Available online at www.sciencedirect.com
SCIENCE DIRECT®

Building and Environment 39 (2004) 483–492

BUILDING AND ENVIRONMENT

www.elsevier.com/locate/buildenv

Life cycle analysis model for New Zealand houses

Nalanie Mithraratne*, Brenda Vale

School of Architecture, The University of Auckland, Private Bag 92019, Auckland, New Zealand

Received 25 July 2003; received in revised form 15 September 2003; accepted 18 September 2003

Abstract

Globally designers are concentrating on minimising the impact their buildings make on the environment. Although many claim their buildings to be sustainable, unless an objective analysis is carried out, it is not possible to determine the impact that a particular building has on the environment. This paper describes a method that has been developed at the University of Auckland for a detailed life cycle analysis of an individual house in New Zealand based on the embodied and operating energy requirements and life cycle cost over the useful life of the building.

Keywords: Life cycle analysis; Life cycle cost; Life cycle energy; Embodied energy; Operating energy

1. Introduction

Throughout the useful life of a house, energy is expended and costs are incurred to maintain and operate it at a habitable level. Although, historically, attention was focussed on the operating energy, the importance of both embodied and operating energy attributable to buildings has been highlighted by recent Australian research [1]. Although it is possible to claim that buildings are sustainable, for a holistic evaluation of the environmental impact a building makes on the environment, an objective analysis is required. While such an analysis should consider both operating as well as construction requirements of various buildings, the evaluation should cover the total useful life of such buildings. Life cycle energy if quantified in terms of primary energy can give a useful indication of the greenhouse gas emissions attributable to houses and therefore the environmental impact.

Although life cycle analysis has been used by researchers for performance analysis of New Zealand residential constructions, all such studies have been limited to a short useful life of 25–50 years [2,3] based on the requirements specified for structural members in the building code [4]. However, the use of this shorter lifetime would undermine the potential long-term benefits from the energy embodied in the building materials used for the construction. Although, Johnstone [5] used 90 years for his life cycle analysis, maintenance schedules used for that study were based on a small sample of government housing, which may not represent the general condition in New Zealand. Further, none of these studies included operating or embodied energy requirements of appliances/equipment or embodied energy of furniture, all of which require frequent replacement due to the short useful life.

The design decisions are evaluated by individual house owners based on the value provided for the money they spend among many other things, and therefore the initial and more importantly the life cycle cost of design decisions becomes a deciding factor. However, as discussed by Adalberth [6], since buildings last a long time compared to building materials and equipment, the data required for an analysis of life cycle energy and cost are numerous and analysis would be tedious and time consuming. It is therefore not practical for a designer to predict the effect a certain design decision would have on the environmental impact of a building over its life. It is even harder to compare one design with another. Therefore, it is often useful for a designer to have a tool, which 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.

The Green Home Scheme [7] developed by the Building Research Association of New Zealand is a rating scheme for

---

* Corresponding author. Tel.: +94-9-373-7599 x83790; fax: +94-9-373-7694.
E-mail address: n.mithraratne@auckland.ac.nz (N. Mithraratne).

0360-1323/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/j.buildenv.2003.09.008

new residential constructions, aimed to provide designers with such a tool. However, the Green Home Scheme approaches environmental impact rating using a broad-brush manner that considers a wide range of criteria. The method described in Section 2 of this paper which has been developed at the University of Auckland as a design tool, provides a more detailed impact analysis of individual residential buildings in New Zealand. This computer model was developed with funding from the Public Good Science Fund of the Foundation for Research, Science and Technology of New Zealand.

2. Description of the model

The life cycle analysis model developed at the University of Auckland, New Zealand is a simple method that can be used to quantify the environmental impact of New Zealand house designs over their useful life. This model, which is based on New Zealand embodied energy data and the useful life of building elements, materials and equipment, for generic construction types used in New Zealand, allows the designer to make changes and rapidly to see the differences between a number of possible designs. Therefore, the designers are able to evaluate their designs based on embodied energy, operating energy and life cycle energy. The decisions can further be evaluated on the initial and life cycle cost of the building. Most importantly, this model evaluates the total impact of the building in terms of energy and cost as it includes items such as appliances and furniture, which have not been included in the studies carried out so far in New Zealand.

Simulations can be carried out either by selecting a sample file that best suits the project in hand and modifying it, or from scratch by generating a new file. Based on the complexity of the design, modelling could take from half an hour to several hours. Although, the model can be used for comparative analyses in terms of life cycle performance, as with any other simulation method, the model is not intended to be used to predict the life cycle performance of a particular design, as predicted performance often may not be matched by the actual.

Although the model is based on generic construction types used in New Zealand identified by an initial market survey of what is being offered to purchasers by the house manufacturers at the current time, this could be adapted easily to include any other building types that may be identified subsequently. The model was designed this way so that it is in a format building designers are familiar with. Currently, other more sustainable building techniques are being investigated as a second stage and will be added to the model knowledge base at a later stage.

The embodied energy of building materials commonly used in New Zealand was initially published by Baird and Chan [8] and has been updated twice since then. The data used for the model are the most recent update for New Zealand building materials by Alcorn and Wood [9]. Maintenance schedules are built into the model so that the embodied energy of maintenance can also be included over the life of the building and are as given in Table 1.

The model uses current prices for building related activities and energy, to estimate the net present value of the total investment. The use of real costs, i.e. current costs with no inflation included (these provide an accurate comparison as the need to predict future rates of inflation is eliminated), discounted from the date on which they occur to the beginning of the occupation and then added would represent the total amount that has to be set aside today to finance the expenses throughout the useful life. Although it may be argued that this does not represent the true picture, provided the model is used for comparison of competing design alternatives, it is possible to measure the life cycle performance in terms of relative life cycle cost. The data used for the model are the average installed prices of building materials and constructions published by the New Zealand Building Economist [10] and current energy prices. Goods and services tax at the current rate of 12.5% has also been added to the final cost.

Greenhouse gas emissions due to New Zealand building materials are still being studied by the Building Research Association of New Zealand. However, the model includes a database of greenhouse gas emissions for New Zealand building materials derived for this research project based on the process energy requirements and additional emissions due to manufacturing processes. Once more complete and reliable data become available, it can be incorporated into the model.

The model also includes an indicator of the environmental impact. With the assumption that the environmental impacts other than greenhouse gas emissions are not location specific, generic construction types used for New Zealand residential constructions were rated based on the information published by Woolley et al. [11,12] for the UK and are as given in Table 2. The environmental impact indicator is achieved by coupling this information with the percentage composition of the life cycle embodied energy. The impact of the use of a certain generic construction type would be the assigned rating multiplied by the percentage of the item in the total life cycle embodied energy. Although it could be argued that this is not a quantitative assessment as value judgement is used to rate the construction types, this provides a reasonable indicator of the impact with the limited information available. Table 3 rates actual space heating energy use with respect to the building code requirement for the common timber framed house. As the purpose of the rating scheme is to promote better performance, the constructions using the standard practice currently would only be able to achieve the lowest ranking of 5. When the total environmental impact is calculated the composition of life cycle energy rather than the embodied energy is used. The impact would be the product of environmental impact rating multiplied by the percentage in the life cycle energy.

Table 1
Replacement cycles for building components and elements

Building component	Materials	Useful life in years
Substructure	Timber piles, concrete slab	> 100
Floor	Floor framing, joists, flooring	> 100
Walls	Timber studs and wall framing, plaster board, insulation, skirting, brickwork, mortar, cavity ties, flashings	> 100
	Fibre cement weatherboard	50
	Wooden panelling	30
	External rendering	60
Roof	Timber/steel roof frame, plasterboard ceiling lining, concrete tiles	> 100
	Steel roofing sheets	40
	Gutters and down pipes	20
Electrical work	Wiring, switch board, power outlets	50
Joinery	Aluminium window frames, external and internal doors, frames, door and window furniture, glazing	60
Plumbing	Hot water service	16
	Sanitary fittings—basins, sinks, baths, shower trays, tapware	30
	Copper, PVC and UPVC pipes	50
	Towel rail, toilet paper holder	20
Finishes	Vinyl flooring	17
	Parquet flooring	50
	Ceramic floor tiles	30
	Wool carpets	12
	Wall paper	10
	Repaint cladding, doors, rim, ceiling	8
	Curtains	8
	Repaint roofing	10
	Kitchen upgrade	30
Furniture		25
Appliances	Electric range and oven	15
	Microwave oven	12
	Refrigerator/freezer	17
	Washing machine	14

The model thus generated which is a stand-alone application, consists of three basic independent components: knowledge base, inference engine and graphical user interface. This approach was selected due to the poor quality of data available at present, which would otherwise inhibit the use of the model. As better quality data become available the knowledge base could be updated with reasonable ease. The knowledge base contains the qualitative and quantitative data such as:

- generic construction types based on elements of a house;
- embodied energy of New Zealand building materials;
- replacement cycles for building materials/components, appliances and furniture;
- installed prices of building materials/components and current price of energy;
- operating energy requirements of appliances, lighting, hot-water system, etc.;
- greenhouse gas emissions due to New Zealand building materials; and
- environmental impacts of generic constructions and space heating energy use.

The inference engine bears the control strategies and rules, necessary to drive information from the knowledge base while the user interface which consist of a series of forms, allows the user to communicate with the model by selection and input of data, thus allowing the knowledge base to provide responses.

At present, the graphical user interface requires the user input based on the quantities of material required to make the house, while the space heating energy requirement has to be separately calculated and transferred. This space heating energy requirement is further modified by the model depending on the heater type used, while other operating energy requirements are calculated by the model based on

Table 2
Environmental impact rating for 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 aluminium 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

Table 3
Environmental impact rating for space heating energy use

Space heating requirement	Rating
Less than 80% 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 number of occupants and the appliances selected. It is hoped to link the model to an architectural drawing package and a thermal simulation package in the future so that the material quantities generated in the drawing package and space heating energy requirement, from the thermal simulation package can form the input to the life cycle model.

The model has been used by the students of the School of Architecture at the University of Auckland for design evaluation since 2000. In addition, the model has been validated using comparative energy studies of New Zealand residential buildings [13].

The rest of the paper discusses the use of the model for an analysis of three forms of residential constructions in the Auckland region over a 100 years lifetime to investigate the use of thermal mass and insulation in a typical New Zealand house.

3. Life cycle energy analysis

3.1. The common New Zealand house

The light-weight timber framed house is the most prevalent specification in New Zealand [14]. Due to the

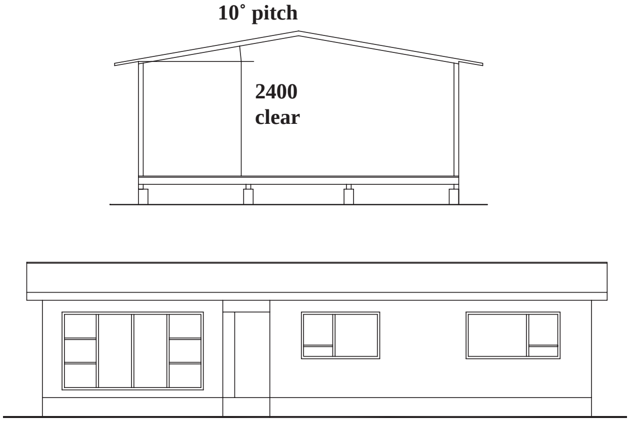

Fig. 1. Section and front elevation of BIAC standard house for NZ.

earthquake code requirements, masonry building is not common in New Zealand. Apart from a limited number of architect designed houses, the majority of new constructions are supplied by companies who prefabricate to a standard specification and may customise to suit individual client requirement. Therefore, the common house is a prefabricated timber frame assembled and fitted out on site with either pole platform or slab on ground foundation depending on the slope of the site. Generally, the wall construction is a timber frame, with 94 mm of glass fibre insulation within the frame. The internal lining is plasterboard while external lining varies from metal, fibre cement or timber weatherboard, to external plaster on mesh. The common raised floor type is particleboard on timber framing insulated with aluminium foil draped over the framework. Although this type of insulation has been shown to have practical problems of proper installation [15], it continues to be the most common. Glazing areas are often extensive, single glazed and usually with aluminium framing. Ventilation is normally achieved by opening the windows and vapour barriers are seldom found in New Zealand constructions. Due to the high number of sunshine hours in both winter and summer, condensation on single glazing dries out on a daily basis in winter, and houses often overheat in summer.

3.2. *BIAC standard house*

The Building Industry Advisory Council (BIAC) standard house (also known as Modal House of New Zealand) is a standard design that has been repeatedly used in the past by many researchers for energy simulations. The house as published by Baird and Chan [8] is shown in Fig. 1 and is described briefly as follows:

- level site,
- floor area 94 m^2 (14 m × 6.7 m),
- three bedrooms with open plan living, dining and kitchen,
- separate bath/shower, WC, laundry,
- sloping ceiling with exposed rafters in living and dining areas and flat ceiling to other areas, and
- 12 lights and 16 power points.

The life cycle analysis model developed was used with the BIAC standard house design to evaluate the use of mass and high insulation in the light construction type commonly used in New Zealand in terms of life cycle performance. The following assumptions were used to facilitate the analysis:

- house is located in Auckland;
- useful life of New Zealand house is 100 years;
- no major refurbishment is carried out during the useful life other than the normal maintenance to maintain the habitable level; and
- embodied energy of New Zealand building materials and construction practices remains static over the useful life.

3.3. *Light construction*

Specifications adopted for this most common construction used in this analysis as ‘light construction’ are as follows:

- particleboard floor on raised softwood framing, double-sided foil draped over floor frame as insulation;
- softwood framed walls with 94 mm of glass fibre insulation within the framework, plasterboard internal lining with paint finish, fibre cement external cladding;
- pitched soft wood truss roof with corrugated metal cladding, flat ceiling lined with plasterboard, roof-ceiling space insulated with 75 mm glass fibre, and
- aluminium framed windows with single clear glazing.

3.4. *Concrete construction*

The ‘high mass’ version of the timber-framed house, used in this analysis as the ‘concrete construction’, has replaced the light timber framed particleboard floor construction with a 150 mm thick concrete floor slab (the thermal mass) and 25 mm thick expanded polystyrene perimeter insulation to a depth of 500 mm.

3.5. *Superinsulated construction*

In addition to these two construction types, a highly insulated (or superinsulated) construction was added to the analysis to investigate the use of additional insulation in New Zealand houses. This highly insulated construction doubled the insulation in the common light construction to achieve an R-value of 4.4 $m^2 \cdot C/W$ all around with double-glazing for windows. Specifications adopted for this highly insulated construction, referred to as ‘superinsulated construction’ in the analysis, are as follows:

- particleboard floor on raised softwood framing, with 200 mm of glass fibre on a plywood layer as insulation;
- softwood framed walls with 200 mm of glass fibre insulation within the framework, plasterboard internal lining with paint finish, fibre cement external cladding;

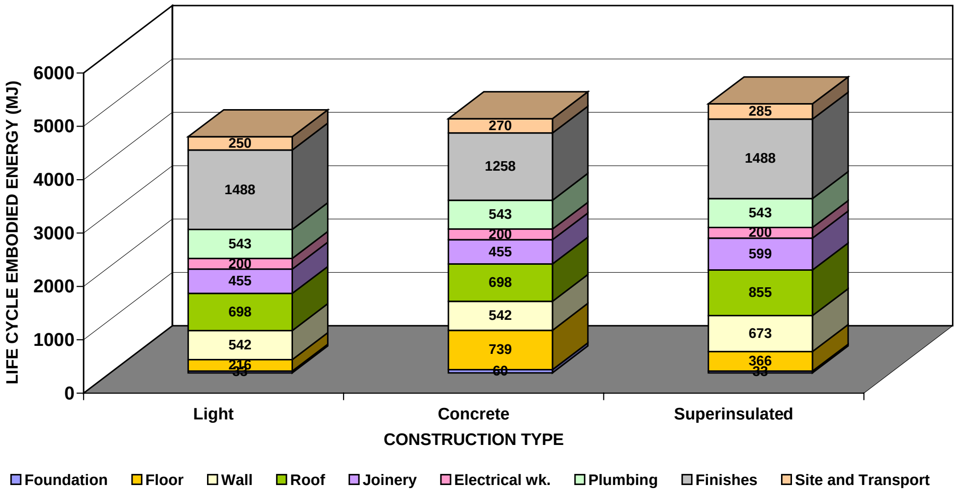

Fig. 2. Composition of 100 year embodied energy for common construction types (furniture and appliances excluded).

- pitched soft wood truss roof with corrugated metal cladding, flat ceiling lined with plasterboard, roof-ceiling space insulated with 200 mm glass fibre; and
- aluminium framed windows with double clear glazing.

The above constructions were modelled for life cycle energy. Embodied energy was calculated using the model while the space heating energy requirement was calculated using annual loss factor (ALF) version 3.0 [16]. ALF is an energy simulation tool developed by the Building Research Association of New Zealand, for New Zealand. Houses were simulated for 18°C whole house heating with whole day heating (i.e. 7.00–23.00 h). Although this assumption would seem some what unrealistic in the present context, where thermal comfort expectations of New Zealanders are presumed to be lower, the houses are modelled over a period of 100 years and research [17] suggest that the thermal comfort expectations of New Zealanders would improve over the years. It was also assumed that main living areas face north-east, which is desirable for early morning warm up of spaces during the winter.

3.6. *Analysis of the results*

A building element with high initial embodied energy content could also have a longer useful life leading to a lower overall embodied energy. Therefore, a comparison of 100-year embodied energy could aid in selecting construction types based on the life cycle embodied energy. Life cycle embodied energy for the three constructions were 4425, 4764 and 5041 MJ/m^2 for light, concrete and superinsulated constructions, respectively. Therefore the common construction is 8% and 14% lower in life cycle embodied energy than the concrete and superinsulated construction types respectively. Fig. 2 is a comparison of 100-year life cycle embodied energy for the three construction types used. For all the construction types, the major elements (floor, walls and roof) collectively represent the bulk of the life cycle energy (34%, 43% and 38%) of the New Zealand house while finishes also make a major contribution due to the shorter useful life at 34%, 26% and 30% for light, concrete and superinsulated constructions, respectively. Even with furniture and appliances added, the major elements represent 24%, 31% and 28% with finishes contributing 24%, 19% and 22% respectively for light, concrete and superinsulated constructions. More importantly furniture and appliances collectively contribute 29%, 27% and 26% of the life cycle embodied energy for light, concrete and superinsulated constructions, respectively. Fig. 3 is a comparison of 100-year life cycle embodied energy with furniture and appliances added in. From the above, it could be concluded that preliminary energy calculations for the main building elements could aid in the selection of design and construction types suitable for any situation.

In order to evaluate the constructions in terms of the life cycle energy, the operating energy requirements were then added to the model. Although space heating energy use would depend on the construction aspects all other operating energy uses would depend on the user behaviour. According to the thermal simulations using ALF, the space heating energy requirement for the BIAC house was 2149, 1958 and 1159 kWh/annum. Since published embodied energy intensities are in terms of primary energy, this space heating energy load was also converted to primary energy with the assumption that all houses use 100% efficient electrical heaters for space heating. According to statistics, 95% of houses in New Zealand use electricity for heating, cooking and hot water [18]. Lighting, water heating, cooking and other appliance energy requirements were established based on previous studies [17] on usage patterns in New Zealand. Fig. 4 shows a comparison of embodied and space heating energy requirements of the New Zealand house over a 100 year life. Other operating energy requirements have been disregarded in this analysis, as these would be similar for

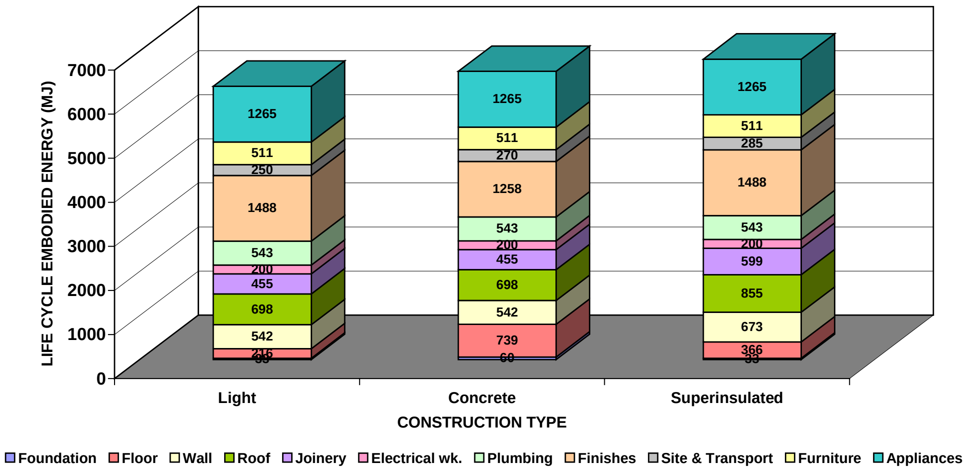

Fig. 3. Composition of 100 year embodied energy for common construction types (furniture and appliances included).

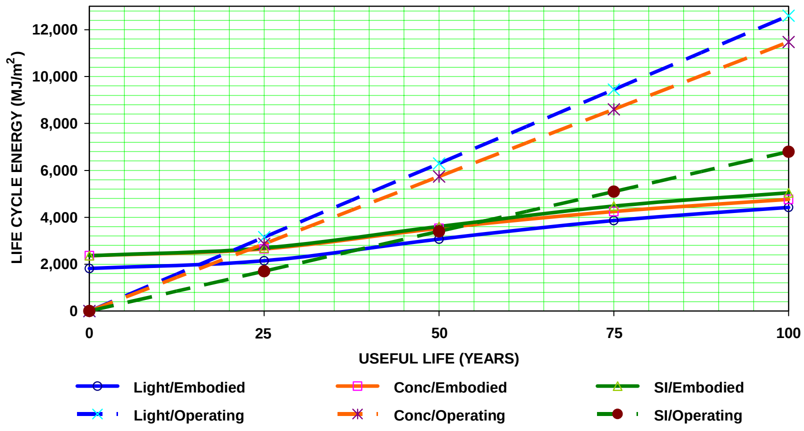

Fig. 4. Comparison of life cycle embodied and operating energy for common construction types (furniture and appliances excluded).

all three constructions. The initial embodied energy values for concrete and superinsulated construction types are 30% more than light construction, while 100 year life cycle embodied energy is only 8% and 14%, respectively more than light construction. If the life cycle operating energy is considered, concrete and superinsulated constructions are 9% and 46%, respectively lower than the light construction type. Overall life cycle energy for the three construction types is, 17017, 16237 and 11832 $\mathrm{MJ/m^2}$, for light, concrete and superinsulated construction types, respectively. Life cycle operating energy contributes 74%, 71%, and 57% of this total life cycle energy for light, concrete and superinsulated construction types, respectively. The use of additional insulation in the common New Zealand house, which reduces the space heating energy load, alone could reduce the life cycle energy by 31% compared to the light construction. Although life cycle energy of concrete construction is 5% lower than the light construction the reduction is not very significant in this case. However, the design used for this analysis was not specifically designed to be a passive low-energy house with careful positioning of the thermal mass, but is the standard design used for most New Zealand house constructions by the developers.

4. Life cycle cost analysis

The life cycle cost of the construction types were then calculated using the model with current energy prices and a 5% discount rate. Life cycle costs thus calculated represent the present value of the total investment required over the useful life to maintain different construction types at habitable level. For light, concrete and superinsulated constructions, the initial cost is 672, 775 and 827NZ$/$\mathrm{m^2}$ respectively, while the life cycle cost is 917, 1021 and 1049NZ$/$\mathrm{m^2}$ respectively. Fig. 5 is a comparison of life cycle energy and life cycle cost with furniture and appliances disregarded. In terms of initial cost light construction is 15% and 23% lower than concrete and superinsulated constructions, respectively. Even in terms of life cycle cost, the light construction type is 11% and 14% lower for concrete and superinsulated constructions, respectively.

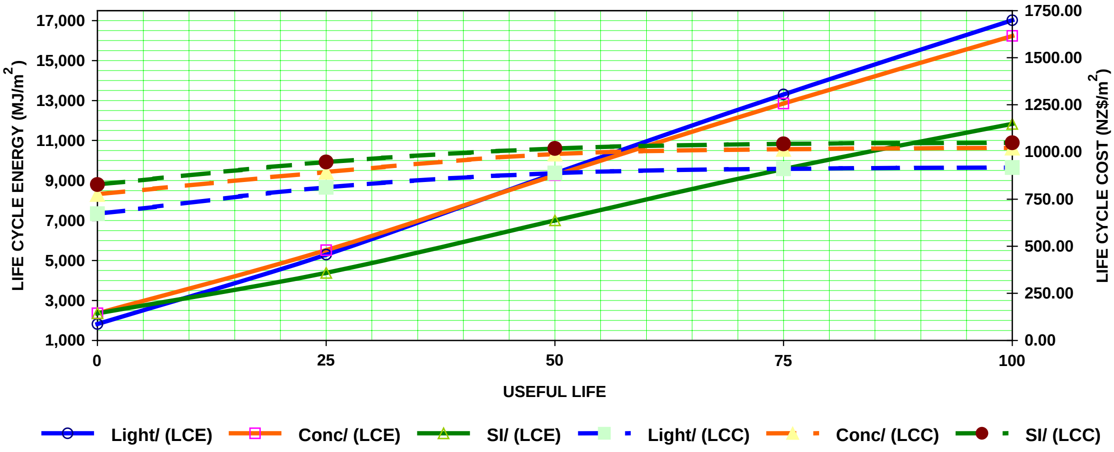

Fig. 5. Comparison of life cycle energy and cost at current energy prices (furniture and appliances excluded).

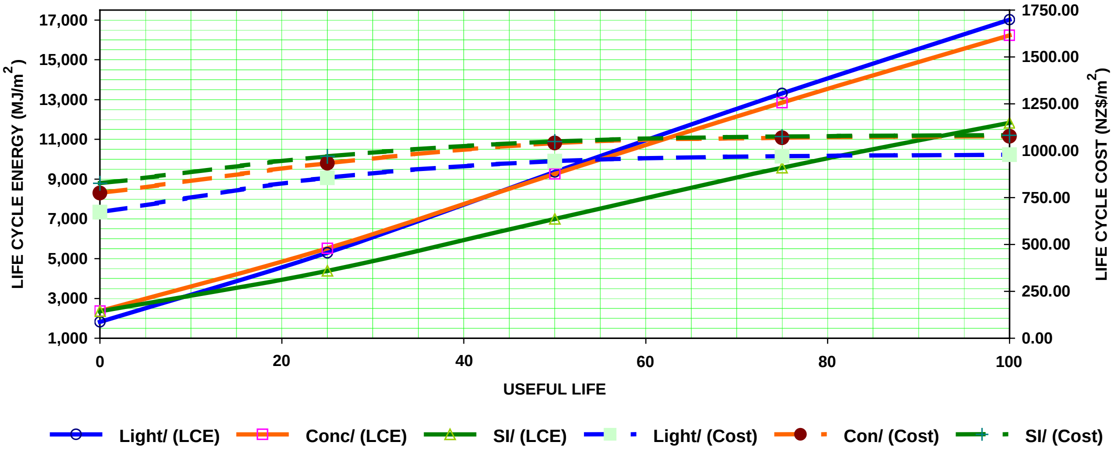

Fig. 6. Comparison of life cycle energy and cost at 100% increase in energy prices (furniture and appliances excluded).

Fig. 6 is a comparison of life cycle energy and cost with a 100% increase in energy prices. Even with 100% increase in the current energy prices, the light construction type remains 10% and 11% lower in life cycle cost than concrete and superinsulated construction types. Therefore, the marginal increase in the initial cost associated with higher insulation does not seem to provide cost benefit to the individual house owner in this instance. However, space heating energy requirements contribute 74%, 71%, and 57% of total life cycle energy for light, concrete and superinsulated construction types, respectively, and the current electricity prices charged in New Zealand are among the lowest in the OECD countries [19]. In any case this additional insulation could buffer the house owner against any sudden increase in energy prices similar to those experienced by the New Zealand industries during the recent energy crisis in the form of high spot prices for bulk electricity, while maintaining the house at a higher internal temperature, which will offer improved comfort and health benefits. Further, this analysis was based on a 5% discount rate, which would represent the rate of return for money invested. However, as argued by Awerbuch [20], the benefits to the society of using less energy would continue for a longer period than considered in economic analyses of this nature.

5. Life cycle environmental impact analysis

The environmental impacts due to the three construction types were then calculated using the rating system devised as given in Tables 2 and 3. The New Zealand Building Code [21] defines the requirements for the internal environment and the space heating energy demand for the BIAC standard house located in Auckland calculated based on the building code to be 2050 kWh/annum. Based on this, and the rating scheme devised earlier, space heating requirements for light and concrete constructions would be rated 5, while superinsulated construction would be 3. Table 4 is a comparison of life cycle environmental impact for three construction types in use. The contribution made by various components to the total varies with the construction type although the contribution by space heating is the most significant. For light,

Table 4
Comparison of environmental impact of the three construction types

	Light construction			Concrete construction			Superinsulated construction		
	Rating	% LCE	Impact	Rating	% LCE	Impact	Rating	% LCE	Impact
Foundation	2	0.29	0.59	3	0.31	0.93	2	0.36	0.73
Floor	2	1.93	3.85	3	3.79	11.37	1	4.03	4.03
Wall	3	4.83	14.50	3	2.78	8.35	4	7.40	29.61
Roof	2	6.23	12.45	2	3.58	7.17	3	9.40	28.21
Joinery	1	4.05	4.05	1	2.33	2.33	1	6.58	6.58
Electrical wk.	1	1.78	1.78	1	1.02	1.02	1	2.20	2.20
Plumbing	1	4.84	4.84	1	2.79	2.79	1	5.97	5.97
Floor finishes	4	9.09	36.34	2	4.04	8.08	4	11.21	44.84
Wall finishes	2	4.18	8.36	2	2.42	4.83	2	5.16	10.32
Site energy	1	2.23	2.23	1	1.38	1.38	1	3.14	3.14
Space heating	5	60.55	302.74	5	75.55	377.74	3	44.54	133.62
Total		100.00	391.74		100.00	426.00		100.00	269.25

heavy and superinsulated constructions the contribution due to construction alone is only 39%, 24%, and 55%, respectively. The total environmental impact of the light construction type is 31% more than superinsulated construction type and it is 9% less than that of the heavy construction type. Although the construction impact analysis using embodied energy could aid in selecting the suitable generic construction type, life cycle impact analysis indicates the performance of the building in use. In selecting a suitable construction type, the total performance has to be considered.

6. Conclusions

The research demonstrates the importance of life cycle analysis in the efficient use of limited resources in the residential building sector. For common constructions currently used in New Zealand houses, operating energy is a significant component of the life cycle energy. Reduction of life cycle energy is not reliant on the use of thermal mass, which is less common due to the requirements of the earthquake code. However, if mass is used combined with passive solar design principles it could enhance performance although this may be difficult to achieve on small sites in Auckland. Provision of additional insulation does significantly improve the performance of the common light timber framed house. Further, though insulation is not a component of sustainable low-energy housing at present it could be effective.

The decision to invest or not in additional insulation would depend on the cost. The initial cost of construction increases with the additional insulation and remains higher throughout the useful life. Although the marginal increase in cost does not provide benefit to the individual house owner, it could buffer the owner against any sudden increases in energy prices while providing improved comfort and additional health benefits. However, economic analysis of this nature does not provide a true picture of the advantages of energy efficiency measures to society.

The environmental impact follows a pattern similar to that of life cycle energy use, and the use of additional insulation significantly reduces the overall environmental impact.

Finishes, appliances and furniture make a significant contribution over the useful life due to the relatively short life of these items. Improvements in performance of these could be expected to improve the performance quite significantly.

- Improved insulation of New Zealand houses would be the first step to lessen their environmental impact.
- For a quick comparative analysis operating energy is a useful shorthand way to predict the overall environmental impact.

Acknowledgements

This research was funded by a grant from the Public Good Science Fund of the Foundation for Research Science and Technology of New Zealand.

References

[1] Fay R, Treloar G, Iyer-Raniga U. Life cycle energy analysis of buildings: a case study. Building Research & Information 2000;28(1):31–41.

[2] Buchanan AH, Honey BG. Energy and carbon dioxide implications of building construction. Energy and Buildings 1994;20:205–17.

[3] Jaques R. Energy efficiency building standards project: review of embodied energy. Proceedings of the Embodied Energy: The Current State of Play Seminar. Deakin University, Geelong, Australia, 28–29th November, 1996. p. 7–14.

[4] Haberecht PW, Bennett AF. Experience with durability assessment and performance-based building codes. First Asia Pacific Conference on Harmonisation of Durability Standards and Performance Tests for Components in Buildings and Infrastructure, Bangkok, Thailand, September 8–10, 1999 (reprint BRANZ Conference Paper No. 72, 1999).

[5] Johnstone IM. Energy and mass flows of housing: a model and example. Building and Environment 2001;36(1):27–41.

[6] Adalberth K. Energy use during the life cycle of buildings: a method. Building and Environment 1997;32(4):317–20.
[7] BRANZ Green home scheme: home owners guide. Wellington: Building Research Association of New Zealand; August 1997.
[8] Baird G, Chan SA. Energy cost of houses and light construction buildings. Auckland: New Zealand Energy Research and Development Committee; 1983.
[9] Alcorn A, Wood P. New Zealand building materials embodied energy coefficients database, vol. II—coefficients. Wellington: Centre for Building Performance Research, Victoria University of Wellington; November 1998.
[10] Willson D, editor. New Zealand building economist, vol. 29(3). Auckland: Plans & Specifications Limited; August 2000.
[11] Woolley TS, Kimmins P, Harrison P, Harrison R. Green building handbook: a guide to building products and their impact on the environment. New York: E and FN Spon; 1997.
[12] Woolley TS, Kimmins P, Harrison P, Harrison R. Green building handbook: a guide to building products and their impact on the environment, vol. 2. New York: E and FN Spon; 2000.
[13] Mithraratne MNS. Life cycle energy requirements of residential buildings in New Zealand. Ph.D. thesis, The University of Auckland, New Zealand, 2001.
[14] Vale B, Mithraratne N, Vale R. Superinsulation for the Auckland climate, in architecture, city, environment. In: Steemers K, Yannas S, editors. Proceedings of PLEA 2000 Conference, 2–5th July, Cambridge. London: James and James; p. 150–4.
[15] Isaacs NP, Trethowen HA. A survey of house insulation. Wellington: Building Research Association of New Zealand; 1985.
[16] Stoeklein A, Bassettt M. The annual loss factor method: a design tool for energy efficient houses, 3rd ed. Judgeford: Building Research Association of New Zealand; 2000.
[17] Wright J, Baines J. Supply curves of conserved energy: the potential for conservation in New Zealand's houses. Wellington: Centre for Resource Management, University of Canterbury and Lincoln College; September 1986.
[18] Statistics New Zealand. New Zealand now: Housing. Wellington: Statistics New Zealand; December 1998.
[19] Ministry of Commerce. New Zealand energy data file: January 2000. Wellington: Energy Modelling and Statistics Unit, Ministry of Commerce; 2000 (compiled by Dang Hien DT.).
[20] Awerbuch S. Issues in the valuation of PV/renewables: estimating the present value of externality streams with a digression on DSM. Proceedings, National Regulatory Conference on Renewable Energy, NARUC, Washington, October 1993.
[21] Building Industry Authority. The New Zealand building code handbook and approved documents. Wellington: Standards New Zealand; 1992.