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LIFE CYCLE ASSESSMENT OF A RESIDENTIAL BUILDING: QUANTITY TAKE-OFF AND DATA INPUT TECHNIQUES

Hamidul Islam, Margaret Jollands, and Sujeeva Setunge
School of Civil, Environmental and Chemical Engineering
RMIT University, Melbourne
Email: margaret.jollands@rmit.edu.au

ABSTRACT

LCA is a useful tool to assess the environmental impact of buildings. However, to do so accurately requires availability of regional life cycle inventory data, relevant scaling factors and reliable estimation of variables. This paper reports on how building plans, quantity take-off and scaling factors can be used to build an LCA model of a residential building. *AccuRate* and *SimaPro* were used to model the data. It was found that the environmental impact varies substantially with the phase of the building life cycle. Varying building life span affects the robustness of results.

Keywords: Quantity take-off, *AccuRate,* Bill of Quantity, *SimaPro,* scaling factor.

1. INTRODUCTION

Residential buildings utilise a variety of materials in floor, wall and roof assemblies. The manufacture of these assemblies is resource and energy intensive, from production, to distribution, construction, operation, maintenance and final disposal, with significant environment impacts throughout the building's life cycle. However, society increasingly demands more environmentally friendly innovative building assemblies, characterised by lower cumulative energy consumption across the whole life cycle. Life Cycle Assessment (LCA) can be carried out to assess environmental impacts over time, when sufficient good quality inventory data are available. Inventory data for a residential building include all the materials, products and services used throughout the building’s life.

The builder’s “quantity take-off” or “Bill of Quantity” (BOQ) provides a complete list of all the components and amounts used to construct a building, as well as the waste that is generated. Quantity take-off is a standard practice across the construction industry. However, the data cannot be directly input to an LCA model. For each component the amount must be converted to units suitable for data input using the life cycle inventory (LCI) database. Scaling factors must be applied to convert, for example, metres of wood of a particular cross-sectional area to volume or mass. Thermal modelling can be used to provide estimates of operational energy in a given climate zone for a given building design. Maintenance required over a building’s lifetime can also be estimated and converted to units suitable for data input using and LCI database. Environmental impacts of disposal at end of life can also be modelled based on current rates of reuse, recycle, incineration and landfill now or assumptions about future rates. Hence the environmental impacts for the whole life cycle of a building can be estimated accurately.

This paper briefly reviews the literature on life cycle assessments in residential buildings and reports on the life cycle assessment of a typical Australian house, giving typical calculations for the BOQ, scaling factors and assumptions. It reports the whole life cycle assessment of a case study residential building including: material extraction or harvesting; on site construction; maintenance; heating and cooling occupancy over 50 year life time and final disposal at the end of life. It compares results for three different life cycle impact assessment (LCIA) methods and looks at the sensitivity of results to of life span. The results are discussed in terms of focus for design to reduce environmental impact.

2. BACKGROUND

LCA has been used in the building sector since the 1990's (Fava, 2006). Previous studies have segmented the building life cycle into stages of raw material acquisition, fabrication, assembly, and construction, use or operation, and finally disposal at end-of-life (Ding, 2007; Szalay, 2007). LCA outcomes have varied significantly depending on the goal definition, methodology used, assumptions made and boundaries. The relevance of results has been limited by use of region specific software tools and databases (Reap *et al,* 2008; Szalay, 2007; Horvath, 1997). This is especially true of studies in the field of building industry, as there are wide variations in building practices and energy sources between regions.

3. METHODS

The BOQ for this case study was developed using the Australian Construction Handbook (Rawlinsons 2009) for an actual residential building built in 2006 in Brisbane. The scaling factors used to convert the BOQ data to data suitable to input to the LCA model were derived from the literature. A streamlined LCA approach was undertaken using PRé's *SimaPro* 7.1.8 LCA software, the AusLCI database was used and the model evaluated using the Australian Impact method with normalisation including Cumulative Energy Demand (CED). AusLCI and CED are complimentary and particularly suitable for this project as they include Australian region specific data (AusLCI, 2009; Newton *et al,* 2009). The Swiss Centre for Life Cycle Inventories *eco-invent* database was also used, as it has been adjusted for the Australian Building Industry (AusLCI, 2009; Tharumaharajah & Grant, 2006; Henriksen, 2006). CSIRO's *AccuRate* software was used to predict operation energy requirements (*i.e.* heating and cooling) which were incorporated into the LCA model. *AccuRate* is Australia's nationally accredited energy rating assessment tool. The Building Code of Australia lists *AccuRate* as suitable for this purpose (Dewsbury *et al*. 2009).

4. DATA SELECTION AND CALCULATIONS

Building Element	Description of Case Study Building System
Internal and External Walls	Timber frame with fasteners, braces and insulation. External walls100 m^2: Fibres cement sheeting and brick with uncoloured mortar. Edge brick sealed with cement. Internal walls 52m^2: 10 mm smooth finish plaster board on stud, no insulation, acrylic paint finish except for wet area walls: linings 6 mm villa board.
Foundation/Basement	Reinforced concrete strip footing and 100 mm concrete slab on ground. The edge beam and internal beam founded 200 mm into founding material (naturally stiff silty clay). 20 MPa at batching plant reinforced concrete.
Floors	Tongue & groove wooden board on the concrete slab except for wet areas: tiles. First floor decking: ply wood. Joist spacing and fixing under the tiled floor as per manuf. specs. Total house floor area: 101 m^2. Garage floor area: 21 m^2
Roof and Ceiling	Roof: colour coated concrete roof tiles. Gable roof with 25º pitch. Ceilings: by 10 mm smooth finish plasterboard cladding with R 2.5 glass wool batt insulation in the upper floor. The total roof area: 102 m^2.
Doors and Windows	External doors: pine frame, lock set with dead bolt. Internal doors and laundry: flush panel. Garage: remote controlled roller door with 2.1×2.7 m colour bond panel. Windows: clear single panel glass, powder coated and aluminium frames with lock sets. Fly screens not included. Total area of doors and windows: 22 m^2.
Painting	External walls (brick, FC, metal) two coats of acrylic glazing. Doors: two coats of gloss acrylic. Joinery and mouldings: two coats gloss enamel.

Table 1 : System Description of Case study Building

The general description of materials and components the case study house is given in Table 1. The house was designed for the Australian residential market and built in Brisbane. It is a double storey, attached timber frame town house with face brick and a concrete slab on the ground floor. The upper floor comprises a master bedroom with en-suite and two smaller bedrooms and second bathroom. The ground floor area comprises living and dining with an open plan kitchen and a WC. Maintenance includes repainting and white goods exchange but excludes a major renovation.

Activity (Based on life span)		**Years occurring after Construction**	**Reference Source**
Major renovation	Replacement of tiles	25	Ding, 2007
	Replacement of plasterboard, fibreboard	25	Rouwette, 2010; Ding, 2007; Blanchard & Reppe 1998
	Replacement of T&G timber floor	25	Rouwette, 2010; Ding, 2007; Blanchard & Reppe 1998
Minor renovation	Exterior and Internal re-painting	10, 20, 30, 40	Rouwette, 2010; Ding, 2007; Blanchard & Reppe 1998

Table 2: Maintenance schedules for residential buildings

Table 2 summarises the literature on maintenance schedules for residential buildings. This was used to create the *SimaPro* model for maintenance in the following way. The case study house is modelled with a 50 year life span, so one replacement at 25 years is included and four repaints. For the sensitivity analysis, the model of a 35 year life span includes three repaints but does not include any replacement (assuming the owners would be planning end of life at 35 years), while the model with a 65 year life span includes one replacement and five repaints. That means the replacement might occur every 25 to 35 years, depending on the foreseen life span.

Data inputs into *SimaPro* and *AccuRate* models were calculated from the BOQ. Each calculation is relatively straightforward, but the accuracy of each model depends on the accuracy of the BOQ. Even one small mistake can cause large errors in impact. The BOQ was calculated from house dimensions, specifications and appropriate factors from Staines (2004) and Rawlinsons (2009). The BOQ for the timber has been verified by a building materials manufacturer. *AccuRate* software was used to calculate the operational energy using its default settings and standard climate data for the Brisbane climate region. The life cycle inventory (LCI) data used in the *SimaPro* model was again painstakingly calculated from the BOQ and suitable assumptions and scaling factors derived from published work, the *AusLCI* and *eco-invent* database.

Some examples of assumptions, data and calculations are given in Tables 3, 4 and 5. For example, one line item in the BOQ is for floor bearers. The typical size and material used for floor bearers and its density was sourced from AS1684.2-1999 (Standards Australia 2001) and Rawlinsons (2009). The length of the floor bearers was calculated from the size of the first floor from the house plans and the typical number of floor bearers needed for that size of floor was found from Rawlinsons (2009). The total length of wood was calculated, and then multiplied by the cross-sectional area to give the volume of wood. The volume times the density gave the mass of wood in kg, and this was input to the *SimaPro* model.

Component	**Assumption and data choice**	**Source**
BOQ	Quantities of building materials are based on "best guess" estimates (i.e. typical values with respect to densities)	Rouwette, 2010
Building materials Disposal	Waste scenario/treatment: landfill only; 30 km/truck distance to landfill site was assumed	*AusLCI*
Maintenance	Replace at the end of estimated lifetime, otherwise double layer repainting or other maintenance applicable	Rouwette, 2010; Ding, 2007; Blanchard & Reppe 1998

Table 3: Sample Assumptions and data requirements

Component	**Data description**	**Data Source**
Timber	Production of construction timber	*AusLCI*
Paint	Paint manufacturing process	European and *Eco-invent*
Landfill	Municipal landfill	*AusLCI*

Table 4: Data Quality and source of Data

Name of Materials	Data Description, Scaling Factor, References	Total Quantity		Total Quantity	
		Unit	Amount	Unit	Amount
Floor bearer	Bearers are 240 mm x 70 mm sawn hard wood, density 0.8 t/m^3 (AusLCI)	m^3	2.6	tonne	2.1
External wall painting	100% acrylic varnish with single double coat (32.2 m^2/gallon for a single coat & 10 *lb*/gallon) converted into kg (*eco-invent*)	m^2	176	kg	49.9
Landfill	Concrete, total m^3 from BOQ input into 2.4 tonne/m^3 (AusLCI)	m^3	20.48	tonne	49.16

Table 5: Sample BOQ items, scaling factors and data inputs for the *SimaPro* model

5. LIFE CYCLE ASSESSMENT

The following standards were used to inform this study: a) ISO 14040: Principles and Framework (ISO, 1997); b) ISO 14041: Goal and scope definition and inventory analysis (ISO, 1998); c) ISO 14042: Life cycle impact assessment (ISO, 2000a); d) ISO 14043: Life cycle interpretation (ISO, 2000b). The following steps were then undertaken.

5.1 Goal and Scope

The goal of this study was to develop a method suitable for evaluating the environmental impact of an Australian residential building. The scope was to carry out an LCA of a case study house built in Brisbane. The functional unit of this LCA study is a two storey three bedroom town house with a 50 year lifetime from construction to disposal. The system boundary is shown in Figure 1.

The system boundary **includes**

- raw material extraction, and production materials (*i.e*. steel plates, timber studs etc)
- manufacturing of building components (*i.e*. window, timber floor)
- transportation from raw material extraction to part fabrication, to the construction site
- construction of the home at the building site, including site earthwork and excavation
- energy consumed during the use phase
- demolition at the end of useful life (*i.e.* land fill only) with transportation to landfill

Assumptions:

- 5% wastage of materials during construction
- Continuous occupancy with zoned discrete heating and cooling periods.
- Natural gas central ducted heating, 70% heating efficiency.
- Electric air conditioning with a coefficient of performance of 3.

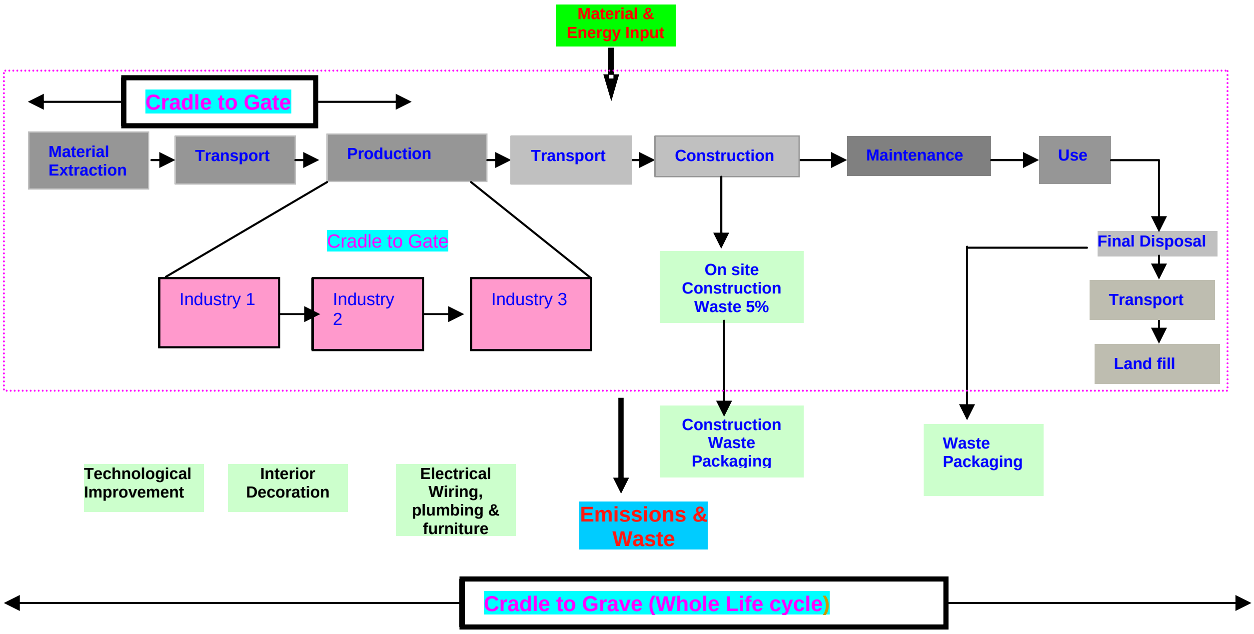

Figure 1 : LCA System boundary (dotted area)

The system boundary **excludes**

- Technological improvements such as high level reuse or recycling of building waste
- Interior decoration, electrical wiring, plumbing, furniture
- Personnel man-hours
- Capital goods (i.e. vehicle and machinery) in the temporary construction site
- Dwelling orientation and shape
- Urban planning infrastructure (roads, sewer, drive-way concrete and landscaping)

5.2 Life Cycle Inventory (LCI) Analysis

LCI analysis is the most resource intensive phase of an LCA. Quality, age, and region of origin of the data are very important. The best data are current and region specific (Szalay, 2007; Tharumaharajah & Grant, 2006). In this study, all required inventory items were found in either the AusLCI or the *eco-invent* databases. The LCI amounts were calculated from each BOQ item using scaling to convert amounts to units suitable for input to the *SimaPro* software.

5.3 Life cycle Impact Assessment (LCIA) Method

This study uses three different LCIA methods chosen from those available in SimaPro:
a) Australian Impact Method with normalisation including Cumulative Energy Demand (AIM-CED)
b) CML2 baseline 2001- Australian Toxicity Factors Method (CML2) and
c) Eco-indicator 99 (E): Australian substances LCIA Method (Eco-indicator 99).

AIM-CED provides an LCI database for a wide range of Australian products and processes. It includes categories for water use and solid waste, so is particularly well suited to this case study, as the residence is in Australia and disposal is included in the LCA model.

CML2 takes a problem oriented (mid-point) approach. Impact categories are divided into “baseline” (as presented in this study), “study specific” (such as loss of biodiversity and noise) and “other” (such as odour) (Guineé *et al.* 2002). It has baseline impact categories absent from AIM-CED that are considered relevant to this study (such as ozone layer depletion and human toxicity). The toxicity data has been adapted for Australian products and processes.

Eco-indicator 99 takes damage oriented (end-point) approach and it also has impact categories that are absent from AIM-CED that are considered relevant to this study (such as ozone layer and fossil fuels). It is also commonly used in European case studies of residential housing. It has been augmented with the addition of Australian substance definitions for fuels for this study.

5.4 Results Interpretation

The outcomes of an LCA are impact category indicators. These integrate both global and local impacts. The global impacts are on human health, ecosystem quality, and resource depletion. The local impacts include eco-toxicity, human toxicity, respiratory organic or inorganic, carcinogens, eutrophication, acidification, land use, and water use. Table 6 shows the major typical impact category indicators and characterisation factors used in result interpretation.

Impact Category	Relevant LCI data (classification)	Common Characterisation	Description of Characterisation Factor
Global Warming	CO_2, NO_2, CH_4 and CFCs	Greenhouse gas emissions in kg (CO_2) equivalents	Converts LCI data to CO_2 equivalents
Solid waste	Quantity disposed of in a landfill	Solid waste in kg	Converts mass of solid waste into volume using an estimated density
Embodied Energy	Total sum of energy use	Energy in MJ	Converts LCI data to embodied energy MJ equivalents
Water use	Total sum of water use	kl of water	Converts LCI data to kilo litre of water equivalents

Table 6: Australian impact Category indicators and Characterisations factors

Figure 2 to Figure 4 show characterisation of the environmental impacts of the case study house in terms of the various life cycle phases using the three LCIA methods described in section 5.3.

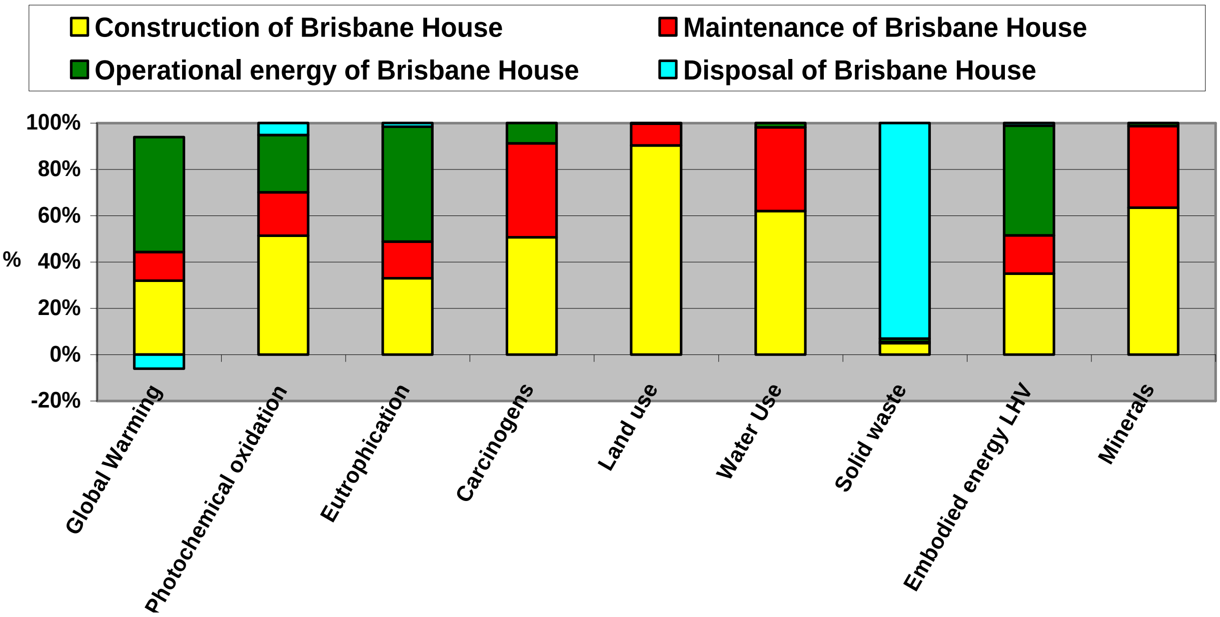

Figure 2: AIM- CED/characterisation of the case study

Figure 2 shows the impacts using the Australian Impact Method Including CED (AIM-CED). The construction phase has the most impact on land use, minerals, water usage and photochemical oxidation (smog). Operation has most impact on global warming (heating and cooling energy for the house during its lifetime), eutrophication and embodied energy. Disposal contributes most to solid waste in land fill. Maintenance has relatively little impact over the building's 50 year life time, except in carcinogens, water uses and minerals, due to the one major renovation at approx. 25 years (Table 2). 93% of global warming impact occurs in the construction and operation phases, which is a similar proportion to that reported in a study by Szalay (2007). The high energy usage in the operation phase reflects the heating and cooling requirements in the Brisbane weather zone. 95% of water usage occurs in the construction and maintenance phases. A 6% credit of global warming occurs in disposal due to sequestration of CO_2 in land-filled timber materials.

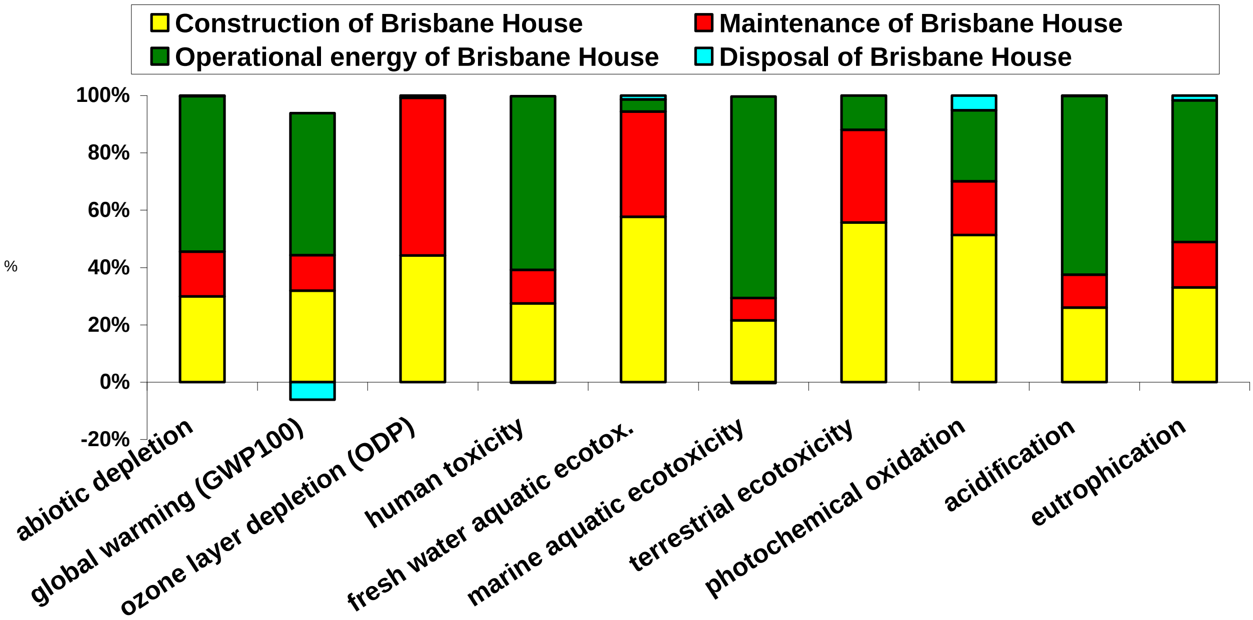

Figure 3: CML2 characterisation of the case study

Figure 3 shows characterisation using the CML 2 baseline 2001 – Australian Toxicity Factors Method (CML2). Three of the impact categories are the same as AIM-CED - global warming, photochemical oxidation and eutrophication. These have similar results to AIM-CED for the contribution from the different life cycle phases, as expected. The additional categories yield a further insight to the impact of the case study. Ozone depletion shows the main impacts occur in the construction and maintenance phases. Human toxicity shows that the main impacts occur in the operation phase. This suggests a reduction in environmental impact could be achieved by optimising house design. Ozone depletion can be reduced by better choice of materials in construction and maintenance, and human toxicity, by reducing operational energy needs.

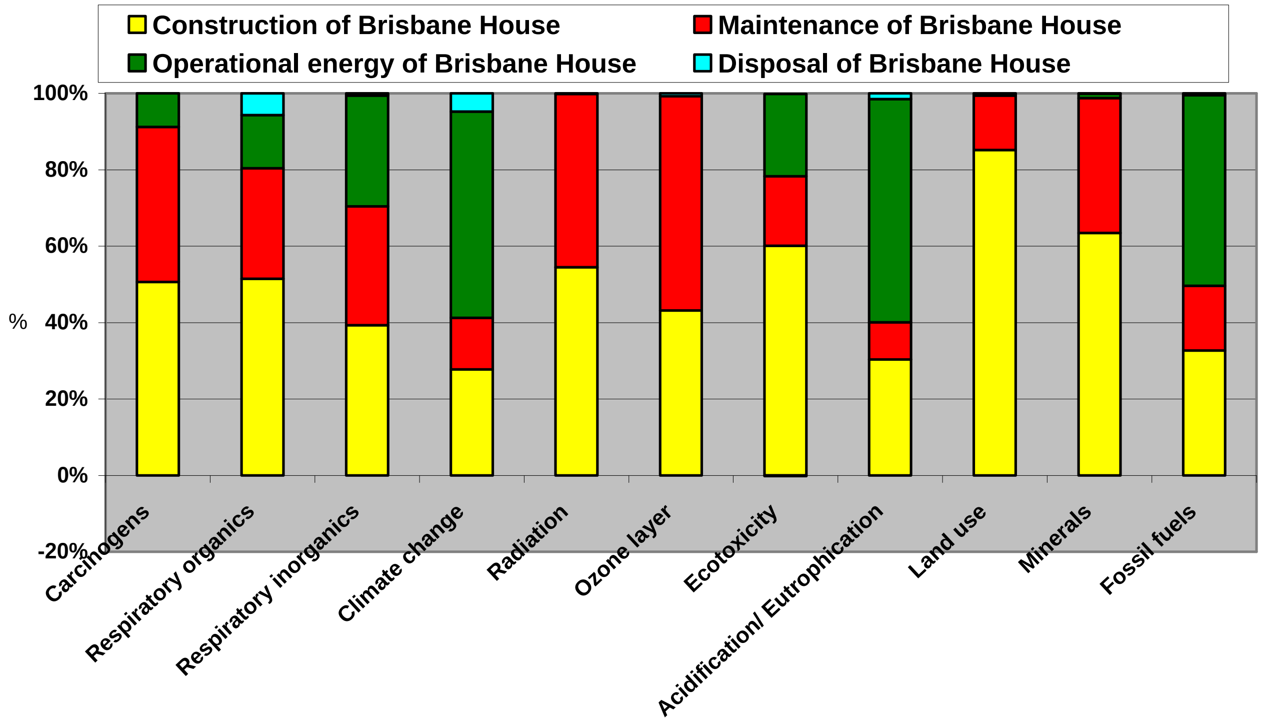

Figure 4: Eco-indicator 99/characterisation of the case study

Figure 4 shows characterisation using the Eco-indicator 99 (E): Australian substances LCIA Method (Eco-indicator 99). Impact categories with the same name as AIM-CED or CML2 show similar results, as expected. It includes new categories respiratory organics and inorganics, radiation and fossil fuels. Construction and maintenance make the major contribution to impact in these new categories except for fossil fuels, which is dominated by the operation phase.

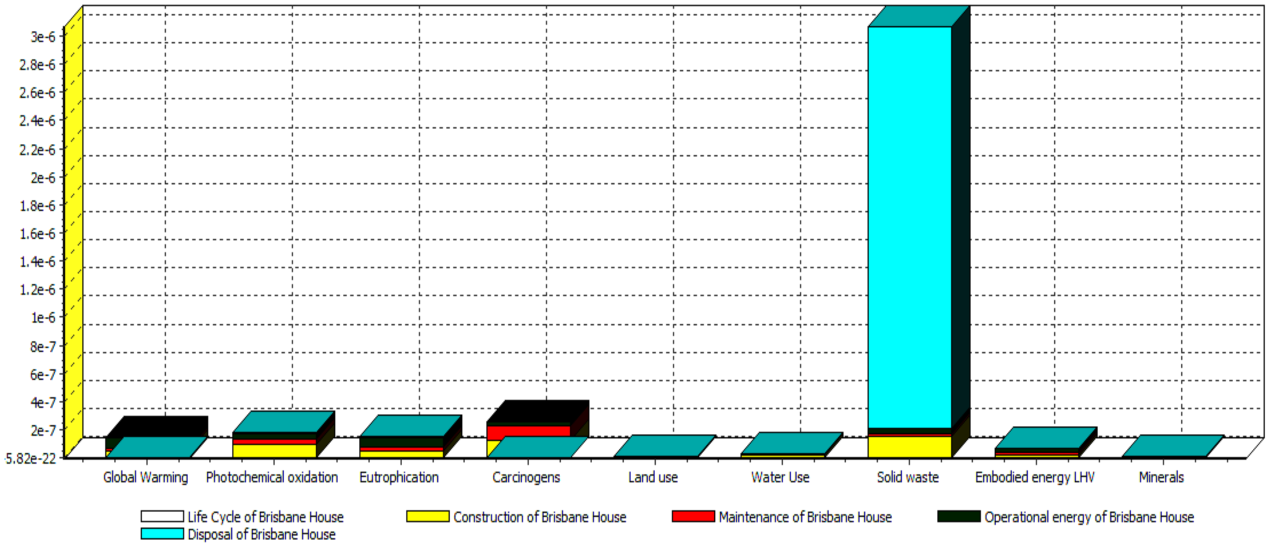

Figure 5: AIM- CED/Normalisation using Australian

Figure 5 shows the normalised impact category indicators value in terms of the various life cycle phases using the AIM-CED. Normalised values represent the absolute value for each indicator divided by the Australian total per capita emission for each indicator. This is useful to evaluate the relative importance of impact categories in everyday life. Figure 5 show the house has a relatively high impact in both the solid waste and carcinogens categories. This suggests environmental impact could be most reduced by reducing solid waste (such as by using less materials during construction or by using recyclable materials).

6. SENSITIVITY ANALYSIS

A sensitivity analysis is carried out to assess the robustness of the results when there are variations in model choices or variables. One of the important variables in our model is the life span of the building. An average lifespan of 50 years was used in the LCA model, and an uncertainty range of 15 years. This is rounded down, for simplicity, from the average lifespan of 56 years reported for an attached dwelling in Brisbane (Kapambwe *et al.* 2008). Figure 6 and Figure 7 shows the effect on four major environmental impact categories of varying the building life span from 35 to 65 years.

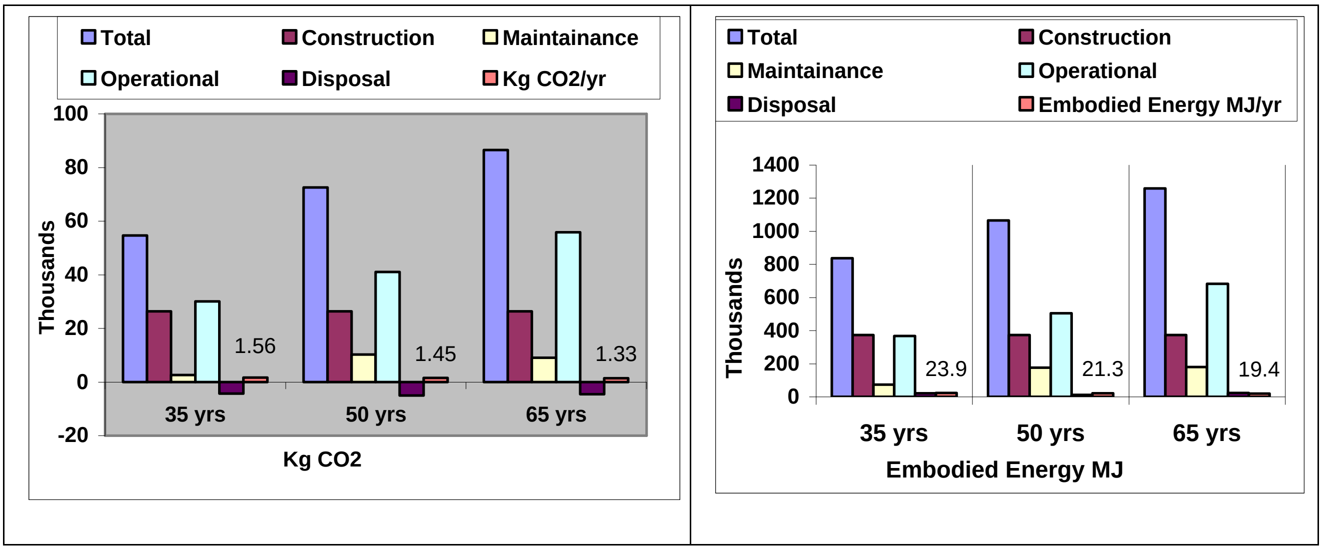

Figure 6: Comparison of Greenhouse Gas Emissions and Embodied energy as lifespan varies

Figure 6 shows that for greenhouse gas emissions and embodied energy, the results are robust: construction and operational energy contribute most at all lifespans. It also shows that while the total impact increases as the life span increases, the main benefit of a longer lifespan is lower annualised GGE and embodied energy. It also shows that beyond 35 years, the main contribution to global warming is from operational energy. So the longer the building life span, the higher the value of design features that save operational energy.

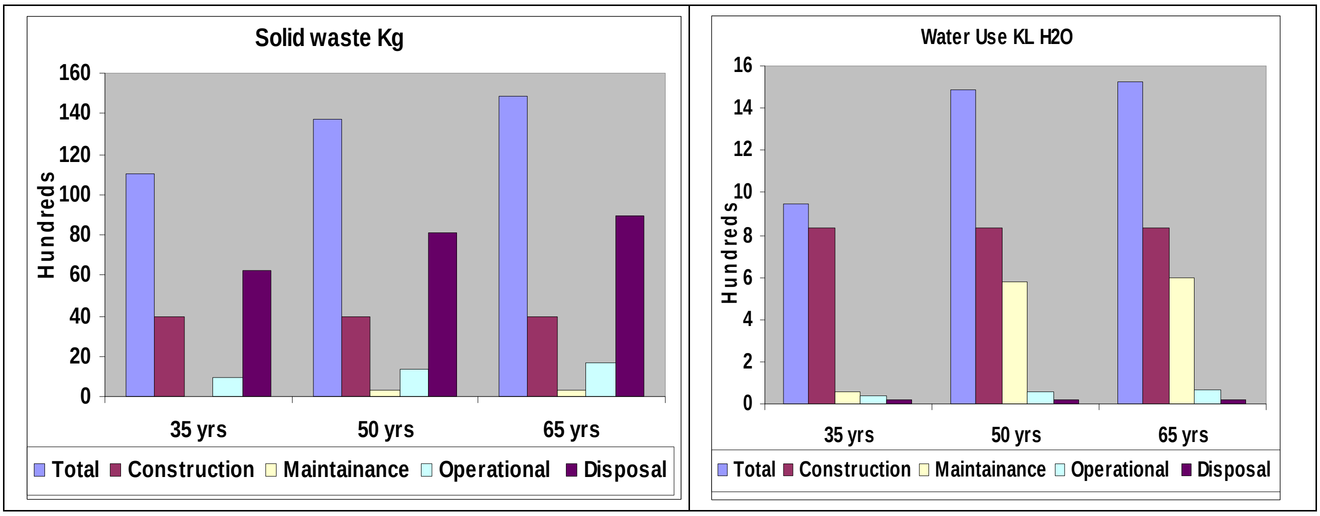

Figure 7: Comparison of solid waste and water use as life span varies

Figure 7 shows that for solid waste the results are robust: the disposal phase has the highest impact on solid waste for all lifespans. However, for water use the most important phase at a short lifespan is construction, while at longer lifespans, maintenance is more important. Higher water usage occurs as one major renovation is carried out during the 50 and 65 years lifespan.

CONCLUSION

The Bill of Quantity (BOQ) is needed to calculate inputs to an LCA model for a residential property. *AccuRate* can be used to estimate operational energy requirements for a residence. The LCA model can be analysed to asses the effect of different lifespan phases on impact categories. Construction has most impact on land use, minerals and water usage while operation has the most impact on global warming, eutrophication and embodied energy. Maintenance has relatively little impact overall except on water use. The focus for redesign to reduce environmental impact could depend on the chosen LCIA method. Normalisation shows that work to reduce environmental impact of this house design in a Brisbane climate should focus on reducing carcinogens and solid waste. Sensitivity analysis shows that the results are robust when building life span is varied, except that water useage depends on when a major renovation is carried out.

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