A COMPARATIVE STUDY:

EMBODIED ENERGY AND COST BENEFIT ANALYSIS OF STUDIO PACIFIC ARCHITECTURE HOUSES

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

1.0 INTRODUCTION

An increasing awareness of the building industry's environmental impact is changing the way the buildings are designed, constructed and operated. With this change, new methods of calculating a building's environmental impact over its life cycle are needed. This has seen a move from qualitative assessment tools (LEED, BREEAM and GreenStar) to quantitative tools such as building Life Cycle Assessment (LCA) (Forsberg & von Malmborg, 2004). However, the current building LCA methods are complicated and poorly integrated into established work practices limiting industry adoption (Zabalza Bribián, Aranda Usón , & Scarpellini, 2009).

The overall aim is to conduct a comparison study of construction system solutions for improving thermal performance of new houses designed by Studio of Pacific Architecture examining; operative energy and carbon emissions, embodied energy and carbon, global warming potential, and cost over 0, 50, 100 and 150 year building lifespans.

1.2 Scope

Thermal envelope only

22 different design changes

2.0 Background

2.1 Operational Energy Calculation

This research is a continuation of the studies carried out by Studio Pacific Architecture (SPA) into improving the thermal comfort and heating energy performance of their residential house designs (Sullivan, Novak, & Donn, 2012). Their research tested the effects of 22 different wall, window, roof, and floor constructions, various building orientations and window-to-wall glazing percentages (WWR). These changes were applied to 9 different house designs. The outcome was a set of design and construction recommendations to improve occupant thermal comfort and lower heating energy consumption during the operation lifecycle phase of buildings (Sullivan, Novak, & Donn, 2012).

2.1.1 Review of Operational Energy Calculation 2012 Research

The key findings of this research were:

1. Use less glazing – maybe limit it to no more than 20% of the wall area?
2. Lay out the house so it is mainly facing north/north-east. If half of the glazing is facing this direction then you can place the rest where you want, with only small losses.
    a. Addendum: and the north facing glazing should be to as many rooms as possible. If you place half the glazing at the north end, but there is only one room there then its effectiveness will be limited.
3. Use a corridor based plan rather than open-plan living. It is important to make sure that heat can be kept in the living room, and not wasted in unoccupied spaces like bathrooms and corridors.
4. If you have a concrete floor slab – use it. It can significantly reduce both heating energy use and the risk of overheating.
5. Upgrading the R-value of the glazing has the most benefits. Use timber windows frames, argon fills, and low-e coatings.
    a. However, if significantly less glazing is being used, and it is well oriented, then this may be no longer true.
6. If you are in a hot climate like Auckland then use mass. It is highly effective in warmer climates and addresses both heating and overheating.

Below Figure 1 shows the summerised operative heating energy reductions for three different insulation levels; low, medium, and high averaged across all nine houses. The graph tabulates the reductions of single and the combined construction element changes. Analysis in the context this research scope highlights the focus to be directed towards the differences between medium level insulation constructions and high-level insulation constructions, i.e. 57% verses 67% heating energy reduction. Does the 10% operative heating energy saving positively offset the additional embodied energy capital and maintenance construction costs over the lifespan of the nine houses?

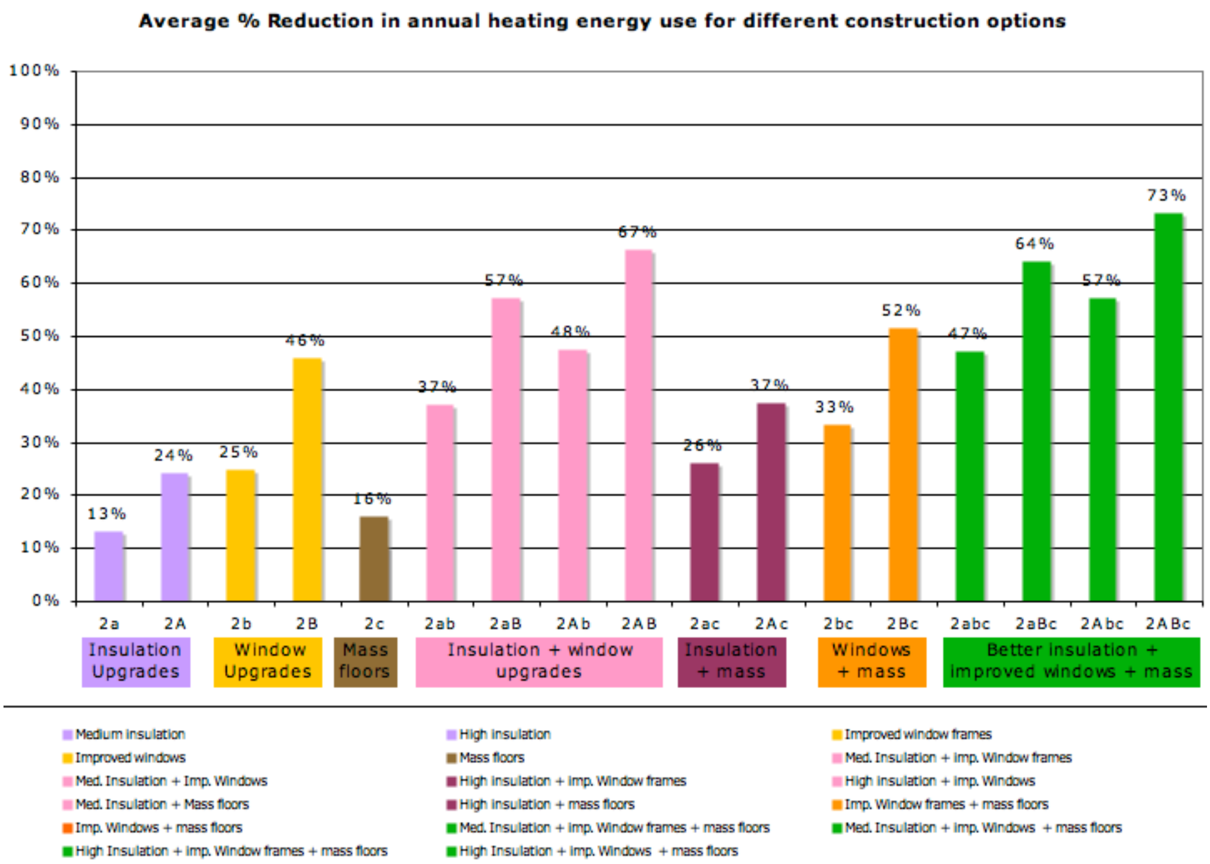


Figure 1: Operative Energy Calculation Results for Low, Medium and High Insulation Levels

2.2 Life Cycle Analysis Calculation

SPA has long been committed to Environmentally Sustainable Design (ESP) and has been an advocate in the building sector for improving the sustainability of the built environment (Sullivan, Novak, & Donn, 2012). With this ethos embedded in their design practices, the logical continuation of the residential operative energy study conducted by Sullivan, Novak, and Donn (Thermal performance modelling: design strategies for improved thermal perfromance in selected NZ houses, 2012) was an examination of the recommended construction changes over an expanded Life Cycle Analysis (LCA) assessment.

Assessing a building's sustainability is the calculation of sustainable indicators that quantify environmental impact over its life cycle (Zabalza Bribián, Aranda Usón , & Scarpellini, 2009). Life Cycle Assessment (LCA) is a quantitative tool that produces sustainable indicators measuring the environmental impact of products (or materials) (Zabalza Bribián, Aranda Usón , & Scarpellini, 2009). Both Ramesh at el (2010) and Alcorn (2010) clarify this definition explaining LCA as:
A process of evaluating the material and energy input and output flows in a system.

The LCA method of assessment quantifies material and energy inputs and outputs, and the on-going environmental effects of a material throughout all phases of the materials life cycle. Originally developed for designing low environmental impact materials, adapting LCA for building assessment requires additional calculation phases (Zabalza Bribián, Aranda Usón , & Scarpellini, 2009). These phases integrate the environmental impacts of the building's materials (Figure 2 phases 1, 2 and 4) with the operational life cycle phase (Figure 2 phase 3) of the buildings life cycle. The sum is the building LCA as the total environmental impact of all four life cycle phases.

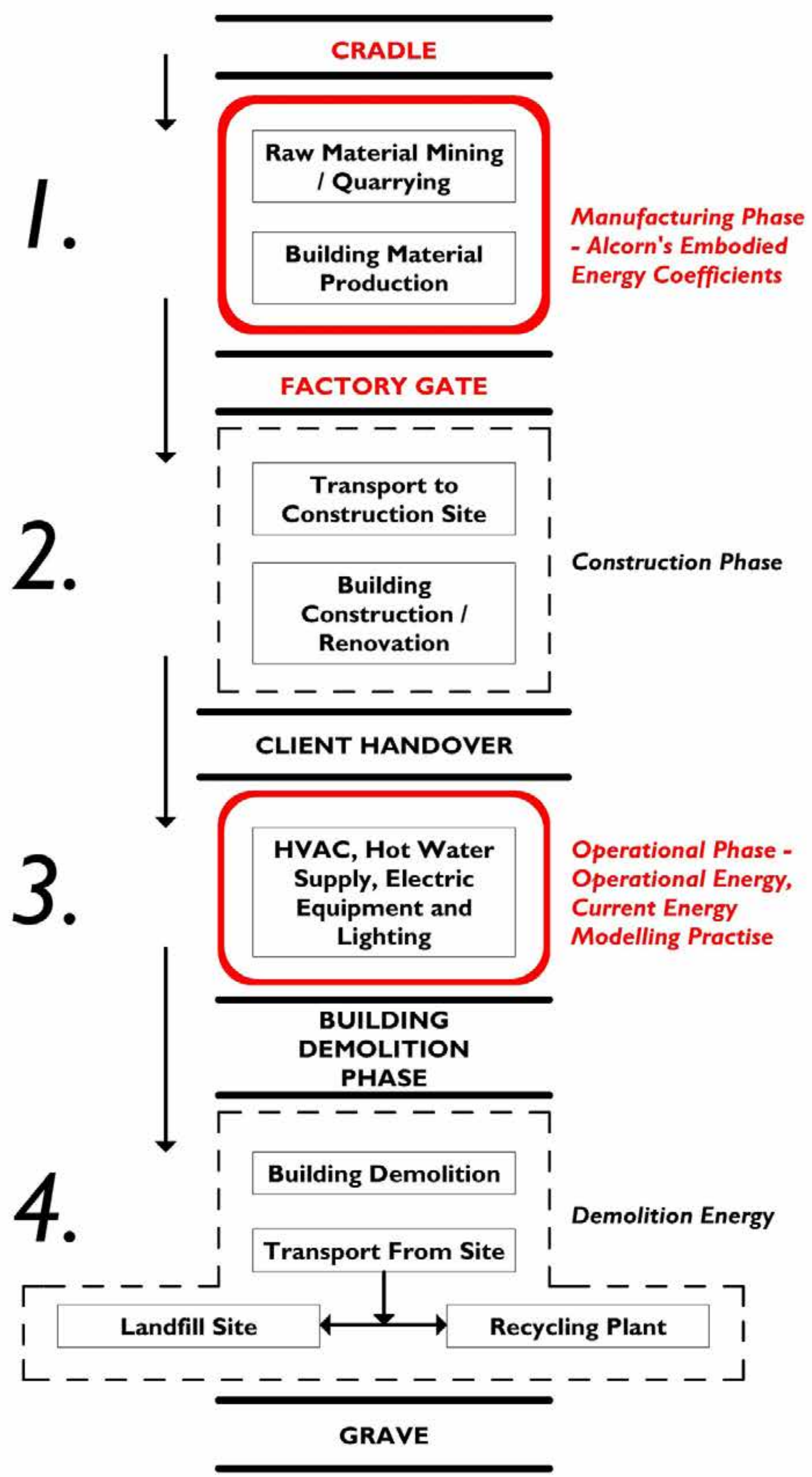


Figure 2: Building Life Cycle Phases and System Boundaries

As the New Zealand building sector currently lacks a New Zealand specific LCA material database this study therefore analyses the environmental impacts of the nine buildings over the manufacturing and operational lifecycle phases. This impact is described in the form of energy and carbon dioxide sustainability indicators that form an Energy Analysis (EA), and Carbon Dioxide Analysis. The sustainable indicators for the manufacturing lifecycle phase are calculated as Embodied Energy (EE) and Embodied Carbon Dioxide (ECO2), whereas the operational lifecycle phase indicators are calculated as operational heating energy energy end-use and operational heating energy carbon dioxide end-use.

2.2.1 Embodied Energy Coefficients

The Embodied Energy (EE) and Embodied Carbon Dioxide (ECO2) values of a building Energy and Carbon Dioxide Energy Analysis (EA) are calculated using the material coefficients from the PhD research of Dr. Andrew Alcorn (Alcorn, 2010). This is a New Zealand specific index of common construction materials, developed using the hybrid input-output analysis method. The coefficients, EE and ECO2 are the sum respective energy and carbon dioxide totals of all the ingredient and energy inputs required in the construction of the building materials. This is termed as a 'cradle to gate' system boundary convention.

Refer APPENDIX 1.0 MATERIAL ASSUMPTIONS, Embodied Energy and Embodied Carbon Dioxide Material Coefficients.

3.0 METHODOLGY

The EE, ECO2, construction and maintenance costs ($), combined with operational heating energy end-use analysis of the nine case study houses was conducted using an excel spread sheet developed specifically for this research task. The spread sheet calculates from square metre area building measurements of the floor, wall, windows and roof (hereby referred to as the thermal envelope construction elements) the material quantities of the primary construction materials comprising of the subject building's thermal envelope. Subsequently, EE, ECO2 and construction unit costs are applied to these areas over a specified building lifespan to include the maintenance replacement impact over these categories. This process is conducted based on the insulation levels low, medium or high for all construction elements of the thermal envelope.

The subject building's operational heating energy end-use consumption has been referenced from the 2012 research carried out by Studio Pacific Architecture (SPA) into improving the thermal comfort and heating energy performance of their residential house designs (Sullivan, Novak, & Donn, 2012). The operative energy figures each specific to the subject building and the insulation level specified for each construction element of the thermal envelope are expressed as MWh figure for the building and multiplied by the specified lifespan. Refer to the research report authored by Sullivan, Novak, & Donn (2012) for further information concerning the methodology of the operative heating energy modelling.

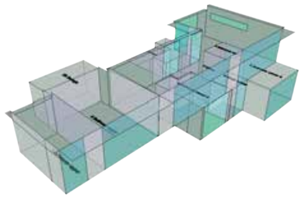
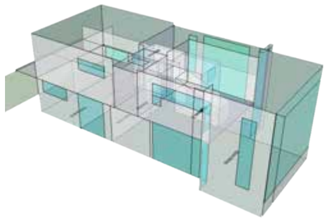
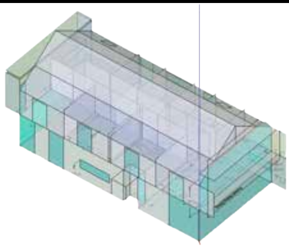
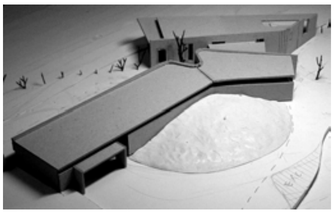
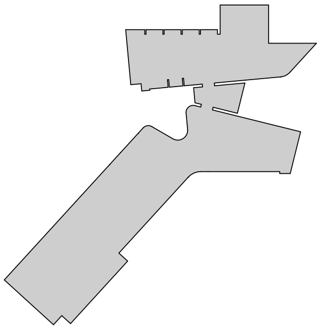
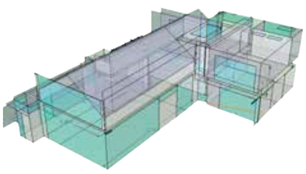
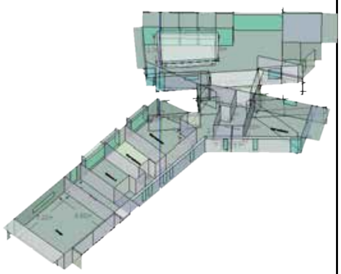
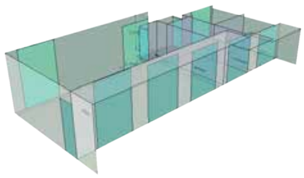
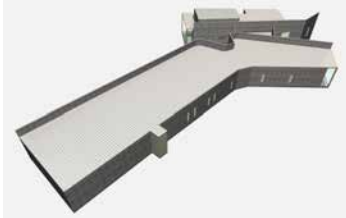
The following report sections detail the assumptions made throughout the process of this calculation.

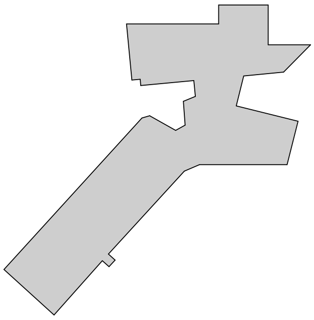
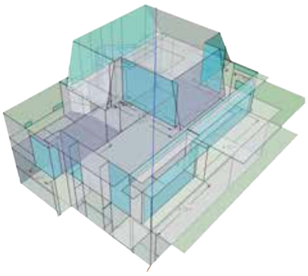
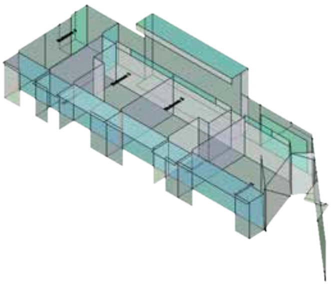
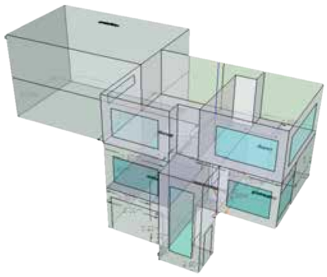
3.1 Case Study Building Assumptions

The building geometry measured and used for construction material quantification was based on the detailed building documentation from Studio Pacific Architecture. Below *figure XXX* shows detailed 3D computer sketch representation of the geometry use for the nine case study houses. Geometry simplification assumptions have been made were necessary, however this has been mitigated through efforts to retain as close as possible equal the gross floor area measurements. Other simplifications assumptions include:

1. Roof slope not modelled, assumed 0 degrees.
2. Wall height has been modelled to finished ceiling level (FCL) unless where wall parapets are present.
3. Where wall height varies i.e. gable end, wall height has been averaged and modelled as flat.
4. Window unit dimensions measured as wall opening dimensions.

Actual building form			
	W1 (2008) GFA: 116m^2 38% glazing to external wall area Timber frame, some floor slab	**W2** (2011) GFA: 143m^2 32% glazing to external wall area Timber frame, concrete floor slab	**W3** (2011) GFA: 210m^2 41% glazing to external wall area Timber frame, concrete floor slab

Operative heating energy building geometry model			
Embodied energy / Carbon Dioxide / construction cost analysis building geometry			
Floor Plan			
Actual building form			
			
	W4 (2010) 263m^2 36% glazing to external wall area Timber frame, some floor slab	**W5** (2011) 235m^2 45% glazing to external wall area Exposed concrete	**M1** (2011) 121m^2 41% glazing to external wall area Timber frame
Operative heating energy building geometry model			
Embodied energy / Carbon Dioxide / construction cost analysis building			

geometry			
Percentage Difference to actual GFA		Less than 1%	
Actual building form			Not Available
	N1 (2012) 161m^2 49% glazing to external wall area Timber frame	**N2** (2011) 94m^2 39% glazing to external wall area Exposed concrete	**W6** (2012) 97m^2 17% glazing to external wall area Timber frame, some floor slab
Operative heating energy building geometry model			
Embodied energy / Carbon Dioxide / construction cost analysis building geometry			
Floor Plan			

3.1 Construction System Assumptions

The research conducted by Sullivan, Novak, & Donn (2012) anlaysised the nine case study houses, varying the thermal resistance and thermal mass of the thermal envelope construction elements aiming to reduce operative heating energy reduction and improve occpant thermal comfort. Thirty construction systems (refer Table 2) were modelled for each building, and combined into twelve combinations (refer Table 1). This research analyses those construction systems and combination scenarios in the context of embodied energy, carbon dioxide, construction and maintenance costs, and building lifespans. The following construction related assumptions have been made:

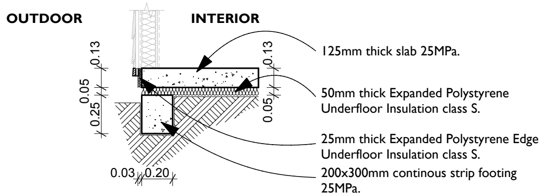
1. All the nine case study houses have different as built thermal envelope construction systems. Sullivan, Novak, & Donn (2012) made the assumption to standardise the construction systems into thirty listed in Table 2. This research as an extention of their work to compliement uses the same construction systems for all nine case study buildings.
    a. The bespoke nature of the nine case study buildings results in a high variance in the construction systems. Where required the construction systems have been design to be within the scope and to accordance with NZS 3604: 2011. This often results in a divergance from the as-built documentation of the nine case study builings.
2. Only the construction elements consisting of the building thermal envelope have been acessed. This excludes roof overhangs, wind walls, site typography, other assiocated foundation excavation and site preperation, and landscaping.
3. Specific joinery requirements for doors have been excluded. Door construction elements have been considered and modelled as window units.
4. Table 2 provides a detailed account of the materials considered and accessed for embodied energy, carbon dioxide, construction and maintenance costs. All other materials, i.e. flashing, fixings and sealants are excluded.

The construction system combination scenarios are as follows in Table 1:

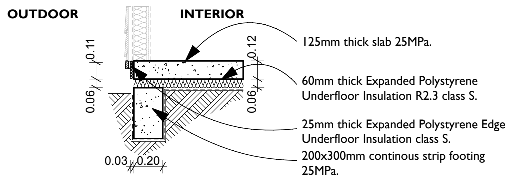
Table 1: Construction system combination scenarios

2ab	Medium insulation + Medium insulation window units (Improved window frames)	**2aB**	Medium insulation + High insulation window units (Improved windows)
2Ab	High insulation + Medium insulation window units (Improved window frames)	**2AB**	High insulation + High insulation window units (Improved windows)
2ac	Medium insulation + Mass floors	**2Ac**	High insulation + Mass floors
2bc	Medium insulation window units (Improved window frames)+ Mass floors	**2Bc**	High insulation window units (Improved windows)+ Mass floors
2abc	Medium insulation + Medium insulation window units (Improved window frames) + Mass floors	**2aBc**	Medium insulation + High insulation window units (Improved windows)+ Mass floors
2Abc	High insulation + Medium insulation window units (Improved window frames)+ Mass floors	**2ABc**	High insulation + High insulation window units (Improved windows)+ Mass floors

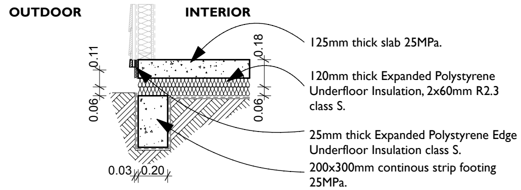
Table 2: Construction system detail assumptions

<table>
<tr><th>Building Element</th><th>Low Insulation Concrete Element</th><th>Medium Insulation Concrete Element</th><th>High Insulation Concrete Element</th></tr>
<tr><td>Floor</td>
<td>

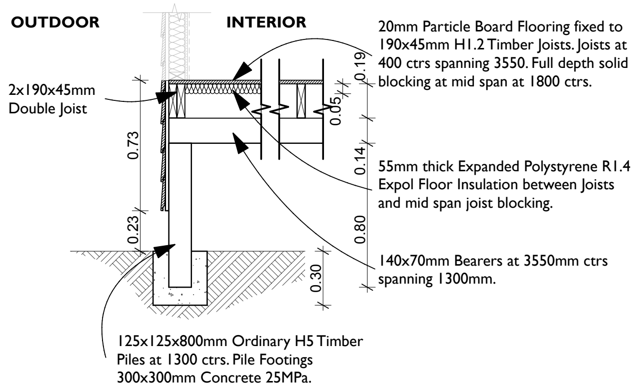
Low Insulation Floor 1.5kPa: Concrete R1.42

Concrete slab (R1.42):
125mm concrete, 50mm polystyrene class S, + 25mm edge insulation. Cavity batten framing ratio 1.5%.
Slab reinforcing, polythene (DPM), and earthworks including compact fill excluded from EE and ECO2 analysis.</td>
<td>

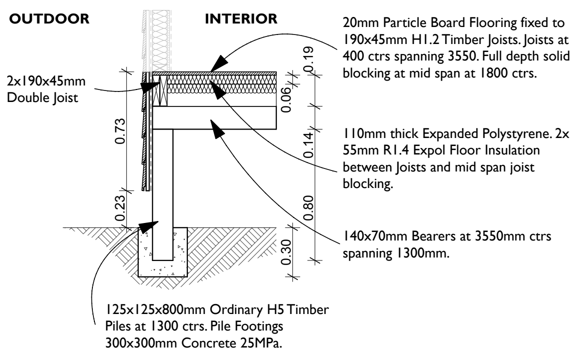
Medium Insulation Floor: Concrete R2.51

Concrete slab (R2.51):
125mm concrete, 60mm extruded polystyrene (R2.3, Goldfoam), + 25mm edge insulation. Cavity batten framing ratio 1.5%.
Slab reinforcing, polythene (DPM), and earthworks including compact fill excluded from EE and ECO2 analysis.</td>
<td>

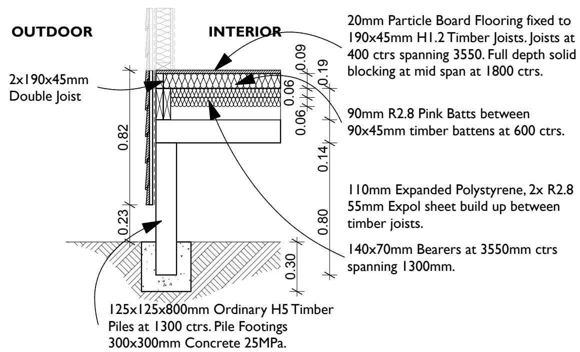
High Insulation Floor: Concrete R4.82

Concrete slab (R4.82):
125mm concrete, 120mm extruded polystyrene (2x R2.3 sheets, Goldfoam), + 25mm edge insulation. Cavity batten framing ratio 1.5%.
Slab reinforcing, polythene (DPM), and earthworks including compact fill excluded from EE and ECO2 analysis.</td></tr>
<tr><th>Building Element</th><th>Low Insulation Timber Frame Element</th><th>Medium Insulation Timber Frame Element</th><th>High Insulation Timber Frame Element</th></tr>
<tr><td>Floor</td>
<td>

Low Insulation Floor 1.5kPa: Timber R1.43

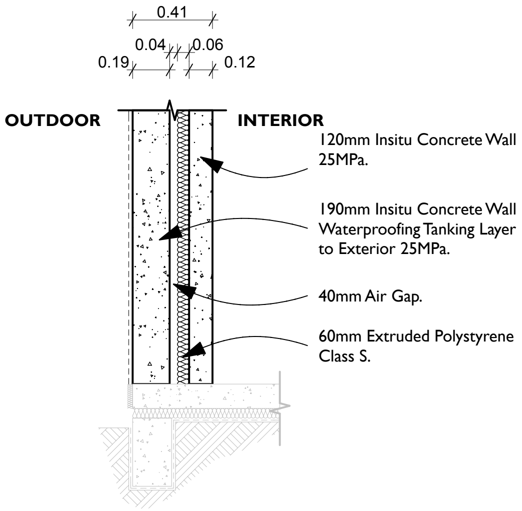
Timber floor (R1.43):
20mm particleboard, 55mm expanded polystyrene (R1.4, Expol) w. 190x45 timber joists @400crs. Joist framing ratio 15%, insulation percentage ratio 85%, bearer framing ratio 2.8%, pile framing ratio 0.7%, cavity batten framing ratio 1.5%.</td>
<td>

Medium Insulation Floor: Timber R2.57

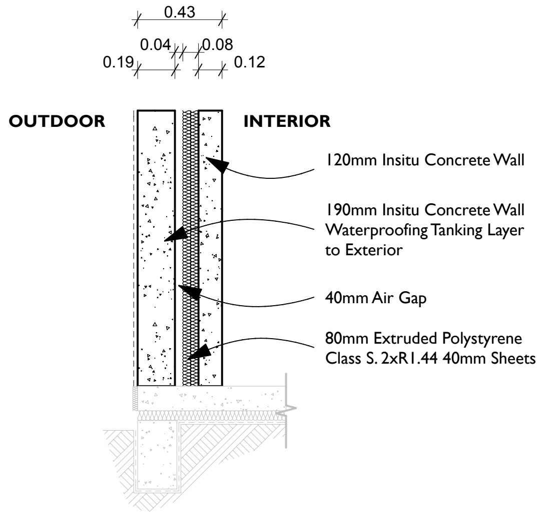
Timber floor (R2.57):
20mm particleboard, 110mm expanded polystyrene (R2.8, 2x55mm Expol) w. timber joists @400crs. Joist framing ratio 15%, insulation percentage ratio 85%, bearer framing ratio 2.8%, pile framing ratio 0.7%, cavity batten framing ratio 1.5%.</td>
<td>

High Insulation Floor: Timber R4.9

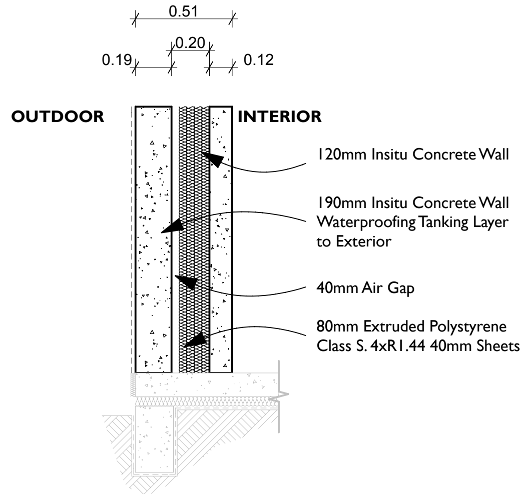
Timber floor (R4.9):
20mm particleboard, R2.8 Pink Batts w. 90x45 timber battens @600crs, 110mm expanded polystyrene (R2.8, 2x55mm Expol) w. timber joists @400crs. Joist framing ratio 15%, insulation percentage ratio 85%, bearer framing ratio 2.8%, pile framing ratio 0.7%, cavity batten framing ratio 1.5%.</td></tr>
</table>

<table>
<tr><th>Building Element</th><th>Low Insulation Concrete Wall Element</th><th>Medium Insulation Concrete Wall Element</th><th>High Insulation Concrete Wall Element</th></tr>
<tr><td>Wall</td><td>

Low Insulation Wall: Exposed Concrete R1.94

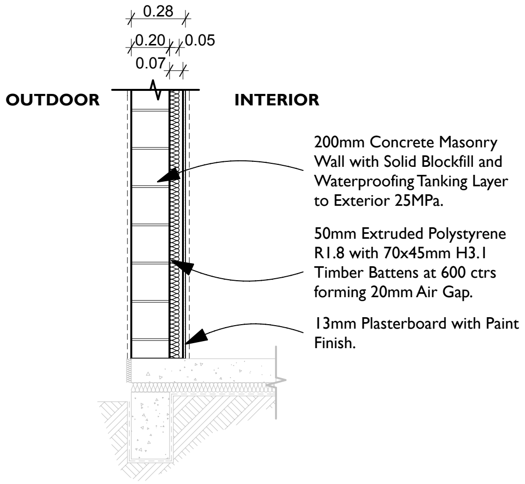
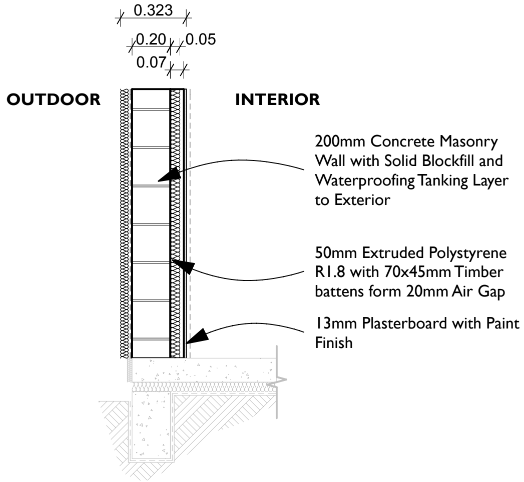
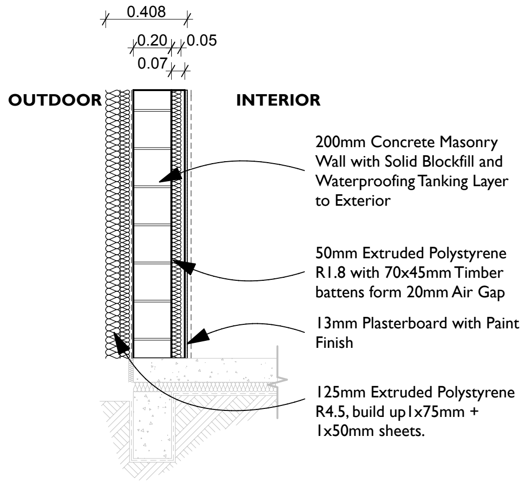
Exposed concrete (R1.94):
190mm concrete, 40mm air gap, 60mm polystyrene class S, 120mm concrete.
Insulation percentage ratio 100%.</td><td>

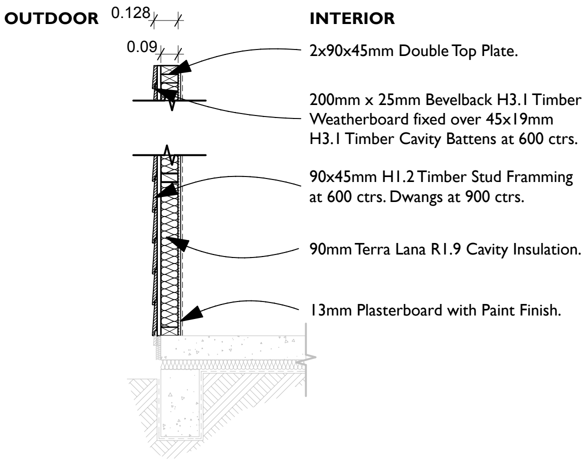
Medium Insulation Wall: Exposed Concrete R3.34

Exposed concrete (R3.39):
190mm concrete, 40mm air gap, 80mm extruded polystyrene (2xR1.44 sheets, Goldfoam), 120mm concrete.
Insulation percentage ratio 100%.</td><td>

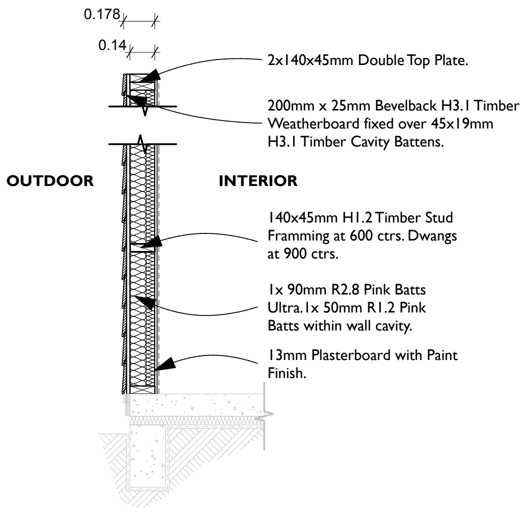
High Insulation Wall: Exposed Concrete R6.29

Concrete (R6.29):
190mm concrete, 40mm air gap, 160mm extruded polystyrene (4xR1.44 sheets, Goldfoam), 120mm concrete.
Insulation percentage ratio 100%.</td></tr>
</table>

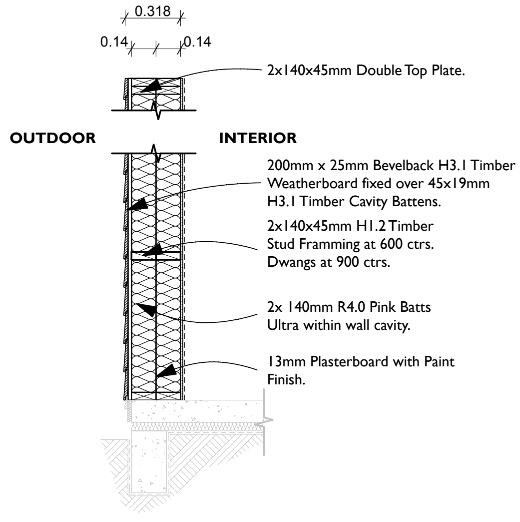
Building Element	Low Insulation Retaining Wall Element	Medium Insulation Retaining Wall Element	High Insulation Retaining Wall Element
Wall	 **Low Insulation Wall: Retaining Wall Concrete R1.94** **Concrete retaining wall (R1.94):** 200mm concrete block, 50mm extruded polystyrene (R1.8, Goldfoam) w. 70x45 timber battens @600crs (20mm air gap), 13mm GIB lining. Cavity batten framing ratio 1.5%, insulation percentage ratio 98.5%.	 **Medium Insulation Wall: Retaining Wall Concrete R3.35** **Concrete retaining wall (R3.35):** 40mm extruded polystyrene (R1.4, Goldfoam), 200mm concrete block, 50mm extruded polystyrene (R1.8, Goldfoam) w. 70x45 timber battens @600crs (20mm air gap), 13mm GIB lining. Cavity batten framing ratio 1.5%, insulation percentage ratio 98.5%.	 **High Insulation Wall: Retaining Wall Concrete** **Concrete retaining wall:** 125mm extruded polystyrene (R4.5, 75mm + 50mm sheets, Goldfoam), 200mm concrete block, 50mm extruded polystyrene (R1.8, Goldfoam) w. 70x45 timber battens @600crs (20mm air gap), 13mm GIB lining. Cavity batten framing ratio 1.5%, insulation percentage ratio 98.5%.

<table>
<tr><th>Building Element</th><th>Low Insulation Timber Frame Wall Element</th><th>Medium Insulation Timber Frame Wall Element</th><th>High Insulation Timber Frame Wall Element</th></tr>
<tr><td>Wall</td>
<td>

Low Insulation Wall:Timber R1.94

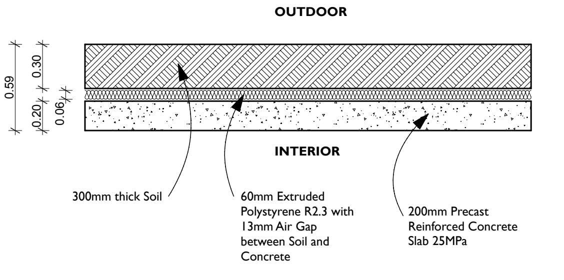
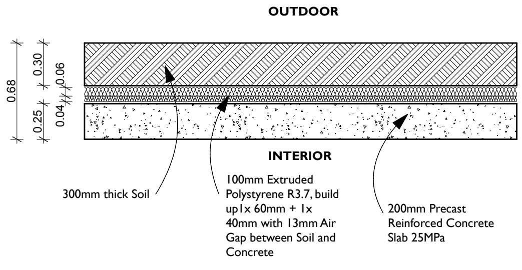
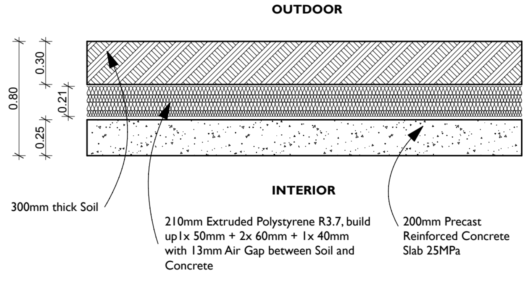
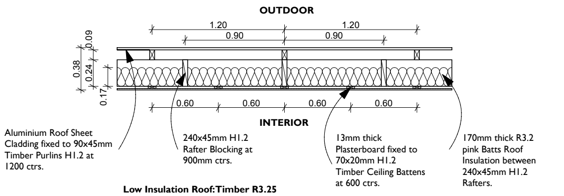
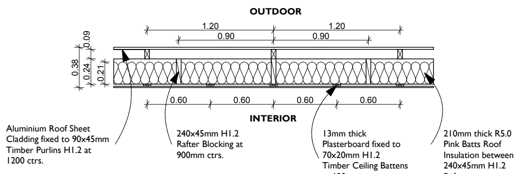
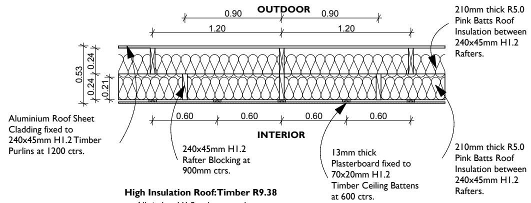
Timber framed wall (R1.94):
Weatherboard cladding, 20mm cavity, R1.9 insulation (Terra Lana) w. 90x45 studs @600crs, dwangs @ 800crs, 13mm GIB lining. Wall framing ratio 11.4%, insulation percentage ratio 88.6 %, cavity batten framing ratio 1.5%.</td>
<td>

Medium Insulation Wall:Timber R3.4

Timber Framed wall (R3.4):
Weatherboard cladding, 20mm cavity, R4.0 Pink Batts (R2.8 +R1.2 batts fill up the wall) w. 140x45 studs @600crs, dwangs @ 800crs, 13mm GIB lining. . Wall framing ratio 11.4%, insulation percentage ratio 88.6&, cavity batten framing ratio 1.5%.</td>
<td>

High Insulation Wall:Timber R6.46

Timber framed wall (R6.46):
Weatherboard cladding, 20mm cavity, Double wall with offset studs: 2x R4.0 Pink Batts w. 140x45 studs @600crs, dwangs @ 800crs, 13mm GIB lining. . Wall framing ratio 11.4%, insulation percentage ratio 88.6&, cavity batten framing ratio 1.5%.</td></tr>
<tr><th>Building Element</th><th>Low Insulation</th><th>Medium Insulation</th><th>High Insulation</th></tr>
<tr><td>Window Unit</td>
<td>Window Unit (U Value 3.89, R Value 0.26):
Aluminium double glazed framed, clear glazing, air fill. Air gap 5mm.</td>
<td>Window Unit (U Value 2.75, R Value 0.36):
Timber double glazed framed, clear glazing, air fill. Air gap 5mm.</td>
<td>Window Unit (U Value 1.93, R Value 0.52):
Timber double glazed framed, low-E coated glazing, argon fill. Argon gap 12mm.</td></tr>
</table>

Building Element	Low Insulation Concrete Roof Element	Medium Insulation Concrete Roof Element	High Insulation Concrete Roof Element
Roof	 Low Insulation Roof Sleep Out:Timber R3.09 **Sleep-out concrete roof (R3.09):** 300mm soil, 13mm air gap, 60mm extruded polystyrene (R2.3, Goldfoam), 13mm air gap, 200mm concrete.	 Low Insulation Roof Sleep Out:Timber R3.09 **Sleep-out concrete roof (R4.49):** 300mm soil, 13mm air gap, 100mm extruded polystyrene (R3.7, 60mm + 40mm Goldfoam), 13mm air gap, 250mm concrete.	 High Insulation Roof Sleep Out:Timber R9.49 **Sleep-out concrete roof (R9.49):** 300mm soil, 13mm air gap, 210mm extruded polystyrene (R8.7, 50mm + 60mm + 60mm + 40mm Goldfoam), 13mm air gap, 250mm concrete.
Building Element	**Low Insulation Timber Frame Roof Element**	**Medium Insulation Timber Frame Roof Element**	**High Insulation Timber Frame Roof Element**
Roof	 Low Insulation Roof:Timber R3.25 **Timber roof (R3.25):** Metal cladding, 90mm air gap (90x45mm purlins at 1100mm centres, above insulation), 170mm R3.2 pink batts w. 240x45 rafters @600crs, blocking @ 900crs, 20mm air gap (45x19mm ceiling battens at 400 centres), 13mm GIB ceiling lining. Rafter framing ratio 14%, insulation percentage ratio 86.0%, purlin framing ratio 4.1%, ceiling batten framing ratio 11.3%.	 Medium Insulation Roof:Timber R4.55 **Timber roof (R4.55):** Metal cladding, 30mm air gap (purlins, above insulation), R5.0 pink batts (210mm) w. 240x45 rafters @600crs, blocking @ 900crs, 20mm air gap (ceiling battens), 13mm GIB lining. Rafter framing ratio 14%, insulation percentage ratio 86.0%, purlin framing ratio 4.1%, ceiling batten framing ratio 11.3%	 High Insulation Roof:Timber R9.38 **Timber roof (R9.38):** Metal cladding, 30mm air gap (above insulation), R5.0 pink batts w. 240x45 purlins @1200crs, 40mm air gap (above insulation), R5.0 pink batts w. 240x45 rafters @600crs, blocking @ 900crs, 20mm air gap (ceiling battens), 13mm GIB lining. Rafter framing ratio 14%, insulation percentage ratio 86.0%, purlin framing ratio 4.1%, ceiling batten framing ratio 11.3%

3.2 Embodied Energy / Carbon Dioxide Coefficient Assumptions

This research unless specifically detailed uses the embodied energy and carbon dioxide material coefficients from the PhD research of Dr Andrew Alcorn (2010).
Refer to APPENDIX 1.0 MATERIAL ASSUMPTIONS, Embodied Energy and Embodied Carbon Dioxide Material Coefficients for a complete listing.

3.2.1 Low E and Argon Gas Embodied Energy / Carbon Dioxide Coefficient Assumptions

Due to the absence of an embodied energy and embodied carbon dioxide material coefficient specific to the New Zealand the following proxy assumptions have been made to calculate these sustainable indicators.

Table 3 shows the embodied energy and carbon dioxide material coefficients used for the Argon gas filling in the high insulation window unit construction system.

Table 3: Argon Gas Embodied Energy and Carbon Dioxide Assumptions

Material	Embodied Energy				Carbon Dioxide			
	Value *1	Unit *1	MJ/l *2	MJ/m3 *2	Value *1	Unit *1	MJ/l	MJ/m3
Argon	0.000187	kWh per litre	0.0006732	6.732E-07	0.00015	kg CO2 per litre	0.00054	5.4E-07
Notes:								
*1 Values sourced from Table 7 pg 44 (Fernie & Muneer, 1996)								
*2 Values converted to required unit measurement where 1 MJ = 3.6 kWh, 1 litre = 0.001 m3								

Table 4 shows the embodied energy and carbon dioxide material coefficients used for the low E glazing in the high insulation window unit construction system. The proxy figure used is 15.9 MJ/kg for clear float glass (Alcorn, 2010). The process for this proxy selection was based on analysis of the Nor Dan reference window unit. Comparing the aluminium embodied energy (MJ/kg) of the reference window unit against Alcorn's (2010) shows a +9% difference. This was deemed acceptable and used as a basis for using the nearest glazing material to 13 MJ/kg i.e. clear float glass. Additionally, the BRANZ proxy value used for tinted glass is the same, adding further justification to this reports assumption.

Table 4: FIX MJ toughened and float MJ coefficients Low E Glazing Embodied Energy and Carbon Dioxide Assumptions

Material	Reference Window Unit			Proxy Embodied Energy Values			
	Embodied Energy MJ per Material	Total Material Quantity per kg	EE MJ/kg	MJ/kg (Clear Float Glass, Alcorn 2010)	MJ/kg (Toughened Float Glass, Alcorn 2010)	MJ/kg (Tinted Glass, BRANZ, 2008)	MJ/kg (Aluminium, Extruded, Factory Painted, Alcorn 2010)
Argon	0						
Timber	195						
Aluminium	409	2	201				220 (109% Percentage Difference)
Glass	289	22	13	15.9 (122% Percentage Difference)	27 (208% Percentage Difference)	15.9 (122% Percentage Difference)	
Manufacture	173						
TOTAL	**1066.5**						
Notes:							
Reference window unit is 1200 x 1200mm Double Glazed Window Unit with 16mm Gap Optimum for Argon Gas Nor Dan Standard 3 Handle Turn and Tilt. Timber Sash and Frame. Low E coating on both glazing panes (Weir & Muneer, 1998).							

3.3 Construction Cost Assumptions

The construction and maintenance cost calculation have been conducted based on the detailed construction rates for Wellington New Zealand from Rawlinsons New Zealand Construction Handbook (2012). Where an appropriate figure was not available a Quantity surveyor has been engaged to provide the required unit figure.

All costs are expressed exclusive of Goods and Services Tax (GST) 15% and presented in present value (discounted value) form at the time of this report. Construction increase, inflation costs, construction margins, professional fees, sundries, and building services are excluded.

Present value form was selected, as the scope of this report was to calculate the construction and maintenance costs associated with the construction of the case study buildings. As net present value is equal to the present value cash inflow (revenue or cash worth of a building at market sale rate) minus present value cash out flow (construction, maintenance, council rates etc.) it is outside the scope of this research as the cash value inflow is not part of this analysis.

3.4 Material Lifespan Assumptions

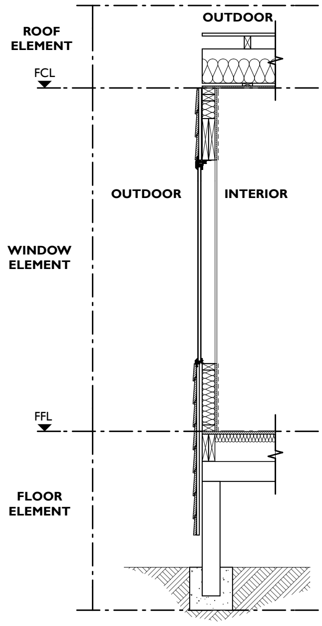
Building material lifespans have been assumed based on the research of Alcorn (2010). Where a specific material lifespan is not listed the nearest alternative is used as a proxy value.
Refer APPENDIX 1.0 MATERIAL ASSUMPTIONS, Summary of which element members were modelled for each construction system for a complete listing.

3.5 Material Quantity Assumptions

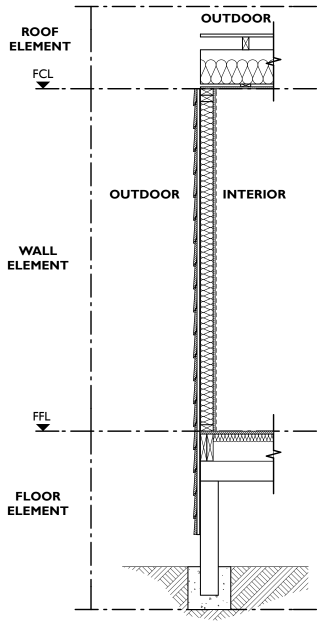
The quantification of the building materials used in the construction systems have been calculated based on the measured building areas of each construction element i.e. floor, wall, window, and roof that comprise the thermal envelope. This section details the assumptions made in development of the calculation formulas used for quantification.

3.5.1 Building Element Definition

Figure 3 shows the defined boundaries used in the classification of the case study building elements. This figure illustrates the defined scope the thermal envelope building components encompass. The floor element encompasses all the building materials up to the point of finished floor level (FFL). The window element includes both the window unit and the wall into which it is fitted. The size of the window unit is the actual width and height from the as-built window schedule documentation. This is up to the edge of the wall frame opening and inclusive of the window unit frame. The width of the wall (hereby referred to as window wall), shown in Figure 4 is based on the width on the window unit and any additional building structure associated with the window unit. The window wall height is as measured from building documentation.

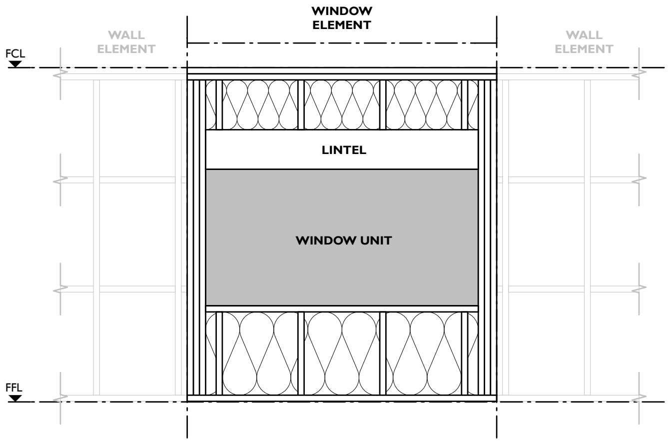


General Building Element Boundary Definition



General Building Element Boundary Definition

Figure 3: General Building Element Boundary Definition



General Building Element Boundary Definition: Front Wall Section Elevation

Figure 4: General Building Element Boundary Definition Window Element Front Sectional Elevation

3.5.2 Framing Ratios

The calculation of non-homogenous building material quantities i.e. a timber framed stud wall with studs at 600mm ctrs and nogging at 800mm ctrs is difficult. It requires determining the proportion of the wall element that is made up of those materials. This report references and adapts the method used in NZS 4214:2006 of using framing ratios to account for thermal bridging when calculating the thermal resistance of a building elements in various residential construction systems. This report uses framing ratios to determine from rough building element volumes the volumetric quantities of individual materials used in the building elements described in report section 3.1 Construction System Assumptions.

Where possible the BRANZ House Insulation Guide specified framing ratios for specific construction systems have been used. However, their use in the context of calculating material quantities for the purpose of embodied energy and cost analysis requires the determination of what they account for. This section is a detailed account of the analysis of a 90x45mm timber frame wall with cavity fixed bevel-back weatherboards, R1.8 insulation in cavity timber frame space: Framing ratio 14%. Total construction R value 1.9 (BRANZ, 2010, p. 67).

3.5.3 Floor Element

Concrete Slab: Material Quantity Calculation

Figure 5 shows the difference between the modelled concrete slab construction verses the actual construction detail. The simplification removes the construction slab strip foundation nib simplifying the construction system. This equates to a 3.3% percentage decrease in the quantified concrete volume between the actual construction and the modelled construction for a 10m x 10m concrete floor slab using the details illustrated in. Refer APPENDIX 3.0 Table 5 for calculation details.

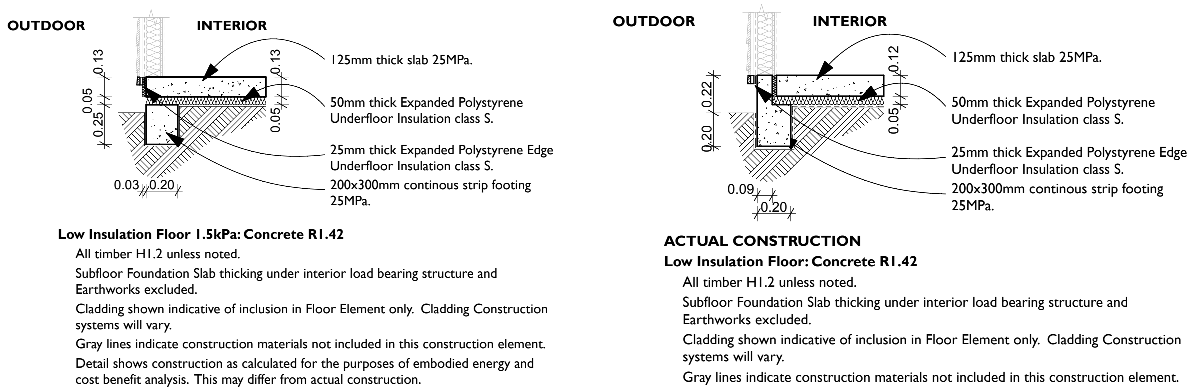


Figure 5: Modelled Construction vs. Actual Construction (Bulleyment, 2004)

Concrete Slab: Construction Assumptions

- 25mm thick concrete slab edge insulation detailed as per Bulleyment (2004).
- Internal wall slab thickening excluded.
- Slab foundation depth 200mm below finished ground level as per minimum requirement NZS 3604:2011 3.4.2.
- Finished floor level was top of slab, excluded the polishing.
- Excluded site typography foundation excavation and backfill etc.
- Excluded polythene, concrete reinforcing, formwork boxing etc.
- Element includes wall cladding below 50mm overhand below finished floor level as per NZS 3604:2011 Figure 7.11.

- Finished ground assumed to be unpaved, distance from FFL to FGL 225mm as per NZS 3604:2011 7.5.2.1 b (ii).

Timber Floor: Material Quantity Calculation

Blocking required at mid span 190/42 = 4.2m
All piles are ordinary, extend 300mm below ground level
Includes cladding below Finished Floor Level
Building Wrap Excluded
Joists span

3.5.3 Wall Element

1. Concrete block infill

3.5.3 Window Element

2. Optimum 10-12mm thick gap for Argon gas filling between double glazing window panes (BRANZ, 2008). Research specifies 12mm.
3. Aluminium window joinery profile used for analysis is Vantage Joinery Thermal Heat fixed casement. The cross sectional area of the profile used for embodied energy and carbon dioxide calculation was measured from downloaded CAD dwg files.
    a. Head profile: 0.001067 m2
    b. Sill profile: 0.000969 m2
4. Timber window joinery profiles
5. Lintels
6.

3.5.4 Roof Element

7. Paint coverage rates
8. Tanking coverage rates
9.
10. Framing ratios
    a. Floor framing – joists, solid blocking, boundary joists
    b. Bearer framing ratios
    c. Pile framing ratios
    d. Wall framing – studs, nogging, top and bottom plates
    e. Cavity battens
    f. Insulation percentage ratios
    g. Roof framing – rafters
    h. Purlins
    i. Cavity battens
    j. Double stud framing
    k.

How did I go about planning / doing this research?
How long does a residential building last for? Typical Lifespan – mortgage period.

Source of the cost information

- *Rawlinsons 2011 Detailed rates*
- *Material lifespans*
- *EE / ECO2 material coefficients*

Methodology of calculating the embodied energy / embodied CO2 / Cost / of the building

- *How accurate am I modelling?*
- ~~*Simplification of the house geometry representations*~~
- *How did I go about calculating the material quantities*
    - *Used a typical element, calculated the quantities for each element member then developed simple formulas for doing this and compared the accuracy*
        - *How did I determine if this was accurate enough?*
- *How did I calculate Present Value*
    - *Discount rate*
    - *Assumed inflation rate*
- *How did I calculate the lifespan replacement rate*
    - *Material lifespan / lifespan of the building then rounded down – always included the 0 year capital cost of construction*

Design of the spreadsheet:

- *CIBSfE labelling system – for analysis purposes*
- *The*

4.0 SPREADSHEET CALCULATION

Description of what the spreadsheet i.e. set of instructions – what it does, how it work, what inputs it requires, what results it produces, figure of how the TABS interact,

5.0 RESULTS

Heating energy only – may account for low operative vs embodied energy relationship i.e. HEEP 34% Heating energy end use.
Present cost vs NPV – Net present value is the revenue – capital investment, if positive this is a good result. This is not applicable to our study as we are calculating the capital inverstment cost + maintance costs only. Revenue comes from the sales of the house, not part of this study.

Results per house + combined average

SENSITIVITY ANALYSIS

NOT GOING TO HAVE TIME FOR THIS

Different discount rates – Ian page did -5.0%, -2.5%, 2.5%, and 5% on initial calculation being 0%.
Differences in material quantity calculation

Varying the WWR
QS Verses Rawlinsons

FUTURE WORK

Market resale costs
Add construction materials
Overhangs, vary window to wall ratios

ISSUES

How am I going to combine these?
How am I going to express the accuracy?

APPENDIX 1.0 MATERIAL ASSUMPTIONS

Embodied Energy and Embodied Carbon Dioxide Material Coefficients

Source: (Alcorn, 2010)

Material	Embodied energy		Embodied CO_2	
	MJ/kg (or other)	MJ/m^3 (or other)	g/kg (or other)	kg/m^3 (or other)
Aggregate	0.04	65	3	4.5
Aluminium, virgin	194	524,050	14,200	38,340
Aluminium, extruded	204	551,700	14,830	40,040
Aluminium, extruded, anodised	230	621,240	16,350	44,140
Aluminium, extruded, factory painted	220	597,700	15,770	42,570
Aluminium, recycled	9	24,410	645	1,750
Aluminium, recycled, extruded	14.6	39,490	1,020	2,760
Aluminium, recycled, factory painted	22	58,890	1,080	2,920
Bitumen fibre board	1.8	11.7 (MJ/m^2)	-460	-1.6 (kg/m^2)
Building wrap	51	2.2 (MJ/m^2)	148 (g/m^2)	
Cement, average NZ	6.2	12,000	1,025	2,000
Cement fibre board	9.3	13,180	725	1,030
Ceramic brick, NZ average	3	5,940	190	375
Ceramic pipe	6.6	13,070	600	1,190
Concrete block	0.9		112	
Concrete 17.5 MPa	0.9	2,020	118	280
Concrete 30 MPa	1.2	2,760	164	390
Copper tube [1]	2.4	21,290	150	1,340
DPM	64		172 (g/m^2)	
Earth (straw stabilised adobe)	0.15	250	-12	-20
Electricity, average, NZ [2]	1.54 (MJ/MJ)		67 (g/MJ)	
Electricity, marginal, NZ [2]	18.7 (MJ/MJ)		199 (g/MJ)	
Firewood	0.06	27	-1,690 [3]	-150 (g/kg) [4]
Glass, float	15.9	40,040	1,740	4,370
Glass, toughened	27	66,880	2,450	6,180
Gypsum plaster board	7.4	7,080	470	450
Hard-fill	0.04	65	3	4.5
Insulation, fibreglass	32	1,540	770	37
Insulation EPS	58	1,400	2,500	60
Insulation XPS	58	2,450	2,500	105
MDF	12	8,280	-320	-220

Material	Embodied energy		Embodied CO_2	
	MJ/kg (or other)	MJ/m^3 (or other)	g/kg (or other)	kg/m^3 (or other)
Nails, galvanised	29		1,750	
Paint, water based	69	89,500	1,640	2,130
Phase-change board	21	24,910	1,390	1,660
PV panel	-15,500 (MJ/m^2) [5]			235 (kg/m^2)
Solar hot water panel	-41,000 (MJ/m^2)[6]			104 (kg/m^2)
Steel reinforcing [7]	8.6	67,420	575	4,530
Steel roofing 0.4mm, factory painted		204 (MJ/m^2)	8,785 (g/m^2)	
Steel roofing 0.4mm, zinc/aluminium		172 (MJ/m^2)	8,060 (g/m^2)	
Steel roofing 0.55mm, factory painted		250 (MJ/m^2)	10,600 (g/m^2)	
Steel wire, galvanised [8]	29	227, 650	1,750	13,730
Stone, dimension, NZ	0.8	1,890	80	197
Strawbale	0.24	31	-1,660	-210
Srawclay	0.2	116	-295	-205
Timber, air dried, roughsawn, treated	2.7	1,261	-1,670	-695
Timber, glulam	7.8	3,490	-1,360	-550
Timber, kiln dried, dressed, treated	8.9	4,090	-1,320	-535
Wind generator	-15,000 (MJ/yr) [9]			1,025 (kg) [10]

Notes:

1. Recycled copper.
2. Five year average.
3. Un-burnt firewood: has a large net absorption of CO_2.
4. Burnt firewood: has a small net absorption, including emissions from cutting and transport, and sequestered carbon in ash, embers, and soot.
5. Net MJ per m^2 of PV cell area. i.e. the total output over the 25 year lifetime, minus manufacturing energy, including mounting etc.
6. Net MJ per m^2 of collector area. i.e. the total output over the 20 year lifetime, minus manufacturing energy, including mounting etc.
7. Recycled steel in New Zealand.
8. Nails and other fasteners are made from galvanised wire from recycled steel.
9. Net MJ per year. i.e. the total output each year, minus manufacturing energy, including mounting etc.
10. Total embodied CO_2 for whole system.

Lifetimes of Building Materials, Components, and Houses

Source: (Alcorn, 2010)

Material	Life	Source
Aluminium windows	35	Bennet (2008)
Concrete block masonry, painted	80	Bennet
Concrete in floors	150	This thesis
Concrete in walls	100	Bennet
DPM	150	This thesis
Earth	150	This thesis
Floor boards	150	This thesis
Glass	100	Bennet
Gypsum plaster board	50	Bennet
Hardfill	150	This thesis
Insulation	50	Bennet
Insulation EPS	50	Bennet
Insulation XPS	150	This thesis
Nails, framing	90	This thesis
Nails, galvanised, cladding	40	Page (2005)
Nails, lining fixing	50	This thesis
Paint, factory applied	15	Page
Paint, normal	8	Page
PV panels	25	Alsema (2000)
Solar hot water system	20	EECA (2001)
Steel reinforcing	150	This thesis
Steel sheet, factory painted & repainted	50	Page
Strawbale	100	This thesis
Timber, roof framing	90	Page
Timber, sub-floor framing	90	Page
Timber, external windows and doors	90	This thesis
Timber, internal doors	150	This thesis
Timber, exterior wall framing	90	Page
Timber, H1.2 treated	90	Page
Timber, interior wall framing	150	This thesis
Timber, shingles	40	Greenspec (2009)
Underfloor foil	50	This thesis
Weatherboard, radiata	70	Page
Wind generator	10	Dunford
Houses, 1860–1980	90	Johnstone (2004)
Houses, 2000 -	130	Johnstone
Houses, service life span	140	Johnstone
House, average residence at an address	8	Page

APPENDIX 3.0

- Summary of which element members were modelled for each construction system
- Excel spreadsheet example calculation of the formulas used verses the measured quantities and the calculated percentage accuracy range
- 2d sketch representation of the example element measured verses modelled
- Images of complexity operative energy modelled verses as built verses embodied energy / cost modelled
- Framing ratio spreadsheets
-

Table 5: Concrete Slab Material Quantification Calculation Margin Of Error

Concrete Floor Slab Actual vs. Modelled Construction Material Quantity Difference						
Description	**Times**	**Cross Section Area (m2)**	**Width or Height (m)**	**Length (m)**	**Total Volume of Member (m3)**	**Percentage Difference**
Actual Floor Element Construction						
Concrete Slab	*1*	*1.250*		*9.910*	*12.388*	
Concrete Strip Footing	*4*	*0.086*		*10.000*	*3.440*	
Total					***15.828***	***100.0%***
Modelled Floor Element Construction						
Concrete Strip Footing	2	*1.25*		*10*	*12.500*	
Concrete Strip Footing	*4*	*0.070*		*10.000*	*2.800*	
Total					***15.300***	***3.3%***

Table 6: Timber Floor Low Insulation Material Quantification Framing Ratios

FRAMING RATIO LOW INSULATION TIMBER FLOOR								
Description	**Times**	**Thickness (m)**	**Width or Height (m)**	**Length (m)**	**Spacing (m)**	**Total Volume (m3)**	**Total Volume of Member (m3)**	**Framing Ratio**
Total Floor Element	**1**	**0.210**	**10.000**	**10.000**	**1.000**	**21.000**		**100.0%**
Joists	*29.0*	*0.045*	*0.190*	*9.910*	*0.400*	*19.000*	*2.457*	*12.9%*
Blocking Mid Span	*72.0*	*0.045*	*0.190*	*0.355*	*3.550*	*19.000*	*0.219*	*1.2%*
Blocking Mid Span	*6.0*	*0.045*	*0.190*	*0.087*	*3.550*	*19.000*	*0.004*	*0.0%*
Boundary Joist	*2.0*	*0.045*	*0.190*	*10.000*	*Not Required*	*19.000*	*0.171*	*0.9%*
Total 140x45 Framing	**109.0**	**0.045**	**0.190**			**19.000**	**2.851**	**15.0%**
Bearers	**4.0**	**0.07**	**0.140**	**10.000**	**3.550**	**14.000**	**0.392**	**2.8%**
Piles	**45.0**	**0.125**	**0.125**	**0.600**	**1.300**	**60.000**	**0.422**	**0.7%**
Concrete Footing	**45.0**	**0.300**	**0.300**	**0.300**	**1.300**	**30.000**	**1.215**	**4.1%**
NOTES:								
BRANZ House Insulation Guide specifies 11.3% for 190mm Joists at 400 Ctrs for Suspended Floor closed perimeter pg. 113.								
Joists 190x45 at 600 Ctrs max span 3550 for 1.5kPa floor as per Table 7.1 NZS3604. Floor framing for interior walls excluded.								
Joist Blocking required mid span as joist depth 190 exceeds 4x width as per 7.1.2.3. Blocking required at 1800mm Ctrs over bearer subfloor line of support 7.1.2.2.								
Bearer loaded dimension((span 1 + span 2)/2) = (3550+3550)/2 = 3550. Bearer span 140x70 1300 span								
All piles are 125x125mm ordinary timber piles, bracing, site typography excluded. Pile spacing as per bearer span Table 6.4 NZS3604. Assumed all piles ordinary 125x125mm with 200mm deep concrete footing (Figure 6.2), 600mm max clearance from ground level (6.4.1.1a NZS3604). Footing size to match Rawlinsons 2012 rate.								

Table 7 Timber Floor High Insulation Material Quantification Framing Ratios

FRAMING RATIO HIGH INSULATION TIMBER FLOOR								
Description	**Times**	**Thickness (m)**	**Width or Height (m)**	**Length (m)**	**Spacing (m)**	**Total Volume (m3)**	**Total Volume of Member (m3)**	**Framing Ratio**
Total Floor Element	**1**	**0.210**	**10.000**	**10.000**	**1.000**	**21.000**		**100.0%**
Joists	*29.0*	*0.045*	*0.190*	*9.910*	*0.400*	*19.000*	*2.457*	*12.9%*
Blocking Mid Span	*72.0*	*0.045*	*0.190*	*0.355*	*3.550*	*19.000*	*0.219*	*1.2%*
Blocking Mid Span	*6.0*	*0.045*	*0.190*	*0.087*	*3.550*	*19.000*	*0.004*	*0.0%*
Boundary Joist	*2.0*	*0.045*	*0.190*	*10.000*	*Not Required*	*19.000*	*0.171*	*0.9%*
Total 140x45 Framing	**109.0**	**0.045**	**0.190**			**19.000**	**2.851**	**15.0%**
Floor Battens	*21.0*	*0.045*	*0.090*	*9.910*	*0.600*	*9.000*	*0.843*	*9.4%*
Boundary Floor Batten	*2.0*	*0.045*	*0.090*	*10.000*	*Not Required*	*9.000*	*0.081*	*0.9%*
Total 90x45 Framing	**23.0**	**0.045**	**0.190**			**19.000**	**0.924**	**4.9%**
Bearers	**4.0**	**0.07**	**0.140**	**10.000**	**3.550**	**14.000**	**0.392**	**2.8%**
Piles	**45.0**	**0.125**	**0.125**	**0.600**	**1.300**	**60.000**	**0.422**	**0.7%**
Concrete Footing	**45.0**	**0.300**	**0.300**	**0.300**	**1.300**	**30.000**	**1.215**	**4.1%**

NOTES:

BRANZ House Insulation Guide specifies 11.3% for 190mm Joists at 400 Ctrs for Suspended Floor closed perimeter pg. 113.

Joists 190x45 at 600 Ctrs max span 3550 for 1.5kPa floor as per Table 7.1 NZS3604. Floor framing for interior walls excluded.

Joist Blocking required mid span as joist depth 190 exceeds 4x width as per 7.1.2.3. Blocking required at 1800mm Ctrs over bearer subfloor line of support 7.1.2.2.

Floor Battens 90x45 at 600 Ctrs max span 1250mm for 1.5kPa floor as per Table 7.1 NZS3604. Floor framing for interior walls excluded.

Bearer loaded dimension((span 1 + span 2)/2) = (3550+3550)/2 = 3550. Bearer span 140x70 1300 span

All piles are 125x125mm ordinary timber piles, bracing, site typography excluded. Pile spacing as per bearer span Table 6.4 NZS3604. Assumed all piles ordinary 125x125mm with 200mm deep concrete footing (Figure 6.2), 600mm max clearance from ground level (6.4.1.1a NZS3604). Footing size to match Rawlinsons 2012 rate.