AUTHOR: **Zebadiah Worth (**BE (Hons)**)**

Co-authors: **Dr Carol Boyle**
Dr Ron McDowall

Presenter: **Zeb Worth**

Title of Paper: **Combined Life Cycle Cost Assessment of Roof Construction.**

Contact Information:
Zeb Worth
Environmental Engineer
Opus International Consultants
PO Box 5848, Auckland
Ph +64 9 376 5986
Mob +64 21 673 871
Zeb.worth@opus.co.nz

Abstract:

This paper develops a methodology for incorporating the in-direct ‘costs’ of life cycle CO_2 emissions and embodied energy with the life cycle economic costs of four different types of roof construction common in New Zealand. A desktop study was undertaken comparing four alternative cladding/framing options for constructing the roof of a hypothetical design building. The two cladding options chosen are steel sheeting and concrete tiles, with the two framing options being softwood timber trusses and lightweight structural steel framing. The material quantities, embodied energy and CO_2 emissions of each roof configuration have been assessed using simplified life cycle models. The combined life cycle cost of each roofing system has been determined by adding the material costs with the estimated ‘costs’ of the embodied energy and CO_2 emissions. Material costs have been determined based on current installed prices and the maintenance costs discounted to net present values. The embodied energy and CO_2 emissions have been calculated using previous input-output models developed for New Zealand building materials. It was generally found that concrete tiled roof structures had lower overall combined life cycle costs when compared to the steel sheeting options, mainly due to the greater durability and lower embodied energy content of the concrete tile cladding. It is hoped that including the environmental ‘costs’ as a monetary value will help housing developers and stakeholders to quickly assess which alternatives are the most sustainable.

1. Introduction

As human populations grow, social and environmental systems are coming under increasing pressure. This makes the need for a sustainable relationship between these systems an important issue. The houses in which we live play a fundamental role in this relationship, acting as part of the interface between the human and natural worlds. The design of these houses is therefore a crucial factor in making this relationship sustainable.

Historically in the design of sustainable housing, much of the focus has been on the operation phase of the building's life, e.g. passive ventilation and lighting, reduced energy and water use etc. This is indeed an important consideration of sustainable building design, as previous studies have shown that up to 80% of the life cycle energy in residential housing can be attributed to this operational phase (Pullen, 1996). However, there are many other factors which can affect the overall sustainability of the buildings we live in.

For example, the energy used in processing and manufacturing the materials out of which the building is constructed, and the maintenance requirements of those materials, can have a significant impact on a building's overall sustainability. Among other things, sustainable building materials should have low embodied energy and low carbon dioxide emissions (Buchanan, 2006). These two attributes are commonly accepted as good indicators of the basic sustainability of building materials as they are relatively easy to quantify and lend themselves readily to direct comparison.

More often than not, the selection of materials is based primarily on the purchase and installation costs of those materials and - given the competitive nature of today's building industry - cost is likely to remain the determining factor in the selection of materials and construction methods. However, in order to establish the true 'cost' of competing alternatives it is necessary to take a more holistic approach. By including the cost of life cycle embodied energy and carbon dioxide emissions of the material with the direct economic costs, a more complete cost basis can be established. For example, choosing concrete tiles over light weight steel sheeting for the roof cladding of a building can require larger supporting members leading to greater material quantities and transportation requirements. Additionally, the manufacturing processes, life span and maintenance requirements of each material will affect the respective embodied energy and CO_2 emissions.

2. New Zealand Roofing Materials

Currently, the most common types of roof construction used in residential developments in New Zealand consist of lightweight corrugated steel sheeting or concrete tiles, supported by pre-fabricated softwood trusses. However, particularly in large scale residential developments, lightweight steel roof framing is being increasingly used. The increased popularity of lightweight steel roof framing is due to a number of perceived advantages over traditional timber framing, including ease of construction, increased strength, more consistent material properties, better fire resistance, improved durability and reduced waste. Many manufacturers and roofing contractors are now specialising in lightweight steel framing, marketing it as a cost effective and environmentally friendly alternative to timber. However, very few, if any, independent studies have been carried out to substantiate these claims.

Before adopting new construction methods or technologies, it is important to know how they compare with the existing practices they will potentially replace. Practices that are promoted as being "greener" solutions do not always live up to this claim. For example, many vinyl flooring companies promote their products as being “green” and sustainable based on the argument that they are made largely from recycled, post consumer waste plastics. While the use of recycled material in the products is at least a step in the right direction, these claims ignore the high levels of toxins, such as dioxins and volatile organic compounds (VOCs), released during the manufacture, maintenance and use of these products. In fact , in 2006 the New York State Supreme Court rejected the flooring industry’s claim for “green” certification of vinyl flooring based on the toxic emissions associated with the products (Healthy Building Network, 2006). Often claims are made based purely on the initial or direct impacts that can be attributed to a product or the data are “greenwashed” to focus only on benefits while ignoring the downsides. In order to meaningfully assess the performance of competing alternatives, it is useful to know how they compare over their entire lives. One method that is being increasingly used to determine the life cycle impacts of products and processes is Life Cycle Analysis (LCA).

3. Life Cycle Analysis (LCA)

LCA is the process whereby the environmental impacts and energy requirements of materials and products are assessed over their life cycle. Inputs and outputs are accounted for during the various stages of a product’s life, from raw material extraction to processing, transport, use and disposal. A life cycle analysis essentially consists of three main stages ; Life cycle inventory; Life cycle impact analysis; and Life cycle improvement analysis (SETAC, 1992).

The first stage (life cycle inventory) is perhaps the most important of these three stages, as this is where the inputs and outputs are quantified and the results of this stage directly affect the following stages. The second stage (life cycle impact assessment) builds on the inventory by assessing the impact of the particular inputs and outputs based on environmental indicators. The last stage (life cycle improvement analysis) generally only applies in product development scenarios, where improvements to processing and manufacturing techniques can be adopted based on the outcome of the inventory and impact analyses.

However, before undertaking any LCA you must first define the goal and scope of the study. In fact this is perhaps the most critical step of all as it is during this phase that boundaries, assumptions and limitations are set. Selecting appropriate boundaries is particularly important when undertaking comparative life cycle studies, as it is vital to ensure that the boundaries take into account all inventory items particular to each option. Detailed guidelines for defining the goal and scope of an LCA study have been developed by the International Standards Organisation (International Standards Organisation, 1998). Adhering to these guidelines ensures a fair and accurate basis is selected when comparing competing options.

4. Goal and scope

4.1 Objectives

This paper is essentially a life cycle inventory study of alternative roof constructions. No conclusions have been drawn as to the environmental impacts associated with the energy inputs, resource depletion or emissions obtained from the inventory analysis. The purpose of this paper is to assess the life cycle ‘costs’ of different types of roof construction common in New Zealand. In particular, the direct economic costs, embodied energy and CO_2 emissions of each roof configuration have been estimated and compared in order to provide a basis for the selection of sustainable roofing materials.

4.2 Limitations

Due to time and data constraints, no account has been taken of occupancy energy consumption in this study, i.e. the effect of different roofing materials on the energy usage required for space heating and ventilation has been neglected. The thermal performance of the different types of construction is assumed to be the same and all ceiling spaces are assumed to be ‘perfectly insulated’. In reality, there may be a significant difference in the thermal performance of the different roofing materials and further investigation is necessary to properly address this issue.

Social impacts (such as aesthetics) are difficult to quantify and highly subjective, and have therefore been excluded from this study. While these considerations are important, their effect has been considered negligible, when compared to the economic and environmental costs, in the selection of roofing materials.

5. Methodology

For this study, simplified life cycle models have been used in estimating the direct economic cost, embodied energy and carbon dioxide emissions of the selected roof types based on available data. A detailed description of the life cycle assessment methodology and framework is available in the International Standards Organisation 14040 Environmental Management series (International Standards Organisation, 1997; 1998). Many of the recommendations set out in these documents are above and beyond the scope of this study. However, the sections of these guidelines relevant to this study have been followed.

The functional unit, as defined in ISO 14041(1998), for this assessment was chosen as the quantity of materials required to cover the roof of the Building Industry Advisory Council’s New Zealand standard house with a design life of 100 years, as described by Mithraratne (Mithraratne and Vale, 2004) and illustrated in Figure 1, with the following characteristics;

- A floor area of 94 m^2 (14 m long with a truss span of 6.7 m);
- Dual pitch roof (Gable) with a roof pitch of 15 degrees (modified from the standard pitch of 10 degrees as 15 degrees is considered the lowest practical pitch for concrete tiled roofs);
- The whole roof assumed to be trussed with flat ceilings throughout;
- The roof framing requirements have been designed for a spacing of 900mm;
- The basis of the roof designs assumes the house is located in the Auckland region and designed to New Zealand Standards (1992);
    - Category IV building;
    - Wind region II with terrain category 3 (44m/s design wind speed).

The following four roof configurations were selected for evaluation in this study, combining the materials commonly used for residential roof construction in New Zealand;

1. lightweight roofing(corrugated steel), timber framed;
2. lightweight roofing, steel framed;
3. concrete tile, timber framed;
4. concrete tile, steel framed.

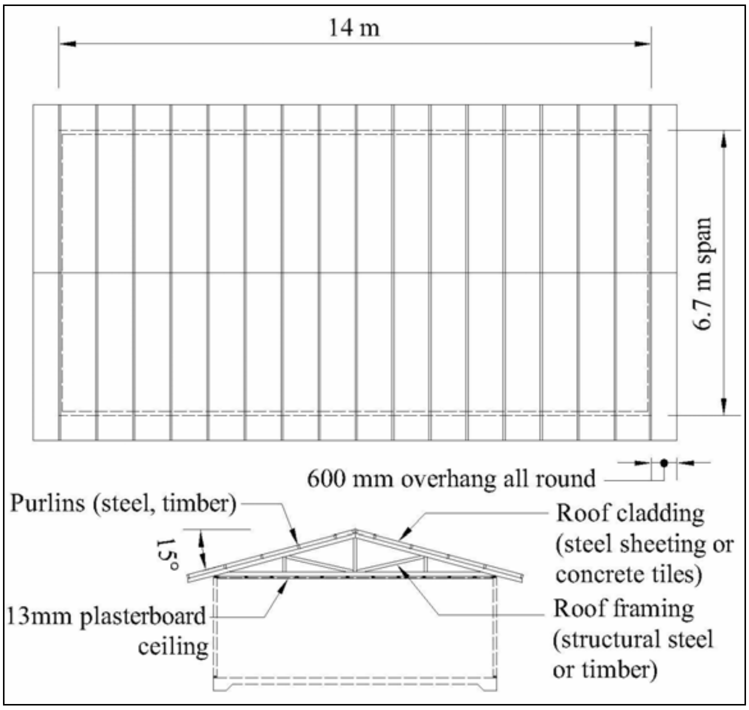

Figure 1: Plan and section of study building (adapted from Mithraratne)

The economic costs of the various building materials were taken from the New Zealand Building Economist (Wilson, 2007) These costs include the transport and labour costs associated with the construction requirements of each material and have been calculated as present costs with no adjustments, i.e. it is assumed that the costs occur at the time of construction. New Zealand GST of 12.5% has been added to both the initial construction cost and the final maintenance costs. Maintenance costs have been estimated as the initial construction costs of each material occurring in the year in which the material is replaced. All future maintenance costs, including those associated with energy and emissions have been calculated to net present value, i.e. the replacement ‘cost’ of the material discounted from the year in which replacement occurs to the present day with a discount rate of 5% and no allowance for inflation. Energy costs are based on the average weighted cost (20.37c/kWh) of domestic electricity as of February 2007 published by the Ministry of Economic Development (Ministry for Economic Development, 2007). The cost of CO_2 emissions is based on the best predicted value of carbon offsets published for the New Zealand Treasury (Allen Consulting Group, 2005). This report was based on New Zealand’s commitments under the Kyoto Protocol and gives a best estimate value of $US7.00 per metric tonne of CO_2. This cost has been converted to a value of $NZ9.59 using the current exchange rate as at 19 May 2007.

Table 1: Expected useful life of roof elements (adapted from Mithraratne 2004)

Material	Expected life in years	Reference
Concrete roofing tiles	50	CSR Roofing
Fibreglass insulation	>100	Mithraratne
Paint	12 years (concrete tile) 10 years (steel)	Mithraratne and Resene Paints
Plasterboard	>100	Mithraratne
Steel roof sheeting	40	Mithraratne
structural steel roof framing	>100	Mithraratne
Timber roof framing	>100	Mithraratne

The calculation of maintenance costs are based on the expected useful life of each material taken from similar studies (Mithraratne and Vale, 2004) and industry publications. These life spans are shown in Table 1. As the expected life of all materials apart from the cladding and paint systems have been determined to be greater than the 100 year lifespan of the design building, maintenance/replacement scenarios have only been developed for these materials.

Embodied energy coefficients have been taken from the Victoria University Centre for Building Performance and Research Embodied Energy Database developed by Alcorn (Alcorn and Wood, 1998) and the revised version of this database (Alcorn, 2003). The final embodied energy of each construction type has been estimated as the embodied energy of the relevant materials plus the energy used erecting the materials. Numerous studies have been done to estimate the percentage of a materials' embodied energy that can be attributed to the construction phase. Most estimate the construction energy requirements to be between 4 and 15% of the total embodied energy. It was decided that the most relevant of these studies was the work of Lord which was a case study of New Zealand construction practices (Lord, 1994). The study gave an overall range of an additional 7-10% of the embodied energy attributable to construction activity. Based on this study, the energy used in the initial construction and maintenance of the roofs has been assumed to be an additional 10% of the total embodied energy content of the materials as described.

CO_2 emissions associated with the various building materials have been calculated using the coefficients published by Alcorn (Alcorn, 2003). The emissions coefficients given take into account all emissions associated with the extraction and processing of each material i.e. 'cradle to gate' emissions. Material emission values have been calculated as the initial emissions associated with each material multiplied by the number of times each material must be replaced during the 100 year design life of the building. Additional transport emissions have been assumed as the emissions associated with the transport of materials to site and from site to landfill at end of life as outlined below.

The materials used in the life cycle inventories have been assumed to be sourced and processed from locally available resources and the cost, energy and emissions associated with importing the materials have been excluded from the calculations. The exception to this is steel, where 80-90% of the structural steel used in New Zealand buildings is imported (Alcorn, 2003). The energy and emissions associated with extraction, transport and processing of the raw materials to the processing factory are included in the values used. It has been assumed, for consistency and simplicity that all materials travel by articulated truck, a further 100 km from the processing factory to the construction site and 20 km to landfill at the end of their life. The additional energy and emissions associated with this transport requirement have been added to the total values obtained for each roof type. All materials have been assumed to be disposed of as solid waste at end of life with the exception of the timber. Fifty percent of the timber has been assumed to be used as firewood at the end of life with the remainder going to landfill.

Table 2 shows the embodied energy (EE) and CO_2 coefficients for each building material used in the roof constructions. The emissions value for timber is negative due to the sequestration of CO_2 by the growing tree. In the case of thermal utilisation of wood waste, the energy available has been calculated using the bioenergy research tools available from Scion Research (Scion Research, 2007) and a value of -16.8 MJ/kg has been used. The embodied energy of replacement materials has been calculated as the initial embodied energy of the materials multiplied by the number of replacements required during the 100 year design life of the building.

Table 2: EE & CO_2 coefficients for NZ building materials (from Alcorn 1998, 2003)

Material	Embodied energy coefficient	CO_2 coefficient
Concrete tiles	0.81 MJ/kg	114 gCO_2/kg
Fibreglass insulation	970 MJ/m^3	770 gCO_2/kg
Mortar (cement)	3,200 MJ/m^3	209 gCO_2/kg
Paint (to concrete)	6.5 MJ/m^2	102 gCO_2/kg
Paint (to steel)	6.1 MJ/m^2	102 gCO_2/kg
Plaster Board	6.1 MJ/kg	421 gCO_2/kg
Steel - structural framing	34.8 MJ/kg	1148 gCO_2/kg
Steel (galvanised sheet)	34.8 MJ/kg	1148 gCO_2/kg
Timber	1,380 MJ/m^3	-1662 gCO_2/kg
Transport	1 MJ/net t km	68.7 gCO_2/MJ
Wood as fuel	-16.8 MJ/kg	104.2 gCO_2/MJ

6. Results

6.1 Materials and labour

The timber framing requirements for each of the two cladding options have been assessed using design software for pre-nailed timber trusses (Pryda, 2007) while the steel framing requirements for each cladding option were estimated through consultation with local roofing contractors. The initial construction costs for each type of roof are shown in Table 4a (steel roof sheeting) and 4b (concrete tile roof). Wastage has been estimated based on the expected percentage of waste generated by the various construction materials (BRANZ, 2002).

Table 4a: Material costs for steel roof sheeting constructions

	Steel roof sheeting material costs	
	Timber trussed	Steel trussed
Subtotal (Excl. GST)	$17,773	$18,613
NPV maintenance cost	$2,586	$2,586
NPV life cycle cost (Incl. GST)	$22,904	$23,848

Table 4b: Material inventory and costs for concrete tiled roof constructions

	Concrete tile roof material costs	
	Timber trussed	Steel trussed
Subtotal (Excl. GST)	$18,111	$17,694
NPV maintenance cost	$2,246	$2,246
NPV life cycle cost (Incl. GST)	$22,903	$22,434

In terms of direct materials and labour costs, including life cycle maintenance, the concrete tiled steel framed roof is the cheapest ($22,434), followed closely by the concrete tiled timber framed and steel sheeting timber framed ($22,903 and 22,904 respectively). The most expensive roof, in terms of direct materials, is the steel sheeting steel framed roof ($23,848). This is due to the use of steel purlins, which have a higher cost than the timber purlins used in the timber framed roof. If timber purlins were used instead of steel purlins, the cost of the steel sheeting steel framed roof would come out to be $22,776, making it in fact second cheapest overall in terms of materials and labour.

6.2 Embodied Energy

Embodied energy inventories for the studied roof types are shown below in Table 5. This table is separated into the initial construction, maintenance and disposal phase embodied energy of each roofing type.

The concrete tiled timber framed roof has the lowest total embodied energy (32,652 MJ) followed by the concrete tiled steel framed roof (57,495 MJ). Both the steel sheeting roofs have significantly higher embodied energy contents (138,941 MJ and 180,282 MJ for the timber framed and steel framed roof respectively) than the concrete tiled roofs due to the high amount of embodied energy in steel (taken as 34.8 MJ per kg for imported virgin galvanised steel). Again, the higher value of steel framed versus timber framed for the steel sheeting roof is largely due to the use of steel purlins. However, if timber purlins were used, the steel framed steel sheeting roof would have a life cycle embodied energy content of approximately 166,259 MJ, making it still the highest embodied energy of all the studied roof types.

Table 5: Embodied energy (EE) by life cycle phase for each roof configuration

	Steel roof sheeting		Concrete tile roof	
	Timber frame	Steel frame	Timber frame	Steel frame
Construction phase				
EE of materials (MJ)	56,343	83,555	27,649	42,498
Construction energy (MJ)	5,634	8,355	2,765	4,250
Maintenance phase				
EE of materials (MJ)	80,251	80,251	13,805	13,805
Construction energy (MJ)	8,025	8,025	1,380	1,380
Disposal phase				
Transport to landfill (MJ)	89	95	217	218
Totals				
Life cycle EE (MJ)	150,343	180,282	45,861	62,151
Thermal use of wood (MJ)	-11,402	-	-13,163	-4,656
Total EE (MJ)	**138,941**	**180,282**	**32,652**	**57,495**

6.3 CO_2 Emissions

Table 6 shows the total CO_2 emissions from each life cycle phase. The concrete tile steel framed roof has the lowest overall emissions (3,839 $kgCO_2$) followed by the concrete tile timber framed roof (4,181 $kgCO_2$). Both steel sheeting options have higher life cycle emissions than the concrete tiled roofs (5,790 $kgCO_2$ and 5,574 $kgCO_2$ for the timber framed and steel framed respectively) mainly due to the emissions associated with the replacement of the steel sheeting which occurs twice during the 100 year life of the building.

Table 6: CO_2 emissions by life cycle phase for each construction type

	Steel roof sheeting		Concrete tile roof	
	Timber frame	Steel frame	Timber frame	Steel frame
Initial Construction ($kgCO_2$)	2,273.90	3,245.83	1,977.69	2,521.50
Maintenance ($kgCO_2$)	2,321.79	2,321.79	816.80	816.80
Disposal ($kgCO_2$)	6.15	6.52	14.94	14.99
Thermal use of wood ($kgCO_2$)	1,188.18	-	1,371.65	485.26
Total Emissions ($kgCO_2$)	**5,790.02**	**5,574.14**	**4,181.09**	**3,838.54**

7 Combined Cost Analysis

Table 7, shows the combined 'costs' of each roofing type. The 'costs' associated with maintenance and disposal, have been discounted to net present values. Energy costs have been calculated based on current energy prices and no allowance has been made for increases in energy prices when calculating the cost of future energy use.

Table 7: Combined life cycle costs for each roof construction

	Cost ($NZ)			
Roof Type	**Direct**	**Energy**	**Emissions**	**Total**
Concrete Tile, Steel Framed	$22,434	$2,493	$25	**$24,952**
Concrete Tile, Timber Framed	$22,903	$1,653	$20	**$24,576**
Steel Sheet, Steel Framed	$23,848	$5,118	$32	**$28,997**
Steel Sheet, Timber Framed	$22,904	$3,578	$22	**$26,504**

Overall it was found that the concrete tile timber framed roof had the lowest combined life cycle cost ($24,576). The second lowest was that of the concrete tile steel framed roof ($24,952). Both steel sheeting options had higher combined life cycle costs than the concrete tile roofs ($26,504 and $28,997 for the timber framed and steel framed options respectively). The assumption of using imported virgin steel for the sheeting contributed significantly to the embodied energy and emissions associated with these roofing types.

8. Sensitivity analysis

8.1 Virgin steel versus recycled steel sheeting

While the vast majority of structural steel used in New Zealand is imported (Alcorn, 2003), this may not necessarily be true in the case of steel roof sheeting. It was, therefore, deemed valid to repeat the calculations using recycled steel for the roof sheeting with embodied energy and CO_2 coefficients of 10.1MJ/kg and 87.5gCO_2/kg respectively. The results of this sensitivity analysis are presented below in figures 2 and 3.

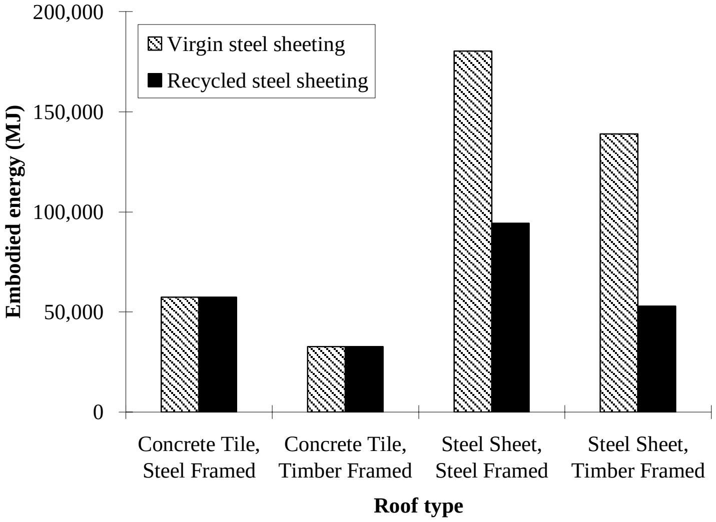

Figure 2: Comparison of <u>embodied energy</u> for virgin vs. recycled steel sheeting

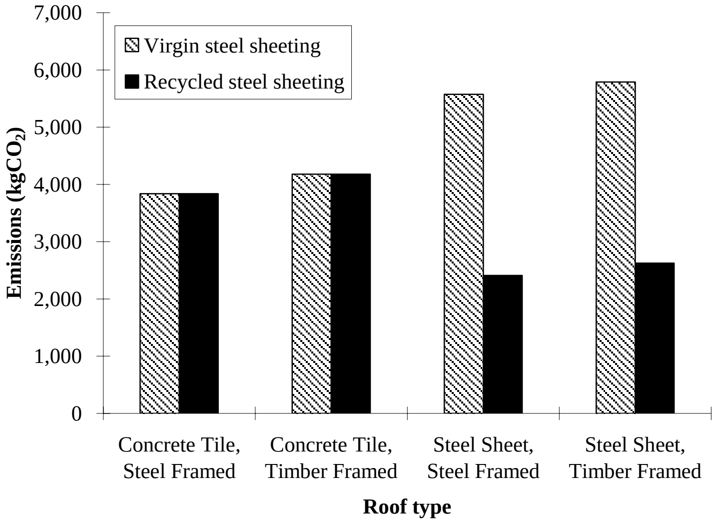

Figure 3: Comparison of CO_2 emissions for virgin vs. recycled steel sheeting

The use of recycled steel for the roof sheeting lead to 62% and 48% reductions in the life cycle embodied energy for the steel sheet timber framed and steel framed roof respectively (52,995 MJ, down from 138,941 MJ for timber framed and 94,296 MJ, down from 180,282 MJ for steel framed). Reductions in the life cycle CO_2 emissions of 55% and 57% for the steel sheet timber framed and steel framed roof respectively, were achieved by the use of recycled steel as the roof sheeting (2,624 $kgCO_2$, down from 5,790 $kgCO_2$, for the timber framed roof and 2,408 $kgCO_2$ down from 5,574 $kgCO_2$ for the steel framed roof). Overall, the total life cycle costs for the steel sheeting options were reduced by 7% and 6% for the timber framed and steel framed roofs respectively by the use of recycled steel. However, only a small impact was noticed in terms of the overall ranking of the different options with the concrete tiled, timber framed roof still having the lowest life cycle cost ($24,576). The steel sheet, timber framed roof replaced the concrete tile steel framed roof with the second lowest cost of $24,780. The two steel framed options showed the highest life cycle costs of $24,952 and $27,274 for the concrete tile and steel sheet roofs respectively.

8.2 Discount factor

The analysis was repeated using various discount factors (3%, 5% and 8%), in order to determine if the selection of discount factor had a significant impact on the overall ranking. Table 9 shows the results of the analysis, using discount rates of 3%, 5% and 8%. Using a discount factor of 3%, the concrete tiled, timber framed roof still had the lowest combined life cycle cost of all options. However, the concrete tiled, steel framed option was found to have the second lowest cost of $27,799. This replaced the recycled steel, timber framed option which was found to have a combined life cycle cost of $28,060 using the lower discount rate.

Using a discount rate of 8%, the recycled steel sheet, timber framed option was found to have the lowest combined life cycle cost ($23,010). This replaced the concrete tile, timber framed option, which was found to have the second lowest cost of $23,044 using the higher discount rate. Overall, the recycled steel sheet, timber framed option showed the greatest sensitivity to the selection of discount rate. However, the selection of different discount factors was considered to have only a minimal effect on the overall ranking of each option.

Table 9: Combined life cycle costs using discount factors of 3%, 5% and 8%

Cladding/framing option	**Total Cost ($NZ)**			**Rank(a)**		
	Discount factor			**Discount factor**		
	3%	**5%**	**8%**	**3%**	**5%**	**8%**
Concrete tiled/Timber frame	$27,423	$24,576	$23,044	1	**1**	2
Steel sheeting (recycled)/Timber frame	$28,060	$24,780	$23,010	3	**2**	1
Concrete tiled/Steel frame	$27,799	$24,952	$23,421	2	**3**	3
Steel sheeting (virgin)/Timber frame	$30,137	$26,504	$24,567	4	**4**	4
Steel sheeting (recycled)/Steel frame	$30,553	$27,274	$25,504	5	**5**	5
Steel sheeting (virgin)/Steel frame	$32,630	$28,997	$27,061	6	**6**	6

(a) 1 equals best

9 Conclusions

The concrete tile roofs generally had the lowest life cycle 'costs' due to the longer effective life and lower maintenance requirements of the concrete tiles compared to the steel sheeting, although the concrete tile steel frame roof had a slightly higher cost than the steel sheet timber frame roof when the analysis was done using recycled steel sheeting. Figure 4 (a & b) shows comparison matrices using virgin steel sheeting and recycled steel sheeting respectively.

			Roof Cladding	
			Steel sheeting	**Concrete tiles**
Framing	**Timber**	**Total Cost**	3	1
		EE	3	1
		CO_2	4	2
	Steel	**Total Cost**	4	2
		EE	4	2
		CO_2	3	1

Figure 4a: Comparison matrix using virgin steel sheeting (1 equals best)

			Roof Cladding	
			Steel sheeting	**Concrete tiles**
Framing	**Timber**	**Total Cost**	2	1
		EE	2	1
		CO_2	2	4
	Steel	**Total Cost**	4	3
		EE	4	3
		CO_2	1	3

Figure 4b: Comparison matrix using recycled steel sheeting (1 equals best)

Since the basis of this analysis was a relatively short span for the structural members, the timber and steel framing quantities for the steel sheeting and concrete tiled roofs were very similar. This is due to the fact that under the New Zealand Structural Loadings code the wind uplift on the lightweight roof was nearly equivalent to the downwards load generated by the concrete tile roof. As these two load cases are treated differently under the loadings code, it would be worthwhile repeating the analysis using different roof spans and/or slopes. Even slightly larger spans may lead to a significant increase in the framing requirements for the concrete tile roofs and subsequently affect the embodied energy and CO_2 emissions. Unfortunately due to time constraints, this extension to the analysis was unable to be undertaken.

10 References

Alcorn, A. (2003). Embodied Energy and CO_2 Coefficients for New Zealand Building Materials. Centre for Building Performance Research. Wellington, Centre for Building Performance Research, Victoria University of Wellington**:** 9, 15, 24-25.

Alcorn, A. and P. Wood (1998). New Zealand Building Materials Embodied Energy Coefficients Database. Volume II - Coefficients. Centre for Building Performance Research Report. Wellington, Centre for Building Performance Research, Victoria University of Wellington**:** Appendix A1.

Allen Consulting Group (2005). The cost of tradeable emissions units under the Kyoto Protocol, New Zealand Treasury Department.

BRANZ (2002). Easy Guide to Reducing Construction Waste, Building Research Association of New Zealand,.

Buchanan, A. (2006). Energy and CO_2 Advantages of Wood for Sustainable Buildings, University of Canterbury**:** 9.

Healthy Building Network. (2006). "Vinyl Industry Concedes to New York State: Vinyl Flooring Not a "Green" Building Material." Retrieved 14 June, 2007, from www.healthybuilding.net/docs/052903vinylrelease.pdf

International Standards Organisation (1997). ISO 14040: Environmental Management: life cycle assessment: Principles and framework.

International Standards Organisation (1998). ISO 14041: Environmental Management: life cycle assessment: goal and scope definition and inventory analysis.

Lord, D. (1994). Modelling Energy and Material Flow in Building Design and Consumption using an electronic spreadsheet. Sustainable Construction,, Tampa, Florida, USA. November 1994.

Ministry for Economic Development. (2007). "Schedule of Domestic Electricity Prices: Updated to 15 February 2007." from http://www.med.govt.nz.

Mithraratne, N. and B. Vale (2004). "Life cycle analysis model for New Zealand houses." Building and Environment **39**(4): 483-492.

Pryda (2007). Pryda Roof, Pryda New Zealand**:** Timber Roof Truss Design Software.

Pullen, S. F. (1996). Data Quality of Embodied Energy Methods. Embodied Energy Methods:The Current State of Play, Geelong.

Scion Research. (2007). "Bioenergy Knowledge Centre Tools." Retrieved 19 May, 2007, from http://www.scionresearch.com/BKC/index.html.

SETAC (1992). A Conceptual Framework for Life Cycle Impact Assessment. Life Cycle Impact Assessment Workshop, Sandestin, Florida, USA, Society of Environmental Toxicology and Chemistry, Pensecola, FL.

Standards New Zealand (1992). General Structural Design and Design Loadings for Buildings, Wellington, New Zealand.

Wilson, D. (2007). The New Zealand Building Economist. **36**.