Development of hybrid life cycle inventories (HLCI) database for embodied energy and carbon intensities of Malaysian construction materials

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Abstract. This paper investigates the completeness of process, input-output (I-O) and hybrid life cycle inventory (LCI) analysis and their applicability as applied to the Malaysian construction materials. The process, I-O, and hybrid analysis were evaluated at the basic materials and products level to identify the gaps between models and further incorporated into the material and product inputs of a selected building. It was found that the largest differences in embodied energy (EE) and embodied carbon (EC) intensities of the materials and products between I-O and hybrid analysis accounted for up to 65.90% and 62.08%, respectively. Further analysis of the EE and EC intensities of the building revealed that the hybrid analysis were significantly higher than I-O analysis estimated to be 44.39% and 43.57% respectively. On average, the EE and EC intensity values using I-O analysis were lower than hybrid analysis due to inherent limitations in this model. Although using I-O data was considered not representative due to inherent limitation, it was considered applicable for energy analysis due to lack of process data in Malaysian building industry.

1. Introduction
The United Nations Environmental Programme [1] currently reported that building construction in developed and developing countries consumed more than one third of total energy use and emitted greenhouse gas (GHG) emissions. Thus, this sector has significant opportunities for GHG emissions reduction that contribute to the global warming. Malaysia is among fast developing countries in the Asian region. Rapid development in human resources and infrastructures is the focal point for the Malaysian government to achieve developed country status in the year 2020. In fulfilling this vision, the requirements on energy sectors (e.g. natural gas, coal, petroleum products, and electricity supply) are compulsory not only for Malaysia, but also other developing countries.

In Malaysia, the energy consumption is increasing rapidly because of economic growth and development since year 2000 to 2010. It can be seen that the energy demand was dominated by the transport sector at 40.5%, the industrial sector at 38.6%, the residential and commercial sector at 13.1%, the non-energy sector at 7.3%, and the agricultural sector at 0.5% [2]. The energy consumed by commercial and residential buildings was accounted for about 13% of total energy consumption and 48% of electricity consumption. The energy-intensive industries such as cement, ceramic, iron and steel were predicted to be major consumers for the future [3].
The energy consumed by the building consists of embodied energy and operational energy. Generally, EE is defined as the energy consumed in all activities required for a process. It is categorised into two components, namely direct energy and indirect energy. Direct energy includes energy consumed on-site during building construction and other energy purchased. Indirect energy consists of the energy embodied in goods and services, as well as energy in upstream boundary of construction processes [4]. Meanwhile, EC is a measure of the carbon dioxide emissions associated with the building construction. This includes carbon emissions during the processing of raw materials, manufacturing of the building materials and components, and transporting to site and fabricating the building components [5].

For building energy and emissions in Malaysia, previous studies mainly focused on operational energy. Due to the comprehensive analysis of operational energy, EE analysis methods become a significant component of the energy rating systems for operational energy use [6]. However, there is lack of studies on the applicability of these methods to the Malaysian construction industry. Recently, there has been inconsistency and wide variation of EE and EC intensities in LCI data, due to the variability, uncertainty and incompleteness of the system being studied. Treloar [7] pointed out factors contributing to these problems, which include completeness of system boundaries, selection of analysis methods (i.e. process, I-O, or hybrid analysis), regional variability, and reliability of data from government and agencies.

Therefore, this research is part of an iterative process in LCI analysis to develop HLCI and evaluate the applicability of I-O and HLCI model in the Malaysian construction materials. While previous researches investigated the key factors and issues contributing to the variations in EE and EC analysis, this research aims to evaluate the applicability of these models in terms of its completeness and accuracy and its significant influence on estimating building’s total embodied impact.

2. Life cycle inventory analysis
Life cycle inventory (LCI) analysis involves the collection of data and calculation procedures to quantify relevant inputs (i.e. materials and energy) and outputs (i.e. emissions and waste) of a product system [8]. LCI analysis is a second phase in life cycle assessment (LCA). In general, LCI analysis is classified into process, I-O and hybrid analysis based on different theory and system scope.

Process analysis is known as a bottom-up methodology. It is used to identify and trace the physical flow of goods and services for the particular processes, products or manufacturing chains [9]. In general, process analysis is defined as the EE analysis using high-resolution detailed site-specific data [10]. It most applicable and accurate for assessing products or processes that are highly energy intensive, and require large amounts of direct energy components [11]. However, process data is not always available to take advantage of detailed process analysis, due to lack of quantity and quality of process data locally and internationally [12]. According to Pomponi and Lenzen [13], process model induces systematic truncation errors due to the incomplete definition of system boundary.

To overcome the incompleteness of system boundary, I-O analysis is widely used. It is a top-down approach, which converts monetary values into physical values. According to Lenzen, et al. [14], this model uses a top-down linear macroeconomic approach to explain the complex inter-industry relationship in terms of monetary transactions in industrial structures. The use of I-O data increases the reliability of LCA by improving completeness and reliability of life cycle inventory analysis compared to the traditional method. Beside its advantages, I-O analysis has several limitations. Thus, using this method to replace process analysis does not always ensure the accuracy of the analysis being studied.

Hybrid analysis was developed to combine the advantages of the more accurate process analysis and the extended system boundaries of the I-O analysis [10]. This analysis comprises two form of distinct method, namely process-based hybrid analysis and I-O based hybrid analysis. Process-based hybrid analysis incorporates process data into I-O analysis during calculation of hybrid EE intensity of material and product (or building). This analysis is suited to analyse large typical product such as entire building [15]. Meanwhile, The I-O based hybrid analysis improves the completeness of the EE
intensities. Crawford [16] pointed out that the results obtained from the process-based hybrid analysis can be combined with further I-O values to extend the system boundary.

3. Model development

3.1. Hybrid based life cycle inventory model

Hybrid analysis integrates more reliable process data into the most comprehensive I-O data during calculation of the energy and carbon intensity. Crawford [17] suggested that in quantifying EE and EC intensity of a product, the first step is to calculate the EE and EC intensity of the basic materials. The hybrid EE and EC intensity of the basic material was determined by adding EE and EC intensity from detailed process analysis with indirect EE and EC intensity from comprehensive I-O analysis. The indirect EE and EC intensity of the material is calculated by subtracting direct EE and EC intensity from the total EE and EC intensity of material sector n from I-O data. This difference represents the indirect EE and EC intensity of the material unaccounted for by the process analysis due to truncation error or setting up the system boundary of material production. The Hybrid EE and EC intensities of basic material are then multiplied by the material’s price as formulated by Equations 1 and 2 below.

\[ HEI_m = EI_D + [(TEI_n - DEI_n) \times C_m] \]  
\[ HECO_{2-e}I_m = ECO_{2-e}I_D + [(TCO_{2-e}I_n - DCO_{2-e}I_n) \times C_m] \]

Where, \( HEI_m \) is the EE intensity of the basic material using hybrid analysis; \( EI_D \) is the direct EE intensity of the basic material from process analysis; \( TEI_n \) is the total EE intensity of the basic material sector using I-O analysis; \( DEI_n \) is the direct EE intensity of the basic material sector using I-O analysis; \( HECO_{2-e}I_m \) is the EC intensity of the basic material using hybrid analysis; and \( C_m \) is the material price.

Total EE and EC intensity of a product was quantified using hybrid analysis. If the process data was unavailable, direct EE and EC intensity of the product were obtained from I-O analysis and was then multiplied by the product’s price. The total EE and EC of the product were quantified by adding all EE and EC intensity of the basic materials with the direct EE and EC intensity of the product as formulated by Equations 3 and 4 below.

\[ \sum_{m=1}^{M} (HEI_m \times W_m \times Q_m) + DEI_{n,pdt} \times C_{pdt} \]  
\[ \sum_{m=1}^{M} (HECO_{2-e}I_m \times W_m \times Q_m) + DCO_{2-e}I_{n,pdt} \times C_{pdt} \]

Where, \( HEEP_{pdt} \) is the total EE intensity of the product using hybrid analysis; \( W_m \) is the material wastage factor; \( Q_m \) is the material quantity to produce the product; \( DEI_{n,pdt} \) is the direct EE intensity of the product sector n from I-O analysis; \( C_{pdt} \) is the total price of the product; \( HECO_{2-e}I_{pdt} \) is the total EC intensity of the product using hybrid analysis; and \( DCO_{2-e}I_{n,pdt} \) is the direct EC intensity of the product sector n using I-O analysis.

3.2. Evaluation of I-O and Hybrid LCI model

The gap analysis was used to quantify differences between I-O and hybrid analysis by focusing on the final LCI results. It is used to assess the differences between models, as an evaluation of the completeness of each model. The gaps analysis as proposed by Crawford [18] was modified to calculate the gaps between I-O and hybrid analysis as given in Equation 5 below:
GAP = \frac{\text{HLCI} - \text{I-O LCI}}{\text{HLCI}} \times 100 \tag{5}

Where, GAP is the percentage completeness of the I-O analysis when compared with hybrid analysis; HLCI is the EE and EC intensity of basic material and product (or material and product input) using hybrid analysis; and I-O LCI is the EE and EC intensity of basic material and product from I-O analysis.

The comparative analysis was previously conducted to evaluate the applicability of I-O data to the hybrid analysis [19]. Similarly, this analysis was also used in this research to evaluate the applicability of I-O and hybrid LCI model to quantify EE and EC intensities of individual materials and products, as well as material and product inputs to the whole building.

4. Result and Discussion

4.1. Evaluation of EE and EC intensities using gap analysis

Tables 1 presents the detailed proportion of EE and EC intensities of building materials and products based on process, I-O, and hybrid analysis. The gap analysis clearly pointed out that the EE and EC intensities of materials and products using I-O analysis can be higher or lower than hybrid analysis. For instance, EE and EC intensity of bituminous waterproofing coating using hybrid analysis were lower than I-O analysis, accounting for 34.29% and 104.63% respectively. The higher EE and EC intensity values using I-O analysis were due to variations in material and product prices and the small proportion of process data available and other variation associated with I-O analysis. The largest gaps in EE intensities in concrete and steel were found to be different with the gaps found in their EC intensities. These differences were due to the effect of carbon emission factors used to convert energy requirements to carbon emissions in EC analysis. While concrete and steel were the common materials used in building construction, using the I-O analysis to quantify both EE and EC intensities led to overestimation or underestimation of the total embodied impact of the building.

The results revealed that the largest gaps exist in EE intensities between I-O and hybrid analysis accounted for up to 65.90% for aluminium virgin, 55.06% for steel virgin, 50.77% for clay brick, 47.26% for structural steel, 45.83% for 40 MPa concrete, and 44.92% for Ordinary Portland Cement (OPC). Meanwhile, the largest gaps of EC intensities were also found to be 61.40% for 40 MPa concrete, 51.24% for aluminium virgin, 47.51% for clay brick, 47.27% for steel virgin, and 42.28% for medium hardwood. It is clearly shown that the top largest gaps in EE and EC intensities were the most commonly used materials and products in building construction. Asif, et al. [20] identified key materials in building construction include concrete, timber, glass, ceramic tiles, and aluminium. Lenzen and Treloar [21] revealed large differences in EE intensities of materials and products (e.g. softwoods, mineral wool insulations, plasterboards, and plastic products) when comparing between wood-framed and concrete-framed building. These gaps stemmed from major discrepancies of these materials due to the influence of a large proportion of indirect energy in the upstream boundary of material production (e.g. mineral wool insulation, plastic, and plasterboard); and different of production layer which are influence from economic structure (i.e. energy consumed by manufacturers of materials used in the buildings; and by the suppliers of these manufacturers).
Table 1. Detailed proportion of EE and EC intensities of building materials and products in Malaysia.

| Material and product sector | Basic material and product | EE intensities (MJ/kg) | EC intensities (kg CO₂eq/kg) | Gap* (%) | Gap* (%) |
|-----------------------------|---------------------------|------------------------|-----------------------------|----------|----------|
|                             | Process LCI               | I-O LCI                | Hybrid LCI                  | LCI      | LCI      |
| Sand, aggregate, and stone  | Granite aggregates        | 0.083                  | 0.236                       | 0.286    | 17.48    |
|                             | Normal river sand         | 0.008                  | 0.201                       | 0.181    | -11.08   |
|                             | Polished granite slab     | 11.000                 | 47.797                      | 52.102   | 8.26     |
| Carpet                     | Nyion carpet               | 60.350                 | 386.927                     | 396.270  | 2.36     |
| Sawmill products           | Heavy hardwood             | 10.400                 | 15.072                      | 23.586   | 36.10    |
|                             | Medium hardwood            | 10.400                 | 11.270                      | 20.259   | 44.37    |
| Wood products              | HDF                        | 16.000                 | 34.150                      | 43.775   | 21.99    |
|                             | MDF                        | 11.000                 | 17.776                      | 25.457   | 30.17    |
|                             | Plywood                    | 15.000                 | 22.201                      | 33.056   | 32.84    |
| Bitumen products           | Bituminous waterproofing   | 51.000                 | 146.425                     | 109.034  | -34.29   |
| Paints                     | Oil-based paint            | 97.000                 | 194.113                     | 274.949  | 29.40    |
|                             | Water-based paint          | 59.000                 | 182.869                     | 226.642  | 19.31    |
| Plastic products           | ABS pipe                   | 95.300                 | 156.191                     | 232.099  | 32.70    |
|                             | HDPE pipe                  | 84.400                 | 114.490                     | 184.675  | 38.00    |
|                             | UPVC pipes                 | 67.500                 | 78.179                      | 135.972  | 42.50    |
|                             | PE sheet membrane          | 83.100                 | 111.963                     | 181.162  | 38.20    |
| Sheet glass and glass       | Clear float glass          | 15.000                 | 38.632                      | 46.051   | 16.11    |
| products                   | Obscured glass             | 15.000                 | 30.977                      | 39.898   | 22.36    |
|                             | Tinted float glass         | 15.000                 | 46.986                      | 52.765   | 10.95    |
| Clay and ceramic products   | Ceramic tiles              | 12.000                 | 37.029                      | 41.049   | 9.79     |
|                             | Clay bricks - common       | 3.000                  | 2.406                       | 4.888    | 50.77    |
|                             | Vitrified clay pipe        | 7.000                  | 21.655                      | 23.989   | 9.73     |
| Cement                     | OPC                        | 5.200                  | 5.238                       | 9.509    | 44.92    |
| Concrete and non-metallic  | 30 MPa concrete            | 1.098                  | 1.057                       | 1.944    | 45.62    |
| mineral products           | 35 MPa concrete            | 1.153                  | 1.104                       | 2.033    | 45.70    |
|                             | 40 MPa concrete            | 1.220                  | 1.161                       | 2.143    | 45.83    |
|                             | 50 MPa concrete            | 1.260                  | 1.197                       | 2.194    | 45.41    |
| Fibre glass insulation     | 28.000                     | 254.407                | 248.012                     | -2.58    | 13.500   |
| Rockwool insulation        | 17.568                     | 138.833                | 137.632                     | -0.87    | 1.2240   |
| Cellulose fibre ceiling    | 10.400                     | 19.633                 | 27.379                      | 28.29    | 1.0900   |
| Plain gypsum board         | 6.750                      | 18.268                 | 22.548                      | 18.98    | 0.3900   |
| Iron and steel products    | Galvanised iron pipe       | 40.000                 | 52.232                      | 83.629   | 37.54    |
|                             | Mild steel pipe            | 34.700                 | 55.683                      | 81.213   | 31.44    |
|                             | Stainless steel pipe       | 56.700                 | 223.278                     | 243.206  | 8.19     |
|                             | Steel virgin               | 35.400                 | 25.473                      | 56.677   | 55.06    |
|                             | Steel sheet decking        | 40.000                 | 139.923                     | 156.879  | 10.81    |
| Non-ferrous metals         | Aluminium virgin           | 218.000                | 107.002                     | 313.756  | 65.90    |
|                             | Reflective foil            | 217.000                | 172.263                     | 371.158  | 53.59    |
| Structural metal products  | Structural steel           | 38.000                 | 38.373                      | 72.753   | 47.26    |

Note:
(a) Gap between I-O and hybrid analysis is calculated by: (HLCI – I-O LCI)/HLCI.
5. Conclusion
This research assessed the completeness and applicability of I-O and hybrid analysis as applied to the selected Malaysian building construction. The process, I-O, and hybrid analysis were evaluated at the basic materials and products level to identify the significant gaps or differences between analysis methods and further incorporated into the material and product inputs of a selected building. The gap analysis found that the largest differences in EE and EC intensities of the materials and products between I-O and hybrid analysis accounted for up to 65.90% and 62.08%, respectively. These largest differences were found in non-ferrous metals (aluminium), iron and steel products, and concrete which were considered as the key materials used in the building construction. Using I-O data as substitute for process data is considered better than not using any data at all. However, the use of I-O analysis is only limited to fill the gaps in upstream boundary of materials and products manufacturing. Therefore, this research initially quantified EE and EC intensities of the materials and products, before calculating the building’s total embodied impact using actual quantities of materials, equipment, plants, etc. to overcome inherits problems such as underestimation of material, product and building’s prices as used in the I-O analysis method.

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