LIFE-CYCLE MODEL FOR NEW ZEALAND HOUSES - THE BUILDING FABRIC AND BEYOND

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ABSTRACT

Building assessment schemes provide an evaluation of the resource use in the construction industry. Most readily available assessment schemes are neither in a format easily understood by those involved in the construction industry nor provide results that promote more sustainable practices. Models developed with location-specific practices have been criticised for their inability to be used for global comparisons of sustainability of activities. The use of overseas data for environmental impact assessment, however, is not always representative of the implications for a given location and is therefore of limited value.

A life-cycle model, developed using New Zealand data and current practices in the residential construction sector, is presented. The user interface of the model is a series of forms based on the building elements and is therefore in a format easily understood by designers. It allows the user to select from a series of generic construction types and thereby promote design evaluations based on comparative life-time performance of alternatives. By keeping various impacts separate, the model also supports design modifications to reduce the impact from the identified indicators. The user can either create a new file and fill in the quantities of material required for various building elements or modify a sample file that fits best the project in hand.

This paper highlights the need to use location-specific data in the development of building assessment schemes and the issues related to the use of traditional Life Cycle Assessment frameworks for the building sector. Current work on expansion of this model beyond the building fabric to include residential services such as water supply, waste water, etc., for greater sustainability of residential construction practices is also discussed.

KEYWORDS:

building assessment schemes; life-cycle impacts; life-cycle energy; life-cycle cost; residential infrastructure

INTRODUCTION

In 1999, the New Zealand Foundation for Research Science and Technology (FRST) contracted the University of Auckland to study current practices in the New Zealand residential construction sector and to identify ways to improve the ability of those involved in design and specification of houses to predict the environmental impact of their decisions over the life time of the houses. This paper presents the computer tool that was developed to serve the above purpose and the current research activities at Landcare Research to extend the initial tool beyond the building fabric to include residential services.

Good intentions and guesswork, without the aid of quantitative analysis, cannot guarantee that the decisions related to building activities are the most environmentally friendly. Building assessment schemes provide an evaluation of resource use in the construction industry although they may or may not use a life-cycle perspective. The use of life-cycle perspective in assessments nonetheless can provide a holistic evaluation by capturing cradle-to-grave resource use and waste generation. A general complaint about the readily available assessment schemes is that they are neither in a format easily understood by those involved in the construction industry nor provide results that promote more sustainable construction practices.

Models developed with location-specific practices have been criticised for their inability to be used for global comparisons of sustainability of activities (Larsson and Cole 2001). The use of overseas data for environmental impact assessment, on the other hand, is not always representative of the implications for a given location. For example, if the embodied energy contents of common building materials used in New Zealand[1] and Australia are considered, they vary markedly as shown in Table 1.

Table 1: Comparison of embodied energy intensity of selected building materials in New Zealand and Australia

Material	**New Zealand, Alcorn & Wood (1998)**		**Australia, Fay (1999)**	**Ratio Australia/NZ**
Aluminium, virgin	191 MJ/kg	191 GJ/t	264.2 GJ/t	1.4
Cement	9.0 MJ/kg	9.0 GJ/t	13.07 GJ/t	1.52
Concrete, ready mix, 30 MPa	3180 MJ/m^3	3.18 GJ/m^3	5.85 GJ/m^3	1.8
Copper	70.6 MJ/kg	70.6 GJ/t	607 GJ/t	8.6
Fibre cement board	116.6 MJ/m^2	0.117 GJ/m^2	0.32 GJ/m^2	2.7
Glass, toughened, 6mm	396 MJ/m^2	0.396 GJ/m^2	0.91 GJ/m^2	2.3
Insulation, glass fibre	970 MJ/m^3	0.970 GJ/m^2	0.25 GJ/m^2	2.6
Paint	6.5 MJ/m^2	0.0065 GJ/m^2	0.02 GJ/m^2	3
Plastic	103 MJ/kg	103 GJ/t	308.39 GJ/t	3
Plaster board 9.5 mm	55.95 MJ/m^2	0.056 GJ/m^2	0.14 GJ/m^2	2.5
Sand	230 MJ/m^3	0.230 GJ/m^3	0.33 GJ/m^3	1.4
Steel, stainless	50.4 MJ/kg	50.4 GJ/t	377.4 GJ/t	7.5
Timber, softwood, kiln dried	2204 MJ/m^3	2.2 GJ/m^3	11.69GJ/m^3	5.3
MDF	8330 MJ/m^3	8.33 GJ/m^3	8.52 GJ/m^3	1.02
Vinyl flooring	105.9 GJ/m^3	0.17 GJ/m^2	0.32 GJ/m^2	2.0

The above comparison shows that the Australian embodied energy intensity is around 8 times more for steel and copper, and about 6 times more for timber, than for the same materials in New Zealand. Although the wide variation in the system boundaries used for energy analysis in New Zealand and Australia, such as inclusion of third-order items like banking, insurance, etc., in Australian values, could lead to this variation, the disparity between the two economies also contributes to this. In Australia, with an energy industry heavily dependent on coal, 3.4 MJ of primary energy is used to produce 1 MJ of delivered energy as electricity (Fay et al. 2000: p.33). However, according to Baines and Peet (1995) quoted by Alcorn (2003: p.9) only 1.53 MJ of primary energy is used to generate and distribute 1MJ of electricity (delivered energy) in the New Zealand energy industry.

Environmental impacts are also dependent on the local production processes and technology, environmental laws, etc. For example, embodied energy[2] of virgin aluminium used in New Zealand is 191 MJ/kg (see Table 1). Alcorn (2001) has indicated that 191 MJ/kg includes the energy used in Australia to extract bauxite, process it into alumina, and transport it across to New Zealand. Total CO_2 emissions attributable to aluminium therefore consist of process energy-based CO_2 (both in Australia and New Zealand), and chemical process emissions both in Australia and in New Zealand. The

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[1] Updated data for New Zealand embodied energy (Alcorn 2003) were not used in this comparison due to variation in the base date which could lead to disparities (due to technological developments during this period), rendering the comparison meaningless.

[2] Embodied energy expressed in primary energy terms is a proxy for environmental implications.

aluminium manufacturing process in New Zealand is primarily energised by hydro-electricity with a CO_2 emission factor of 0.1kg CO_2/kWh. This is significantly lower[3] than electricity related CO_2 emissions of most developed countries. Carbon emissions due to electricity use vary widely depending on the fuel mix used by countries for generation, as shown in Table 2. It is therefore essential that assessment schemes use location-specific data if the results are to be relevant to a given situation.

Table 2: Carbon dioxide emission factors for electricity in selected countries[4]

Country	**Fuel mix**	**CO_2 emissions factor (kg/kWh)**	**Information Source**
New Zealand (2004)	Hydro 63.9% Gas 16.1% Coal 9.7% Geothermal 6.4% Wind 1.1% Other 2.7%	0.1 to 0.6	Ministry for Economic Development (2005) and Camilleri (2000)
UK (2005)	Natural gas 39.3% Coal 33.4% Nuclear 20.6% Renewable 3.8% Other 2.9%	0.46	Electricityinfo.org. (2006)
Australia (2005)	Black coal 54.8% Brown coal 21.9% Gas 14.2% Hydro 6.8% Oil 1.3% Other 1%	1.051	Australian Institute of Energy (2006) and Uranium Information Centre (2006)
France	Nuclear 78% Hydro 11% Fossil Fuels 10% Solar/wind 0.2% Other 0.6% (2003)	0.056 (1995)	International Energy Agency (2004) and Bustamante (2006)
Japan	Fossil Fuels 64% Nuclear 23% Hydro 11% Geothermal 0.3% Other 2.4% (2003)	0.44 (1998)	International Energy Agency (2004) and US Environmental Protection Agency (2006)
Taiwan (1999)	-	0.7	US Environmental Protection Agency (2006)
Thailand (1999)	Gas Coal Fuel oil	0.75	US Environmental Protection Agency (2006)

Buildings last a long time, making a life-cycle analysis a time-consuming and tedious task. As such, it is usually not practical for a designer to compare one design with another or to predict the effect a certain decision would have on the environmental impact of a building over its life. It is therefore useful to have a tool that will allow a building to be assessed at the design stage, so that various design options and strategies can be compared with one another based on the performance over their useful lifetime. Further, if individual effects are kept separate, it allows competing designs to be compared based on those indicators that are considered significant, and the designs can then be modified to reduce the impact of the identified indicators. Such a model can therefore facilitate a more detailed

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[3] Actual emissions are highly variable due to the hydro component which depends on the rainfall in a given year.

[4] As fuel mix used for electricity generation is highly variable between years, fuel mix and emissions shown in the table may not be for the same year.

impact analysis and can aid the decisions of those designing and specifying individual residential buildings.

Models should not, however, be used to predict the life-cycle performance of a particular design, as predicted performance will be influenced by the users of the building and will seldom match actual performance – in much the same way as the habits of different drivers affect the petrol consumption of apparently similar cars. If used for comparative analysis of alternative designs, and for assessing possible improvements to a design by modifications to and replacement of construction types and elements used, such analysis could on the other hand, provide useful information during the design phase.

LIFE-CYCLE MODEL FOR NEW ZEALAND HOUSES

Development of detailed life cycle analysis based models for building evaluations is hindered by the poor quality of data on environmental performance currently available. One way to overcome this problem is to use expert systems that have been successful for environmental evaluations in the past (Geraghty 1983; Culaba and Purvis 1999). The model based on life-cycle analysis that was generated to represent New Zealand construction practices is a stand-alone application that consists of three basic independent components: knowledge base, inference engine, and graphical user interface. This layout allows the model to be updated with reasonable ease as better quality data become available and also adapted easily for situations in other locations.

The knowledge base of the LCA model for New Zealand houses

The knowledge base contains the qualitative and quantitative data, including:

- generic construction types based on the elements of a house;
- embodied energy of NZ building materials, appliances, furniture;
- replacement cycles for building materials/components, appliances and furniture;
- installed prices of building materials/components and prices of appliances, furniture and energy;
- operating requirements (energy and CO_2 emissions) for space conditioning, appliances, lighting, hot-water system, etc.;
- greenhouse gas emissions for NZ building materials, appliances and furniture; and
- environmental impact (other than greenhouse gases) of generic construction types and space heating energy.

Six generic construction types were established based on a market survey of what is being offered to house buyers. The model is based on these generic construction types so that it is in a format familiar to building designers. The database can, however, be added to at any time to incorporate any future types.

The data on embodied energy of building materials used for the model are those published in 1998 for New Zealand building materials (Alcorn and Woods 1998). The most recent figures published in 2003 (Alcorn 2003) were not used as these are limited in their coverage of common building materials. The embodied energy of domestic appliances and furniture has not been included in the previous energy studies carried out in New Zealand, and data representative of New Zealand manufacturing and distribution systems for these items are not available. Australian studies (Treloar 1996; Fay 1999; Fay et al. 2000) have used 8–10MJ/A$ for appliances and 8MJ/A$ for furniture. Noting that the Australian values for copper and steel are 8 times that of the NZ value (as shown in Table 1) and one New Zealand dollar is 0.8 of an Australian dollar, the embodied energy of New Zealand-made domestic appliances was estimated to be 1.0MJ/NZ$. On the same basis, noting that the Australian value for timber is 6 times that of the NZ value, the embodied energy of New Zealand-made furniture was estimated to be 1.06MJ/NZ$. These values were used in the model to represent the embodied energy of appliances and furniture used in New Zealand.

Estimates of replacement cycles used in the model are as published in Mithraratne (2001). The number of times the components have to be replaced during the lifetime of the building was established using the formula: *(Useful life of the building/ useful life of the component)–1*.

Average installed prices for building materials and components used in the model are as published by the New Zealand Building Economist (Wilson 2006). The cost of electricity used for operating energy is calculated based on the standard user charges by Mercury Energy (2007) in Auckland. GST (Goods and Services Tax) at the current rate of 12.5% has been added to these figures as the above prices and charges do not include GST. The prices of appliances and furniture used in the house are based on trade literature.

Space heating energy requirement has to be calculated separately using a thermal simulation programme and transferred to the life cycle model. The actual energy use, however, is also dependent on both the heater type and the fuel type used. These data are built into the model so the total energy use is estimated. Energy uses by the domestic appliances and lighting are based on the usage pattern, number used in the house and the average electricity use for these purposes based on the Household Energy End-use Project (HEEP) study results (Isaacs et al. 2005). Electrical energy use for water heating and cooking for an average 3-person house founded on the HEEP study results is used to calculate energy use for these activities in larger houses, derived from the number of occupants.

Greenhouse gas (GHG) emissions are location specific due to the significant contribution by the energy industry of any economy. During the manufacture of building materials, GHGs are emitted from chemical reactions in the production process and process energy use. The CO_2 equivalent GHG emission factors for building materials that have been published (Alcorn 2003) are limited in their coverage. Hence, CO_2 equivalent GHG emissions for building materials used in the model are based on 1999 energy related CO_2 emissions factors and process energy use as discussed in Mithraratne 2001. GHG emissions due to appliances and furniture are calculated based on their embodied energy and the energy related CO_2 emissions factors. CO_2 emissions due to electricity used for lighting, cooking and domestic appliances are calculated by the model using the total electricity use and the electricity-related emissions factor.

Environmental impacts other than GHG emissions of New Zealand houses

Environmental impacts other than GHG emissions are evaluated based on the rating of the generic construction types using expert judgement as shown in Table 3. A score of 1 indicates the least impact among the types considered for that element, with higher ratings indicating higher impact. This rating, coupled with the percentage composition of life cycle energy for the element, is used in the model to provide an indication of the impact. This would allow designers to decide on the generic construction types to be used in NZ houses based on the life cycle environmental impact.

Table 3: Environmental impact rating of generic construction types

Generic Construction Types	Rating
Foundation	
Timber piles on concrete footing	1
Concrete piles on concrete footing	2
Reinforced concrete continuous footing	3
Floor Construction	
Timber framed with aluminum foil insulation and particle board flooring (R=1.33)	1
Timber framed with 200 mm of glass fibre insulation and 3 mm plywood and particle board flooring (R=4.4)	2
Reinforced concrete slab (R=1.62)	3
External Wall Construction	
Tongue & grooved solid timber	1
'Earth brick' wall	2
Timber-framed glass fibre insulated with fibre cement weather board cladding (R=2.2)	3
Timber-framed 200-mm glass fibre insulated with fibre cement weather board cladding (R=4.4)	4
Timber-framed glass fibre insulated with brick veneer (R=2.1)	5
Roof Construction	
Timber-framed, concrete-tiled roof glass fibre-insulated with flat gypsum plaster board ceiling (R=1.8)	1
Timber-framed, metal-clad roof with glass fibre-insulated flat gypsum board ceiling(R=1.9)	2
Timber framed metal clad roof with 200-mm glass fibre-insulated flat gypsum board ceiling (R=4.4)	3
Floor Finishes	
Parquet flooring	1
Ceramic floor tiles	2
Wool carpets	3
Vinyl flooring	4
Wall Finishes	
Wall papering	1
Wall painting	2

The environmental impact rating for space heating energy use applied in the model is as shown in Table 4. The heating requirement for the most common construction is used as a base level and is assigned the poorest rating. Environmental impact due to space heating is calculated using the rating and percentage composition of life-cycle energy. This is used to derive a combined rating for the construction type for relative performance evaluation.

Table 4: Environmental impact rating of space heating energy use

Space Heating Requirement	Rating
More than 85% of the code requirement	6
Less than 85% of the code requirement but more than or equal to 65%	5
Less than 65% of the code requirement but more than or equal to 50%	4
Less than 50% of the code requirement but more than or equal to 35%	3
Less than 35% of the code requirement but more than or equal to 20%	2
Less than 20% of the code requirement but more than 0%	1
Zero space heating energy	0

The user interface of LCA model for New Zealand houses

The graphical user interface consists of a series of forms to be filled in based on the quantities of material required to make the house, founded on building elements (foundation, floor, walls, etc.).

Depending on the stage at which the analysis is undertaken detailed quantities may or may not be available. If detailed quantities are available, the user may create a new file and input data specific to the design. The model also comes with five sample files for a house with a floor area of 100 m^2, based on the generic construction types. At an early design stage, the user can open the sample file that best suits the project at hand and modify the quantities. The results are shown both in numerical and graphical forms for embodied and operating requirements for individual elements and categories. Depending on the complexity of the house construction project being evaluated, the actual time needed for the analysis may vary from half an hour to several hours.

The model with an earlier (1996 based) data set was used by the students of the School of Architecture at the University of Auckland for design evaluations in early 2000. In addition, the model has also been validated using comparative energy studies of New Zealand residential buildings (Mithraratne 2001; Mithraratne and Vale 2004a, b). The details of the model and various analyses of New Zealand residential construction practices using the model are published in Mithraratne et al. (2007).

The results suggest that operating energy is a significant component of the life cycle energy. Additional insulation considerably improves the life-cycle performance of the common New Zealand house by reducing the space heating energy requirement. Although climate and house size impact on the performance, introduction of additional insulation alone could be used to reduce the overall impact. Furniture and appliances make a significant contribution over the useful life of the building due to the relatively short useful life of these items. The results highlight the critical role of occupant actions during the post-construction phase in determining the overall performance.

Life-cycle model beyond the building fabric

This life-cycle model is limited to the building fabric and activities within the building. Inclusion of residential support systems such as water services, energy services, garbage disposal and road networks, etc., in life-cycle assessments could increase the opportunities for improved sustainability in the residential sector. Since 2005, research at Landcare Research has therefore concentrated on extending this model to include urban residential services. Work to date has concentrated on alternative systems for water supply to houses in urban developments within Auckland. Alternatives considered were:

- mains supply providing the total residential demand,
- rain tanks supplying the total residential demand, and
- mains supply supplemented by rain tanks, so 65% of the total residential water demand (for non-potable uses) is supplied by rain tanks.

A life-cycle study of the mains supply system serving Auckland city, where 62% of water supplied is being used in the residential sector, was undertaken to establish resource use at various stages and for different activities by the system (Mithraratne and Vale 2007a). It was found that the system operating requirements far exceeded the construction requirements, even though construction materials were an important determinant of the construction resource use. The study also considered the impact of settlement characteristics, such as development pattern, building density, site configuration, etc., on long-term performance and found that the resource use is governed by the materials used for the network and the length of the network necessary to supply each house rather than by the settlement characteristics. This study highlighted the significance of reducing water consumption as a way to increase resource efficiency and to reduce environmental impacts.

In terms of using rain tanks to supply the total residential water demand in the current housing stock, it was found that this is feasible only in larger houses, noting that the floor area of the New Zealand house has increased by 33% between 1970 and 2000 (Centre for Housing Research 2004). The use of rain tanks alone to supply the total residential demand eliminates the network losses that together with fire demand have been estimated to be 12% of the total supply in Auckland. However, this would require a large rain tank (25 m^3). Accommodating such large tanks may be difficult in smaller sites while water quality and fire fighting requirement would be further concerns with the use of only a rain tank for domestic water supply. An alternative is to supplement the mains supply with a smaller rain tank (9 m^3) supplying only the non-potable water requirements of the house. The use of the three alternative systems to provide a similar service to New Zealand houses found that the rain tank material (concrete or plastic) is crucial in terms of the total performance of the system. The best option in terms of life-cycle performance is to use a concrete rain tank system to supply the total domestic demand. This is lower in life cycle energy, carbon emissions and cost compared with any of the other alternatives (Mithraratne and Vale 2007b).

CONCLUSION

- Assessments using a life-cycle perspective provide a holistic evaluation of the implications of development decisions.
- The use of data representative of the specific activities being considered is vital if the results are to be meaningful and promote more sustainable practices.
- The actual long-term performance of development activities is quite different from the perceived performance.

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