaggregation constant	5.200	1.030	3.149	4.180	8.349	-7.298	0.740	0.093	0.223	0.315	0.963	-4.259
	Maximum increase in material price	5.200	1.362	5.061	6.423	10.261	13.927	0.740	0.141	0.353	0.494	1.093	8.699
	Maximum increase in EF for elec.	-	-	-	-	-	-	0.740	0.111	0.271	0.382	1.011	0.568
	Whole-case[a]					**9.611**	**6.711**					**1.065**	**5.894**
Concrete (35 MPa)	Reference material (Minimum case)	1.074	0.145	0.777	0.922	1.851	0.000	0.142	0.015	0.055	0.070	0.197	0.000
	30% increase in tech. efficiency	1.030	0.101	0.574	0.676	1.604	-13.304	0.137	0.010	0.041	0.051	0.178	-9.386
	Maximum increase in ET	1.151	0.222	0.953	1.175	2.104	13.702	0.148	0.022	0.069	0.090	0.217	10.360
	Maximum increase in PEF	1.081	0.152	0.819	0.972	1.901	2.710	0.143	0.016	0.058	0.074	0.201	2.164
	Without disaggregation constant	1.075	0.146	0.644	0.789	1.718	-7.145	0.140	0.013	0.046	0.059	0.186	-5.418
	Maximum increase in material price	1.136	0.207	1.049	1.256	2.185	18.071	0.148	0.021	0.074	0.095	0.222	13.067
	Maximum increase in EF for elec.	-	-	-	-	-	-	0.142	0.016	0.056	0.072	0.198	0.981
	Whole-case[a]					**2.110**	**14.033**					**0.220**	**11.767**
Clear float glass	Reference material (Minimum case)	15.000	7.879	27.323	35.202	42.323	0.000	0.910	0.995	2.106	3.101	3.016	0.000
	30% increase in tech. efficiency	15.000	5.515	21.555	27.070	36.555	-13.629	0.910	0.697	1.677	2.373	2.587	-14.239
	Maximum increase in ET	15.000	10.608	33.878	44.486	48.878	15.488	0.910	1.257	2.646	3.903	3.556	17.909
	Maximum increase in PEF	15.000	8.402	28.853	37.256	43.853	3.616	0.910	1.078	2.240	3.318	3.150	4.447
	Without disaggregation constant	15.000	7.957	23.057	31.014	38.057	-10.081	0.910	0.824	1.751	2.575	2.661	-11.775
	Maximum increase in material price	15.000	8.999	31.206	40.204	46.206	9.173	0.910	1.137	2.405	3.542	3.315	9.922
	Maximum increase in EF for elec.	-	-	-	-	-	-	0.910	1.062	2.173	3.235	3.083	2.209
	Whole-case[a]					**44.256**	**4.568**					**3.272**	**8.474**
Aluminium virgin	Reference material (Minimum case)	155.000	11.364	86.025	97.388	241.025	0.000	9.160	1.696	7.509	9.205	16.669	0.000
	30% increase in tech. efficiency	155.000	7.955	74.699	82.653	229.699	-4.699	9.160	1.187	6.491	7.678	15.651	-6.107
	Maximum increase in ET	155.000	14.362	107.913	122.275	262.913	9.082	9.160	1.696	8.030	9.726	17.190	3.126
	Maximum increase in PEF	155.000	12.218	91.039	103.257	246.039	2.081	9.160	1.849	8.031	9.880	17.191	3.134
	Without disaggregation constant	155.000	11.523	75.056	86.578	230.056	-4.551	9.160	1.347	6.204	7.551	15.364	-7.830
	Maximum increase in material price	155.000	13.325	100.872	114.197	255.872	6.160	9.160	1.989	8.805	10.793	17.965	7.775
	Maximum increase in EF for elec.	-	-	-	-	-	-	9.160	1.832	7.831	9.663	16.991	1.930
	Whole-case[a]					**260.480**	**8.072**					**17.007**	**2.027**

Note:
a) Difference compared to reference case and previous accumulated changes.

List of Figures

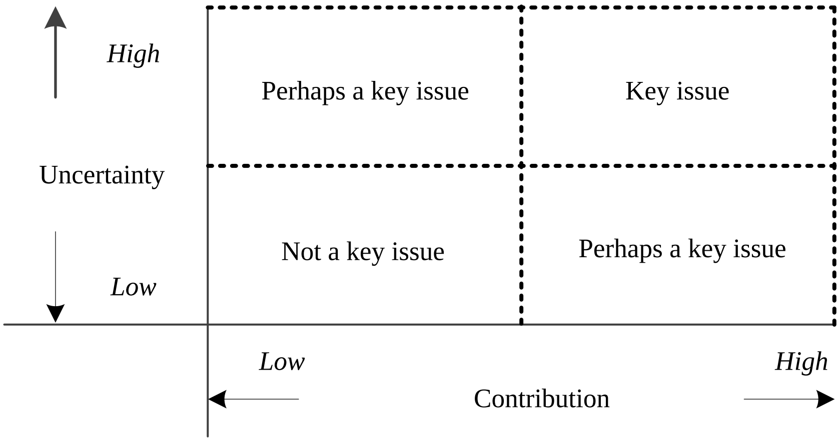


Figure1: Key issues of uncertainty and contribution of inputs in evaluation of life cycle inventory analysis results (Heijungs 1996).

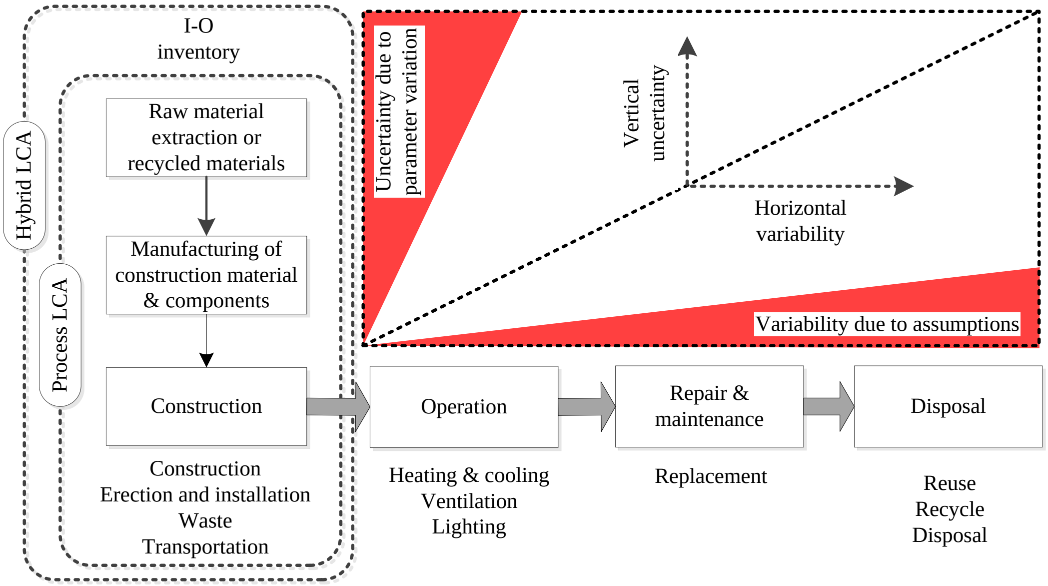


Figure 2: Uncertainty and variation level in hybridising EE and EC assessment

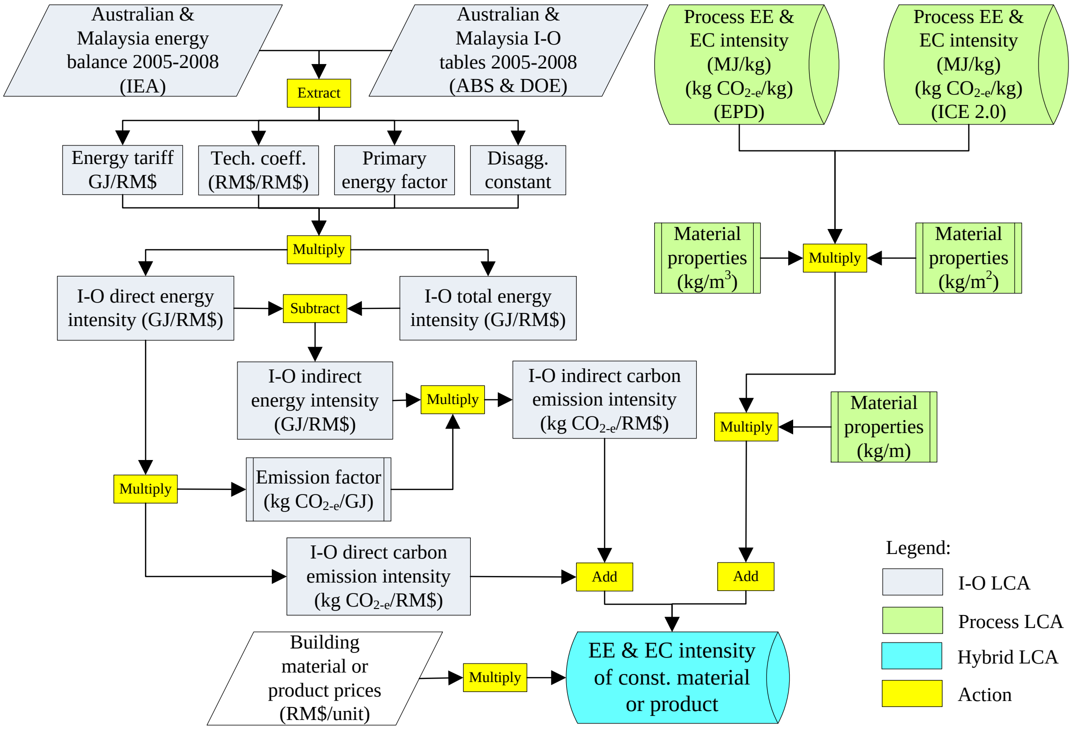


Figure 3: Flowchart for Hybrid EE and EC inventory methodology

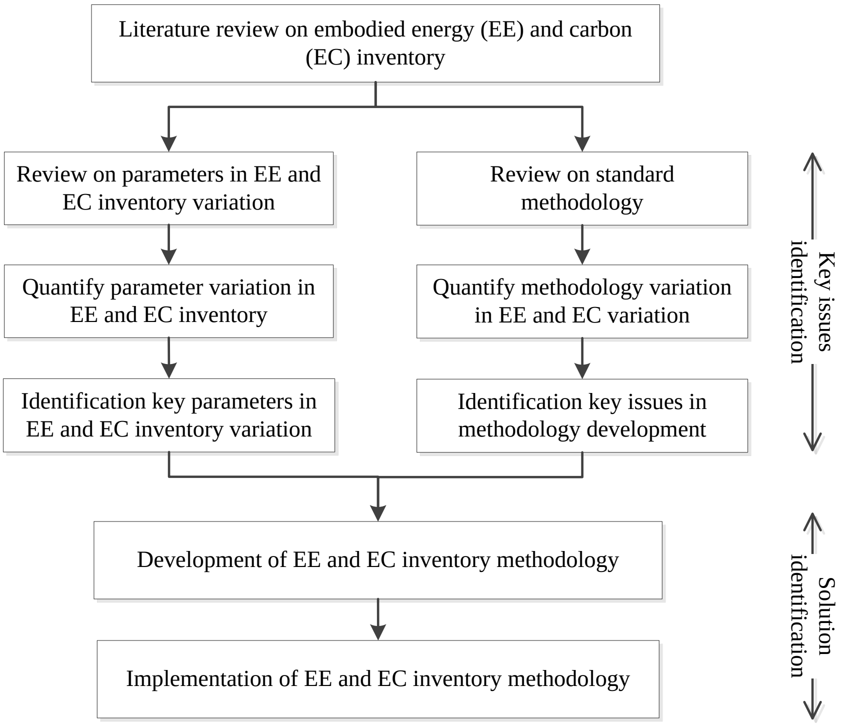


Figure 4: Proposed approach to assess variability and uncertainty in EE and EC inventory methodology

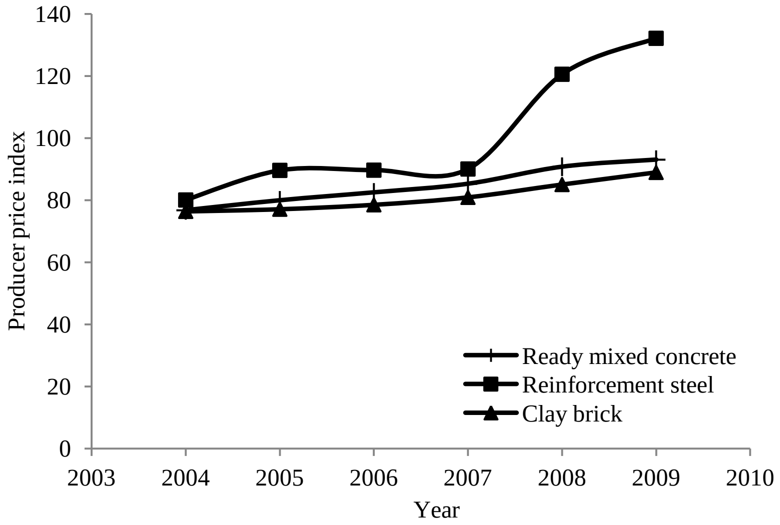


Figure 5: Price variation in selected construction materials based on producer price index for the period 2004-2009

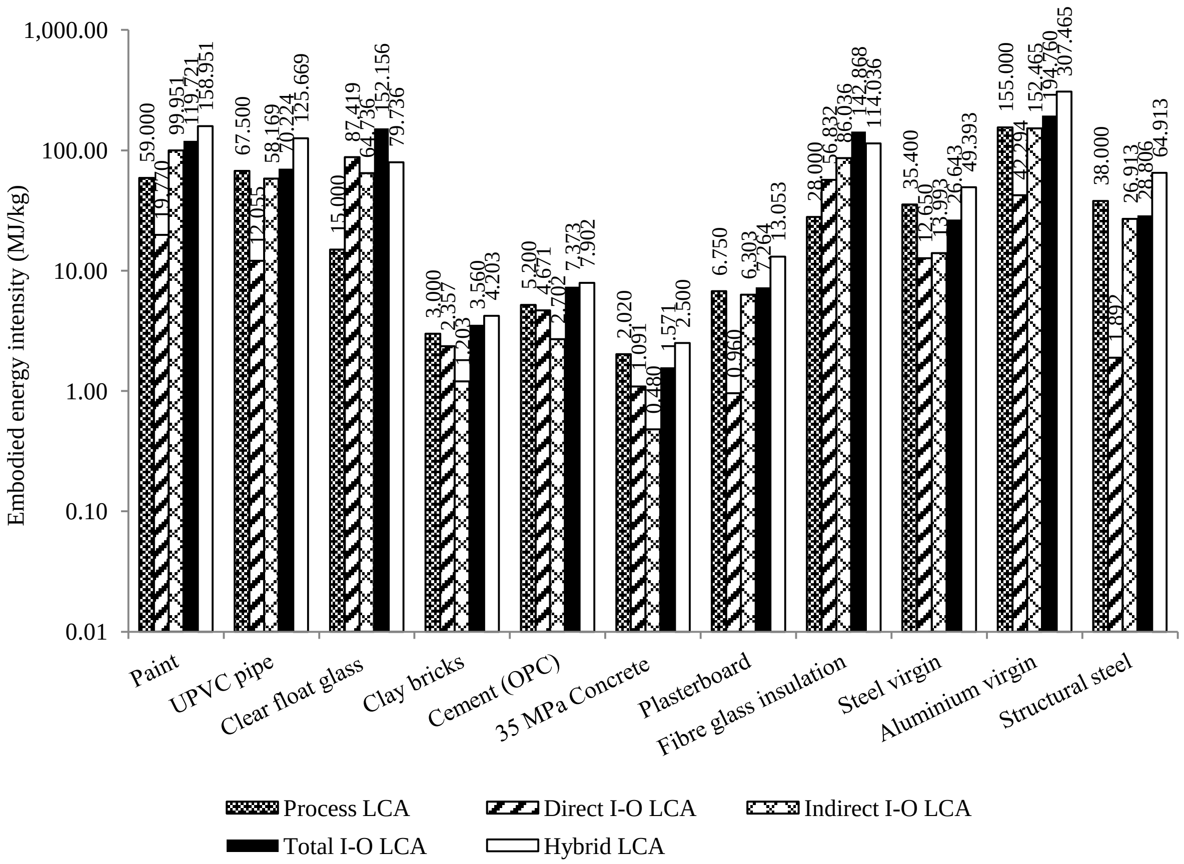


Figure 6: Reference case of EE for different construction materials and products in Australia

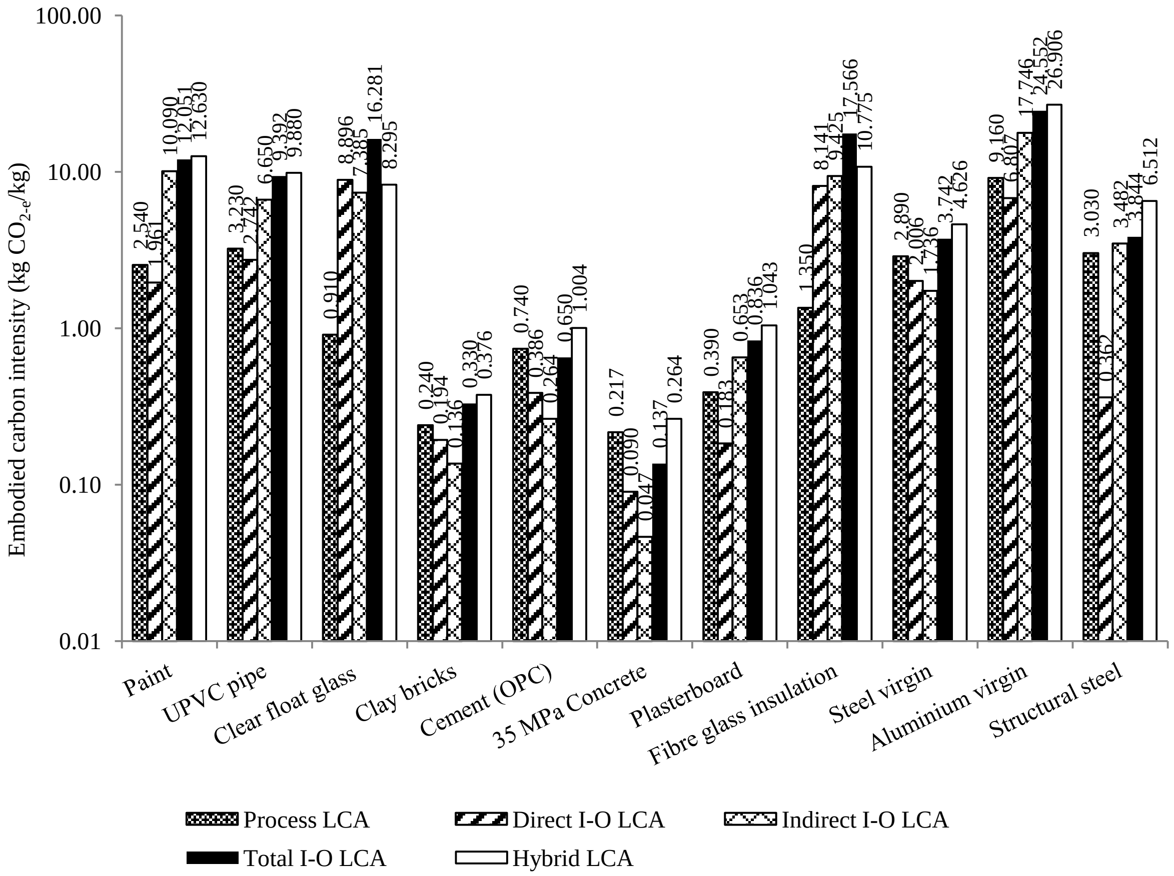


Figure 7: Reference case of EC for different construction materials and products in Australia

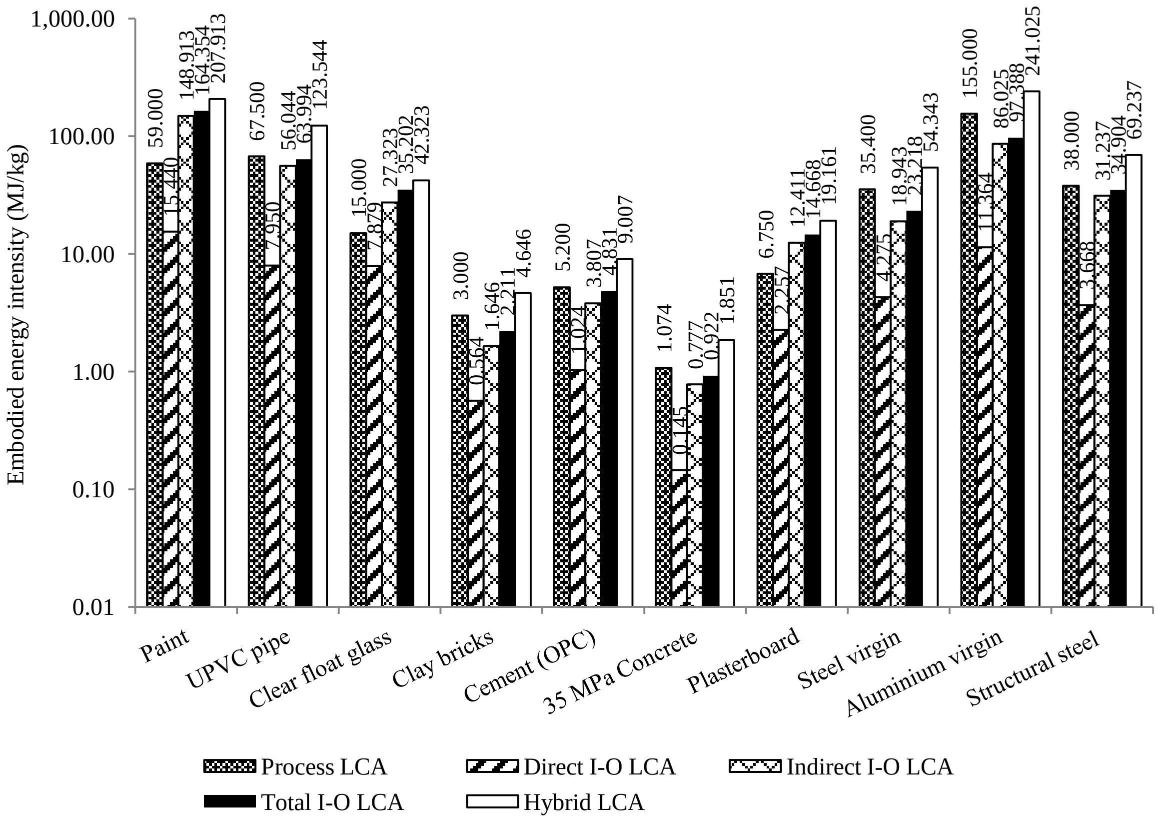


Figure 8: Reference case of EE for different construction materials and products in Malaysia

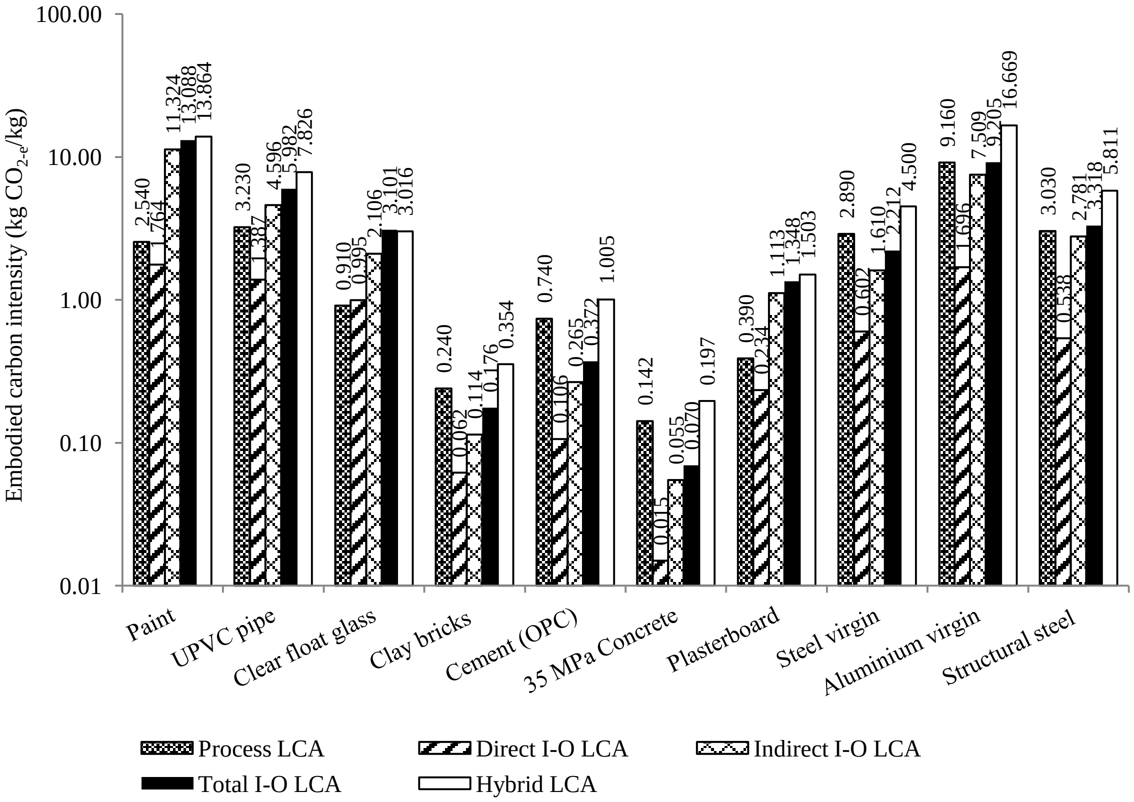
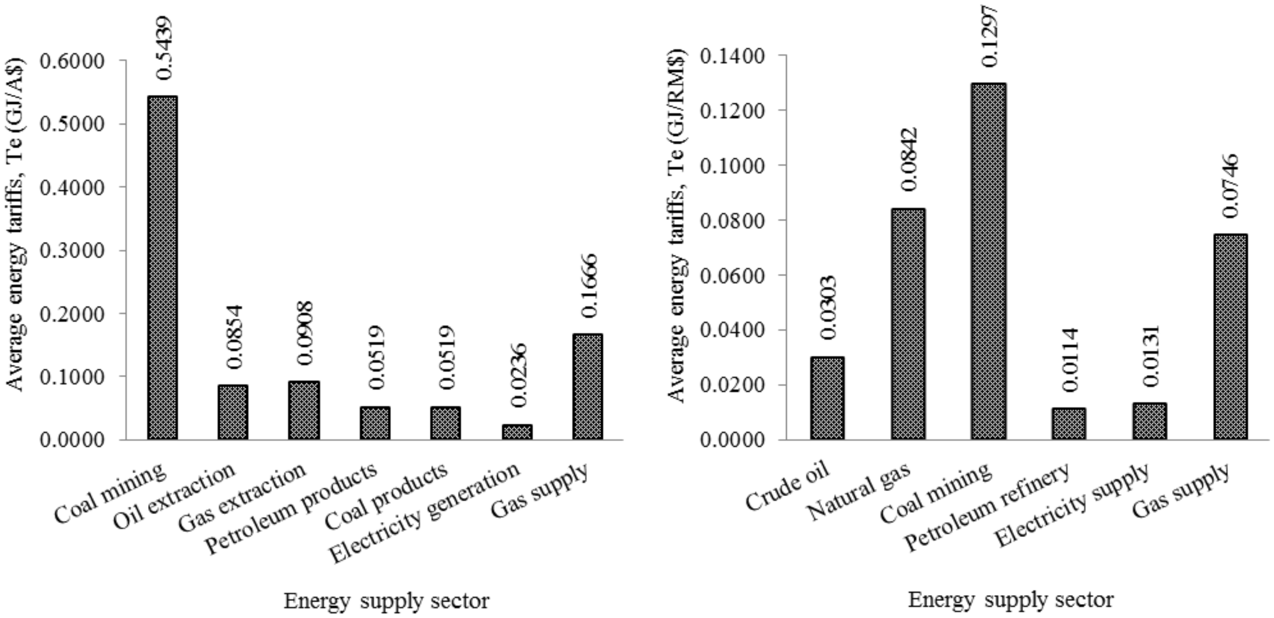


Figure 9: Reference case of EC for different construction materials and products in Malaysia



(a)

(b)

Figure 10: Average energy tariffs for energy supply sectors in 2005 as reference case in (a) Australia and (b) Malaysia

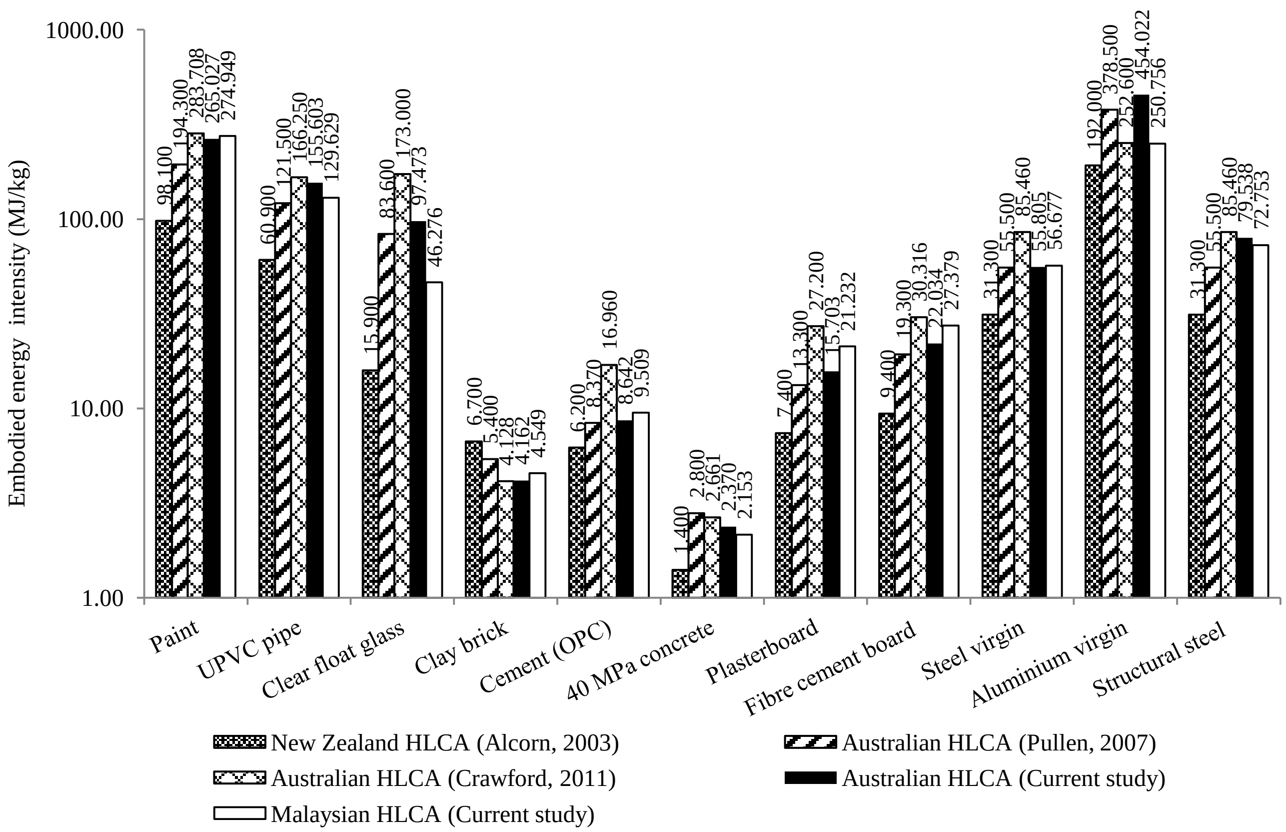


Figure 11: Comparison of developed HLCA model with previous studies conducted in Australia, New Zealand and Malaysia

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