

ENVIRONMENTAL LIFE CYCLE ASSESSMENT OF ANALOGOUS NEW ZEALAND 'EXEMPLAR HOUSE' DESIGNS

James E. McDevitt¹ and Robert W. Allison²

ABSTRACT

To reduce the environmental impact of residential construction a holistic understanding of the building life cycle is necessary. Life Cycle Assessment (LCA) is well suited to the task of calculating the impacts associated with building products and systems so it is used in this study to assess building material options for a typical New Zealand house design. The LCA and underlying data adhered to international standards and framework. Four house designs comparing concrete and timber flooring, steel and timber framing and fibre cement and timber cladding were investigated. The different designs were modified to have the same thermal performance using NZS4214:2006. Consequently the difference in environmental performance can be attributed to the wooden building products.

Substituting steel with timber framing results in a 20–30% decrease in global warming emissions, eutrophication and photochemical oxidation, but an increase in land and water use. Exchanging concrete with timber flooring results in a similar trend but there is a significant reduction of solid waste. Substituting fibre cement cladding with timber weatherboards yielded had little difference on the LCA-metrics. It is an over-simplification to focus on environmental performance as other building product characteristics are important.

KEYWORDS

Life Cycle Assessment; New Zealand; residential construction; material selection; sustainability; timber; concrete; steel; fibre cement

INTRODUCTION

There is increasing interest in including elements of sustainability into conventional decision making. Improving social, economic and environmental performance highlights the construction industry's activities because buildings have significant socio-economic relevance in society and consumers (Ortiz, Bonnet et al. 2009). Consequently there is a significant consumer-led desire for sustainability in the residential construction sector.

¹Corresponding Author. Scientist, Sustainable Design Group, Scion, Level 14, 86-90 Lambton Quay, PO Box 10345, Wellington 6143, New Zealand. Email: james.mcdevitt@scionresearch.com

²Research Leader, Manufacturing and Bio-products Group, Scion, 49 Sala St, Rotorua, New Zealand.

Wood is promoted as a sustainable material in product marketing and scientific literature (Archambault 2006; Irland 2007; Fisher 2008; Kam-Biron and Podesto 2011). Whilst there are some tangible attributes of wood that may suggest that it is an environmentally-friendly material substantiating these claims is not straightforward. There are several methods that can be used to evaluate the environmental performance of supply chains, including ecological footprints (e.g. Wiedmann, Minx et al. 2006; Beynon and Munday 2008), material flow analysis (e.g. Risku-Norja and Maenpaa 2007), input-output tables (e.g. Dietzenbacher 2005; Hoekstra and van den Bergh 2006; Ferng 2009; Xu and Zhang 2009) and hybrid or extended input-output data (e.g. Lin 2009). To date, Life Cycle Assessment (LCA) is the pre-eminent method to estimate the environmental impact of a product or service based on sound scientific principles (Reap, Roman et al. 2008a, b).

Life Cycle Assessment is a standardised scientific method for systematic analysis of any kind of flow (e.g. mass and energy) associated with the life cycle of a product, service or system (Baumann and Tillman 2004). According to the International Organization for Standardization 14040:2006 and 14044:2006 standards, an LCA study consists of four phases: (1) goal and scope; (2) life cycle inventory; (3) life cycle impact assessment; and (4) interpretation (ISO14040:2006 ; ISO14044:2006). The goal and scope stage outlines the rationale of the study, the anticipated use of the results of the study, the boundary conditions, the data requirements and the assumptions made to analyse the product system under consideration. The goal of the study is based upon the specific questions which need to be answered; the target audience and stakeholders; and the intended application. The scope of the study defines the system's boundary in terms of technological, geographical, and temporal coverage; attributes of the product system; and the level of detail and complexity addressed by the study. The life cycle inventory stage qualitatively and quantitatively documents the materials and energy used (inputs) as well as the products and by-products generated along with their environmental releases (outputs) for the product system being studied. The life cycle inventory data can be used on its own to understand total emissions, wastes and resource use associated with the material or product being studied, and/or used to improve production or product performance. More typically it is then further analysed and interpreted to provide insights into the potential environmental impacts from the system and how these might be mitigated (Life Cycle Impact Assessment and Interpretation).

Residential buildings in several geographic regions have been subject to LCA studies to fulfil a range of objectives. There is a considerable variety in the underlying assumptions, purpose and methodologies for these LCA studies and consequently the outputs and findings are diverse. Table 1 details some relevant environmental footprints from studies that are comparable to this study.

The common basis for an LCA is the functional unit which serves as an equitable measure of the performance of the system studied. Prior residential house LCA studies have used a variety of functional units including; $m^2.yr^{-1}$ (e.g. Ortiz, Bonnet et al. 2009; Carre 2011); $house.yr^{-1}$ (e.g. Upton, Miner et al. 2008); and $house^{-1}$ (e.g. Drysdale and Nebel 2010; Cuéllar-Franca and Azapagic 2012). Studies that utilise a $house^{-1}$ measure are constrained to comparisons using the same house design; whereas studies that are normalised to a unit of area open opportunities for comparison.

The assumptions associated with building lifetime vary considerably. A review of international studies indicates that a lifetime between 50 to 100 years is reasonable (e.g. Adalberth 1997; Oswald 2003; Love and Szalay 2007; Drysdale and Nebel 2010). It is noteworthy that

TABLE 1. Footprint ranges for a selection of geographically relevant studies; the data is presented normalized to m² floor area per year, where (-) indicates that the impact was not calculated.

Impact	Unit	Carre (2011)	Love and Szalay (2007)	Drysdale and Nebel (2009)
Land Use	Ha.a	11.4-23.9	—	—
Water Use	kg	156-499	—	—
Impact of water use	kg H ₂ O eq	—	—	—
Resource Depletion	MJ Surplus	5.3–15.7	—	—
Cumulative Energy demand	MJ LHV	72–192	188–219	181–363
Global warming	kg CO ₂ eq	5.6–13.6	8.1–9.9	8.4–16.8
Photochemical Oxidation	kg C ₂ H ₄	0.003–0.006	0.003–0.004	0.002–0.005
Eutrophication	kg PO ₄ ³⁻	0.003–0.01	0.0027–0.0034	0.002–0.004
Solid Waste	kg	2.1–4.2	—	—
Country		Australia	New Zealand	New Zealand
House area	m ²	202	195	146
Assumed lifetime	years	50	60	100

in several studies authors make the distinction between the technical and economic/useful lifetime of a building (Oswald 2003). The actual lifetime of a building is very influential and difficult to forecast, so it is commonplace to subject this parameter to a sensitivity assessment to evaluate its importance (e.g. Drysdale and Nebel 2010).

Building LCA studies are also used to investigate the hotspots associated with a construction (e.g. Kotaji, Schuurmans et al. 2003; Kofoworola and Gheewala 2009) as well as the impact of design decisions (e.g. Maddox and Nunn 2003; Ding 2007). Prior studies that have investigated different building envelope systems and materials have typically modified the thermal performance of the different designs so legitimate comparisons can be made around heating issues (e.g. Lippke, Wilson et al. 2004). Studies that involve materials and design options tend to find inconsistencies in the environmental performance between options (Zabalza Bribián, Valero Capilla et al. 2011). Indeed house rating schemes typically involve a number of impact assessment categories (Schmidt 2012).

Residential constructions all over the world are being subjected to green building rating schemes (e.g. BREEAM, LEED). A green building scheme in New Zealand is being championed by the Australian and the New Zealand Green Building Council (NZGBC) (GBCA 2012). These building rating schemes are used to influence finance and design decisions. LCA is increasingly used as the basis for the environmental assessment (Schmidt 2012). Most of the current rating schemes are essentially an environmental labelling scheme where a third party awards a licence based on its own programme (Baumann and Tillman 2004). There is a growing movement towards externally auditable, internationally standardised declarations. Thus, considering the rising importance of sustainability considerations and the use of LCA in residential housing evaluations, the aim of this project is to undertake a LCA to quantify the environmental footprint for an “exemplar residential house” using analogous designs. This will be used to evaluate the potential environmental impact of including wood in houses in New Zealand to prepare the forestry sector for incoming green building rating schemes.

METHOD

Scope and system boundary

This LCA extends from the production of the raw materials and products, through to their use and replacement and then to their eventual disposal. This is depicted in Figure 1. The omissions from the system boundary are excluded because they are assumed to be immaterial e.g. demolition process (Kellenberger and Althaus 2009). Or as with furnishings, impossible to model in a meaningful way due to variability and lack of reliable data. It is assumed that the house is located in Christchurch, a Zone 3 climatic region according to NZ4218:2004.

Functional unit

In order to make comparisons between the analogous designs a functional unit of $\text{m}^2 \cdot \text{yr}^{-1}$ of house operation in Christchurch is used. The lifetime is assumed to be 60 years. Results are presented in reference to this unit unless explicitly stated.

Life cycle inventory

Exemplar house design

The “Exemplar House” was specifically designed by Willson (2002) as an example for research on residential costing for a ‘typical’ house in New Zealand. The exemplar house is a basic two storey design with three bedrooms and a garage with a total floor area of 195 m^2 . The floor plans and cross sections are depicted in Figure 2. The exemplar house was chosen for this study, since it is a well established reference construction used widely in educational institutes.

FIGURE 1. The system boundary of the exemplar house investigated in this study.

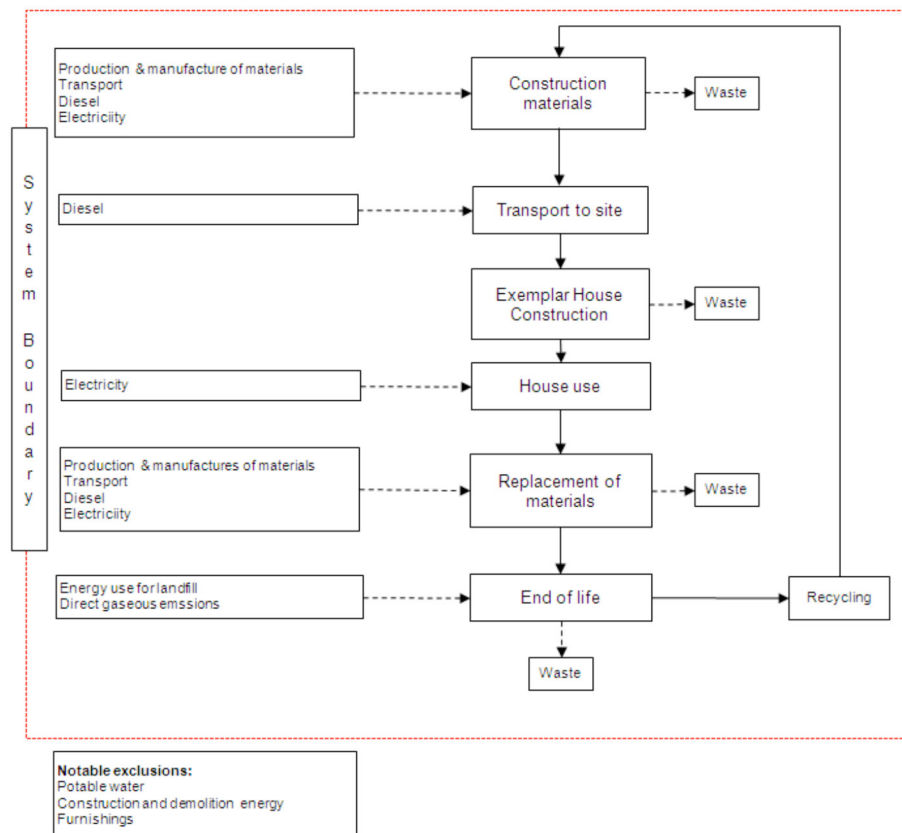
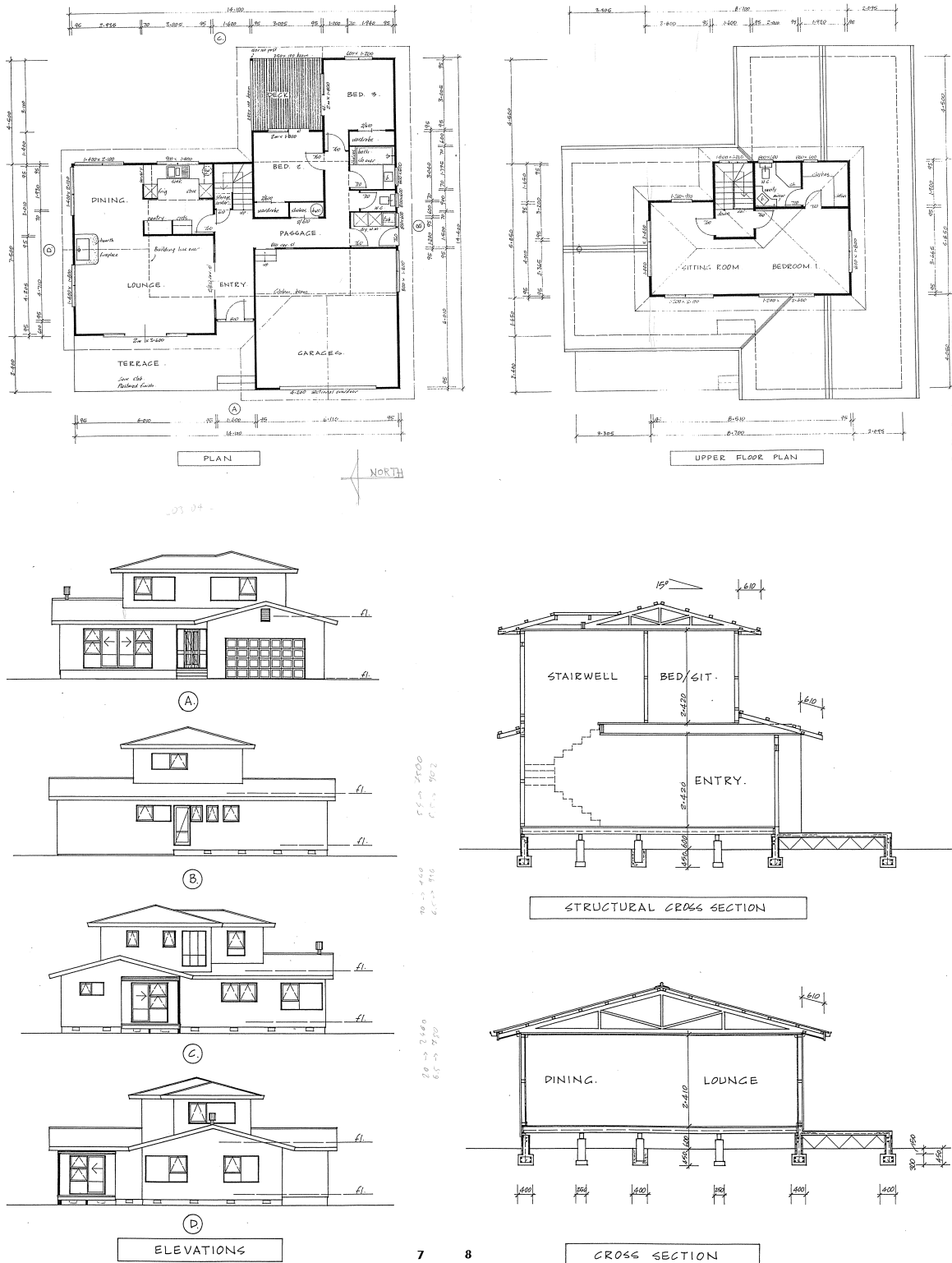


FIGURE 2. Floor plans, elevations and cross sections of a version of the exemplar house based on Willson (2002). Note the designs with a concrete floor would not be elevated.



7 8

TABLE 2. Key dimensions of the exemplar house.

System	Description	Floor	Length (m)	Height (m)	Area (m ²)	Total (m ²)	
External Walls	West	ground	14.1	2.6	36.66	59.28	
		top	8.7	2.6	22.62		
	South	ground	12	2.6	31.2	46.41	
		top	5.85	2.6	15.21		
	East	ground	14.1	2.6	36.66	59.28	
		top	8.7	2.6	22.62		
	North	ground	12	2.6	31.2	46.41	
		top	5.85	2.6	15.21		
	Internal walls		ground	15.5	2.4	37.2	63.12
			top	10.8	2.4	25.92	
Windows	West	ground	3.6	2	7.2	14.2	
		ground	0.8	2	1.6		
		top	2.1	1.2	2.52		
		top	2.4	1.2	2.88		
	South	ground	2.4	0.6	1.44	2.88	
		top	1.8	0.8	1.44		
	East	ground	2.1	1.4	2.94	13.62	
		ground	1.8	0.9	1.62		
		ground	1.8	2	3.6		
		ground	1.2	0.6	0.72		
		top	1.8	1.2	2.16		
		top	1.6	0.6	0.96		
		top	1.8	0.9	1.62		
		top	1.8	0.9	1.62		
	North	ground	1.8	1.4	2.52	11.46	
		ground	2.1	1.4	2.94		
ground		1.8	2	3.6			
top		2.4	1	2.4			
Door	West	ground	0.8	2	1.6	1.6	

The building dimensions are summarised in Table 2 and used to calculate the material quantities.

In addition to the dimensions outlined in Table 2, the floor area is 195 m², of which 90% is carpeted and the remainder is modelled as vinyl or bare.

House designs and life cycle inventories

Four analogous house designs are simulated in this exercise and the key points of difference are detailed in Table 3. Design A, the concrete floored, timber frame design with fibre cement cladding. An increasingly common housing configuration in New Zealand (Page and Curtis 2011). Design B is included to explore the impact of using weatherboards compared with the base scenario. Design C is included to examine the impact of using steel framing on environmental performance. Design D is included to investigate what happens if we substitute solid concrete with suspended wooden floors.

TABLE 3. The different designs included in this study, note the timber floor is modeled as being suspended above the ground.

Design	Floor	Frame	External Cladding
A	Concrete	Timber	Fibre cement
B	Concrete	Timber	Weatherboard
C	Concrete	Steel	Fibre cement
D	Timber	Timber	Weatherboard

Aside from the design variations all other components and key aspects of the house were assumed to remain the same. Common assumptions between designs include: a 10% compression of insulation material, unventilated envelope air gaps (or very poorly ventilated), the internal ($0.09 \text{ m}^2 \cdot ^\circ\text{C}/\text{W}$) and external surface resistance ($0.03 \text{ m}^2 \cdot ^\circ\text{C}/\text{W}$), and an internal lining of 10 mm plasterboard that has an R-value of $0.04 \text{ m}^2 \cdot ^\circ\text{C}/\text{W}$ (NZ4218:2004). The wall systems were modelled to have comparable thermal performance that meet the minimum requirement for a zone three region (NZBC 2011), thereby the use phase was kept constant between scenarios. The thermal performance was estimated using NZ4218:2004 and kept comparable by modifying the insulation for each wall system design.

The scenarios involving weatherboard assume that the weatherboard is “backed”, weighs $8.6 \text{ kg}/\text{m}^2$ (Douglas Gaunt pers comm) and has an R-value of $0.28 \text{ m}^2 \cdot ^\circ\text{C}/\text{W}$ (NZ4218:2004). Fibre cement cladding is also assumed to be “backed”, the weight was modelled as $15.2 \text{ kg}/\text{m}^2$ and the R-value was modelled as $0.1 \text{ m}^2 \cdot ^\circ\text{C}/\text{W}$ (NZ4218:2004). The weight of the external cladding was calculated using the external dimensions of the exemplar house (minus the window and door area) and multiplying that by the weight of the cladding option.

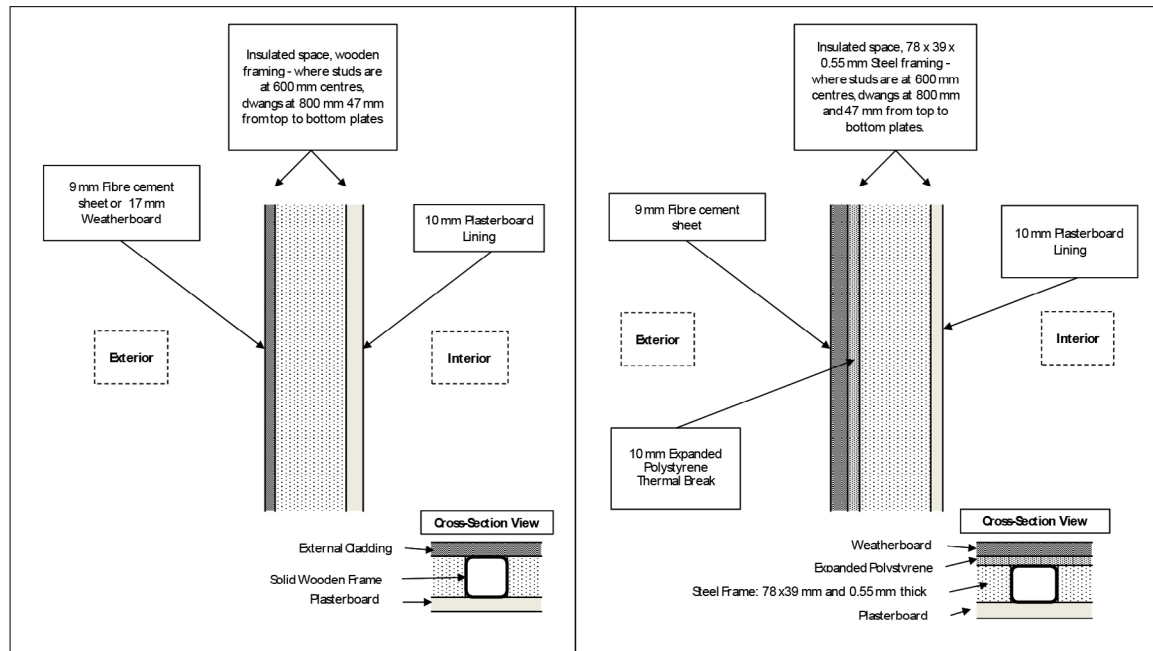
Timber and a steel framing options were modelled to comply with the New Zealand standards. The timber framing scenario complied with NZ3604:2011 and it is modelled with studs at 600 mm centres, horizontal bracing members at 800 mm and 47 mm from top to bottom plates. This configuration gives a framing area of 0.15 m^2 per m^2 of wall. The steel framing option also complied with the New Zealand Standard for residential structures made of steel frames. There is a difference in the dimensions of the steel beam (78 x 39 mm, with a steel thickness of 0.55 mm) compared to the solid wooden beam (94 x 47 mm). Consequently the area associated with the steel framing is 0.12 m^2 per m^2 of wall. Because steel is highly conductive to heat, a thermal break is necessary, so a 10 mm expanded polystyrene sheet was included in this scenario. The wall framing configurations are depicted in Figure 3.

The remaining volume of space in both the steel and wood framing options is filled with glass wool insulation. The inventorial process data for the production and manufacture of glass wool insulation was obtained from the EcoInvent database (Frischknecht, Jungbluth et al. 2005).

Two flooring scenarios are modelled, a concrete and a timber floor. The concrete floor is comprised of 53 tonnes of concrete and capable of retaining a thermal mass that is equivalent to an R-value of $2.2 \text{ m}^2 \cdot ^\circ\text{C}/\text{W}$. To ensure comparability the timber floor was modelled to also achieve a comparable thermal conductivity. This was done using the quantity of insulation recommended by pinkbatts.co.nz (R1.6 Snugfloor) integrated with a wooden framing system that includes foil lining.

Insulation in the roof is assumed to be replaced entirely every 20 years. At the end of the useful life of the house it is deconstructed and the useless component parts are sent to landfill.

FIGURE 3. The wall designs and cross sections (note: not to scale).



The inventorial emissions associated with the landfill are from the model detailed by Garrett (2010), adjusted according to McDevitt and Seadon (2010) and EcoInvent (Frischknecht and Rebitzer 2005). A dynamic approach to landfill emissions was adopted consistent with the methodology detailed in the PAS2050 (BSi 2008) and Nebel and Drysdale (2009). The carbon sequestered by wood uses a degradation ratio ($0.4\%.\text{yr}^{-1}$) using adjusted figures from Ximenes, Gardner et al. (2008). It is modelled that 85% of the steel is recycled. Steel recycling is considered an open loop system where credit for avoided burdens is factored in (Broadbent 2012). Similarly the aluminium window frames are assumed to be recycled in an open loop system. The remaining materials constitute the solid waste for the different scenarios.

The inventory associated with the timber production is from Sandilands et al. (2008)—which relates to *Pinus radiata* production. The solid wood processing inventory is from Sandilands and Nebel (2009)—notably we assume a 16% moisture content. The concrete inventory was obtained from the EcoInvent database, an inventory that relates to global adjusted production. The life cycle inventory information for the fibre cement board was extrapolated from the GaBi database using a process that corresponded to the inputs for a figure for fibre cement production in Germany. The life cycle process inventory for the weatherboard uses the inventory from Sandilands, Nebel et al. (2008) for the forestry production and manufacturing, and treatment data from the GaBi database. The steel inventory obtained from EcoInvent corresponds to a global average production of “primary steel using a blast oxygen furnace”. This is the most common type of manufacturing process to make steel framing. All materials are assumed to be produced in New Zealand.

The life cycle inventory data for the materials in the different house designs was from EcoInvent (Frischknecht and Rebitzer 2005), the GaBi4.4 database (PE International 2009) and a range of literature sources. The energy use for the operation of the house was calculated using the BRANZ ALF tool (www.BRANZ.co.nz/alf) and for each design an annual use of $4151 \text{ kWh}.\text{yr}^{-1}$ was modelled. We assume that the garage is unheated with a temperature leakage rate of

0.5 °C/h and that a heating schedule where only evening (17:00-23:00) heating to 18 °C, seven months a year (Apr–Oct) is used as this was found to be a most common heating schedule (BRANZ 2006). A range of background inputs are from the literature and published sources, including the 2008 electricity panorama for New Zealand (Coehlo 2011); diesel production (McDevitt and Seadon 2011); and New Zealand landfill operations (Garrett 2010).

Summary of material quantities for the different designs.

The material quantities in the four house designs are summarised in Table 4.

TABLE 4. Key material quantities for the four designs investigated in this study.

Material	Unit	A	B	C	D
<i>Materials that are different between designs</i>					
Fibre cement basebed & soffits	kg	3213.0	0	3213.0	0
Weatherboard Cladding	kg	0	1817.9	0	1817.9
Timber pile	kg	0	0	0	336.7
Framing timber	kg	10367.8	10367.8	0	10367.8
Framing Steel	kg	0	0	5734.5	0
Insulation Fibreglass	kg	93.6	84.7	83.9	96.2
Insulation Expanded Polystyrene	kg	0	0	34	0
Liquid Concrete	kg	55735.8	55735.8	55735.8	2563.2
<i>Materials in common between designs</i>					
Steel bolts/plates/ straps	kg		27.6		
PVC spouting, coil, joiners	kg		81.7		
Sawn timber H3.1	m ³		0.6		
Exterior H3.1 finish/battens	m ³		0.7		
Interior UT mould, jamb, liner	m ³		1.8		
Particle Board sheets	m ³		1.0		
Building paper	m ²		355.0		
Polythene DPC	m ²		173.3		
Steel Roofing	kg		10350.3		
Windows glass	kg		450.0		
Windows aluminium frame	kg		144.1		
Plasterboard (Internal GIB)	kg		4518.2		
Wet wall lining (coated HB)	kg		59.2		
Doors	no		19.0		
Paint	litres		82.6		
Wallpaper	m ²		346.0		
Carpet	m ²		180.0		
Vinyl	m ²		15.0		
Retain wall/ fence timber/ Half Rounds H4	m ³		2.1		
Hardfill	m ³		13.5		
Sand blinding 25 mm	m ²		168.3		
Reinforcing steel	kg		788.8		
Concrete blocks	kg		1311.6		

Data quality and gaps

As part of the inventory exercise in this project the data sources used have been assessed for quality in terms of timeliness, geography, technology, completeness, representativeness, consistency and reproducibility. The results are summarised in Table 5. The data quality categories are drawn from prior work by Weidema and Wesnaes (1996) and follow the guidance stated in ILCD (2010b). The information in Table 5 is our judgement and interpretation of the past studies relative to their use in this study. Generally better quality data comes from more recent studies, covers more of the technological systems, emanates from the same geographic region, and is consistent and reproducible.

Allocation

According to the principles and framework outlined in ISO14044:2006, co-product allocation was avoided through system boundary expansion wherever practical. In other circumstances the default allocation method between co-products was based on mass if no discernable economic difference in the product streams was found. Allocation for recycled material e.g. steel was assumed to be open loop, with the recycling of virgin content substituting virgin material after allowance for material degradation. Environmental benefits are equivalent to the impacts of the recycling process, including the material lost in the recycling process, minus the avoided production of either the virgin or recycled material respectively.

TABLE 5. Data quality assessment of key data and data sources in this study.

	Time frame (yrs)	Geographic region	Technology	Completeness	Representativeness	Consistency	Reproducibility
<i>Background Parameters</i>							
Materials and Designs	<20	New Zealand	Industrial	>95%	High	High	High
Transport assumptions	<10	New Zealand	Industrial	>50%	Med	High	High
Household heating and cooling	<5	New Zealand	Industrial	>90%	Med	High	High
<i>Key Life Cycle Inventories</i>							
Sawn Timber Framing	<10	New Zealand	Industrial	>80%	Med	High	Low
Steel Framing	<10	International	Industrial	>80%	Med	High	Low
Concrete	<10	International	Industrial	>80%	Low	Med	Low
Fibre cement Cladding	<10	Germany	Industrial	>80%	Low	Med	Low
Weather board	<10	International	Industrial	>80%	Low	Med	Low
<i>Background Life Cycle Inventories</i>							
Electricity	<3	New Zealand	Industrial	>80%	High	High	Med
Diesel	<10	New Zealand	Industrial	>90%	Med	High	Med

Life cycle impact assessment

The compilation of life cycle inventory data and chemical emissions is of little use in decision making due to the sheer quantity and complexity of the data. Therefore, through the use of characterisation factors that provide a numerical description of the impact of a chemical emission or resource use, we are able to convert the data into a more convenient format. Characterisation methods in LCA typically draw from environmental chemistry, toxicology, ecology and quantifiable physio-chemical relationships. The intricacy of environmental chemistry and increasing interest in LCA as a decision support tool has led to several competing methodologies and associated impact categories. The quantity of impact categories is increasing but also the existing ones are being updated regularly. Therefore the choice of impact categories can have an influential effect on the final results, longevity and bearing of a study that quantifies LCA-metrics. There are broadly two types of impact categories; midpoint and endpoint. Due to time and data constraints only midpoint indicators are included in this study.

Midpoint impacts are a description of a single impact result of a chemical emissions or resource use (Baumann and Tillman 2004). Midpoint indicators are the most common form of LCA data and the most widespread application is for carbon footprints. Importantly, an additional metric relating to the impact of water use is also included (Table 6). The impact categories included in this study were chosen because they are likely to feature in the New Zealand Green Building Council's green building rating scheme.

Limitations of the study

This life cycle assessment describes theoretical supply chains and systems. Currently this study does not fall under the ISO14044:2006 definition of a comparative assertion. Consequently the findings are not intended for making marketing claims of equivalence or superiority

TABLE 6. The impact categories calculated in this study, a description and the corresponding reference.

Impact category	Description
Global warming	The potential radiative forcing of greenhouse gas chemicals in a steady state atmosphere (IPCC 2007).
Photochemical Oxidation	The emission of substances to air that causes a smog-like pollution (Guinée, Gorrée et al. 2002).
Eutrophication	The potential nutrification of ecosystems (Guinée, Gorrée et al. 2002).
Land Use	An accounting approach to the use of land that includes the total exclusive use of land for a given period of time for occupation.
Water Use	An accounting approach to the appropriation of water by a system (Hoekstra, Chapagain et al. 2009).
Solid Waste	Total quantity of solid waste produced that is sent to reprocessing in landfill.
Resource Depletion	The additional energy required to extract low quality mineral and fossil resources, due to depletion of higher quality, easily extracted reserves.
Cumulative Energy demand	Net energy accounting that includes fossil, renewable, electrical and feedstock energy incorporated into materials such as plastic.
Impact of water use	The impact of the appropriation of water using the method outlined by Pfister, Koehler et al. (2009)

between products. Whilst all reasonable effort was made to capture most relevant processes, the emissions and resource use associated with capital, labour and the demolition process have been omitted in line with Kellenberger and Althaus (2009). We assume and model uniformity in building products, location and systems that is unlikely to exist in reality.

Findings

A particular challenge in LCA research is to legitimately compare and contrast materials that fulfil a similar function. Conceptual difficulties with comparisons are compounded by methodological issues such as different system boundaries, unsuitable impact assessment methodologies and inadequate inventorial data. In developing the wall framing, flooring and insulation systems the aim was to achieve a comparable thermal envelope. Walls have an aesthetic influence over house design which is unaccounted for. It is unlikely that a constructor would calculate a wall system to have the minimum thermal performance on a case by case basis, and material substitutions may have an additive effect that results in exceeding the minimum requirements. The analysis between materials focuses on a selection of impact metrics but other design considerations are important. The performance of the different designs will undoubtedly be different under seismic load or fire hazard, and the functioning in these conditions is extremely important and cannot be ignored.

Some simplifications are necessary to effectively model a system. For example the different ways to generate electricity relate to the year 2008 but the lifetime of the house is assumed to be 60 years. There are likely to be substantial differences in the emissions associated with electricity production over a 60 year period but these have not been quantified in this study. Further there is likely to be significant unquantified underlying variability associated with all the materials and products used in the house designs. Quantifying uncertainty and variability is an active area of research and whilst there are several options they are all essentially models to validate another model and therefore the analytical prowess is limited. Communicating the variability associated with different metrics is potentially difficult and may lead to spurious conclusions. Consequently the data and findings from this study should be regarded as indicative not definitive.

Life cycle impact assessment methods

There is no international acceptance for all the selected impact category indicators in this study. To facilitate the discussions on the validity of the indicators used in this study we follow the specifications outlined in ILCD (2010a).

The impact categories relating to land use, water use, energy and solid waste are accounting approaches. They are relatively straightforward, robust, geographically relevant and transparent, but they do not demonstrate a cause and effect mechanism and therefore it is questionable whether they are characterised and aggregated impacts *per se*. Conversely eutrophication, photochemical oxidation, and resource depletion utilise characterisation factors but it is debatable whether the characterisation factors are relevant to the New Zealand context. Background biotic, abiotic and technological advances are all influential parameters in these impact assessment methods yet they are unaccounted for.

Global warming deserves special attention because it is the most developed of the impact categories. Whilst the causes for global warming may still be debated in some quarters, the mechanisms behind global warming are reasonably well understood and the mathematical

description of this is harmonised. The applicability of global averages to the New Zealand context is contentious because of a relatively high ultraviolet radiation and atmospheric moisture that reduces the radiative forcing efficacy of greenhouse gases (IPCC 2007). On the other hand global warming is a trans-boundary atmospheric impact and because there is a desire for action on this issue, arguments for site specificity are perhaps unhelpful.

Without exception all the impact data and models are available upon request but there are only authoritative bodies for the global warming metric (Intergovernmental Panel on Climate Change) and the volumetric water footprint (Water Footprint Network). There are a number of publications that accompany the other impact categories; some of these are detailed in Table 6.

The degree of “stakeholder acceptance and suitability for communication in a business and policy context” (ILCD 2010a pg 8) for all the metrics is variable between impacts. Energy, global warming, solid waste, water and land use are well regulated and very much part of the regulatory landscape in New Zealand. Further, the link between residential construction and these impact categories is obvious. However the resource depletion, photochemical oxidation and eutrophication impact categories are not well embedded in regulatory affairs and the link with residential construction is not immediately obvious. It is noteworthy; however, that these impacts are included in a wide range of building rating schemes (Seo 2005; Schmidt 2012).

The water impact method by Pfister, Koehler et al. (2009) that is used in this study is one of a suite of methods (e.g. Frischknecht, Steiner et al. 2009; Milà i Canals, Chenoweth et al. 2009; Margni, Koehler et al. 2010) that purport to quantify the impact of water use. Water has significant social, cultural and economic considerations and these are largely unaccounted for to date. Resource depletion is also very difficult to quantify in a meaningful way because the assessment of below ground resources such as crude oil are highly speculative and commercially sensitive.

The nine metrics calculated in this study represent a limited but important portion of the total environmental impact that could be expected from the residential building modelled in this study. Yet, there is likely to be a social, cultural and economic impact and this is unaccounted for.

Footprints and hotspots

The overall environmental impact of building materials and systems calculated in this study was found to be disparate and varied; confirming prior work by several authors (e.g. Bolin and Smith 2011; Guardigli, Monari et al. 2011; Zabalza Bribián, Valero Capilla et al. 2011). Because the designs were adjusted to behave similarly during operation the differences calculated are due to the materials.

In the majority of the data there is a strong correlation between the quantity of wood in the house designs and the water use footprint (Table 7). Given the biological nature of timber and the role water plays in the physiological functioning of trees, it was obvious that this would be the case when comparing with materials made from mineral resources. Interestingly, the impacts of water use for the designs with varying material inputs were remarkably similar (Table 7). This may in part, be creditable to the low characterisation factors for New Zealand using the Pfister, Koehler et al. (2009) method. This is because the water use impact characterisation factors used are linked to perceived water stress and New Zealand has a relative abundance of water. It is noteworthy that the production of materials is the dominant phase

for all the calculated metrics relating to water use in this study (Figure 4). This can be attributed to the assumptions regarding wastewater that followed advice detailed in Ercin, Aldaya et al. (2011), the sheer magnitude of water associated with all timber production and the relative durability of wooden building products.

In general, the data in Table 7 falls within the likely range found in other studies (e.g. Table 1). The resource depletion metric is driven by the use phase (Figure 4) but the difference between the footprints of the different designs is due to the material differences. Steel production is characterised relatively highly because it is a finite resource and this accounts for the difference. The calculated cumulative energy calculated (114.5-149.6 MJ LHV/m².yr⁻¹) in this study are relatively low compared to the figures calculated in Love and Szalay (2007) but compare favourably with Carre (2011) and Drysdale and Nebel (2009) (Table 1).

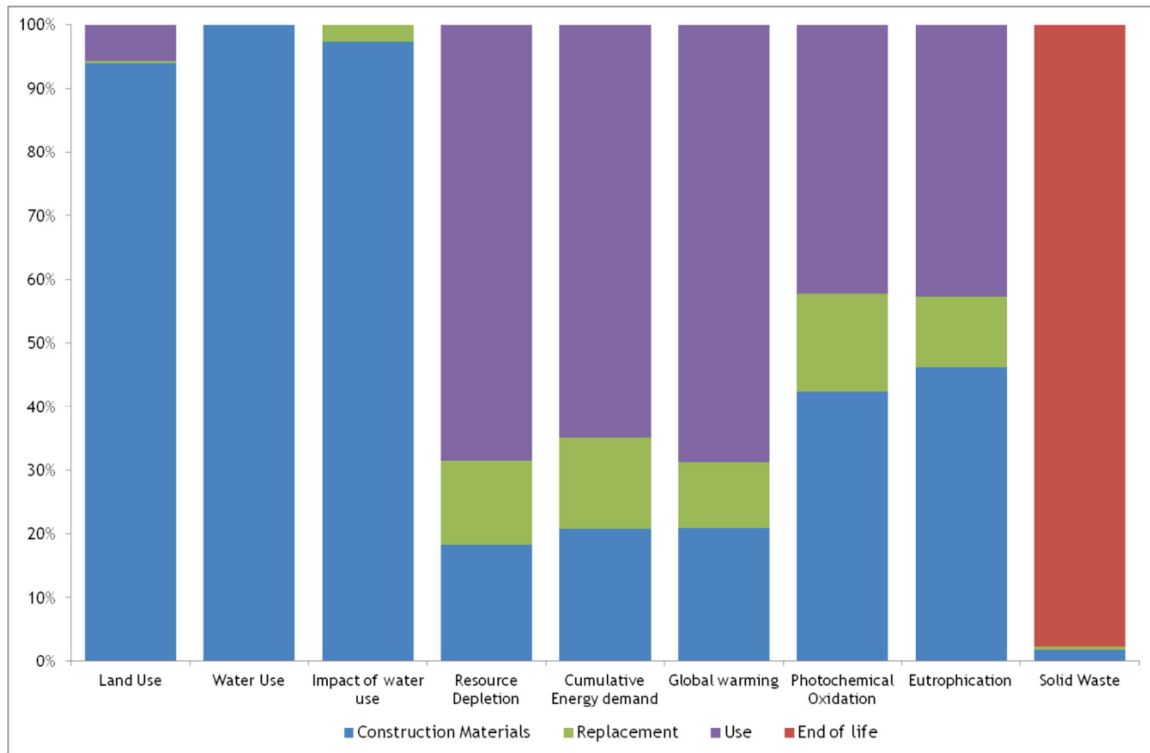
A review of studies where global warming has been quantified suggests that a range between 5.6-46.8 CO₂eq/m².yr⁻¹ is typical for a residential house (Maddox and Nunn 2003; Love and Szalay 2007; Drysdale and Nebel 2009; Carre 2011). In this study we calculated a range of 7.7-10.3 kg CO₂eq/m².yr⁻¹ which puts the house investigated in this study in the lower quartile of the previously published studies. The majority (47.4-67.6%) of the CO₂eq emissions come from the use phase (Figure 4)—a finding corroborated by other studies (Carre 2011; Cho, Kim et al. 2012; Ximenes and Grant 2012). Therefore the relatively low CO₂eq emissions can be in part explained by the prevalence of hydro-electricity and renewable electricity generation in New Zealand (MED 2009). However different system boundaries and underlying assumptions and treatment of data are also responsible for data variability and uncertainty. For example Maddox and Nunn (2003) did not include insulation in their Australian clay brick building LCA. Significant efforts were made in this study to ensure we modelled a comparable thermal envelope in order to make legitimate comparisons and the final modelled thermal envelopes were within 2% between designs.

The photochemical oxidation and eutrophication emissions are within the range specified in Table 1. The solid waste metric is dominated (>95%) by the end of life phase for all designs (Figure 4). However data for the design with a wooden floor (design D) suggest that wooden flooring had significantly less solid waste over the whole life cycle (Table 7). Domestically and abroad there is a movement towards the commoditisation of waste and therefore this is an attractive characteristic. Furthermore the earthquake performance of lightweight timber strengthens the case for further investigation and analysis.

TABLE 7. The overall footprints for all the LCA-metrics for the four house designs, the results are presented relative to the functional unit (m².yr⁻¹).

LCA-Metric	Unit	A	B	C	D
Land Use	m ² .a	0.4	0.4	0.1	0.4
Water Use	kg	308.2	298.2	10.0	351.4
Impact of Water Use	kg H ₂ Oeq	0.0004	0.0004	0.0004	0.0003
Resource Depletion	MJ Surplus	9.8	9.8	12.2	9.5
Cumulative Energy Demand	MJ LHV	118.8	119.0	149.6	114.5
Global Warming	kg CO ₂ eq	8.3	8.3	10.3	7.7
Photochemical Oxidation	kg C ₂ H ₄ eq	0.0023	0.0023	0.0029	0.0021
Eutrophication	kg PO ₄ eq	0.0023	0.0023	0.0032	0.0020
Solid Waste	kg	4.2	4.1	3.5	0.6

FIGURE 4. The relative contribution of the different life cycle phases for design A the concrete floor, timber frame, fibre cement cladding house. This design was used for the relative contribution because all the designs exhibit a similar relative contribution for all the calculated metrics.



Comparison between materials

The impact of timber framing versus steel framing is assessed by comparing designs A and C. The impact of timber floors versus concrete floors is assessed by comparing designs B and D. By comparing design A and B we can work out the impact of substituting weather board with fibre cement cladding. This can help identify the impact of including timber in residential constructions. Table 8 describes the differences in the calculated impact categories as a percentage.

In general timber framing has a lower impact across most of the indicators but has higher water and land use. The forestry production process is the main driver behind the amplified land and water usage. The difference between weatherboard and fibre cement cladding is relatively minor but it exhibits the same trend as the other comparisons. It is noteworthy that the magnitude of difference between fibre cement and timber compared with steel or concrete and timber is significantly smaller. This is most likely due to the use of wood fibre in the fibre cement data set. The solid waste associated with timber framing is considerably greater than that of the steel framing. This is because as a default we assume that 85% of the steel framing is recycled, so as well as receiving a credit for avoided burdens steel framing also reduces the solid waste output. The timber flooring compared with concrete flooring is relatively moderate in contrast. Similar to the timber versus steel framing comparison, timber has lower impacts across most of the categories except for land and water use. A notable difference however is that timber floors produce 84% less solid waste than a concrete floor; this is clearly linked to the mass of the floor.

TABLE 8. Weatherboard versus fibre cement external cladding; steel versus timber framing; and concrete versus timber floors, differences are expressed as a % relative to the non-timber option.

LCA-Metric	Cladding: Weatherboard vs. Fibre cement	Framing: Timber vs. Steel	Flooring: Timber vs. Concrete
Land use	2.8	251.8	4.6
Water use	3.3	2974.3	17.8
Impact of water use	0.2	4.8	-26.3
Resource depletion	-0.2	-20.0	-3.4
Cumulative energy demand	-0.2	-20.6	-3.7
Global warming	-0.3	-19.7	-7.5
Photochemical oxidation	-0.3	-22.3	-8.5
Eutrophication	-0.3	-29.4	-12.3
Solid waste	2.2	19.7	-84.4

CONCLUSIONS AND RECOMMENDATIONS

The goal of this project was to analyse the effects of material choices on the environmental impact of a typical house in New Zealand. Four combinations of wall framing, cladding and floors were modelled using the software tool Gabi4.4. Life cycle assessment proved to be a useful tool to develop insights into the environmental performance of building materials. Given the emerging role of LCA in green building assessments (Schmidt 2012) case study exercises such as this may contribute to the development of the value proposition of building products and materials.

The impacts calculated in this study do not cover the entire impact of a residential construction and they are not all internationally standardised. The inventorial data were of an acceptable quality but could be improved. In many cases generic or database data were used. These data are not directly transferable to the New Zealand context because of differences in background data such as electricity and diesel production as well as process operational differences. Despite methodological limitations and constraints due to inventorial data, the use of LCA is increasing in design decisions. Therefore the compilation of the life cycle inventory of New Zealand wood building products will be necessary to equip the sector with appropriate information for future requirements. Furthermore, operational changes to the value chain of building products may change their impact. For example recycling wood or concrete may profoundly change their impact so these opportunities deserve further investigation.

Methodological limitations notwithstanding, results indicate that wood building products tend to have lower global warming, eutrophication and photochemical oxidation emissions. Conversely timber products have a relatively large amount of land and water associated with their use, though the impact of water use is low. Specific interventions such as timber flooring have a noticeable reduction in solid waste (Table 8) and potentially improved earthquake performance (Buchanan, Carradine et al. 2011). So these options warrant further investigation considering New Zealand's plate tectonics and the recent Waste Minimisation Act as well as the Green Building Rating scheme.

ACKNOWLEDGEMENTS

The authors would like to thank Douglas Gaunt (Scion) for his invaluable guidance and help with the house designs; and Simon Love for his assistance with the exemplar house model. This study was funded by the Solid Wood Initiative, NZWood and an internal grant from Scion.

REFERENCES

- Adalberth, K. (1997). "Energy use during the life cycle of buildings: A method." *Building and Environment* 32(4): 317-320.
- Archambault, M. L. (2006). "Making the brand: Using brand management to encourage market acceptance of forestry certification." *New York University Law Review* 81(4): 1400-1432.
- Baumann, H. and A.-M. Tillman (2004). *The Hitchhikers guide to LCA. An orientation in life cycle assessment methodology and application*. Lund, Sweden, Studentlitteratur AB.
- Beynon, M. J. and M. Munday (2008). "Considering the effects of imprecision and uncertainty in ecological footprint estimation: An approach in a fuzzy environment." *Ecological Economics* 67(3): 373-383.
- Bolin, C. A. and S. T. Smith (2011). "Life cycle assessment of borate-treated lumber with comparison to galvanized steel framing." *Journal of Cleaner Production* 19(6-7): 630-639.
- BRANZ (2006). Energy Use in New Zealand Households. Report on the Year 10 analysis for the Household Energy End-Use Project (HEEP). BRANZ study report No. SR 155.
- Broadbent, C. (2012). LCI data for steel products. A Report produced for: James McDevitt (Scion), Data provided by: Clare Broadbent (World Steel Association).
- BSi (2008). Publicly available specification for greenhouse gas emission measurement of goods and services.
- Buchanan, A., D. Carradine, et al. (2011). "Performance of houses during the Christchurch earthquake of 22 February 2011." *Bulletin of the New Zealand Society for Earthquake Engineering* 44(4): 342-357.
- Carre, A. (2011). A Comparative Life Cycle Assessment of Alternative Constructions of a Typical Australian House Design, FWPA.
- Cho, Y. S., J. H. Kim, et al. (2012). "LCA application in the optimum design of high rise steel structures." *Renewable and Sustainable Energy Reviews* 16(5): 3146-3153.
- Coehlo, C. (2011). New Zealand's electricity generation dataset: A Life Cycle Inventory for carbon footprints. Contract: 17148 (Massey University)/12247 (Ministry of Agriculture Food and Forestry).
- Cuéllar-Franca, R. M. and A. Azapagic (2012). "Environmental impacts of the UK residential sector: Life cycle assessment of houses." *Building and Environment* 54: 86-99.
- Dietzenbacher, E. (2005). "Waste treatment in physical input-output analysis." *Ecological Economics* 55(1): 11-23.
- Ding, G. K. C. (2007). "Life cycle energy assessment of Australian secondary schools." *Building Research and Information* 35(5): 487-500.
- Drysdale, D. and B. Nebel (2009). Life Cycle Assessment of the Waitakere NOW Home. A report prepared for Beacon Pathway Limited (Report SY-3570B).
- Drysdale, D. and B. Nebel (2010). Life Cycle Assessment of Beacon's Waitakere NOW Home°. *Sustainable Buildings 10*. Wellington, New Zealand.
- Ercin, A. E., M. M. Aldaya, et al. (2011). "Corporate water footprint accounting and impact assessment: The case of the water footprint of a sugar-containing carbonated beverage." *Water Resources Management* 25(2): 721-741.
- Ferng, J. J. (2009). "Applying input-output analysis to scenario analysis of ecological footprints." *Ecological Economics* 69(2): 345-354.
- Fisher, G. (2008). "Europe's environmental expectations rising." *International Fiber Journal* 23(2): 26-28.
- Frischknecht, R., N. Jungbluth, et al. (2005). "The ecoinvent database: Overview and methodological framework." *International Journal of Life Cycle Assessment* 10(1): 3-9.
- Frischknecht, R. and G. Rebitzer (2005). "The ecoinvent database system: a comprehensive web-based LCA database." *Journal of Cleaner Production* 13(13-14): 1337-1343.

- Frischknecht, R., R. Steiner, et al. (2009). *The Ecological Scarcity Method Eco-Factors 2006. A Method for Impact Assessment in LCA*. Bern, Switzerland, Federal Office for the Environment.
- Garrett, P. (2010). Landfill disposal model for organic and inorganic waste in New Zealand. A report to MAF.
- GBCA (2012). Life Cycle Assessment in Green Star: Discussion Paper.
- Guardigli, L., F. Monari, et al. (2011). *Assessing environmental impact of green buildings through LCA methods: A comparison between reinforced concrete and wood structures in the European context*.
- Guinée, J. B., (Ed.), M. Gorrée, et al. (2002). *Handbook on life cycle assessment. Operational guide to ISO standards*. Dordrecht., Kluwer Academic Publishers.
- Hoekstra, A. Y., A. K. Chapagain, et al. (2009). Water Footprint Manual - State of the Art. *Water Footprint Network, Enschede, The Netherlands*.
- Hoekstra, R. and J. C. J. M. van den Bergh (2006). "Constructing physical input-output tables for environmental modelling and accounting: Framework and illustrations." *Ecological Economics* 59(3): 375-393.
- ILCD (2010a). "Framework and requirements for LCA models and indicators."
- ILCD (2010b). "General guidelines for LCA - Detailed guidance."
- IPCC (2007). Climate Change 2007. IPCC Fourth Assessment Report. The Physical Science Basis.
- Irland, L. C. (2007). "Developing markets for certified wood products: Greening the supply chain for construction materials." *Journal of Industrial Ecology* 11(1): 201-216.
- ISO14040:2006 Environmental Management - Life Cycle Assessment - Goal and scope definition and inventory analysis International Organization for Standardization, Geneva, Switzerland.
- ISO14044:2006 Environmental Management - Life Cycle Assessment - Requirements and Guidelines
- Kam-Biron, M. and L. Podesto (2011). *The growing role of wood in building sustainability*.
- Kellenberger, D. and H. J. Althaus (2009). "Relevance of simplifications in LCA of building components." *Building and Environment* 44(4): 818-825.
- Kofoworola, O. F. and S. H. Gheewala (2009). "Life cycle energy assessment of a typical office building in Thailand." *Energy and Buildings* 41(10): 1076-1083.
- Kotaji, S., A. Schuurmans, et al. (2003). "Life-cycle assessment in building and construction: A state-of-the-art report, 2003." *Life Cycle Assessment in Building and Construction*.
- Lin, C. (2009). "Hybrid input-output analysis of wastewater treatment and environmental impacts: A case study for the Tokyo Metropolis." *Ecological Economics* 68(7): 2096-2105.
- Lippke, B., J. Wilson, et al. (2004). "CORRIM: Life Cycle Environmental Performance of Renewable Building Materials." *Forest Products Journal* 54(6): 8-19.
- Love, S. and Z. Szalay (2007). Life Cycle Assessment of the Exemplar House: Confidential report for the Department of Building and Housing, New Zealand.
- Maddox, B. and J. Nunn (2003). LCA Fact Sheet: Life cycle analysis of clay brick housing - based on a typical project home. Newcastle, Australia, the Centre for Sustainable Technology, the University of Newcastle.
- Margni, M., A. Koehler, et al. (2010). "A framework for assessing freshwater use within LCA: Results and working progress from the UNEP/SETAC Life Cycle Initiative Project on Water Use in life LCA."
- McDevitt, J. E. and J. Seadon (2010). Carbon footprint of three waste timber products in an average communal landfill in New Zealand: Final report.
- McDevitt, J. E. and J. Seadon (2011). Life cycle assessment data sets greenhouse gas footprinting project: Diesel. A report for MAF and Zespri International.
- MED (2009). New Zealand Energy data file.
- Milà i Canals, L., J. Chenoweth, et al. (2009). "Assessing freshwater use impacts in LCA: Part I—inventory modelling and characterisation factors for the main impact pathways." *The International Journal of Life Cycle Assessment* 14(1): 28-42.
- Nebel, B. and D. Drysdale (2009). Methodologies for carbon footprinting for the forestry sector. A report to MAF.
- NZBC (2011). New Zealand Building Code Clause H1 Energy Efficiency - Third Edition. N. Z. D. o. B. a. Housing.
- Ortiz, O., C. Bonnet, et al. (2009). "Sustainability based on LCM of residential dwellings: A case study in Catalonia, Spain." *Building and Environment* 44(3): 584-594.
- Oswald, G. (2003). Ökologische Bewertung im Holzwohnbau. Dissertation, TU-Graz.

- Page, I. C. and M. D. Curtis (2011). Study Report SR 261: Physical Characteristics of New Houses. PE International (2009). GaBi 4.4 Professional Life Cycle Software, www.gabi-software.com. University of Stuttgart, Germany.
- Pfister, S., A. Koehler, et al. (2009). "Assessing the Environmental Impacts of Freshwater Consumption in LCA." *Environmental Science Technology* 43: 4098-4104.
- Reap, J., F. Roman, et al. (2008a). "A survey of unresolved problems in life cycle assessment. Part 1: Goal and scope and inventory analysis." *International Journal of Life Cycle Assessment* 13(4): 290-300.
- Reap, J., F. Roman, et al. (2008b). "A survey of unresolved problems in life cycle assessment. Part 2: Impact assessment and interpretation." *International Journal of Life Cycle Assessment* 13(5): 374-388.
- Risku-Norja, H. and I. Maenpaa (2007). "MFA model to assess economic and environmental consequences of food production and consumption." *Ecological Economics* 60(4): 700-711.
- Sandilands, J. and B. Nebel (2009). Guidelines for Greenhouse Gas Footprinting for Engineered Wood Products, Scion: 60.
- Sandilands, J., B. Nebel, et al. (2008). Greenhouse Gas emissions of the Forestry Sector in New Zealand.
- Schmidt, A. (2012). Analysis of five approaches to environmental assessment of building components in a whole building context. Report commissioned by Eurima, FORCE Technology, Applied Environmental Assessment.
- Seo, S. (2005). Review of technical/Scientific basis of existing environmental assessment and rating tools for buildings and building products. Report for Forest and Wood products Research and Development Corporation. CSIRO.
- Upton, B., R. Miner, et al. (2008). "The greenhouse gas and energy impacts of using wood instead of alternatives in residential construction in the United States." *Biomass and Bioenergy* 32(1): 1-10.
- Weidema, B. P. and M. S. Wesnaes (1996). "Data quality management for life cycle inventories - An example of using data quality indicators." *Journal of Cleaner Production* 4(3-4): 167-174.
- Wiedmann, T., J. Minx, et al. (2006). "Allocating ecological footprints to final consumption categories with input-output analysis." *Ecological Economics* 56(1): 28-48.
- Willson, R. J. (2002). The exemplar house: A specific example of residential costing. Plans and Specifications Ltd.
- Ximenes, F. and T. Grant (2012). "Quantifying the greenhouse benefits of the use of wood products in two popular house designs in Sydney, Australia." *The International Journal of Life Cycle Assessment*: 1-18.
- Ximenes, F. A., W. D. Gardner, et al. (2008). "The decomposition of wood products in landfills in Sydney, Australia." *Waste Management* 28(11): 2344-2354.
- Xu, Y. and T. Zhang (2009). "A new approach to modelling waste in physical input-output analysis." *Ecological Economics* 68(10): 2475-2478.
- Zabalza Bribián, I., A. Valero Capilla, et al. (2011). "Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential." *Building and Environment* 46(5): 1133-1140.