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The impact of value engineering on embodied greenhouse gas emissions in the built environment: a hybrid life cycle assessment

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Abstract

While traditional value engineering (VE) is primarily driven by cost saving, this study aims to comprehensively and reliably investigating the impact of traditional VE on the embodied greenhouse gas (GHG) emissions in the Australian built environment. An Australian-specific hybrid life cycle assessment (LCA) is developed and applied to a mixed-use building complex located in central

Sydney, Australia. A list of GHG emissions intensities (GEIs) for 118 construction products is derived from hybrid LCA, demonstrating an average increase of 20% than the corresponding process-based GEIs. By applying the hybrid GEIs, the assessment of the case study building proves that traditional VE can potentially provide environmental benefits through the dematerialisation of the building. These benefits are small in this instance, with a capital cost reduction of 0.72% equating to an embodied GHG reduction of 0.32%, or a total of -267 t CO₂e (i.e. -3kg CO₂e/m² gross floor area), but if such savings were rolled out across the entirety of new building stock in Australia, the accumulated GHG emissions reduction would be significant. Concrete, reinforcing steel and timber formwork are the hotspots for cost and embodied GHG emissions reduction. Manufacturing and electricity are the originating industries that jointly contribute to more than 80% of the embodied GHG emissions.

Keywords: value engineering; building; embodied greenhouse gas emissions; capital cost; hybrid life cycle assessment; environmentally-extended input-output analysis.

1 Introduction

Globally, construction projects are responsible for 30-40% of the greenhouse gas (GHG) emissions both directly and indirectly across each life cycle stage of the projects (Crawford 2011; Ibn-Mohammed et al. 2013). While the majority of guidelines and studies focuses on the emissions attributed to the operational energy use, the measurement and mitigation of emissions embodied in the vast quantities of construction materials during the design stage remains uncommon in practice. This is due to the lack of consistent data and the time implication of adding an additional practice in the already time-restricted design process (Ibn-Mohammed et al. 2013). To improve the practicability and efficiency of this practice, value engineering (VE), which is primarily conducted for cost saving, can be utilised to assist the measurement and mitigation of embodied GHG emissions in early stages of projects.

Originating in the manufacturing industry in the 1940s, value engineering (VE) is a systematic approach to increase the ratio between the performance (function) of an entity (defined as a project, product, process, service, system or organization) and the resources required to achieve it (SAVE International 2007; Miles 2015; Standards Australia 2018). Since the 1980s, this approach has been extended to the construction industry for cost reduction, time-saving and/or quality improvement by adopting alternative materials, designs and/or manufacturing techniques (Dell'Isola 1988; Kelly et al. 2015). From VE's point of view, taking embodied GHG emissions into consideration adds a mixture of tangible and intangible costs and benefits to a construction project in both short term and long term, which may alter the actual value of a project (Kibert 2016; Ashworth and Perera 2015). For instance, the efficient use of materials might potentially reduce both embodied GHG emissions (tangible benefit) and capital costs (tangible benefit) (Langston and Langston 2008); however, the use of recyclable materials and/or renewable energy for materials manufacturing might increase project costs (tangible cost) while mitigating embodied GHG emissions (tangible benefit) and improving reputation (intangible benefit) (Gou et al. 2013; Khoshbakht et al. 2017; Hwang and Tan 2012). Therefore, understanding and accurately quantifying the trade-offs between cost and embodied GHG emissions

reductions are important for VE practices to ensure an overall improvement of project value (Oke and Aigbavboa 2017; Robinson 2015; Robati et al. 2018).

A number of studies have attempted to investigate the relationship between costs and embodied GHG emissions of buildings at multiple levels (Ji et al. 2014; Hahn et al. 2010; Kim et al. 2012; Hong et al. 2013; Silvestre et al. 2013; Chou and Yeh 2015; Cabeza et al. 2014; Oregi et al. 2017; Schmidt and Crawford 2018, 2017; Fouche and Crawford 2017; Stephan and Stephan 2016, 2017; Silvestre et al. 2014). For instance, at the building materials level, Park et al. (2013) conducted a study on steel reinforced concrete (SRC) and found that reducing the ratio between steel and concrete could be an effective way to reduce the costs and embodied GHG emissions. At the building components level, Takano et al. (2014) studied structural frames, inner wall components (insulation and sheathing) and surface components (exterior cladding and flooring) of buildings in Finland. They found the material selection for structural frames had a more significant impact on embodied GHG emissions and costs than inner walls and finishes. At the whole building level, Langston and Langston (2008) evaluated the energy embodied in building materials and the capital costs of thirty buildings in Melbourne concluding a strong positive correlation ($r^2 = 0.9542$) between the two. Despite the availability of studies on building costs and embodied GHG emissions, very few relate them to VE practices. This is a missed opportunity as the implementation of VE practices would affect building costs and embodied GHG emissions holistically and simultaneously.

Another research gap identified from the literature concerns the completeness and reliability of GHG emissions quantification. Although life cycle assessment (LCA) is the well-established and widely accepted method to quantify the embodied emissions of construction materials, how life cycle inventory (LCI) analysis is conducted varies across different studies (ISO 2006b; Ortiz et al. 2009). As an integral component of LCA, LCI analysis requires an extensive compilation of data covering all resources and energy consumed as well as all emissions and wastes released along the life cycle stages of a product or project (UNEP/SETAC 2011). Due to the inaccessibility of foreground data and/or limited time and labour, it is common to see studies adopting GHG emissions factors/coefficients/intensities, expressed as kg CO_{2e} per unit of material or energy, directly from a mixture of sources (e.g. environmental product declarations (EPD) (ISO 2006a), the ICE database

(Hammond and Jones 2006), product specification datasheet, etc.) (Takano et al. 2014; Park et al. 2013). This type of treatment compromises the reliability of assessments because the sources and the calculation of underlying LCI data are unclear, and the resulting GHG emissions factors/coefficients/intensities are often outdated and poorly matched up to the study location and scope. For studies which do collect and use project-specific LCI data, the assessments still suffer from a major limitation if they are based on the conventional process-based LCI analysis (Kim et al. 2012; Gu et al. 2008). Using this approach, the collection of all inputs and outputs cannot be exhaustive, especially for processes taking place in the upstream supply chain. This leads to systematic truncation errors, which may underestimate the results by up to 80% (Lenzen 2008a; Suh 2004; Suh et al. 2004; Junnila 2006; Ferrão and Nhambiu 2009; Zhai and Williams 2010; Acquaye et al. 2011; Rowley et al. 2009; Crawford 2008; Ward et al. 2018; Crawford et al. 2018; Stephan et al. 2018; Stephan et al. 2019).

To improve the practicability and efficiency of embodied GHG emissions measurement and mitigation in early stages of projects, this study suggests going beyond conventional VE practices by considering the embodied GHG emissions of a project at the same time. More importantly, the completeness and reliability of the GHG emissions quantification should be enhanced by developing and applying more comprehensive, transparent, up-to-date, and case-specific LCI analysis. A mixed-use building complex located in central Sydney, Australia, was modelled to demonstrate how conventional VE practices in Australia, which were mainly driven by cost saving, could unintentionally alter this building's embodied emissions. An Australian-specific hybrid LCI analysis combining conventional process-based LCA with environmentally-extended input-output analysis (EEIOA) was applied to ensure a reliable and comprehensive assessment. A contribution analysis was conducted to disclose the main emissions and cost hotspots among building elements. Based on that, a decomposition analysis was carried out to investigate the major emitting sources that could be managed by value consultants, construction materials manufacturers and policy makers, respectively. The findings of this study will be of specific interests to these stakeholders helping them to make a concerted effort to reduce both embodied emissions and costs of construction projects without sacrificing project quality.

2 Methods and Data

As set out in the introduction, one of the main contributions of this study was to develop and apply an Australian-specific hybrid LCI database. Since it was the prerequisite for complete and reliable GHG emissions assessment, this part started with the development of the hybrid LCI model (section 2.3) and the calculation of hybrid GHG emissions intensities (section 2.1). Following that, section 0 presented the details of the building complex and explained how to apply those intensities to quantify the embodied GHG emissions before and after VE practices. Finally, the methods employed for contribution analysis and decomposition analysis were described in section 2.4.

2.1 Hybrid life cycle inventory analysis

Life cycle inventory (LCI) analysis is the processing of “compiling and quantifying of inputs and outputs for a product throughout its life cycle (ISO 2006b)”. Since the data collection in conventional process-based LCI analysis was often limited in depth as well as in breadth, this study chose to integrate the environmentally-extended input-output analysis (EEIOA) to broaden and deepen the process-based LCI analysis, forming a hybrid LCI analysis (Crawford et al. 2018). EEIOA is developed from a macroeconomic technique input-output analysis (IOA) that uses inter-industrial monetary transactions to represent the complex interdependences of industries in a modern economy (Miller and Blair 2009). When attaching environmental data to the IOA, the economic interdependences can be translated into environmental interdependences between industries to assess the corresponding environmental impacts associated with each industry in relation to itself and other industries (Foran et al. 2005; Ortiz et al. 2009; Yu et al. 2017; Kitzes 2013). In contrast to process-based LCI analysis, EEIOA is a top-down approach covering all activities as well as the associated environmental impacts taking place within a national economy and beyond. Therefore, adding data from EEIOA to complement the process-based LCI analysis enhances the completeness of the system (Suh and Huppes 2000; Suh et al. 2004; Suh and Huppes 2005; Baboulet and Lenzen 2010; Bontinck et al. 2017; Crawford et al. 2017).

Fig. 1. Graphical representation of hybrid LCI developed in this study, taking the process of producing 1 m³ of 40 MPa concrete as an example;

blank boxes represent inputs from conventional process-based LCI, and yellow boxes represent inputs from EEIOA.

Fig. 1 takes the process of producing 1 m³ of 40 MPa concrete as an example to demonstrate how hybrid LCI analysis provides a more comprehensive assessment. Blank boxes represent inputs that are typically compiled by process-based LCI analysis and yellow boxes represent inputs from EEIOA. By and large, the documentation of final stage inputs is supposed to be complete and certain, but the inevitability of cut-offs in process-based LCA excludes some physical products (e.g. stone) as well as intangible services (e.g. property operator service, wholesaling service, etc.). As we move further up the supply chain, more and more inputs are left out by process-based LCI analysis and are filled using data from EEIOA. Apart from generating more comprehensive results, the system completeness of hybrid LCI analysis ensures the contribution and decomposition analysis are more reliable as no relevant processes are omitted.

2.2 Hybrid GHG emissions intensities of construction materials

An Australian-specific hybrid LCI analysis was conducted focusing on the GHG emissions intensities of a range of commonly used construction materials (expressed as kg CO₂e per unit of material, meaning the GHG emissions embodied in a material starting from the extraction of raw materials from the ground, transportation, refining, processing, to the ready-to-use final product). This study utilised the approach described in a previous hybrid LCI analysis that combined a process coefficient matrix, an EEIO coefficient matrix and an upstream cut-off matrix in a hybrid table of dimensions 8315 x 8315 (Yu and Wiedmann 2018). The Australian National Life Cycle Inventory Database (AusLCI) (<http://www.auslci.com.au>) (Grant 2015) was adopted and formulated as the process coefficient matrix showing all inputs and outputs associated with the production of one unit of product/process in physical units, extended at the bottom of each column with GHG emissions data. This matrix was connected with the latest and most detailed Australian EEIO coefficient matrix through the upstream cut-off matrix. The EEIO coefficient matrix represented input requirements of various industries as well as the associated direct GHG emissions for producing one monetary unit of product/service of those industries. Initially, the EEIO coefficient matrix for the accounting year of 2008/09 was derived from the Australian Industrial Ecology Virtual Laboratory (IELab, <http://ielab.info>) (Lenzen et al. 2014; Lenzen et al. 2017). A RAS iterative scaling technique referring

to Lenzen et al. (2009) was conducted subsequently to update the matrix from 2008/09 to 2014/15 to enable an up-to-date assessment. Input-output tables of 2008/09 and 2014/15 from the Australian Bureau of Statistics (ABS 2012, 2017) and the national GHG Inventory from the Australian Greenhouse Emissions Information System (AGEIS) for the year of 2015 (AGEIS 2018) were used for the update. As for the upstream cut-off matrix, which represented the inputs from the EEIO system that were missing in the AusLCI system, this study chose the lower double-counting correction scenario developed by Yu and Wiedmann (2018) to deliver a conservative, yet realistic assessment. Once the hybrid LCI matrix was complete, the hybrid GHG emissions intensities of 118 commonly used construction materials were calculated using Equation (1) of Yu and Wiedmann (2018). By turning the upstream cut-off matrix off, the corresponding process-based GHG emissions intensities were generated as well to determine the discrepancies of results caused by applying different LCI methods.

2.3 Building characteristics and value engineering techniques

The building complex under study was a mixed-use building, accommodating offices, shops and residential units (Fig. 2 and Table 1).

Fig. 2. Central Sydney building complex investigated in this study.

193

Table 1 Case study building details.

Parameter	Unit	Block 1	Block 2
Ground floor dimensions	m	41.0 × 32.8	23.26 × 20.93
Average floor-to-floor height	m	3.41	3.25
Number of floors above the ground level	-	18	20
Total height above the ground level	m	64.89	68.30
Number of floors below the ground level (basement)	-	5	5
Gross floor area (both above and below the ground level)	m ²	43,229	41,228

194

195 During the design phase of the project, 189 value engineering (VE) items were approved to change
 196 the design and material specification with the primary aim being to reduce capital costs (Fig. 3). In
 197 this study, only changes in external finishes (22% of all items), internal finishes and fittings (19%),
 198 and substructure and superstructure (14%) were considered as these were explicitly itemised with
 199 material magnitudes on the bills of quantity. Table 2 summarised the main VE items for these
 200 components.

BMS: Building Management System | BAS: Building Automation System
 | EMS: Energy Management System | IHD: In-Home Display

201

202 Fig. 3. Proportion of value engineering items applied to the case study building and considered in this
 203 study.

204

Table 2 Primary value engineering items applied to the case study building.

Building component	Value engineering item	Potential impact on capital cost*	Potential impact on GHG emissions*
Substructure and superstructure	• Adapt the structural design to accommodate lighter façade loads	Medium	High
	• Substitute the non-load bearing concrete walls to rationalise structural design of the building	High	High
	• Increase mesh or post tensioning for exposed slabs to meet crack control requirements	Medium	High
External finishes	• Adjust the external cladding system to comply with Green Star aspiration requirements	High	High
	• Replace concrete pavers to roofs with ballast materials	Low	High
	• Replace sandstone blocks with a concrete finish	High	Low
Internal finishes and fittings	• Adjust the basement blockwork details to rationalise blockwork extents	Low	Low
	• Expand the use of non-load bearing walls	Medium	Low
	• Adjust all metalwork to rationalise combined block 1 and block 2 basement	Medium	Low
	• Replace timber wall panels with a plasterboard finish	Medium	Medium
	• Replace hard floor finishes with carpet for Block 2	High	Low
	• Replace solid timber with a tiled finish for balcony areas	High	High
	• Adjust internal glazing for the modified suites in the Block 1	High	High
	• Replace mirrored screens in showers with tiles	High	High

205

* Low: less than 5%; Medium: between 5 to 10%; High: more than 10%

The implementation of these VE items will bring about a change in building materials, which will eventually change the capital cost of the building and the GHG emissions embodied in building materials which are generated from A1-A3 stages (as defined by BSI (2011)) of the building life cycle. To quantify these changes, the amount of building materials used before and after VE was quantified with assistance from the project contractor and categorised into 46 building elements (Appendix A). Multiplying the change of each building element by the corresponding cost (Rawlinsons 2017), the impacts of current VE practices on the capital cost could be obtained. Similarly, multiplying the change of each building element by the corresponding GHG emissions intensities (calculated in this study in Section 3.1), the impacts of current VE practices on the embodied emissions of the building could be obtained.

2.4 Contribution analysis and decomposition analysis

Along with an assessment of the embodied GHG emissions impact of VE practices, this study also disaggregated the embodied GHG emissions of the building to reveal those building components and elements that contributed the most. This is useful for building professionals to understand the main emissions and cost hotspots of the project. Based on that, the hybrid GHG emissions intensities of main contributing building materials were decomposed by their final-stage inputs according to Teh and Wiedmann (2018). With that, the corresponding materials manufactures can effectively manage their first-tier suppliers to reduce their GHG emissions. Finally, following Teh and Wiedmann (2018) again, the embodied GHG emissions of the building were decomposed by origins to track down the ultimate emitting industries that were associated with the building's embodied GHG emissions. Since these industries are making contributions along various tiers of the supply chain, it is the policy makers and industries who can make use of this information to reduce the GHG emissions from original sources.

3 Results and Discussion

3.1 Hybrid versus process-based GHG emissions intensities

Before assessing the embodied GHG emissions implications of current VE practices used in the Australian built environment, the Australian-specific GHG emissions intensities (GEIs) of 118 construction materials were calculated (full list in Appendix B). Fig. 4 shows that the process-based GEIs are 3% to 59% lower than their corresponding hybrid GEIs and the average truncation error among these construction products is about 20%. This is in agreement with previous studies that found truncation errors usually ranging from 10% to 50% (Bullard et al. 1978; Lenzen 2008b; Crawford 2008; Lenzen 2008a). It also implies that conventional process-based LCA would underestimate the GHG emissions embodied in buildings by about 20%. The most significant differences occur when the process-based LCI data are too few to represent the complete product inputs and/or the upstream GHG emissions added by the complementary EEIO system play a much more important role. For these 118 construction products, the main EEIO inputs are from various service industries which are not easily quantifiable in process-based LCI analysis, including 'Rental, Hiring and Real Estate Services (21%)', 'Wholesale Trade (15%)', 'Professional, Scientific and Technical Services (11%)' and 'Transport, Postal and Warehousing (10%)'.

3.2 GHG emissions implications of current value engineering practises

Based on the bill of quantities before and after VE, this section analysed how and to what extent the design changes impacted the embodied GHG emissions and capital cost. Out of 46 building elements, only 28 are actually altered by the VE processes, as shown in Fig. 5. These VE processes decrease the cost of 11 building elements while increasing the rest, leading to a total capital cost saving of 397,000 AUD. Similar to the finding from Langston and Langston (2008), a change in cost is accompanied by a change in embodied GHG emissions in the same direction, i.e. if costs are reduced, so are embodied GHG emissions and vice versa. However, since the degree of change is different between cost and embodied GHG for each building element, the ones showing considerable changes in cost do not

Fig. 4. Hybrid GHG emissions intensities (GEIs) of 118 construction products, relative to their corresponding process-based GEIs.

necessarily relate to significant changes in embodied emissions. For instance, for external stone cladding and timber flooring, the cost reductions are substantial, yet there are practically no savings in embodied GHG emissions. Another major finding is that the application of hybrid LCI analysis gives rise to more significant changes in embodied GHG emissions when moving from the non-VE to the post-VE scenario. More specifically, the changes observed from process-based analysis are lower than their corresponding changes obtained from hybrid analysis by 3% to 47%, due to the systematic truncation. At the building elements level, the largest discrepancies are associated with 'Plasterboard suspended ceilings (47%)', 'Framed and lined plaster partitions (41%)', 'Mirrors and glazing (36%)', 'Paint (30%)' and 'Internal waterproofing (28%)', which is in conformity with the findings from section 3.1.

Fig. 5. Embodied GHG emissions and cost changes to building elements through value engineering.

By aggregating all building elements into their corresponding building components, the effects of VE on embodied GHG emissions and cost of superstructure, external finishes, internal finishes, fitting elements and external works were analysed (Fig. 6). For the superstructure, less use of concrete, steel reinforcement and timber formwork contribute to both embodied GHG emissions reduction and cost

reduction, which plays the decisive role in the overall changes of embodied GHG emissions and cost at the building level. For external finishes, different materials used for the roof, the Alpolic canopy in particular, leads to increased embodied GHG emissions, but since the saving in external stone cladding results in a large cost reduction, the overall cost for external finishes is decreased through VE. This indicates, at the building components level, cost reduction does not always bring about embodied emissions reduction. For internal finishes, lengthened internal walls increases both cost and embodied GHG emissions. Interestingly, for fitting elements, process-based analysis and hybrid analysis give different findings. By replacing internal glazing and hardwood timber floors with tiles, the cost of fitting elements is reduced, but process-based LCA suggests an increase in embodied emissions whereas hybrid LCA shows the opposite. This implies that hybrid LCA not only generates more comprehensive results, it may also lead to different conclusions, thereby influencing decision making.

Fig. 6. Embodied GHG emissions and cost changes to building components through value engineering.

Fig. 7. Embodied GHG emissions and cost of the building before and after value engineering.

As a result of the changes made to all building elements through VE, the capital cost of the building is decreased by 397,000 AUD (from \$55,026,000 to \$54,629,000, an overall reduction of 0.72%). Meanwhile, the process-based LCA suggests a reduction of embodied GHG emissions by 0.30% from 71,010 t CO₂e to 70,796 t CO₂e (from 841 kg CO₂e/m² to 838 kg CO₂e/m²), and the hybrid LCA concludes an embodied GHG emissions reduction by 0.32% from 82,212 t CO₂e to 81,945 t CO₂e (from 973 kg CO₂e/m² to 970 kg CO₂e/m²) (Fig. 7). This trend confirms the potential positive impact of conventional VE techniques in reducing building materials and reducing embodied GHG emissions. However, the overall emissions savings are small, providing an opportunity for an optimised VE procedure that places a stronger emphasis on reducing the GHG emissions of buildings concurrently with cost. Apart from the impacts assessed at the building level, Fig. 7 also illustrates the contributions from the six building components before and after VE. The result indicates superstructure is the dominating contributor to both embodied GHG emissions and cost of multi-storey buildings (as per previous research – see Oldfield (2012)), although again, the portions taken up by buildings components vary between process-based analysis and hybrid analysis. Therefore, there is a significant opportunity to optimise structures to reduce materials and to reduce embodied GHG emissions and cost simultaneously.

3.3 GHG emissions and cost hotspots across the building elements

From a value engineer's perspective, understanding the hotspots that have significant impacts on both embodied GHG emissions and cost is crucial so that the VE procedure can be optimised to increase the project value. Fig. 8 presents these hotspots for the case study project. Excluding the elements whose contributions are less than 5% to either embodied emissions or cost, 40MPa concrete, reinforcing steel and timber formwork are the three dominating elements. Cementitious topping is explicitly displayed as well because it is contributing to nearly 30% of embodied GHG emissions, but the cost of it is negligible.

Fig. 8. Embodied GHG emissions and cost hotspots across all building elements after value engineering.

With the hotspots being identified, not only can value engineers target these building elements to effectively increase the project value, manufacturers of these building materials should be encouraged as well to produce lower GHG emissions intensive materials, which will ultimately help improve the project value from the outset. This section decomposed the GHG emissions embodied in 40MPa concrete, reinforcing steel and external plywood by their final stage inputs, which could inform

manufacturers of the main inputs with high embodied GHG emissions so that efforts can be made to reduce GHG emissions in these areas.

The decomposition analysis of 40 MPa concrete by final-stage inputs suggests its embodied GHG emissions are primarily associated with ordinary Portland cement (Fig. 9). Compared to the decomposition of process-based analysis, hybrid analysis has increased the embodied emissions of all inputs. In addition, services inputs (not covered by process-based analysis) like ‘rental, hiring and real estate services’ and ‘accommodation and food services’ represent a noticeable share in hybrid analysis. In order for concrete manufacturers to reduce the embodied GHG emissions of 40 MPa concrete, adopting fly ash or ground granulated blast furnace slag blended cement could be considered, which can potentially bring about a reduction of 25% and 16%, respectively. A more ambitious alternative is to take on geopolymer concrete whose embodied GHG emissions is 42% lower than ordinary Portland cement concrete’s (Turner and Collins 2013). Similarly, the GHG emissions embodied in the final-stage inputs of external plywood and reinforcing steel are shown in Fig. 10 and Fig. 11, respectively. Again, hybrid analysis provides a more comprehensive result that slightly alters the share of each input. For external plywood, both decompositions prove the significant contributions from electricity, melamine formaldehyde resin and round wood. But beyond that, hybrid analysis has been able to capture various services inputs (‘rental, hiring and real estate services’ and ‘wholesale trade’ in particular), which are included in “Others” in the figure. From this decomposition, plywood manufacturers are suggested to use round wood and melamine formaldehyde resin more efficiently, besides which the uptake of cleaner electricity would be helpful as well. As for the embodied GHG emissions decomposition of reinforcing steel, the contribution from blast oxygen furnace (BOF) fabricated steel is three times larger than that from the electric arc furnace (EAF) fabricated steel. Since EAF steel’s GHG emissions intensity is only about half of BOF steel’s (Teh et al. 2018), increasing the ratio between EAF steel and BOF steel would lower the embodied GHG emissions of reinforcing steel.

Fig. 9. GHG emissions intensity decomposition of 40 MPa concrete by final-stage inputs; There are 35 final-stage inputs in total, but 29 of them are contributing less than 1% individually, therefore they are aggregated into “Others” in the graph for clearer demonstration.

Fig. 10. GHG emissions intensity decomposition of external plywood by final-stage inputs; There are 26 final-stage inputs in total, but 20 of them are contributing less than 1% individually, therefore they are aggregated into “Others” in the graph for clearer demonstration.

Fig. 11. GHG emissions intensity decomposition of reinforcing steel by final-stage inputs; There are 20 final-stage inputs in total, but 15 of them are contributing less than 1% individually, therefore they are aggregated into “Others” in the graph for clearer demonstration.

3.4 Embodied GHG emissions decomposition by origins

As the second largest industry in Australia by the GDP share, the construction industry is responsible for nearly one fifth of Australia’s GHG emissions, of which construction materials represent one fifth (Yu et al. 2017). Comparing the embodied GHG emissions per square metre of the case study building with the results for other buildings, it is found that this building’s embodied emissions falls towards the higher end (Fig. 12) (Moussavi Nadoushani and Akbarnezhad 2015; De Wolf et al. 2017; Gan et al. 2017; eTool 2014; Robati et al. 2018; MPA 2016; BCO 2012; RICS 2012). Although these embodied emissions assessments are not absolutely comparable due to the use of different methods, the differentiated quality of data and the different definitions of system boundary (Langston and Langston 2008; Dixit et al. 2010; Huang et al. 2010; Crawford 2014), amongst other factors, it still indicates a need for embodied emissions reduction for this building.

Fig. 12. Embodied GHG emissions of buildings per m² across different studies.

In addition to value engineers and building products manufacturers who can influence consumer side and intermediate demand side GHG emissions reduction, policy makers are critical for mitigating GHG emissions at its origins. Fig. 13 informs this policy focus by identifying the most influential emitting sources. Again, embodied GHG emissions of the whole building quantified by hybrid LCA is larger than the process-based results by 17.4% thanks to a more complete system coverage and the inclusion of service inputs. The use of different approaches also changes embodied GHG emissions distribution among emitting industries, especially for ‘agriculture, forestry and fishing’, ‘mining’ and ‘transport, postal and warehousing’. For instance, in process-based analysis, the ‘agriculture, forestry and fishing’ industry is only responsible for 1.2% of the embodied GHG emissions, while in hybrid analysis, this industry’s responsibility is raised to 3.2%, which means an absolute increase of GHG emissions by 208% from this industry. In spite of the differences between these two types of analysis, it is the ‘manufacturing’ and ‘electricity, gas, water and waste services’ that jointly contribute to more than 80% of the GHG emissions. In fact, construction industry itself only plays a marginal role. Therefore, decisions and policies made to lower the GHG emissions from manufacturing and electricity industries would indirectly benefit the construction industry and reduce building level embodied GHG emissions.

Fig. 13. Embodied GHG emissions decomposition of the case study building by originating industry.

4 Conclusion

While research on the embodied GHG emissions of buildings is growing, their calculation in practice, during the design and realisation of a building, remains uncommon (Ibn-Mohammed et al. 2013). This is due to the lack of consistent data and the time implication of adding an additional practice in the already time-restricted design process. This study suggested using value engineering practices in the construction industry as an ideal framework to allow for the determination and reduction of embodied GHG emissions. Value engineering is a mature, common, and mandatory practice for all New South Wales (NSW) government projects with a value exceeding AUD \$5million (Daddow and Skitmore 2005). It requires detailed bills of quantities, outlining material specifications and magnitudes, which are primarily used to determine the materials cost of buildings, but can also be used to determine embodied GHG emissions as long as the emissions intensities of materials are available. Different from the existing GHG emissions intensities which are either collected from various sources or derived from process-based LCI analysis, this study developed a list of hybrid GHG emissions intensities (GEIs) for 118 construction materials (Appendix B). This enabled a more comprehensive and reliable assessment because the system coverages are complete, and the source data are transparent, up-to-date and Australian specific. On average, the conventional process-based GEIs are 20% lower than their corresponding hybrid GEIs, implying process-based analysis would underestimate the GHG emissions embodied in buildings by approximately 20%. This gap is mainly attributed to the exclusion of services inputs from process-based LCI analysis, such as “rental, hiring

and real estate services”, “wholesale trade”, “professional, scientific and technical services” and “transport, postal and warehousing”. In addition, hybrid LCA may draw different conclusions from process-based LCA depending on the specific components being analysed.

The case study outlined in this paper demonstrated that traditional VE, driven by cost factors alone, can potentially provide environmental benefits through the dematerialization of the building, although the building elements showing considerable cost reductions do not necessarily relate to the significant reductions in embodied GHG emissions. These benefits are small in this instance, with a capital cost reduction of 0.72% equating to an embodied GHG reduction of 0.32%, or a total of -267 t CO₂e (i.e. -3kg CO₂e/m² GFA), but if such savings were rolled out across the entirety of new building stock in Australia, the accumulated GHG emissions reduction would be significant. Furthermore, if design and material changes were driven by targets to reduce cost and embodied GHG emissions simultaneously, research suggests more significant emissions savings could be made. For example, Foraboschi et al. (2014) found that optimising a multi-storey building’s floor structure could reduce structural embodied energy by up to 43%.

This study also explored the cost and embodied emissions hotspots of the case study building, which suggested value engineers and building materials manufacturers to focus on concrete, reinforcing steel and timber formwork. For policy makers, this study informed that it is the ‘manufacturing’ and ‘electricity, gas, water and waste services’ industries that jointly contribute to more than 80% of the embodied GHG emissions, implying decisions and policies made to lower the GHG emissions from these two industries would indirectly benefit the construction industry.

Value engineering is often criticized in the industry, as it is perceived to be making a building cheaper, and as such, removing items of value – potentially items that assist in improving energy efficiency, and reducing operational GHG emissions, such as shading systems, high performance glazing, or energy generation technologies. In this case study, none of the value engineering changes impacted the building fabric, so no changes in operational GHG emissions were anticipated. However, in other circumstances, changes to building materials and systems may need to be considered across a broader scope than cradle-to-gate, to determine if material reductions equate with holistic emissions savings across a building’s full life cycle.

Declarations

1. Abbreviations (in alphabetic order)

ABS: Australian Bureau of Statistics; AGEIS: Australian Greenhouse Emissions Information System; AusLCI: Australian National Life Cycle Inventory Database; BAS: Building Automation System; IELab: Industrial Ecology Virtual Laboratory; BMS: Building Management System; BoQ: Bills of Quantities; CO₂e: Carbon Dioxide Equivalent; CFIs: Carbon Footprint Intensities; EEIOA: Environmentally Extended Input Output Analysis; EMS: Energy Management System; EPD: Environmental Product Declaration; GFA: Gross Floor Area; GHG: Greenhouse Gas; IHD: In Home Display; LCA: Life Cycle Assessment; LCI: Life Cycle Inventory; SRC: Steel Reinforced Concrete; VE: Value Engineering.

2. Declarations of interest

None.

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668 Appendix A

669 Table A1 Bills of quantities (BoQ), cost, process GEIs and hybrid GEIs of 46 building elements.

Building Components	Building Elements	Quantity		Unit	Cost	Process GEIs	Hybrid GEIs
		before VE	after VE		(AUD per unit)	(kg CO ₂ e per unit)	(kg CO ₂ e per unit)
Substructure	50MPa Concrete	92	92	m ³	250	628.04	697.86
	Reinforcing steel	11	11	t	2405	1628.60	2008.40
Superstructure	Timber formwork	214660	214146	m ²	39	24.05	31.46
	32MPa Concrete	2009	2649	m ³	230	412.06	466.59
	40MPa Concrete	25550	24795	m ³	240	496.12	555.53
	50MPa Concrete	3324	2656	m ³	250	628.04	697.86
	65MPa Concrete	6408	5923	m ³	260	797.69	858.88
	Reinforcing steel	4897	4869	t	2405	1628.60	2008.40
	Post tensioning steel	530	530	t	7062	1628.60	2008.40
	Steel formwork	316	341	t	1275	4937.86	5691.12
	Precast concrete planters	353	353	m ³	230	310.00	337.04
	Precast concrete facade	354	354	m ³	230	310.00	337.04
External finishes	Glazed Façade - Block 1	18398	18398	m ²	222	85.00	132.48
	Glazed Façade - Block 2	15041	15041	m ²	222	85.00	132.48
	External aluminium and glass reinforced concrete cladding	11426	11525	m ²	13	450.85	524.01

	External stone cladding	265	17	m ²	130	0.69	0.79
	External timber cladding	6	6	m ³	1556	400.05	706.49
	Roof concrete pavers	649	649	m ²	33	12.78	16.64
	Ballasted roof and waterproofing	1894	3788	m ²	5	1.16	1.34
	Ballasted roof and waterproofing	324	648	m ²	18	0.51	0.71
	Roof Alpolic canopy	4152	6361	m ²	26	245.46	265.57
	Roof composit cement fiber	493	986	m ²	40	11.45	15.16
Internal finishes	Blockwork and brickwork	10059	10032	m ²	128	3.06	3.91
	Acoustic and thermal insulation	20687	20780	m ²	7	15.30	16.77
	Plasterboard suspended ceilings	50775	52096	m ²	11	4.93	9.35
	Cement fiber suspended ceilings	112	112	m ²	12	7.84	9.09
	Mineral tiles suspended ceilings	3763	3763	m ²	14	19.22	23.34
	Veneer timber suspended ceilings	459	549	m ²	6	8.93	11.03
	Framed and lined plaster partitions	85379	87714	m ²	3	1.23	2.08
	Framed and lined AAC wall partitions	35538	36194	m ²	4	40.30	43.82
	Plastering and rendering	1667	1667	m ²	8	0.26	0.37
	Internal waterproofing	38720	38644	m ²	18	0.51	0.71
	Cementitious topping	15857	15857	m ³	6	1261.13	1326.38
	Paint	192839	193224	m ²	18	0.26	0.37
	Resilient finishes	1403	1538	m ²	19	30.41	36.18
Fitting elements	Screens	4216	4216	m	104	18.18	26.64
	Aluminium frame	5025	5025	m ²	13	124.60	165.00
	Timber frame	8417	8417	m ²	23	69.55	108.04
	General galvanised metalwork	5436	5436	m ²	35	10.60	12.14
	Shower screens metalwork	1553	1553	m ²	19	22.35	25.83
	Balustrades and handrails metalwork	3017	3044	m	204	9.93	11.44
	Carpet flooring	29821	29897	m ²	66	11.28	11.59
	Timber flooring	11684	10027	m ²	120	8.93	11.03
	Tiling	35760	42274	m ²	48	19.22	23.34
	Mirrors and glazing	2992	1752	m ²	104	85.00	132.48
External works	External waterproofing	7610	7497	m ²	18	39.96	48.29

Appendix B

Table B1 Process GEIs and hybrid GEIs of 118 construction products.

ID	Product (unit)	process GEIs (kg CO ₂ e per unit)	hybrid GEIs (kg CO ₂ e per unit)	ID	Product (unit)	process GEIs (kg CO ₂ e per unit)	hybrid GEIs (kg CO ₂ e per unit)
1	Adhesive mortar (kg)	1.3538	1.7772	60	Glazing, double (2-IV), U<1.1 W/m ² K (m ²)	54.708	88.088
2	Alkyd paint, 60% in H ₂ O (kg)	2.9617	4.1785	61	Glazing, triple (3-IV), U<0.5 W/m ² K (m ²)	74.149	105.49
3	Alkyd paint, 60% in solvent (kg)	3.2103	4.5738	62	Glued laminated timber, indoor use (m ³)	379.29	679.5
4	Aluminium alloy (kg)	8.3014	9.1377	63	Glued laminated timber, outdoor use (m ³)	400.05	706.49
5	Aluminium product manufacturing (kg)	5.3373	5.8146	64	Gravel, crushed (kg)	0.012935	0.014891
6	Aluminium, production mix (kg)	14.187	15.356	65	Gypsum fibre board (kg)	0.34451	0.7065
7	Anhydrite floor (kg)	0.079206	0.12301	66	Gypsum plaster board (kg)	0.43158	0.52334
8	Autoclaved aerated concrete block (kg)	0.47692	0.51853	67	Hardwood sawlog (m ³)	138.25	196.98
9	Bitumen sealing (kg)	1.2525	1.5076	68	Hardwood timber production (m ³)	75.545	106.21
10	Bitumen (kg)	0.69121	0.80798	69	Hardwood veneer log (m ³)	211.53	296.77
11	Blast furnace slag cement (kg)	0.58692	0.66521	70	Hot impact extrusion, steel (kg)	2.2227	2.4617
12	Brass (kg)	3.4432	4.7487	71	Hot rolling, steel(kg)	0.34559	0.38424
13	Brick (kg)	0.25268	0.30157	72	Lead, primary(kg)	2.411	2.9134
14	Bronze (kg)	3.6865	5.3441	73	Light clay brick (kg)	0.15289	0.19571
15	Cement cast plaster floor (kg)	0.19937	0.22219	74	Light mortar (kg)	0.53892	0.63884
16	Cement mortar (kg)	0.24044	0.27325	75	Lightweight concrete block, expanded clay (kg)	0.44791	0.6144
17	Ceramic tiles (kg)	0.9608	1.1672	76	Lime mortar (kg)	0.69557	0.8478
18	Chromium steel (kg)	4.819	5.5849	77	Limestone (kg)	0.0020256	0.0049134
19	Chromium steel product manufacturing (kg)	3.2107	3.5965	78	Mastic asphalt (kg)	0.2534	0.30146
20	Cladding, crossbar- pole, aluminium (kg)	205.39	258.44	79	Natural rubber based sealing (kg)	2.3083	3.2216
21	Clay plaster (kg)	0.045707	0.077184	80	Nylon 66 (kg)	8.2922	8.5256
22	Clinker (kg)	0.98198	1.0084	81	Ordinary portland cement (kg)	1.0089	1.0611
23	Cold impact extrusion, aluminium (kg)	2.7214	3.0105	82	Oriented strand board (m ³)	433.54	653.95
24	Cold impact extrusion, steel (kg)	1.5249	1.6746	83	Packaging film, LDPE (kg)	3.136	3.7826
25	Concrete 20 MPa 30% fly ash (m ³)	236.38	280.77	84	Packaging, corrugated board, mixed fibre, single wall (kg)	1.6149	2.5114
26	Concrete 20 MPa 30% GGBFS(m ³)	257.93	310.91	85	Particle board, indoor use (m ³)	336.97	464.64
27	Concrete 20 MPa(m ³)	320.52	368.58	86	Particle board, outdoor use (m ³)	438.33	574.48
28	Concrete 25 MPa 30% fly ash (m ³)	266.54	313.97	87	plasterboard 10 mm (m ²)	4.9275	9.3537
29	Concrete 25 MPa 30% GGBFS (m ³)	290.45	347.42	88	Plywood, indoor use (m ³)	1040.9	1367.8
30	Concrete 25 MPa (m ³)	358.56	410	89	Plywood, outdoor use (m ³)	1202.5	1572.9
31	Concrete 32 MPa 30% fly ash (m ³)	304.17	353.98	90	Polybutadiene (kg)	4.0023	4.2033
32	Concrete 32 MPa 30% GGBFS (m ³)	331.86	392.71	91	Polyethylene, HDPE, granulate (kg)	2.009	2.1205
33	Concrete 32 MPa (m ³)	412.06	466.59	92	Polyethylene, LDPE, granulate (kg)	2.1898	2.3838

34	Concrete 40 MPa 30% fly ash (m3)	364.57	418.26	93	Polyethylene, LLDPE, granulate (kg)	1.9279	2.1217
35	Concrete 40 MPa 30% GGBFS (m3)	398.55	465.77	94	Polypropylene (kg)	2.2743	2.5041
36	Concrete 40 MPa (m3)	496.12	555.53	95	Polystyrene foam slab (kg)	4.7814	5.2419
37	Concrete 50 MPa 30% fly ash (m3)	463.97	526.67	96	Polyurethane, rigid foam (kg)	4.7294	5.2219
38	Concrete 50 MPa 30% GGBFS (m3)	506.31	585.87	97	Polyvinylchloride (kg)	2.0376	2.4628
39	Concrete 50 MPa (m3)	628.04	697.86	98	Reinforcing steel (kg)	1.6286	2.0084
40	Concrete block (kg)	0.16549	0.2199	99	Rock wool (kg)	1.3697	1.5699
41	Concrete roof tile (kg)	0.24115	0.31392	100	Roof tile (kg)	0.38792	0.45341
42	Copper (kg)	4.0392	5.386	101	Sand (kg)	0.0050035	0.0061866
43	Cork slab (kg)	1.7472	2.9926	102	Sanitary ceramics (kg)	2.7081	3.6053
44	Corrugated board, mixed fibre, single wall (kg)	1.1656	1.6625	103	Sawn timber, paran pine (SFM), kiln dried, u=15% (m3)	687.25	848.62
45	Corrugated board, recycling fibre, single wall (kg)	1.0436	1.4991	104	Section bar extrusion, aluminium (kg)	1.694	1.8305
46	Door, inner, glass-wood (m2)	69.547	108.04	105	Section bar rolling, steel (kg)	0.24134	0.2619
47	Door, inner, wood (m2)	55.168	83.593	106	Sheet rolling, aluminium (kg)	0.96497	1.0371
48	Door, outer, wood-aluminium (m2)	124.6	165	107	Sheet rolling, chromium steel (kg)	0.81874	0.91028
49	Door, outer, wood-glass (m2)	122.55	168.23	108	Sheet rolling, copper (kg)	0.48057	0.55976
50	Extrusion, plastic film (kg)	0.85846	0.94016	109	Sheet rolling, steel (kg)	0.46876	0.52582
51	Extrusion, plastic pipes (kg)	0.63465	0.69664	110	Softwood timber production (m3)	28.684	44.425
52	Fibre cement corrugated slab (kg)	1.0688	1.1824	111	Steel, low-alloyed (kg)	1.9171	2.3118
53	Fibre cement facing tile (kg)	1.4418	1.7333	112	Stucco (kg)	0.095633	0.11582
54	Fibre cement roof slate (kg)	1.1229	1.4862	113	Synthetic rubber (kg)	3.4224	4.1266
55	Fibreboard hard (m3)	806.28	1011.8	114	Window frame, aluminium, U=1.6 W/m2K (m2)	754.07	845.42
56	Fibreboard soft (m3)	270.69	345.36	115	Window frame, plastic (PVC), U=1.6 W/m2K (m2)	292.18	368.37
57	Flat glass, coated (kg)	1.2118	1.7757	116	Window frame, wood-metal, U=1.6 W/m2K (m2)	395.48	504.72
58	Flat glass, uncoated (kg)	1.0497	1.5796	117	Window frame, wood, U=1.5 W/m2K (m2)	214.66	324.36
59	Glass wool mat (kg)	3.632	4.226	118	Zinc, primary (kg)	5.7038	6.6524

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The impact of value engineering on embodied greenhouse gas emissions in the built environment: a hybrid life cycle assessment

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Highlights

- Hybrid GHG emissions intensities (GEIs) of 118 construction products are generated
- Process-based GEIs are 20% lower than their corresponding hybrid GEIs
- Value engineering can reduce embodied emissions through dematerialisation
- Concrete, steel and timber are the hotspots for cost and emissions reduction
- Manufacturing and electricity jointly contribute to more than 80% of the emissions