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Using LCA to assist the selection of wall systems in the early stage of building design

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Abstract: Choice of materials for a buildings' façade significantly affects its life cycle environmental performance (LCEP). However, accurate assessment of the environment impact of different wall materials from a life cycle assessment (LCA) viewpoint is too complex for designers to determine in the early design stages of design. Assessing the life cycle environmental impacts (LCEI) caused by manufacturing, maintenance and disposal require knowledge of variables that are often unknown at the early stage of design. This paper evaluates the potential for developing principles that may assist designers to estimate the impact of material selection on the building LCEP at the early stage of design. The paper examines a small number of variables (material weight, service life, and recyclability/ reusability) to both highlight the level of LCA complexity and uncertainty at different phases of material life cycle and to show that it may be possible to determine more elementary heuristic principles that may help designers make LCEI decisions at the early stage of design.

Keywords: LCA; façade material selection; early stage design; embodied energy and CO_2 emissions.

1. Introduction

Buildings are responsible for significant environmental impacts through all their life cycle including construction, operation, and end of life. The importance of considering the life cycle environmental impacts (LCEI) of a building has been elaborated by several studies (Fay *et al.*, 2000; Thormark, 2002; Dixit *et al.*, 2010; Monahan and Powell, 2011). They have shown that the environmental impact of initial construction can be just as significant as those affected by their operations.

A multitude of interrelated variables affect a building's Life Cycle Assessment (LCA), making it too complex for designers to base decisions on, particularly at the early design stage. Any attempt to find common criteria or principles for design decision making from the results of previous studies is problematic because different studies determine LCA results using different parameters (such as site-specification, applied databases, analysis method for example).

Building envelope design is a common area identified for energy-saving opportunities. The significant impact of building envelope design has been identified by several studies, (Cheung et al., 2005; Ramesh et al., 2011; Zabalza Bribián et al., 2011). Choice of materials for a building's external walls significantly affects a building's energy performance during use and life cycle environmental performance (LCEP). While the energy performance during the use phase is reasonably well understood and commonly applied to façade design, there is a lack of designer-friendly information on the overall environmental impacts of manufacturing, maintenance and disposal which has limited the ability to reduce the building LCEI.

This study highlights the level of complexity of calculating LCEI, and therefore the difficulty of developing elementary heuristic principles to assist designers, by considering three façade material variables: material weight; service life; and disposal/recycling/reuse. For this research, the environmental performance of alternative façade assemblies is assessed using the energy consumption and CO_2 emissions throughout their life cycle. A simulation-based optimization methodology was developed for comparing the environmental impacts of different façade materials to elaborate the difficulty of employing LCA at the early design stage. It uses a multi-residential building in Sydney Australia as the project and site, as knowing the building scale and study location allows reasonable assumptions to be made for material production and transport, material useful life, dismantling and disposal technologies, and heating and cooling demands over the assumed 50-year building lifetime. A comparative LCA method was selected as a sustainability-measuring tool to compare the environmental impacts of producing different facades.

2. Background: Complexity of Life Cycle Assessment

There is a growing body of literature on LCA around building production. Most studies typically analyse the role of different construction materials and quantify them in terms of the embodied energy and the environmental impacts.

The most critical decisions regarding building efficiency in terms of the minimization of LCEIs and energy consumption are often made at the beginning of the design process. Early decisions thus significantly influence the life cycle energy performance of the building (Figure 1).

The availability of data in the initial stages of design is a major problem for designers. A huge amount of data and a certain degree of expertise in the field are required for LCA. Furthermore, building plans, including details of external walls, partitions, slabs, roof, and the selected cladding system, need to be well defined to accurately perform LCA. Because architects and engineers have limited expertise in LCA and the building form and fabric is fluid at the early design stage, most design decisions at this stage are based subjectively upon on the designer's experience rather than quantitative indicators.

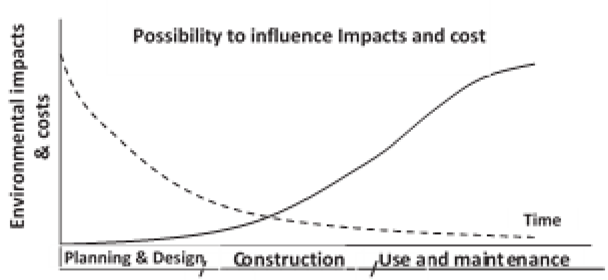


Figure 1: Influence of design decisions on life cycle impacts and costs (UNEP, 2003)

Inventory assessment of building materials and the process of construction and demolition are the main aspects of the environmental impact assessment. However, a major difficulty with this kind of analysis is that the material production processes are not always standardised due to the unique character of each building. The availability of assessable information about the environmental impacts of the production and manufacturing of construction materials, the actual process of construction and demolition are limited (Ramesh *et al.*, 2012).

The majority of tools used to assess the impact associated with building products are often limited in their ability to provide comprehensive, reliable and comparable environmental information across their whole life cycle. There are few consistent environmental impact results of building LCA outcomes to be found within the literature because of the application of different parameters, factors, datasets, system boundaries, interpretation methods, erroneous or overly-specific assumptions. In addition, values of embodied energy and equivalent emissions of carbon vary by country due to the energy mix, transformation processes, efficiency of the industrial and economic system of the country, and the variability of these factors over time, making calculation even more difficult (Sartori and Hestnes, 2007).

The other important criteria for decisions made from a life cycle perspective involve ensuring that a solution to reduce energy consumption for one life cycle stage does not increase overall life cycle energy demands. Results from previous studies of life cycle energy requirements demonstrate that a particular material or assembly may perform differently when applied in a different situation. For instance, materials with low initial embodied energy do not necessarily have low life cycle energy (Utama and Gheewala, 2009; Crawford *et al.*, 2011). We analysed nine selected LCA studies of building materials and products(Asif *et al.*, 2007; Kofoworola and Gheewala, 2008; Monahan and Powell, 2011; Zabalza Bribián *et al.*, 2011; Monteiro and Freire, 2012; Crawford, 2013; Thiel *et al.*, 2013; Dodoo *et al.*, 2014; Lee *et al.*, 2015) and found that these studies used different assumptions, materials, databases and analysis method. It is therefore difficult to draw comparisons among the studies and find generalisable design principles that could be employed by designers at the early design stage.

3. Methodology

A quantitative and qualitative analysis was undertaken for a limited number of façade materials on a multi-storey residential building to assess the impact of material weight, durability, and recyclability/ reusability on their life cycle energy demand.

3.1. Definition of a reference building as a case study

A four storey residential building in Sydney (33°52.071′ S, 151°12.4392′ E) with an assumed 50-year life is taken as a reference building for this study. The building shape is rectangular (long axis east-west) with total floor areas of 3135 m^2. At the ground floor, one unit is substituted by an office. Overall the building includes 31 residential units, 1 office, corridors and vertical distribution zones.

For the purposes of this paper a hypothetical external wall system consisting of the following 4 main materials was considered: Cement-bonded particleboard, Expanded Polystyrene (EPS), Cross Laminated Timber (CLT) and plasterboard (Table 1). The embodied energy and the equivalent CO_2 emissions of the façade materials were analysed using three different scenarios:

- **Scenario 1:** The embodied energy and the equivalent CO_2 emissions of the external wall panels analysed with two different weights (Table 1)

- **Scenario 2:** The impact of materials service life on the building's life cycle energy demand analysed based on three different assumptions: (i) total embodied energy calculated considering service life of each layer; (ii) the whole external wall panel replaced in the middle of the building's life; (iii) no material substitution occurring during the building life.
- **Scenario 3:** Different waste scenarios to determine the impact of end of life phase on building LCA.

Table 1: Description of External wall's assemblies

Materials	Base Case Thickness	Base Case Density kg/m^3	Heavy Case Thickness	Heavy Case Density kg/m^3
Cement-bonded Particleboard	10 mm	1200	16mm	1200
EPS	60 mm	28	90 mm	28
CLT	94 mm	500	108 mm	500
Gypsum Plaster Board	12 mm	900	12 mm	2800

3.2. Life Cycle Assessment

Building life cycle energy demand and emissions are affected by various parameters directly or indirectly. Construction, operation, renovation and demolition are direct, while production of materials used in construction and technical installations are indirect effects (Sartori and Hestnes, 2007). The life cycle energy of a building's external facade was analysed in this study. It included initial embodied energy (associated with manufacture of products and materials), recurrent embodied energy (required for maintenance of components and materials), and the disposal energy (for demolition and disposal of materials or possible reuse or recycling after the building's useful life). Life cycle energy finally includes operational energy, used for operating Heating, Ventilating and Air Conditioning (HVAC) systems in order to maintain indoor comfort conditions.

3.3. Material Manufacturing & Construction Phase

3.3.1. Initial Embodied Energy (IEE)

The total energy used to transform raw materials into ready to use building products is initial embodied energy. Quantifying the embodied energy of a product or process is complex due to the variation of its design and location of manufacture and use. Technology, fuel supply infrastructure, region, product specification and analysis method affect the embodied energy assessment (Ngo Tuan *et al.*, 2009).

SimaPro 8.2.0 (Australian database-AusLCI unit processes) was applied in this study to quantify the embodied energy and CO_2 emissions. The software databases include a variety of parameters such as construction materials, transportation, installation and waste treatment. The cumulative energy demand (version 2.02) method used to quantify the embodied energy and, the equivalent CO_2 per Kg was analysed by ACLAs best practice LCIA Recommendation (version 2.0).

The constant parameters were defined for each material and all input from the techno sphere (materials and fuels) were described based on AusLCI unit process records. Energy consumption of transportation of materials from plant to construction site was added based on assumed truck weight and distance. As an overseas manufactured material, CLT required consideration of all legs of its transportation from Austria. All other installation processes (e.g. the crane at the construction site) were considered as constants in this analysis not affecting comparative results for the sake of this study.

3.3.2. Recurrent Embodied Energy (REE)

The recurrent embodied energy is calculated based on the number of times each individual material is assumed to be replaced during the useful life of the building. This can significantly increase the total embodied energy. The material service life and the building useful life (which ends with demolition) are the effective parameters for analysing REE. These parameters are uncertain due to their dependency on uncontrollable factors such as users' behaviour, climate, and maintenance. The materials' service life was drawn from the literature (Table 2). The life cycle embodied energy of the building's external walls, including initial and recurrent embodied energy, was calculated using Eq.1(Crawford R.H. , 2009).

Table 2: service life of external wall

Materials	Cement-bonded Particleboard	EPS	CLT	Gypsum Plaster Board
Years	30^	25*	50#	30^

*(Crawford R.H. , 2009), ^(FWPA, 2007), # (Jaakko Poyry Consulting, 1999)

$$LCEE_a = \sum\left(\frac{UL_b}{UL_m} \times EE_m\right) \quad (1)$$

Where $LCEE_a$ = Life cycle embodied energy of the building assembly, a; UL_b = Useful life of the building; UL_m= Useful life or replacement period of material, m; EE_m = Embodied energy of material, m, includes initial embodied energy and disposal energy.

3.4. Operation Phase

Building envelope design affects heating and cooling demand as it is the main area where thermal losses and gains occur (Koo et al., 2014). Thermal properties of the reference building were modelled in DesignBuilder. The initial model was selected from a Department of Energy (DOE) reference building of mid-rise residential apartments in the USA. Configurations of the model were changed for Sydney's climatic location. All settings for construction, lighting and HVAC configurations were inherited from the DOE and heating and cooling are based on gas and electricity respectively. Configurations were set to be compliant with the building code of Australia (ABCB, 2014), in particular deemed-to-satisfy provisions. All internal load schedules were changed accordingly based on (NatHERS, 2012).The optimized window system was a double glazed unit with timber frame and window to wall ratio of 40% for all external walls without any internal or external shading. The final model is fully described in (Bashirzadeh Tabrizi and Fiorito, 2016).

3.5. Demolition and Disposal Phase

Few reliable studies exist for the LCEI associated with the demolition of buildings and disposal of materials. Crowther showed that the amount of energy required for the disposal phase is extremely low in comparison with the energy demand of a building during its whole life cycle — less than 1% of total embodied energy (Crowther, 1999). However, considering end-of-life choices for building materials—including reuse, recycling, reprocessing, energy recovery, and landfill—could vary the result significantly.

Qualitative analysis was applied to analysing the LCEI of different waste scenarios for the building, as variables affecting end of life analysis are uncertain. Early assumptions about energy for dismantling facilities, emissions from dismantling and handling, transport to dismantling facilities and final disposal of waste materials might totally change at the end of the 50-year building life.

4. Results and Discussion

This section presents the results and discussion of the significance of different variables for life cycle environment assessment of the hypothetical façade system.

4.1. Scenario 1

Results: The comparison between the life cycle EE demands of each of the 4 different materials in the hypothetical façade system was first examined in terms of their weight. The impact of changing panel weights is illustrated in Figure 2a-2b. The heavier panel had an increased embodied energy of 60% for cement-bonded particleboard, 49% for EPS, 11% for CLT and 211% for plasterboard. A similar result was observed for the equivalent CO_2 emissions. Increased emissions for cement-bonded particleboard were 60%, EPS 50%, CLT 14% and plasterboard 211%. The impact of changing wall material density or thickness on the reference building's operational energy (heating and cooling) is elaborated in Figure 3.

2a 2b

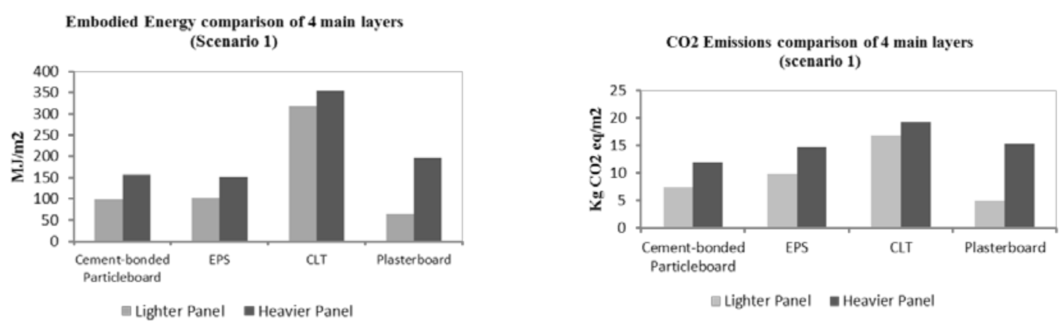


Figure 2a-2b: Embodied energy and CO_2 emissions comparison of panel layers with different weights

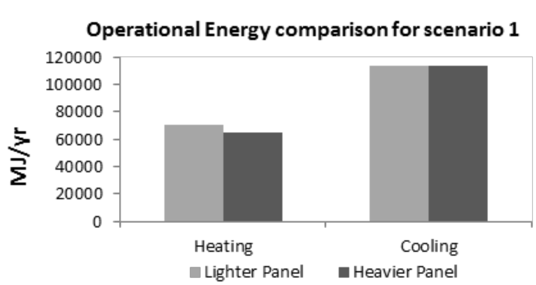
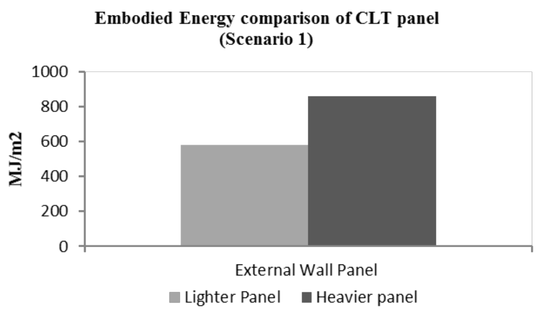


Figure 3: Operational energy comparison of two CLT panels with different weights

Discussion: From the results it is evident that changing material weights does not affect operational energy in a significant way (differences less than 0.7% were recorded for heating energy demand). However, the choice of facade panel layers with various weights has a significant effect on EE. A building with the façade constituted by lighter materials consumed 48% less energy and produced 57% less CO_2 emissions (Figure 4a-4b).

4a



4b

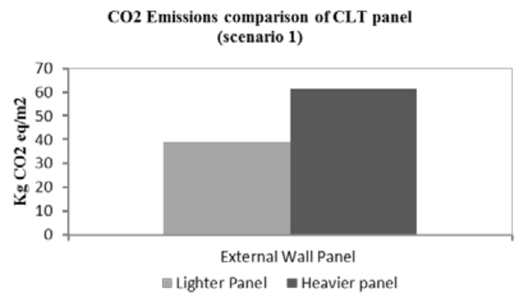


Figure 4a-4b: Embodied energy and CO_2 comparison of two facade panels with different weights

4.2. Scenario 2

Results: Figure 5 shows the influence of differing service lives of wall materials. It shows that energy demand of replacing materials through the building life significantly affects the total EE. However, the effective variables are both uncertain and interrelated in this phase, making it difficult to determine exact results even for a very tightly constrained case study such as this. Consequently, this study analysed the impact of REE on total embodied energy in terms of three common assumptions: (i) total EE of the panel considering each material's service life (793.84 MJ/m2). (ii) total EE of the whole facade panel substitution at the middle of building life (1166.2 MJ/m2), (iii) total EE of facade not being replaced during building 's life (583.1 MJ/m2).

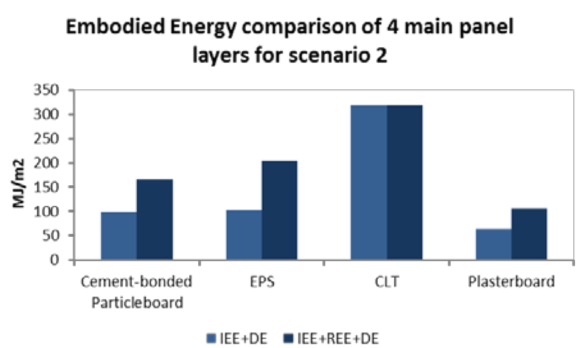


Figure 5: Embodied energy comparison of panel layers with considering REE

Discussion: Overall it can be noticed that total embodied energy significantly changes by considering the REE (Figure 6). This study shows the 50% increase for total EE demand of the multi-storey building's external facade.

4.3 Scenario 3:

Building materials as Construction and Demolition (C&D) waste encounter various waste treatments: disposal to landfill; indirect or direct recycling; reusing the material or product. The difficulty of investigating of each treatment is highlighted by selecting timber as an example in this section (as timber is used in both particleboard and CLT in this case study)(Taylor and Warnken, 2008).

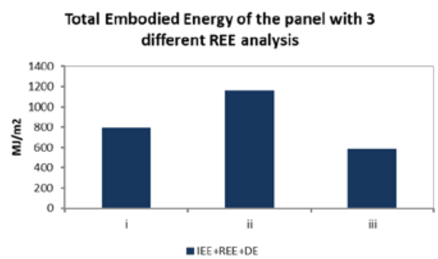


Figure 6: Embodied energy comparison of panel layers with considering REE

Wood recovery and recycling (2008) advises that reuse (keeping original form and function) is the best recovery opportunity for waste timber; next is direct recycling into other timber products such as particleboard; then indirect recycling non-timber products (such as landscape mulch); then energy generation (process heat and/or electricity). Increasing demand for reusing building materials is derived from sources such as architects, home renovators, and hobbyists/craftspeople. However, factors such as transport costs, and the space available for receiving, sorting and display of the timber materials make this business complex. Recycling processes are influenced by many uncertain factors and a lack of information about the recycling process energy demands and possible environmental impacts of 'contaminants' and preservative treatments on the direct or indirect recycled products. Using timber waste for energy generation raises issues such as air pollution. Methane, a potent greenhouse gas, is produced during the anaerobic decomposition of timber waste in landfills. Recovering timber prevents the release of greenhouse gases. It is evident that the environmental impact of products or materials at the end of life is more complicated than can be quantified by LCA tools.

5. Conclusion

This study examined the LCEI of a hypothetical façade system constituted by 4 materials, for 3 scenarios: varying material weight; varying service life, and varying end of life options (landfill/reuse/recycle).

From scenario 1, varying material weight, it can be seen that considering a materials' mass at the early design stage is important due to: (i) Its influence on the end of life scenario. Lowering construction waste mass decreases, the environmental impact of this phase and helps landfill shortage problems (ii) Material weights affect all interrelated transportation phases. This seems more important when a material is imported (like CLT panel in this study) compared to local materials, as transportation was mainly responsible for the amount of CLT embodied energy and CO_2 emissions. Transportation energy demands were calculated based on Kg*Km, therefore the weight of the materials significantly increases their LCEI for long distances. (iii) Increasing 30mm thickness of insulation of external walls generated 18849.47 $KgCO_2$ more and consumed 234929.24 MJ more energy for the case study building without any energy saving in the use phase.

Scenario 2 demonstrated that material service life was significant in terms of LCEI and that it has the potential to be the basis of heuristic advice for designers (e.g. 'long service life and low maintenance is likely to reduce LCEI'), but that the interrelatedness and uncertainty of variables make simple advice problematic.

Scenario 3, varying end of life treatments, confirms the complexity of attempting to apply a comprehensive LCA in the early design stages. Considering various alternative waste scenarios — disposal to landfill, recycle or reuse — can significantly change the LCEI results of building materials. For instance, because it is hard to assume the impact of certain parameters on recycling or reusing materials process at the end of a building's service life (particularly as technologies may change significantly during that time), it may be impossible to quantify their LCEI at the early design stages.

Overall, this research indicates that designers should be made aware that the level of complexity and certainty/uncertainty is different in each LCA phase. This small study illustrated the changing degree of certainty with three scenarios and the need to rely on both quantitative and qualitative analysis methods or different phases. The first scenario demonstrated the impact of material weight on the building energy demands and the equivalent CO_2 emissions as a result of certain parameters and consequently gave reliable and replicable results. REE calculation in the second scenario was based on uncertain variables (most of them dependent on user behaviour). However, considering the same assumptions would have led to the same results. Qualitative analysis was needed for investigating the LCEI in scenario 3 due to the lack of reliable end of life information and the high level of uncertainty of effective parameters.

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