The 2013 World Congress on
Advances in Structural Engineering and Mechanics (ASEM13)
Jeju, Korea, September 8-12, 2013

Validation of carbon emission intensity in precast concrete structure using hybrid life cycle assessment

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ABSTRACT

There has been a growing interest in quantifying the direct and indirect energy and carbon emission embodied in construction materials and building component production. By understanding how energy is consumed, designers can significantly reduce environmental impact by selecting materials with low embodied energy and carbon emission intensity. Previous research showed that indirect emission could be higher than direct emission for energy-intensive materials such as cement and reinforcement steel. It is argued that quantifying direct emission alone could underestimate the total amount of energy and carbon emission and subsequently its impact to the environment. However, indirect energy and emission assessment is a challenging task involving upstream process of construction materials production. To address this issue, this paper demonstrates the application of hybrid life cycle assessment to assess indirect carbon emission variation embodied in precast concrete structures. Results showed that the indirect emission embodied in the materials and components production of precast concrete structure accounts for as much as 40%.

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Thus, this paper suggests that both direct and indirect emission assessment must be incorporated in evaluating its environmental impact.

1. INTRODUCTION

Building industry consumes 40% of primary energy during life cycle stages of material productions, transportation, operation, maintenance, demolition and disposal. Most of the energy consumed is mainly related to the utilization phase of a building, while production of building materials such as concrete and steel are attributed to the industry sector such as concrete and other non metallic mineral sector and iron and steel product sector. In developed countries, production of building materials contributes to 8-12% of the total carbon emission. In Asian countries like Malaysia, the industrial sector (e.g. manufacturing and construction) accounts for 38.6% of total energy demand and was claimed to be a major contributor to the environmental impact (Mohd Safaai et al. 2011). The energy-intensive industries, for instance cement and steel, were predicted to be a major consumer in the future. The relative importance of the building production phase is also expected to increase in the future since the energy used during the utilization phase can be substantially reduce with well-proven technologies (Nässén et al. 2007).

The literature on embodied emission intensity in material production indicates a considerable discrepancy between the bottom-up and top-down analyses. Table 1 shows a variation of embodied emission intensities of various building materials. The high variation of embodied emission can be found between the two analyses which in turn influence the Life Cycle Assessment (LCA) of building components and structures. Previous studies identified various parameters influencing variation in embodied energy consideration such as methodological selection, primary and delivered energy, age of data, manufacturing technology, source of data, and completeness of data (Dixit et al. 2010; Dixit et al. 2012).

The aim of this paper is to gain an understanding of energy and carbon emission during material productions. This can be achieved through a systematic comparison between materials from top-down (Input-Output-based analysis) and bottom-up (process-based analysis) analyses. Furthermore, the paper identifies parameter variations that strongly influence the carbon emission resulting from material production. Finally, a precast concrete structure was used to demonstrate the influence of such variation on carbon emission in a building production.

Table. 1 Embodied carbon emission intensity for selected building materials

Materials	Embodied Carbon (kg CO_{2-e}/kg)		
	DB 1[a]	DB 2[b]	DB 3[c]
Cement (OPC)	0.740	0.994	0.522
20 MPa concrete	0.107	0.114	0.180
30 MPa concrete	0.137	0.159	0.190
40 MPa concrete	0.153	0.189	0.200
Aggregates	0.005	0.003	0.132
Steel Virgin	2.890	1.242	4.340

Note:
a) Process LCA (Hammond and Jones 2011)
b) Hybrid LCA (Alcorn 2003)
c) Hybrid LCA (Pullen 2007)

2. HYBRID LCA

2.1 Direct and indirect emission analysis and carbon emission data

The Input-Output (I-O) tables of Malaysian economic structure were employed to convert monetary value to physical value through normalization. These include integration of matrices for product purchased by industry for domestic use as well as imports. Neglecting imports from supply chain of domestic products can underestimate up to 41.6% of total energy and carbon emission (Acquaye and Duffy 2010). The tables used in this paper consists of 120x120 commodities (industry/product) incorporating the whole supply chain of product flow in Malaysian economic (Department of Statistics 2010).

Indirect energy and emission per unit of final consumption are calculated using Leontief inverse matrix and multipliers of energy and emission in each sector. These multipliers were derived based on the detailed energy balanced provided by International Energy Agency (IEA) database and were validated by using Malaysian energy balance to ensure the reliability of data provided. These multipliers convert the product flow in the supply chain to physical energy values. However, these values were deflated to the base year 2005 according to the latest Malaysian I-O tables. These tables have 5 years lag times thus influence the variability and consistency of indirect emission analysis. These variations were discussed in section 2.2 to 2.4.

Direct emission analysis was calculated based on inventory carbon and energy (ICE) provided by Bath University and adopted in the analysis (Hammond and Jones 2011). The development of database was based on the bottom-up LCA approach (process-based analysis). It was assumed to be accurate for direct emission analysis but underestimate total energy and carbon of products or materials due to truncation errors in upstream processes. Although incomplete, it is more accurate than the top-down (I-O based) analysis (Treloar et al. 2001).

The Hybrid LCA (HLCA) combines the results obtained from the process-based LCA (PLCA) and I-O based LCA (I-OLCA) so that the completeness of system boundary in upstream materials production process can be increased. The indirect emission intensity of a particular materials sector can be identified by subtracting Eq. (2) from Eq. (1) respectively. The difference between total and direct emission intensity is then multiplied by material cost as shown in Table 6. In order to identify emission intensity for a material (e.g. cement, aggregate, water and reinforcement steel), the indirect emission intensity is combined with direct emission intensity using HLCA as given in Eq. (3) below.

$$DCO_{2-e}I = \sum_e^E D_{RCe} \times T_e \times P.E.F_e \times C_e \times I_e \quad (1)$$

$$TCO_{2-e}I = \sum_e^E T_{RCe} \times T_e \times P.E.F_e \times C_e \times I_e \quad (2)$$

$$ECO_{2-e}I_m = ECO_{2-e}I_D + [(TCO_{2-e}I - DCO_{2-e}I) \times C_m] \quad (3)$$

Where, $DCO_{2\text{-}e}I$ is the direct emission intensity for a particular sector or product output (GJ/RM$); D_{RCe} is the direct requirement coefficient of energy sector e (RM$/RM$); E is the total number of energy supply sector, e in I-O table; T_e is average energy tariff (GJ/RM$); $P.E.F_e$ is the primary energy factor of energy supply sector e (dimensionless); C_e is the disaggregation constant for energy sub-sector, e.; I_e is the emission factor of energy supply sector, e; $TCO_{2\text{-}e}I$ is total emission intensity for a particular sector or product output (kg CO_{2-e}/RM$); T_{RCe} is total requirement coefficient (Leontief inverse) of energy supply sector *e* (RM$/RM$); $ECO_{2-e}I_m$ is emission intensity of a material or product; $ECO_{2-e}I_D$ is direct emission intensity from PLCA; C_m is the cost of material or product.

2.2 Disaggregated energy supply sector

The parameter to disaggregate the energy supply sector can be used to overcome double counting in energy and emission analysis. In Malaysian I-O tables, the aggregated supply energy sector can be found in crude oil (IOPC 1110) and natural gas sector (IOPC 11200) (aggregate natural gas and crude oil sector) and electricity (IOPC 40100) and gas supply sector (IOPC 40200) (aggregate electricity and gas supply sector). Disaggregated energy supply sector was derived for the period of 2005 to 2010 to identify variability and consistency of this parameter. Based on Table 2, the standard of variation for each energy supply sector indicates less variation over period of time.

Table. 2 Disaggregated constant for Malaysian energy supply sector for period of 2005-2010

I-O Sector MSIC2000*	Disaggregated Energy supply sector	Disaggregation constant, C_e						Standard deviation
		2005	2006	2007	2008	2009	2010	
11100	Crude oil	0.72	0.74	0.75	0.79	0.71	0.73	0.03
11200	Natural gas	0.28	0.26	0.25	0.21	0.29	0.27	0.03
10100	Coal mining	1.00	1.00	1.00	1.00	1.00	1.00	0.00
23100	Petroleum refinery	1.00	1.00	1.00	1.00	1.00	1.00	0.00
40100	Electricity supply	0.53	0.86	0.83	0.83	0.84	0.89	0.03
40200	Gas supply	0.14	0.17	0.17	0.16	0.11	0.10	0.03

*MSIC2000 - The Malaysia Standard Industrial Classification 2000

2.3 Primary and delivered energy

Primary energy is referred to as the energy required from natural resources (e.g. coal or natural gas) by producer (e.g. electricity or petroleum refinery) whereas delivered energy is the energy consumed by final consumers. Conversion of delivered energy to primary energy using primary energy factor (PEF) is site specific. The consideration of primary energy takes into account the loss in transmission and distribution as well as for plant own use for specific countries. Treloar et al. (2001) overestimated PEF that lead to high energy intensity for construction materials (Treloar 1998). The variability of PEFs lead to variation in embodied energy and carbon emission intensity. The consistent and up-to-date energy database provided by International Energy Agency (IEA) was obtained to estimate primary energy factor (PEF) for Malaysian energy balance. This creates consistency and more reliable estimation for PEF. Table 3 shows derivation of PEF from Malaysia energy balance for the period of 2005 to 2010. Standard deviation of PEF for electricity generation was higher compared to other PEF due to the variability of fuel mix input to electricity generation plants.

Table. 3 Primary energy factor (PEF) for Malaysian energy supply sector for period of 2005-2010

I-O Sector MSIC2000*	Energy supply sector	Primary energy factor (PEF)						Standard deviation
		2005	2006	2007	2008	2009	2010	
11100	Crude oil	1.00	1.00	1.00	1.00	1.00	1.00	0.00
11200	Natural gas	1.62	1.62	1.64	1.74	1.50	1.25	0.17
10100	Coal mining	1.00	1.00	1.00	1.00	1.00	1.00	0.00
23100	Petroleum refinery	1.01	1.04	1.04	1.06	1.01	1.01	0.02
40100	Electricity supply	4.18	4.04	3.96	4.37	3.61	3.77	0.27
40200	Gas supply	1.14	1.10	1.08	1.08	1.12	1.12	0.02

*MSIC2000 - The Malaysia Standard Industrial Classification 2000

2.4 Emission Factor

Emission factors were employed to estimate emission intensity for specific materials or products. An emission factor converts indirect I-O energy intensity into indirect I-O emission intensity per unit monetary value which is then multiplied with the material or product sector output. Emission factor for electricity depends on fuel mix into electricity generation plant. Electricity emission factor was derived from Malaysia’s energy balance as given in Table 4. Figure 1 illustrates variation of electricity from Malaysian generation plants for the period of 2005 to 2010.

Table. 4 Fuel combustion emission factor, I_e

Fuel combusted	Energy content factor	Emission factor, kg CO_{2-e} /GJ (relevant oxidation factors incorporated)			Emission factor, kg CO_{2-e} /GJ
		CO_2	CH_4	N_2O	
Crude oil (Scope 1)	45.3 GJ/t	68.90	0.06	0.20	69.16
Natural Gas (Scope 1)[a]	39.3 x 10^{-3} GJ/m^3	51.20	0.10	0.03	51.33
Black Coal (Scope 1)[b]	27 GJ/t	88.20	0.03	0.02	88.25
Petroleum product (Scope 1)[c]	38.6 GJ/kL	69.20	0.10	0.20	69.50
Electricity (Scope 2)[d]					244.66

Note:
a) Scope 1 - direct/point source emissions
b) Sub-bituminous also called black coal. It is commonly used as fuel to electricity generation. Coal used in Malaysia is classified as sub-bituminous coal. For coal mining, emission from black coal is used
c) For petroleum product, emission from diesel/fuel oil is used
d) Scope 2 - indirect source emissions

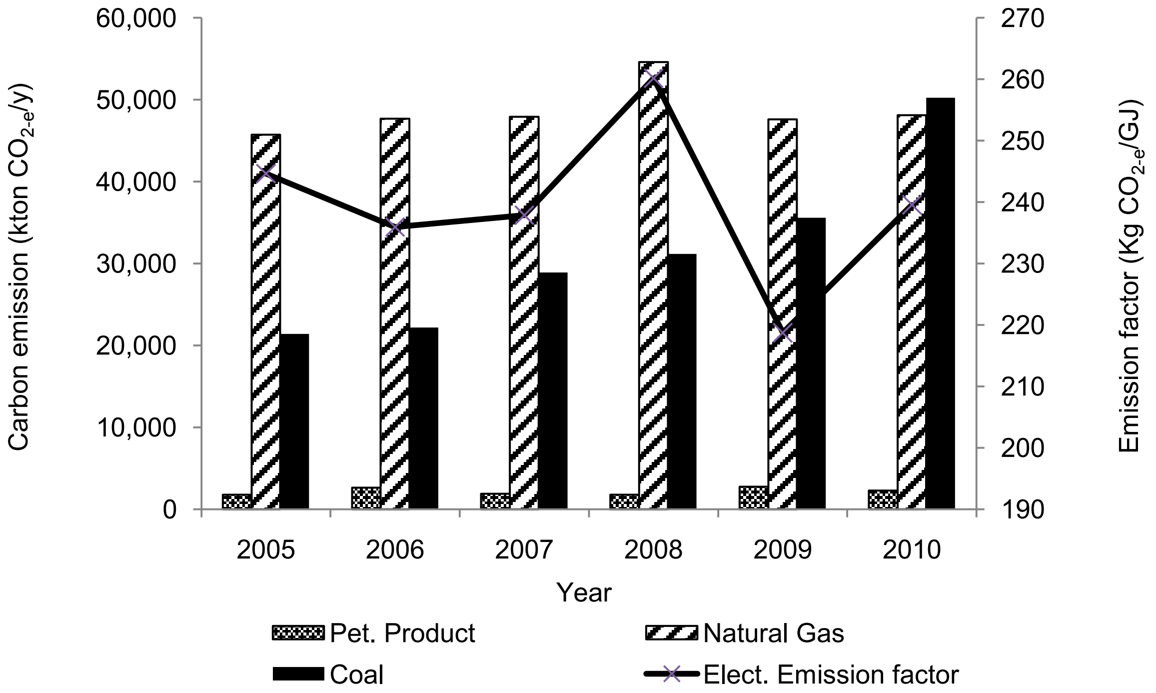


Fig. 1 Emission factor for electricity generation sector in period of 2005-2010 based on emission emitted from the Malaysia power plant

3. RESULTS AND DISCUSSIONS

It has been demonstrated in the paper that the empirical evidence for emission assessment for specific material and building production level using PLCA, I-OLCA and HLCA. Emission intensity of materials were derived based on energy-based GHGs such as CO_2, N_2O, and CH_4 which has different impact to global warming and can be weighted according to global warming potential (GWP). The ratio of the warming caused by a substance by a similar mass of carbon dioxide is termed as carbon dioxide equivalent ($CO_{2\text{-}e}$). The GWPs for each of emission were summed up to give total $CO_{2\text{-}e}$ for specific materials.

3.1 Evaluation of specific energy and carbon emission for materials

The HLCA combines the results obtained from PLCA and I-OLCA so that the completeness of system boundary in upstream materials production process can be increased. The indirect emission intensity of a particular materials sector can be identified by subtracting Eq. (2) from Eq. (1) respectively. The derivation of indirect I-O emission for cement from the Malaysian I-O tables is demonstrated in Table 5. The difference between total and direct emission intensities is then multiplied by material cost as shown in Table 6. In order to identify emission intensity for a material (e.g. cement, aggregate, water and reinforcement steel), the indirect emission intensity is combined with direct emission intensity using HLCA as given in Eq. (3) and graphically illustrated in Figure 2.

The investigation on specific carbon emission of materials is vital to the overall emission of a product or building. Acquaye and Duffy (2010) proposed a policy for carbon emission reduction by specifying low-emission materials. Emission intensity of selected materials was estimated using PLCA, I-OLCA and HLCA. Using PLCA produced higher emission intensity compared to I-OLCA. The differences of PLCA results compared to I-OLCA results were 179.6% for cement, 177.9% for 30 MPa concrete grade, 26.3% for aggregates and 115.6% of reinforcement steel respectively. For 30 MPa concrete grade, the underestimated emission intensity by I-OLCA is due to the contribution of direct I-O emission being smaller (0.016 kg $CO_{2\text{-}e}$/kg) than the indirect I-O emission (0.061 kg CO_{2-e}/kg) which indicates that most of the emission from combustion of fossil fuel in the kiln in cement production are located in upstream process of concrete production. Analyzing these results with different concrete grade revealed that cement (energy-intensive material) contributes significantly to concrete production accounting for 76-82% of total concrete production by using HLCA. Hybrid LCA was performed to take advantages of complete system boundary in the upstream process. Eventually, using hybrid model increases 61.1% (0.198 kg CO_{2-e}/kg) and 30.8% (0.137 kg CO_{2-e}/kg) of 30 MPa concrete grade emission intensity compared to I-OLCA and PLCA only. The results highlight the effect of selecting different model in estimating of emission intensity of materials. This can significantly contribute to the variation of emission intensity when materials are aggregated in products or buildings production phase. Hybrid LCA is thus able to address the weakness of both the PLCA and I-OLCA models, and provide more meaningful and accurate assessment of emission.

Table. 5 The direct and total emission intensity from Malaysia 2005 I-O table for cement using I-OLCA analysis from I-O product classification (IOPC) 26941

Energy supply sector	Emission factor, (kg CO_{2-e}/GJ)[a,b]	Average energy tariffs, T_e (GJ/RM$)	Disagg. constant, C_D	Primary energy factors, PEF	Total req. coefficient, T_{RC} (RM$/RM$)	Direct req. coefficient, D_{RC} (RM$/RM$)	Total emission intensity, TEI (kg CO_{2-e}/RM$)	Direct emission intensity, DEI (kg CO_{2-e}/RM$)
Crude oil	69.16	0.0303	0.72	1.00	0.3064	0.0000	0.46312	0.00000
Natural gas	51.33	0.0842	0.28	1.62	0.3064	0.0000	0.59737	0.00000
Coal mining	88.25	0.1297	1.00	1.00	0.0040	0.0001	0.04619	0.00091
Petroleum refinery	69.50	0.0114	1.00	1.01	0.5531	0.2991	0.44102	0.23848
Electricity supply[c]	244.66	0.0131	0.86	4.18	0.0578	0.0277	0.66826	0.32016
Gas supply	51.33	0.0746	0.14	1.14	0.0578	0.0277	0.03458	0.01657

[a] Relevant oxidation factors incorporated
[b] Includes Scope 1 assessment which measure CO_2, CH_4, and N_2O from direct/point source emissions except electricity supply
[c] Include Scope 2 assessment which measure CO_2, CH_4, and N_2O from indirect source emissions.

Table. 6 The Estimation of embodied emission intensity of basic materials inventories from Malaysia 2005 I-O table using HLCA.

Description	Cement	Aggregate	Water	Reinforcement Steel
Total emission intensity, $\sum TCO_{2\text{-}e}I$ (kg $CO_{2\text{-}e}$/RM$)	2.2505	0.9956	1.2763	1.4048
Direct emission intensity, $\sum DCO_{2\text{-}e}I$ (kg $CO_{2\text{-}e}$/RM$)	0.5761	0.1708	0.5980	0.3645
Price, RM$/kg (2005)	0.1831	0.0186	0.0010	1.7797
Total emission intensity, $TCO_{2\text{-}e}I$ (kg $CO_{2\text{-}e}$/kg)	0.4120	0.0185	0.0013	2.5002
Direct emission intensity, $DCO_{2\text{-}e}I$ (kg $CO_{2\text{-}e}$/kg)	0.1055	0.0032	0.0006	0.6487
Indirect emission intensity (kg $CO_{2\text{-}e}$/kg)	0.3066	0.0154	0.0007	1.8515
Direct emission intensity, $ECO_{2\text{-}e}I_D$ (kg $CO_{2\text{-}e}$/kg)	0.7400	0.0052	0.0017	2.8900
Total emission intensity, $ECO_{2\text{-}e}I_m$ (kg $CO_{2\text{-}e}$/kg)	1.0466	0.0206	0.0024	4.7415

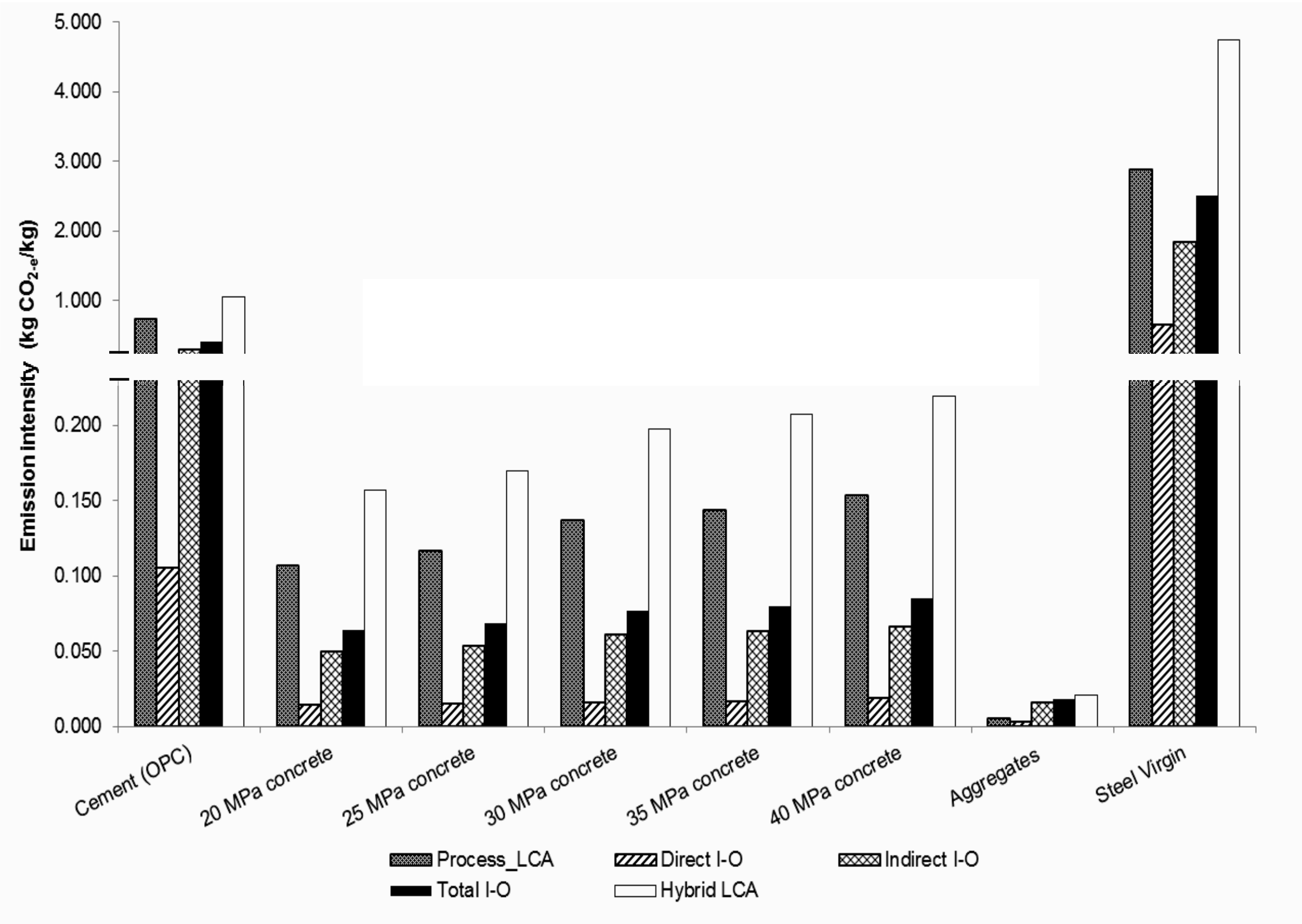


Fig. 2 Carbon emission intensity for materials using PLCA, I-OLCA, and HLCA

3.2 Validation of specific energy and carbon emission for materials with previous studies

This section described a comparison between the result of HLCA for selected material production with that from previous studies which used Australian and New Zealand I-O tables. The I-O tables published by bureau of statistic often have a lag time up to 5 years. However, it is commonly accepted that technological coefficient in I-O tables for intermediate sector are stable for mature technology over a period of time. Technological coefficient can vary when compared to different countries due to the difference in the efficiency of technologies used to achieve sustainable development. For instance, technological efficiency might be different when comparing between Malaysian and Australian cement production plants. A graphical comparison between studies is shown in Figure 3.

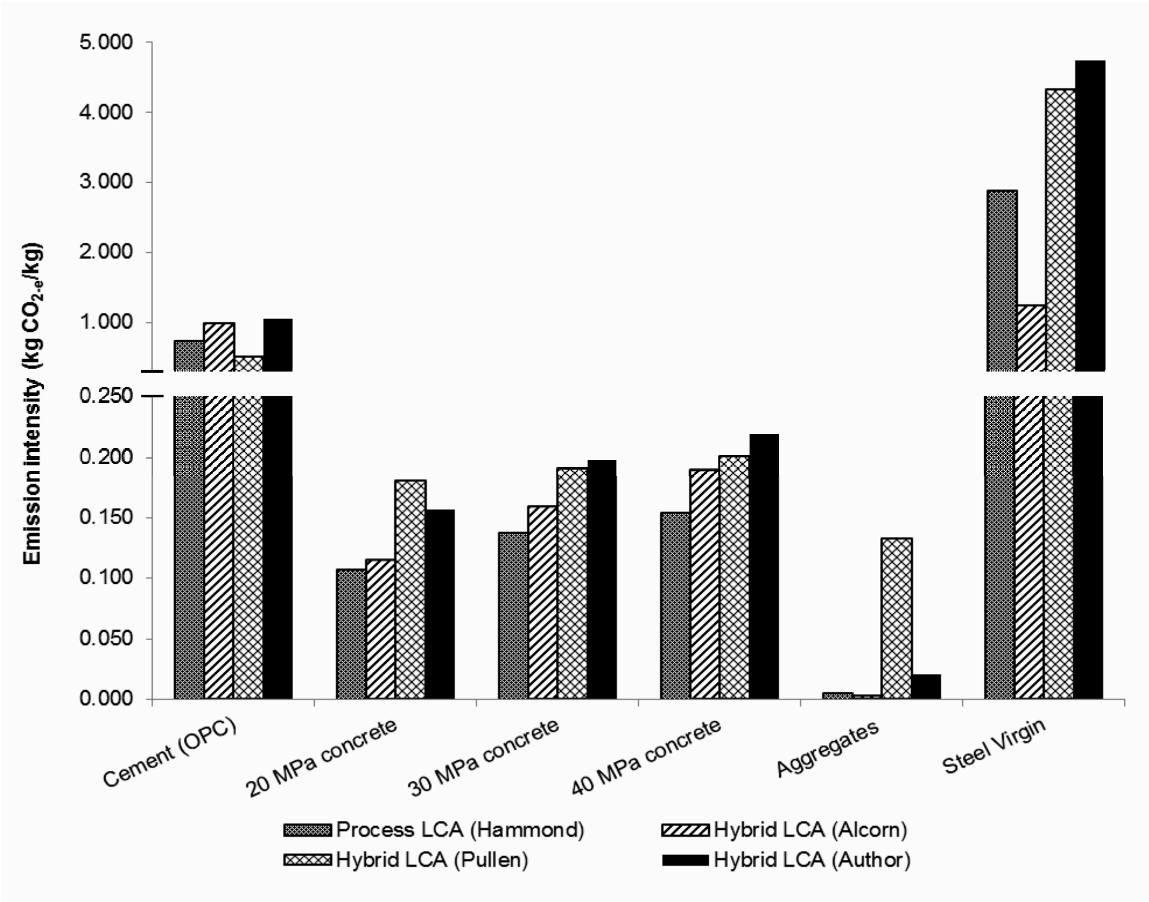


Fig. 3 Comparison of carbon emission intensity for materials using PLCA, I-OLCA, and HLCA

In general, HLCA applied to Malaysia I-O tables seems to be higher for emission intensity materials, accounting for 1.047 kg $CO_{2\text{-}e}$/kg for cement, 0.198 kg $CO_{2\text{-}e}$/kg for 30 MPa concrete grade, and 4.741 kg $CO_{2\text{-}e}$/kg for reinforcement steel respectively. Small gaps of emission intensity for concrete and reinforcement steel between Malaysia and Australia case studies were identified and explained. This gap can be obviously seen in reinforcement steel. The differences between studies were influenced by the variation in parameters used such as primary energy factor (PEF), aggregated I-O sector for selected product, price variation and age of data.

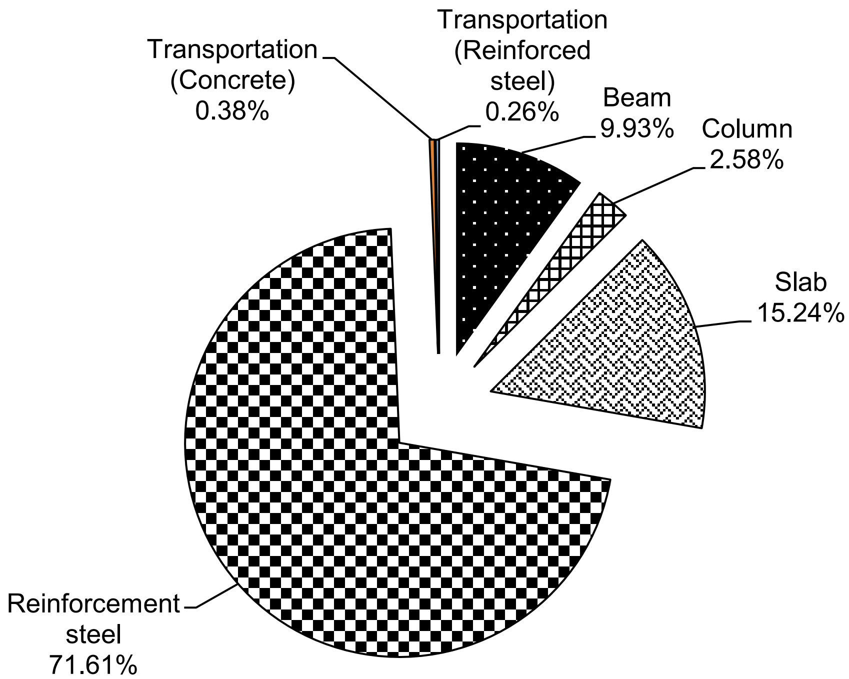
With regards to small variation of PEF based on Malaysian energy balance between 2002 to 2010, the larger gap of emission intensity of materials between Malaysia and New Zealand was due to the smaller PEF used for New Zealand I-O tables as reported by Alcorn (2003). This can be seen in derived electricity PEF for New Zealand which was 1.53, being lower than 4.18 for Malaysia. This in turn significantly influenced the derivation of material emission intensity. For instance, the emission from reinforced concrete products or structures production is largely influenced by emission intensity of reinforcement steel and concrete.

3.3 Evaluation of energy and carbon emission for building production

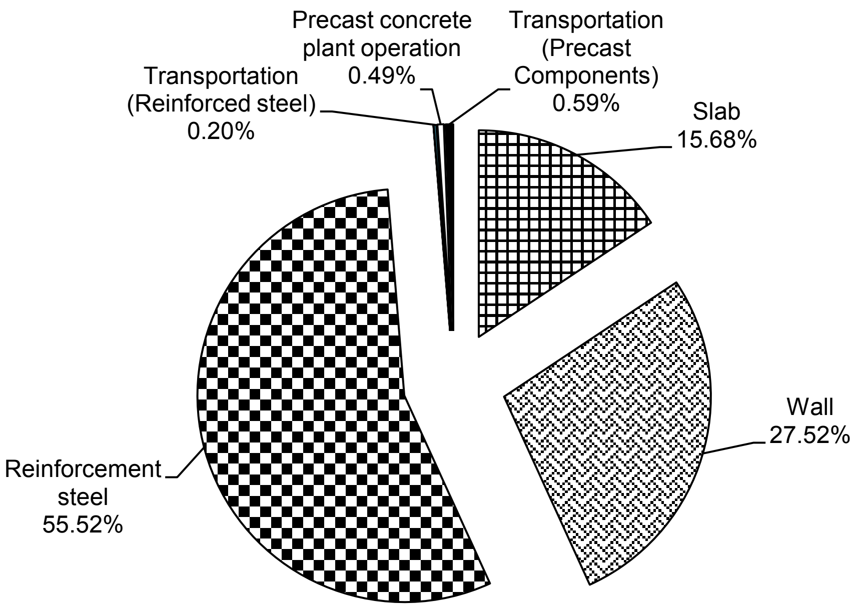
The influence of variation in material emission intensity using different PLCA, I-OLCA, and HLCA methodology in building production is demonstrated in this section. Figures 4(a) and 4(b) show the distribution of emission from material productions, mobile emission and stationary emission (plant operation) in conventional system and IBS system using a precast concrete wall structure. The results show that the materials productions for both systems were a major contribution to total emission of building structure accounting for more than 90% of the total emission. Therefore, the selection of low-emission materials should be part of a national policy making for the material production stage. Peng and Pheng (2011) identified 76% of emission from precast concrete production originated from manufacture of raw material. However, the study was based on PLCA which underestimated the amount of emission. By using HLCA, the significant increases of total emission in precast concrete production were identified.

The reason behind this was that the amount of emission can be measured from upstream process of raw material production.

Using precast concrete wall panel can reduce 16.71% of emission from reinforcement steel production but increase 15% of concrete usage in precast concrete wall production. However, this was compensated by the reduction in reinforcement steel which has high emission intensity compared to other materials. Emission from transportation of reinforcement steel, concrete and precast concrete products was less than 1% of total emission. However, this was based on local transportation and can increase when international transportation was involved in material production (Peng and Pheng 2011). Stationary emission such as plant operation was 0.49% of total emission for precast concrete production which contributed less to emission reduction.



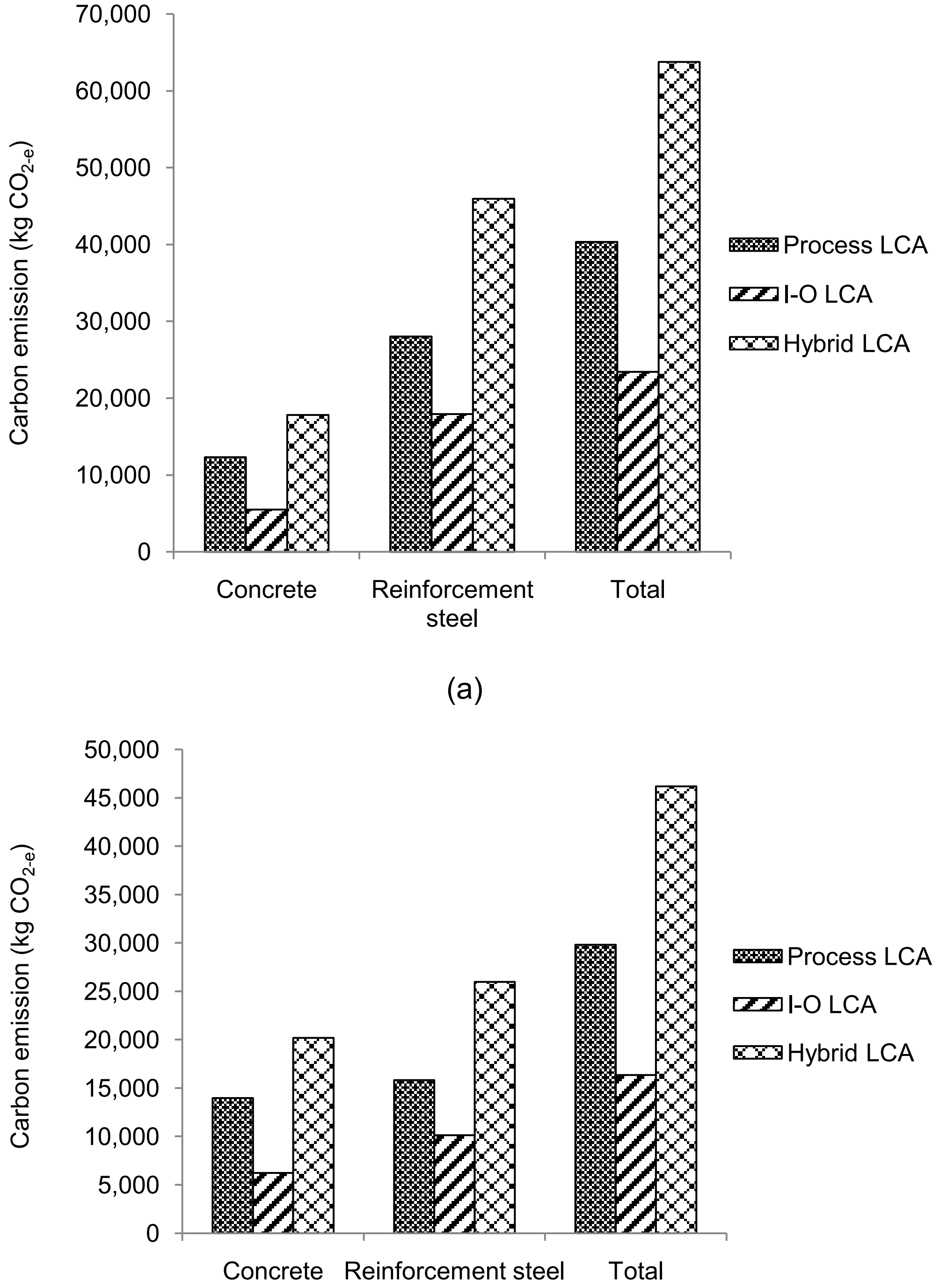
(a)



(b)

Fig. 4 Carbon emission distribution for (a) conventional system and (b) precast concrete wall panel system per floor using HLCA

Figure 5(a) and 5(b) demonstrate the HLCA model capable of increasing up to 40% of emission estimation in reinforcement steel for both building system which draw attention to construction industry in focusing on indirect emission in quantifying impact to environment. About 30% of emission was estimated in upstream process of concrete production for both systems. In addition, cement manufacturing accounts for 70-80% of total emission in ready-mix concrete (Marceau et al. 2007) and 26.1% of total emission for precast concrete production (Peng and Pheng 2011). When making the comparison at the building production level, it was found that using PLCA can underestimate 36.7% of emission for conventional building system and 35.4% of emission for precast concrete structure. Based on HLCA, total emission for conventional and precast concrete production was 63.77 ton $CO_{2\text{-}e}$ and 46.192 ton $CO_{2\text{-}e}$ per floor of building respectively which accounted for 27.09% reduction on total emission by using precast concrete wall panel system.



(b)

Fig. 5 Carbon emission of building system using PLCA, I-OLCA, and HLCA for (a) conventional reinforced concrete frame (b) precast concrete wall panel.

4. CONCLUSIONS

Based on the assessment of embodied emission at the materials, products and building level, a number of conclusions can be drawn. Firstly, by understanding how energy is consumed, designers can significantly reduce environmental impacts by selecting materials with low carbon emissions intensity. In this study, emission inventory for specific materials using HLCA model for Malaysian I-O tables was developed. Both conventional (PLCA) and HLCA were compared with previous studies to identify variability and consistency of parameters used in deriving of material emission intensity. Furthermore, using PLCA can underestimate up to 40% of emissions at material production level. To overcome this weakness, this study developed the HLCA model and demonstrated that up to 30% of emissions for both conventional and precast concrete structure can be quantified in the upstream process of building production. In addition, previous research showed that indirect emissions could be higher than direct emissions for energy intensity materials such as cement and reinforcement steel. This study has empirically demonstrated the application of HLCA model to the material emission intensity and building structure system. Finally, quantifying direct emissions alone could underestimate the amount of carbon emissions and subsequently their impact to the environment. However, indirect emission assessment is a challenging task involving upstream process of construction materials production. Thus, this paper suggests that both indirect and direct emission assessment must be incorporated in evaluating the environmental impact.

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