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Designing with External Wall Insulation at Residential Scale

A comparative energy-based study of design with external insulation

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Preface

This report assesses the thermal performance of external wall insulation compared to traditional wall insulation at residential scale. The energy implications of external wall insulation are also analysed to understand how this emerging system could benefit the New Zealand construction industry.

Acknowledgments

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Special acknowledgements to Danrong Zhao for her contributions in establishing a methodology to assess external insulation in section 6. Also, to Hannah Walsh for the capital costs of the townhouse and commercial office building in sections 6.4.2 and 7.4.2.

Notes

The main focus of this report is on the application of external insulation on a residential townhouse in New Zealand. However, a commercial office building was also assessed to test the energy implications of designing with timber, concrete and steel structural materials. This was done to enable another summer research assistant to produce a comprehensive report that details energy usage, operational costs, embodied energy and capital costs.

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List of Abbreviations

ACH	Air Changes per Hour
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
BEES	Building Energy End-Use Study
BRANZ	Building Research Association of New Zealand
CO_2	Carbon Dioxide
EE	Embodied Energy
EPW	EnergyPlus Weather file
EWI	External Wall Insulation
GFA	Gross Floor Area
HEEP	Household Energy End-Use Project
HVAC	Heating, Ventilation and Air Conditioning
ISO	International Standards Organization
IWI	Internal Wall Insulation
kWh	Kilowatt per hour
kWh/m^2.year	Kilowatts per hour per metre squared per year
LPDL	Lighting Power Density Load
m^2	Metres Squared
NZBC	New Zealand Building Code
NZS	New Zealand Standard
TBE	Thermal Bridging Elements

List of Key Definitions

This list clarifies key definitions used in the report, obtained from NZS4214 and NZS4218.

Baseline Insulation Model	The energy model of the building that has typical insulation between framing.
Building Element	A building element is a part of a building, such as wall, floor, roof or window. Often it consists of one or more components such as a concrete floor slab, or an assembly of several components, including cladding, cavity, timber frame, insulation material, and lining.
Building Envelope	The exterior surfaces of the whole building enclosing all conditioned and unconditioned spaces.
Conditioned Space	Spaces within the building envelope that are expected to be conditioned with an HVAC system, specifically habitable spaces.
External Insulation Model	The energy model of the building that has typical insulation between framing AND insulation on the exterior of the framing (external insulation).
External Wall Insulation	Insulation that is continuous across all structural members without thermal bridges, except for fasteners and service openings. It is installed on the exterior of the building envelope's opaque surface (wall, roof, etc).
Internal Wall Insulation	Insulation that is placed between framing on the exterior walls of the building envelope.
Opaque Conduction	The thermal conduction through an opaque material.
Opaque Material	Non-transparent material – not allowing light to pass through.
R-Value (Total Thermal Resistance)	The R-Value of a building element is the sum of the surface thermal resistances of each side of a building element, and the thermal resistances of each component within the building element. It is determined by

	calculation, or by measuring the temperature difference between the internal air on one side and the external air on the other side of a building element, when there is a unit heat flow in unit time through unit area.
Thermal Conductivity (k):	The heat flow (thermal transition) in unit time through unit area of a uniform homogenous material of unit thickness when the difference of temperature is maintained between its two surfaces (W/mK).
Thermal Envelope	The roof, wall, glazing, skylights, doors, and floor construction between conditioned spaces and outside.
Thermal Resistance ($m^2.°C/W$):	A measure of resistance to the flow of heat. It can be determined by measuring the temperature difference which is maintained between surfaces or planes when there is constant heat flow between them in unit time through unit area.
Unconditioned Space	Spaces within the building envelope that are not conditioned with an HVAC system (this may include a garage, conservatory, atrium, attic, subfloor, etc).

Studio Pacific Architecture Privacy Notes:

Case Study A	Case study A refers to the residential townhouse as a part of the Launch Bay development in Auckland, New Zealand.
Case Study B	Case study B refers to the commercial office building at 149 Featherston Street in Wellington, New Zealand.

This information is only intended for Studio Pacific Architecture, and no external parties.

Abstract

Temperature increases in the atmosphere and oceans are a result of anthropogenic greenhouse gas (GHG) emissions caused by human behaviour. Energy use from buildings accounted for 19% of global GHG emissions in 2010, demonstrating the importance of reducing energy consumption in the built environment. A potential way of reducing energy consumption in buildings is by using external wall insulation (EWI). EWI can block out thermal bridges on the façade to decrease the overall heat loss in winter, and heat gain in summer. Subsequently, this would mean lower heating and cooling loads and hence lower overall energy use. This research, then, assessed EWI through an established methodology of (1) determining the most important façade details to model; (2), modelling the details in THERM; (3) calculating the total R-Value of the façade; and (4) running an energy simulation. Through the application of external insulation to a residential townhouse in Auckland, New Zealand, the energy has reduced 25% from the baseline insulation model. In addition, operational costs are 26% less; however, the capital costs are 1.5% more to externally insulate the walls and will take 9.3 years to pay off. Therefore, this research demonstrates that although external wall insulation is 1.5% more expensive, the reductions in energy and operational costs demonstrate a viable and energy efficient insulation alternative that must be implemented in residential construction in New Zealand to reduce energy consumption.

1. Introduction

With the warming of the global climate system being observed since the 1950s, evidence has shown an increase in temperature of the atmosphere and oceans (O'Grady, 2018). Temperature increase is unequivocally linked with human behaviour, namely anthropogenic GHG emissions caused by population and economic growth (O'Grady, 2018). This increase has put an onus on the ecological systems and processes under which they have thrived since their existence. To reduce GHG emissions – before effects of mass climate and ecological destruction – buildings, and their energy use must receive special attention. Lucon et al. (2014) stated that in 2010, buildings accounted for 32% of total global energy use and 19% of global GHG emissions. Although there is not yet a New Zealand specific figure between these two aspects, Lucon et al. (2014) has proven that mass energy use in buildings has large GHG emission implications (BRANZ, 2018). Therefore, in the New Zealand built environment, changing standard building practices with energy efficient alternatives is integral to saving energy and hence GHG emissions. The use of external wall insulation in residential buildings could reduce energy consumption due to reduction in thermal bridging. Blocking thermal bridges will reduce heat loss through walls, resulting in lower overall heating loads, reducing energy consumption. The purpose of this study, then, is to assess the thermal performance of external wall insulation, identifying the energy consumption implications for a New Zealand climate.

1.1. Scope

The scope of this research entails the assessment of external insulation on an architecturally designed residential townhouse in Auckland, New Zealand. Only the façade (external wall) elements are focused on to understand specific energy consumption implications.

1.2. Research Questions

Due to the scope in section 1.1, the research questions are as follows:

- How would a methodology be established for conducting a comparative analysis of various insulation methods?
- What are the energy implications of using external insulation at residential scale?
- From the energy implications, what would a 'best practice' model look like for designing external insulation at residential scale? Specifically considering energy consumption, operational energy costs, capital costs and building performance.

2. Background

No matter how well a building is sealed or insulated, some heat loss will always occur through the building envelope (BRANZ, 2014a). However, the amount of heat loss through the envelope is determined by its thermal quality, dictating the indoor and outdoor temperature differential (O'Grady, 2018). The thermal quality of the envelope is dependent on a water control layer, an air control layer, a vapour control layer and a thermal control layer (O'Grady, 2018). In New Zealand, the thermal control layer is typically wall insulation made from polyester fibre or glass wool insulation between timber studs, dwangs, and top and bottom plate (See figure 1. BRANZ, 2010). Although this is standard practice, it comes with a major downfall – thermal bridging.

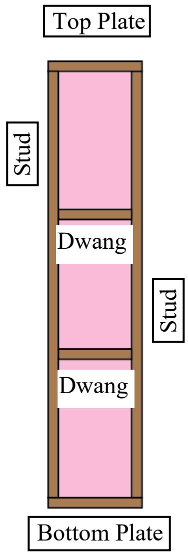


Figure 1: Typical framing, 400 crs.

2.1. Thermal Bridging

The International Standards Organization (ISO) 10211:2017 defines a thermal bridge as:

> "A part of the building envelope where uniform thermal resistance is significantly changed by full or partial penetration of the envelope by materials with a significantly higher thermal conductivity, such as timber studs in a wall/ceiling junction."

In other words, thermal bridging allows mass heat loss through materials of significantly higher thermal conductivity that are connected to a building's cladding and/or lining (BRANZ, 2014a). As seen in figure 3, a baseline wall detail for a low-rise residential building has thermal bridging through the timber studs. Other detail areas such as the wall/slab and wall/roof junction will also have thermal bridging. According to BRANZ (2001), around 28% of a typical timber wall contains framing, demonstrating the mass area of facade that allows thermal bridging. In addition to increased heat loss, thermal bridging has also been linked to condensation and mould growth on internal walls (BRANZ, 2014a). This is due to 'cold spots' forming on the internal side of the thermal bridging area due to the increased difference between indoor and outdoor temperatures. These cold spots form condensation and hence begin to grow mould. Due to this, the baseline insulation and building envelope strategy in New Zealand must be assessed and improved upon.

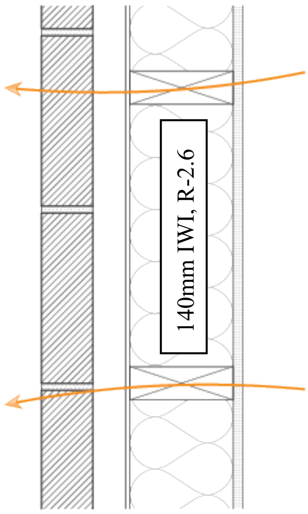


Figure 3: Baseline wall insulation.
Orange = Thermal Bridge

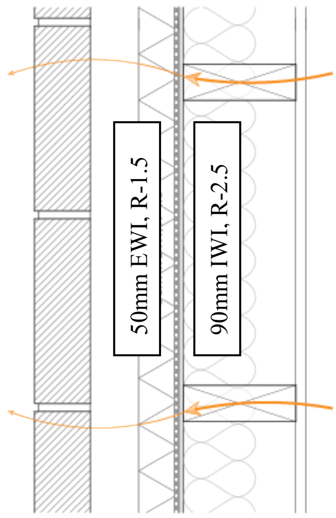


Figure 2: Typical wall external insulation.
Orange = Reduced Thermal Bridge

2.2. External Insulation

One solution to reducing heat loss and mould growth is using external wall insulation (EWI). External insulation (aka continuous insulation) is defined by ASHRAE Standard 90.1 as:

> "Insulation that is continuous across all structural members without thermal bridges, except for fasteners and service openings. External insulation is installed on the exterior of the building envelope's opaque surface."

In other words, external wall insulation is determined by its exterior position relative to the structural members in the wall, as long as thermal bridging is prevented. The ratio of internal to external insulation is also a factor in designing external insulation as a building could overheat with too much insulation (Wang, 2017). Joseph Lstiburek (2017) suggests that, for a climate similar to Auckland, a ratio of 35% external insulation R-Value to the total insulation R-Value must be used to prevent likelihood of overheating. This ratio will increase and decrease depending on the severity of the climate. The external insulation design in figure 2 has R-2.5 between framing and R-1.5 on the exterior envelope, with a total R-Value of R-4. The ratio of external insulation to total R-Value is therefore 37%, which demonstrates this wall has close to the correct insulation ratios to ensure it does not overheat.

	Baseline Insulation	**External Insulation**	
Values	**Insulation Between Framing**	**Insulation Between Framing**	**External Insulation**
Thickness	140mm	90mm	50mm
R-Value	R-2.6	R-2.5	R-1.5
Material	Polyester	Polyester	Mineral Rockwool
Product	Mammoth Wall Blanket	Autex Thermal Pads	Rockwool ThermalRockS

Table 1: Baseline and external insulation thicknesses, R-Values, materials and products

Due to the correct ratio of R-Values in the typical external wall insulation detail in figure 2, the thicknesses and materials identified in table 1 will be applied to the relevant details identified in case study A, enabling this research to determine the effectiveness of external insulation on thermal performance and energy consumption.

2.2.1. External Insulation Buildings

Research on external insulation in newly constructed buildings found very little information. However, the research did find that external insulation was often retrofitted on existing buildings using rigid external insulation (Hopper, 2013., Glew, 2017). Other findings on external insulation mainly focused on either hygrothermal tests or energy simulation on the building envelope (Wang et al, 2017., Goncalves et al, 2020., Xu et al, 2019). Therefore, the main factor in completing this research is the lack of new buildings that construct with external insulation, despite the theoretical benefits as described in section 2.1 and 2.2.

2.3. Energy Modelling Tools

For this research, the Honeybee plugin for Grasshopper is used to create energy models. Honeybee specifically supports detailed thermodynamic modelling to create, run and visualise energy models using *EnergyPlus* and *OpenStudio*. EnergyPlus is the engine behind Honeybee that runs the energy simulation, while OpenStudio dissects the results. The Ladybug plugin for Grasshopper is used for the EPW file, as well as interpreting different climatic conditions in the results. Rhino and Grasshopper provide a simple user interface in which to use Honeybee and Ladybug. In addition, the THERM plugin for Honeybee must be used to ensure that the building envelope demonstrates accurate heat loss.

THERM:

THERM is a two-dimensional heat transfer modelling software built into the Honeybee plugin for Grasshopper. Honeybee models "homogenous convection" while THERM models a "geometrical convection" of the building envelope elements. A homogenous convection entails a one-dimensional heat transfer through a component; therefore, it does not consider thermal bridges (see figure 5. O'Grady, 2018). However, geometrical (or point) convection is when three building components meet (ISO, 2017. See figure 4). This geometrical convection is called a point thermal bridge – heat loss is accounted for; therefore, THERM must be used to consider thermal bridging in the building envelope. In addition, THERM's heat transfer analysis allows for an evaluation of a detail's energy efficiency, R-Value, temperature patterns and condensation.

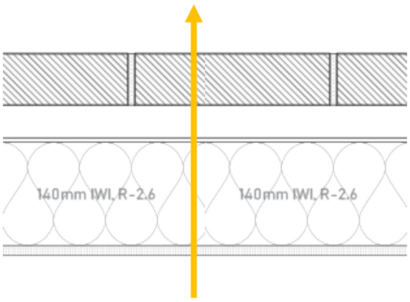


Figure 5: Homogenous wall (no timber studs) that can be modelled in honeybee

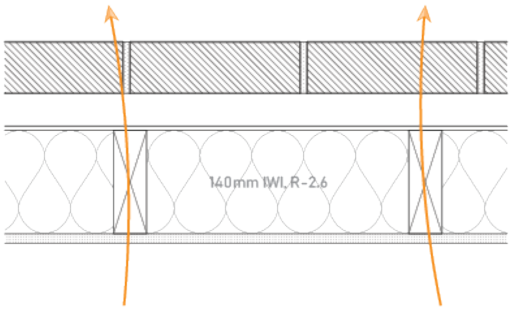


Figure 4: Geometrical wall (actual detail) that can be modelled in THERM

3. Case Study A – Base Model

3.1. Definition of Case Study A

Case study A focuses on a two-storey residential townhouse in Auckland, New Zealand. The townhouse consists of two units split vertically, each with a lounge, living room, kitchen, four bedrooms and a garage. The design and construction of the townhouse is typical of a residential building in New Zealand – timber framing with insulation, concrete slab and a pitched timber roof. Generic building information can be seen in table 2.

Information	**Value**
Floor Area	510m²
Floor Height	3m
Façade Area (excluding windows)	394m²
Façade Area (including windows)	479m²
Window Area	85m²
Window-to-Wall-Ratio	North: 23% East: 8%

	South: 6% West: 31%

Table 2: Townhouse information

3.2. Simulation Inputs for Base Model

The simulation inputs for the townhouse are based on the architectural drawings, schedule of selections, New Zealand standards, ASHRAE standards and other reputable literature.

Thermal Zones

Thermal zoning is done for several reasons. Firstly, it splits up zones that are conditioned differently – e.g. unique schedules, loads and heating/cooling set point (Shin, 2019). Secondly, it allows EnergyPlus to calculate solar gains accurately if the thermal zones are square (Shin, 2019). Therefore, the thermal zones of the townhouse were based off the occupancy and activity in each room – splitting them into 6 different zones (see figure 6 & 7).

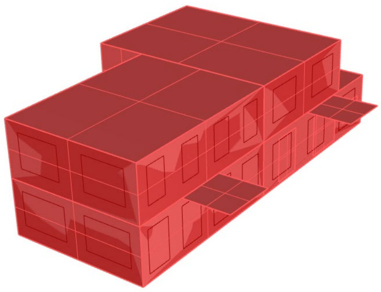


Figure 8: Geometry of energy model

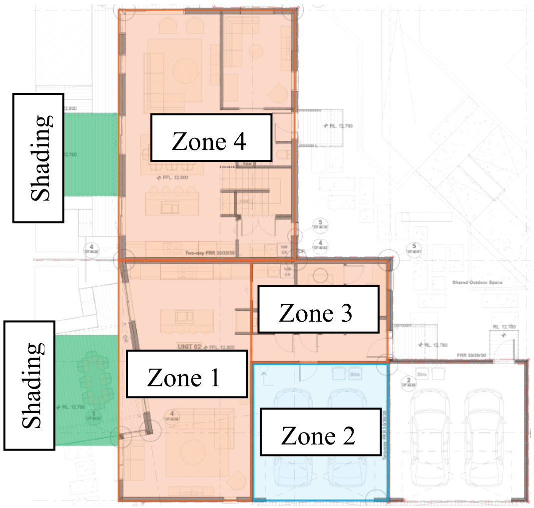


Figure 6: Thermal zones, ground floor
Orange = Conditioned. Blue = Unconditioned

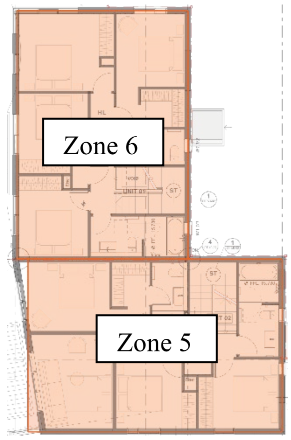


Figure 7: Thermal zones, ground floor

As seen in table 3, the garage is the only zone that is not conditioned. This is because there is no ducting shown on the mechanical specifications, and it is rarely occupied. All other zones are conditioned; however, the ground and first floor have different set point schedules for space conditioning. This is because the bedrooms do not need to be conditioned to the same extent as the main living spaces on the ground floor – kitchen, dining, lounge (ASHRAE, 2010).

Thermal Zones	Conditioned?	Set Point Schedule
TZ1	Yes	Set Point Schedule 1
TZ2	No	No Set Point Schedule
TZ3	Yes	Set Point Schedule 1

TZ4	Yes	Set Point Schedule 1
TZ5	Yes	Set Point Schedule 2
TZ6	Yes	Set Point Schedule 2

Table 3: Thermal zone conditions & set point schedules

Modelling Assumptions

1) The angled wall on first and second floor has been assumed to be straight. The floor area difference is 2m² which will have little effect on the overall energy usage. This has been done as zones must be square for EnergyPlus to calculate energy use.

2) Only one garage has been modelled. The second garage (far right) is not in contact with any internal or external walls of the house and will therefore not impact the energy use. This will also increase the accuracy of the simulation.

3) The ceiling of the townhouse on the first floor has been modelled as a flat roof. The construction is the same, but it just does not have an attic space. This has been done as zone ceilings can only be flat in EnergyPlus.

Climate Data

The climate for the townhouse is in Auckland, New Zealand. Therefore, the weather file used for energy simulations was the closest one to this location (NZL_AUK_Whenuapai-RNZAF.Auckland.931120_TMY). This weather file was obtained from the Ladybug Tools EPW map website (see appendix 2).

Opaque Constructions

For the base model, opaque, homogenous constructions were modelled for the walls, slab and roof. EnergyPlus only recognises homogenous constructions – materials layer upon layer – and hence does not model thermal bridging. However, the base model must be created to build upon. Two different wall types were modelled for different areas of the wall – EWT-01 and EWT-02 (see figures 9-12). The roof construction represented the whole ceiling area and the slab represented the whole slab. Perimeter slab edges were not considered in this simulation. The windows in the building are a Low-E coated insulated glazing unit (IGU) – one layer of 4mm toughened glass, one layer of 12mm argon gas filled air gap, and another layer of glass. All specific construction layers, details and property values for each material (density, thermal conductivity and specific heat) are in appendix 2.

Note: Orange = EWT-01, Blue = EWT-02, Red = Not modelled

Figure 10: West elevation, townhouse

Figure 9: North elevation, townhouse

Figure 12: East elevation, townhouse

Figure 11: South elevation, townhouse

Building Equipment

The building equipment load for both stories of the townhouse is 24.5 W/m². This figure was obtained from NZS4218. For the associated schedule, see appendix 2.

Occupancy, Density & Metabolic Rate of People

The density of people was determined by the number of bedrooms in each unit. There are 4 bedrooms in each unit, including one master. Assuming that the master has two people and the rest of the rooms have one person, the total amount of people in the whole townhouse is likely to be 10. Therefore, the density of the townhouse will be 51m²/person. For the hours of occupancy and metabolic rate schedule, see appendix 2.

Lighting Power Density Level (LPDL)

The LPDL level for both stories of the townhouse is 6 W/m². Although this figure was for a motel/hotel room, it was assumed that a medium density townhouse has a similar LPDL. This figure was obtained from NZS4243. For the associated schedule, see appendix 2.

Heating and Cooling Set Points

The thermal comfort requirements set out in NZS4218, ASHRAE Standard-55 and the mechanical specifications will be used for the heating and cooling set points for the townhouse.

Set Point Schedule 1	12am-8am	8am-11am	11am-6pm	6pm-10pm	10pm-12am	**Sources**

Heating Set Point Mon-Sun (°C)	18.5	20.5	20.5	20.5	18.5	Mechanical Engineer Specifications, NZS4218, ASHRAE Standard 55
Cooling Set Point Mon-Sun (°C)	20	25	25	25	20	

Table 4: Set point schedule 1

Set Point Schedule 2	12am-8am	8am-11am	11am-6pm	6pm-10pm	10pm-12am	**Sources**
Heating Set Point Mon-Sun (°C)	16	16	16	16	16	Mechanical Engineer Specifications, NZS4218, ASHRAE Standard 55
Cooling Set Point Mon-Sun (°C)	20	25	25	25	20	

Table 5: Set point schedule 2

Infiltration

The infiltration rate for residential buildings as set out in NZS4218 is minimum 0.5 air changes per hour (ACH). This recommended ACH rate has been converted to $m^3/s\text{-}m^2$ in honeybee to reflect the correct infiltration proportional to the volume of each zone.

Natural Ventilation

Natural ventilation has been modelled for both the ground and top floors. When the indoor temperature reaches 24°C, the windows will be opened, and when the temperature drops below 20°C, the windows will be closed. These values are from NZS4218. However, the use of natural ventilation in the model assumes two things:

1. Occupants' have the intuition to open the windows when temperature reaches above 24°C and close them when it drops below 20°C.
2. The occupants are home when these temperatures reach this point, or they do not leave windows open when the house is unoccupied.

All other input parameters for natural ventilation can be seen in appendix 2.

External Shading

There are two main exterior shading elements that will affect the building's solar gains – the pergolas and the adjacent apartments (see figure 13 & 14). The pergola is 3m above the ground on the north side of the building to provide shade for seating, and projects 2m out. The apartments are less than 15m from the townhouse and is 45m tall. These shading elements have been added in Honeybee to ensure the solar gains are accurate to the site.

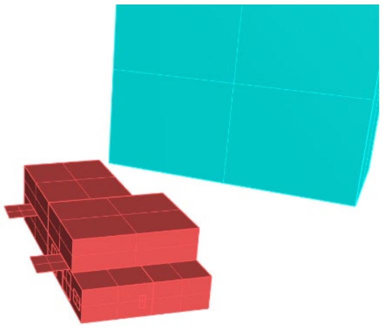


Figure 13: Townhouse external shading geometry

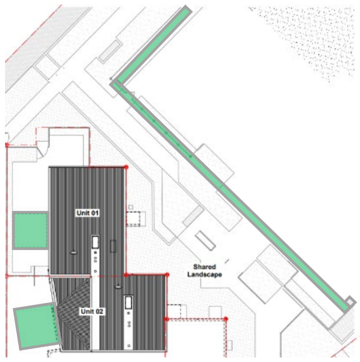


Figure 14: Townhouse external shading plan

4. Case Study B – Base Model

4.1. Definition of Case Study B

Case study B focuses on a 12-storey mixed-use retail and office building in Wellington CBD, New Zealand. This is not a typical office building as it was on track to become the southern hemisphere's first high-rise timber building. The floors, columns and beams were designed as cross laminated timber (CLT), and edge beams made from glulam, making it one of the most interesting and important structures in modern timber construction. However, it was never built due to the price of the build. Generic building information can be seen in table 6.

Information	Ground (G)	Mid (1-7)	Top (8-11)
Floor Area	309m²	310m²	309m²
Floor Height	4m	4m	4m
Façade Area (including windows)	304m²	304m²	304m²
Window-to-Wall-Ratio	North & West: 75%	North & West: 75%	North, East, South & West: 75%

Table 6: Office building information

4.2. Simulation Inputs

The simulation inputs for the office building are based on the architectural drawings, schedule of selections, New Zealand standards, ASHRAE standards and other reputable literature.

Thermal Zones

High-rise buildings pose unique challenges to building energy simulation. To obtain the most accurate energy results in high-rise building simulation, every floor of the building must be modelled. This does however cause several issues including increased set up and simulation time, and potential incompatibility with a mass number of zones (Ellis, 2005). If the office building model were run with every floor, there would be 62 zones and over 300 surfaces. However, Ellis et al (2005) conducted a study that demonstrated less than 1% discrepancy when modelling every floor compared to modelling one floor and multiplying it to represent the whole building. Due to this finding, Ellis' process has been undertaken in the building simulation; the office building has been split into the ground floor, mid floors and top floors (see figures 15-18). This is to ensure there is accurate calculation of solar gains at different levels – the surrounding buildings will shade the lower floors more than the top floors. The ground floor was not multiplied, the mid floors were multiplied seven times, and the top floors were multiplied four times. This simulation has only 17 zones and just over 100 surfaces; therefore, it will be easier for EnergyPlus to calculate, and provide just as accurate results.

Note: Orange zones = Conditioned. Blue Zones = Unconditioned. Green = External Shading.

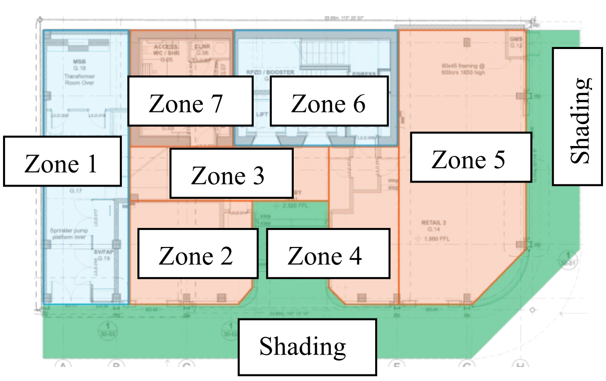


Figure 16: Ground floor thermal zones, office building

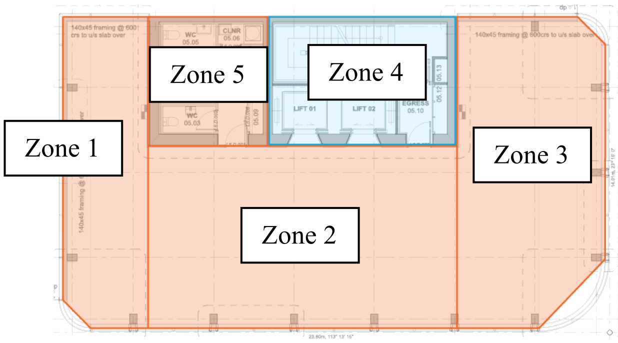


Figure 15: Mid floor thermal zones, office building

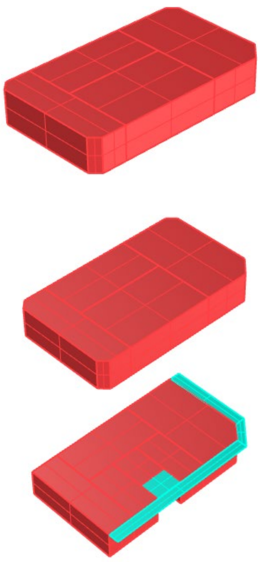


Figure 17: Office building energy model

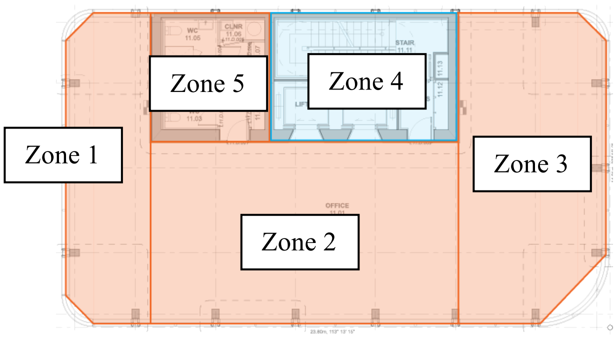


Figure 18: Top floor thermal zones, office building

Due to the difference in occupancy from the ground, mid and top floors, there must be a different set point schedule. The mid and top floors are office floors and will therefore have the same set point schedule, while the ground floor is retail so it will be conditioned to a lesser extent (see table 7 & 8). The ground floor has a services area which will not be conditioned due to the space being unoccupied. In addition, the stairwell and lift shaft in the core on every level (blue zone) will not be conditioned, also due to being unoccupied.

Thermal Zones (Ground)	**Conditioned?**	**Set Point Schedule**
TZ1	No	No Set Point Schedule
TZ2	No	Set Point Schedule 1
TZ3	Yes	
TZ4	Yes	
TZ5	Yes	
TZ6	No	No Set Point Schedule
TZ7	Yes	Set Point Schedule 1

Table 7: Thermal zones ground floor, office building

Thermal Zones (Mid & Top)	**Conditioned?**	**Set Point Schedule**
TZ1	Yes	Set Point Schedule 2
TZ2	Yes	
TZ3	Yes	
TZ4	No	No Set Point Schedule
TZ5	Yes	Set Point Schedule 2

Table 8: Thermal zones mid and top floor, office building

Modelling Assumptions

1) Due to the limitations of EnergyPlus surface identification, the curved windows are unable to be modelled as specified. Therefore, figure 19 demonstrated the curved windows assumed to be diagonal windows.

2) The retail spaces, lobby and toilets on the ground floor are assumed to have the same loads and schedules.

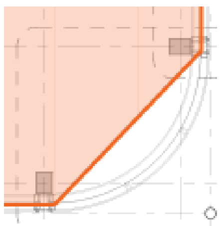


Figure 19: Office building corner modelling assumption

3) In the architectural plans, there are aluminium louvres that act as intake and extract vents on the outside of the building. There is no way for EnergyPlus to model these; therefore, they have not been included.

4) Above level 11, the last office floor, is the plant room for the building. The plant room has not been modelled, instead the ceiling surface for level 11 has been assigned with the boundary condition of adiabatic – meaning there will be little to no heat transfer between floors.

Climate Data

The climate for the office building is in the Wellington CBD, New Zealand. Therefore, the weather file used for energy simulation was the closest to this location (NZL_Wellington.Wellington 934360_IWEC). This weather file was obtained from the Ladybug Tools EPW map website (see appendix 3).

Opaque Constructions

Like the townhouse, opaque, homogenous constructions were modelled for the walls, slab and roof in this base model. One type of wall was modelled which represented all walls in the building – a spandrel panel (see appendix 3). The roof construction represented the whole ceiling area and the slab represented the whole slab. Perimeter slab edges were not considered in this simulation. The windows in the building are a Low-E coated insulated glazing unit (IGU) – one layer of 4mm toughened glass, one layer of 12mm argon gas filled air gap, and another layer of glass. All specific construction layers, details and property values for each material (density, thermal conductivity and specific heat) are in appendix 3.

Note: Orange = Spandrel panel. Blue = Window. Yellow = Concrete core. Pink = Concrete block wall

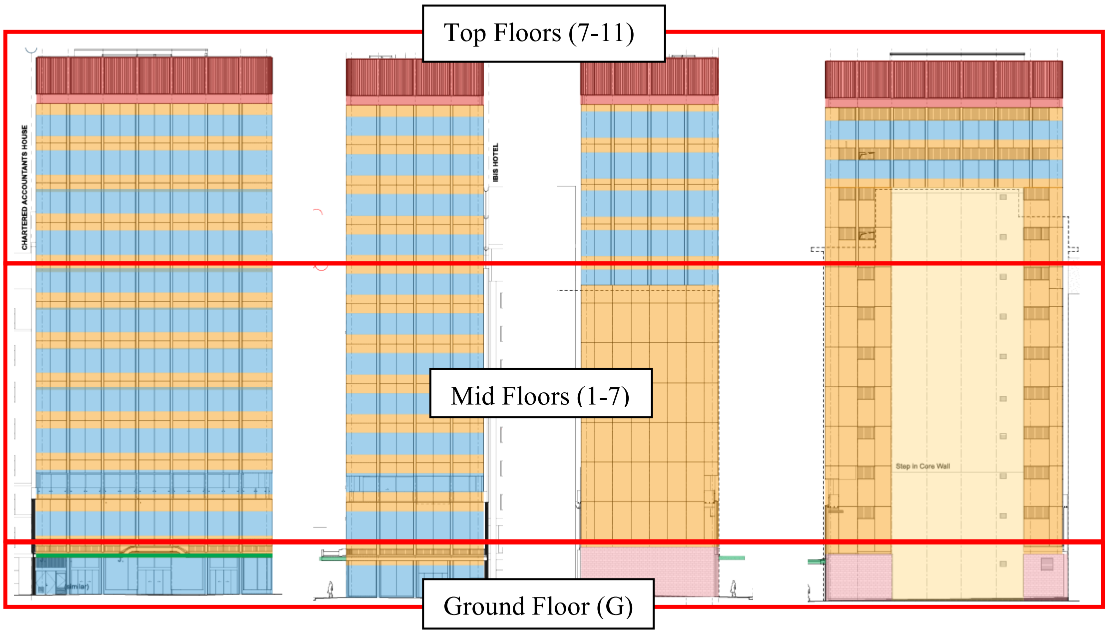


Figure 20: North, west, east and south elevations, highlighting each construction type

Building Equipment

The building equipment load for the ground floor retail is 2.7 W/m², while the load for the mid and top office floors is 8.1 W/m². These figures were obtained from NZS4243. For associated schedules for the retail and office floors, see appendix 3.

Occupancy, Density & Metabolic Rate of People

The building will be densely occupied from 8am-6pm (NZS4243, 2007). The density of people was determined by the number of people on each office floor. According to a report by Colliers (2018), the average area of office space per person is 14.6m². The retail density will be assumed half this at 7m² per person as there will a higher number of people going through a smaller retail space. For the hours of occupancy and metabolic rate schedule, see appendix 3.

Lighting Power Density Level (LPDL)

The LPDL level for the ground floor retail is 13 W/m², while the mid and top office floors are 9 W/m². These figures were obtained from NZS4243. For associated schedules for the retail and office floors, see appendix 3.

Heating and Cooling Set Points

The thermal comfort requirements set out in NZS4243 and ASHRAE Standard-55 will be used for the heating and cooling set points for the office building (see table 9 & 10).

Set Point Schedule 1 (Retail)	12am-8am	8am-11am	11am-6pm	6pm-10pm	10pm-12am	**Sources**
Heating Set Point Mon-Sun (°C)	18	18	18	18	18	NZS4243, ASHRAE Standard 55
Cooling Set Point Mon-Sun (°C)	26	23	23	23	26	

Table 9: Set point schedule 1, retail, office building

Set Point Schedule 2 (Office)	12am-8am	8am-11am	11am-6pm	6pm-10pm	10pm-12am	**Sources**
Heating Set Point Mon-Sun (°C)	18	20	20	18	18	NZS4243, ASHRAE Standard 55
Cooling Set Point Mon-Sun (°C)	26	24	24	24	26	

Table 10: Set point schedule 2, office, office building

Infiltration

The infiltration rate for commercial buildings as set out in NZS4303 is minimum 0.5 air changes per hour (ACH). This recommended ACH rate has been converted to $m^3/s\text{-}m^2$ in honeybee to reflect the correct infiltration proportional to the volume of each zone.

External Shading

The office building has a lot of external shading that will affect the solar gains. There is an overhang on the building located on the ground floor that is 4m above ground and projects 1.5m. Otherwise, surrounding buildings shade the site significantly throughout the year. These shading elements have been added in Honeybee to ensure the solar gains are accurate to the site (see figure 21 & 22).

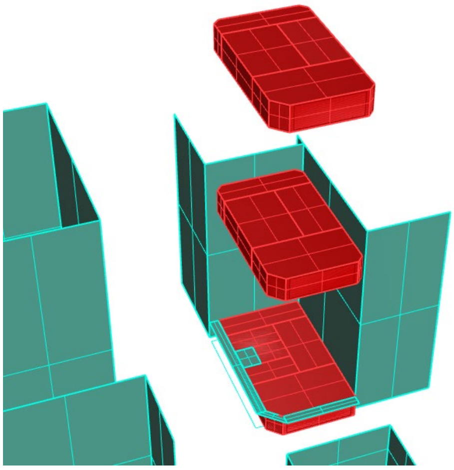


Figure 22: Office building external shading geometry

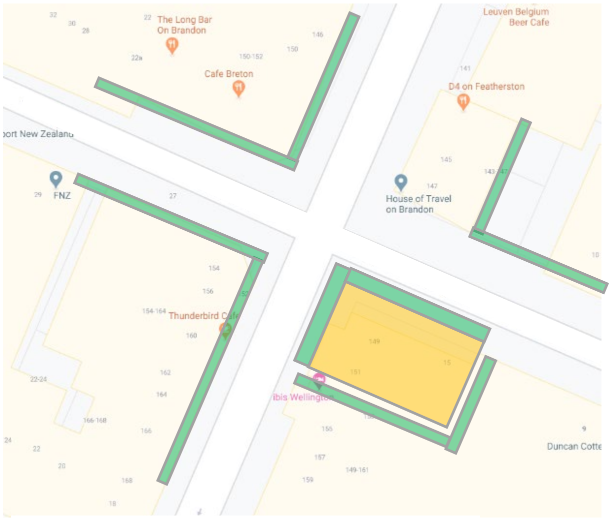


Figure 21: Office building external shading plan

5. Establishing a Methodology

A methodology must be established to assess the thermal performance of external insulation on case study A, and the thermal performance benefit of different structural materials for case study B. In a typical architectural drawing set for low and medium density residential housing, there can be up to 40 details for the façade elements. In an ideal world, all these details would be thermally modelled to obtain the most representative R-Value for the building. However, it is likely that many of the details will be representative of a small amount of the thermal bridging on the façade surface area. Due to this, the thermal modelling priority table has been created to enable a systematic analysis of each detail to determine its modelling importance. A template for this table can be seen in table 12 on page 29. In addition, due to the limitations of Honeybee established in section 2.3, two-dimensional heat transfer modelling program THERM will be used to ensure accurate representation of thermal bridging. THERM enables accurate modelling of building envelope details that are likely to affect the heat loss/gain, and hence overall R-Value. The overall R-Value will impact the energy use for both the baseline models and altered models, establishing a point of discussion of the findings.

Therefore, the methodology template for assessing the thermal performance of external insulation and different materiality of structural elements is a four-step process:

1. Use thermal modelling priority table to determine details to model
2. Use THERM to model two-dimensional heat transfer in details
3. Calculate total R-Value of building façade
4. Run energy simulation with changed R-Values

5.1. Case Study A Methodology Template

This section details the template of the methodology to assess the thermal performance and energy impact of external insulation in a residential townhouse

5.1.1. Thermal Modelling Priority Rating Scale Residential

The rating for the thermal modelling priority of details is based on a 10-point scale. The thermal bridging element percentage of the total façade surface area starts at 0% for *Very Low* and stops at 10+% for *Very High* (see table 11). In order to represent the building façade accurately and not model every detail, the details that represent less than 2% of the thermal bridging element percentage of the total façade surface area have not been modelled. The value of 2% has been chosen as the threshold for modelling as lower values are not likely to have a significant effect on the overall R-Value.

Rating Scale	Thermal Modelling Priority	% of TBE
1 (Worst)	Very High	10+
2	Very High	9-10
3	High	8-9
4	High	6-7
5	Medium	5-6
6	Medium	4-5
7	Low	3-4
8	Low	2-3
9	Very Low	1-2 (THRESHOLD)
10 (Best)	Very Low	0-1

Table 11: Thermal modelling priority rating scale

5.1.2. Thermal Modelling Priority Table Template Residential

	House	Classification			Detail Analysis					Priority			
Details Modelled (DM)	Detail Number	Construction Detail	Drawing Page	Vertical or Horizontal Element?	Facade Surface Area of Detail (m²)	Percentage of Total Facade Surface Area (%)	Thermal Bridging Element (TBE)	Surface Area of Thermal Bridging Element (m²)	Percentage of Thermal Bridging Elements from Total Facade Surface Area (%)	Thermal Modeling Importance	R-Value (THERM)	Heat Loss of Detail (W/m²K)	Thermal Resistance Importance of Detail
	1	External Wall in metal cladding	OT 92-01	Horizontal	70.84	41.5	90*45 Timber Stud	15.4	9	Very High	2.21	32.1	8
		Details Modelled Totals			**DM Facade Surface Area: 162.9m²**	**DM Percentage: 95.5%**		**DM TBE Surface Area: 58.6 m²**	**DM Thermal Bridging: 34.4%**				
Details Not Modelled (DNM)	2	Window Jamb to Wall	A5.13	Horizontal	2.18	1.3	140*45 Timber Framing	2.18	1.3	Very Low	N/A	N/A	N/A
		Details Not Modelled Totals			**DNM Facade Surface Area: 7.7m²**	**DNM Percentage: 4.5%**		**DNM TBE Surface Area: 7.65m²**	**DNM Total Thermal Bridging: 4.5%**				
		Total Facade Surface Area			**170.6**	**100**	**Total Thermal Bridging Surface Area**	**66.3**	**38.9**				

Table 12: Thermal modelling priority table, townhouse template

Thermal Resistance Importance Rating Scale

The rating scale for the thermal resistance importance is also based on a 10-point scale but is dependent on two factors. These factors are the thermal bridging element percentage of the total façade surface area and total heat loss of each detail. This scale is important as it determines what areas of the building require the most attention due to percentage of thermal bridging and heat loss. The heat loss is determined by the total façade surface area of the detail divided by the modelled R-Value in THERM.

Rating Scale	Thermal Resistance Importance	% of TBE	Heat Loss (W/mK)
1 (Worst)	Very High	10+	90+
2	Very High	9-10	80-90
3	High	8-9	70-80
4	High	6-7	60-70
5	Medium	5-6	50-60
6	Medium	4-5	40-50
7	Low	3-4	30-40
8	Low	2-3	20-30
9	Very Low	1-2	10-20
10 (Best)	Very Low	0-1	0-10

Table 13: Thermal resistance importance rating scale

Thermal Resistance Importance Overall Priority Score

From the thermal resistance importance rating scale, an overall priority can be obtained (see table 14). Due to this, each modelled detail can be assessed with its relative priority, in order to sequentially apply external insulation.

Overall Priority Score			
Modelled Details House	**Thermal Modelling Priority**	**Thermal Resistance Effect**	**Total Score (Low = High Priority)**
External Wall in metal cladding	1	7	8 – High

Table 14: Thermal resistance importance overall priority score

5.2. Case Study B Methodology Template

This section details how the applied methodology will assess the thermal performance and energy impact of changing structural materials in an office building.

5.2.1. Thermal Modelling Priority Table Template Commercial Office

The thermal modelling priority table for the commercial office will be similar to the residential table. The main difference between them is that the commercial office is focusing on the façade surface area instead of the thermal bridging element surface area. This is because the thermal modelling of the office is focusing on a comparative analysis between timber, concrete and steel structures, not mitigating thermal bridges. A template for the commercial office thermal modelling priority table can be seen in table 16 on page 32.

5.2.2. Rating Scale Commercial Office

As a commercial office building is typically much larger than a residential building, the rating scale has been increased up to 20. The only determinant factor for the thermal modelling priority is the total percentage of façade surface area on all floors. Again, the threshold for not modelling details is 2%.

Rating Scale	Thermal Modelling Priority	% of Surface Area
1	Very High	20+
2	Very High	19-20
3	Very High	18-19
4	Very High	17-18
5	High	16-17
6	High	15-16
7	High	14-15
8	High	13-14
9	Medium	12-13
10	Medium	11-12
11	Medium	10-11
12	Medium	9-10
13	Low	8-9
14	Low	6-7
15	Low	5-6
16	Low	4-5
17	Very Low	3-4
18	Very Low	2-3
19	Very Low	1-2 (THRESHOLD)
20	Very Low	0-1

Table 15: Thermal modelling priority table, office building

	Office Building	Classification					Detail Analysis				Priority	
	Detail Number	Construction Detail	Drawing Page	Vertical or Horizontal Element?	Floor Level	Detail Reccurence Per Floor	Façade Surface Area of Detail Per Floor (m²)	Percentage of Façade Surface Area Per Floor (%)	Total Façade Surface Area of Detail (m²)	Percentage of Façade Surface Area of Details on all Floors (%)	Comparative Analysis Benefit	Thermal Modeling Importance
Details Modelled	1	Non-Insulated Roof to Plant Room	92-01	Vertical	Roof	1	157	51.5	157	51.5	Yes	Very High
		Details Modelled Ground Totals					**Ground: 0m²**	**Ground: 0%**	**Ground: 0m²**	**Ground: 0%**		
		Details Modelled Mid Totals					**Mid: 0m²**	**Mid: 0%**	**Mid: 0m²**	**Mid: 0%**		
		Details Modelled Top Totals					**Top: 0m²**	**Top: 0%**	**Top: 0m²**	**Top: 0%**		
		Details Modelled Ground, Mid and Top Floors Totals							**Total Surface Area: 0m²**	**Total SA Percentage: 0%**		
		Details Modelled Roof Totals					**Total Surface Area: 157m²**	**Total SA Percentage: 51.6%**	**Total Surface Area: 157m²**	**Total Percentage: 76.7%**		
Details Not Modelled	2	Concrete Block Wall	S71-01	Horizontal	Ground	1	92	30.3	92	1.8	No	Very Low
		Details Not Modelled Ground Totals					**Ground: 2m²**	**Ground: 31%**	**Ground: 94m²**	**Ground: 2.8%**		
		Details Not Modelled Mid Totals					**Mid: 0m²**	**Mid: 0%**	**Mid: 0m²**	**Mid: 0%**		
		Details Not Modelled Totals					**Total Surface Area: 4m²**	**Total SA Percentage: 31.7%**	**Total SA: 94m²**	**Total SA Percentage: 2.8%**		
		Total Facade Surface Area					**304**		**3355**	**3%**		
		Total Roof Surface Area					**305**		**305**	**76.70%**		

Table 16: Thermal modelling priority table, office building template

5.3. Areas Modelled in THERM

After determining what details are most important to model, an R-Value for the detail is obtained. Templates for displaying the results are as follows in section 5.3.1.

5.3.1. Residential and Commercial Office Detail Templates

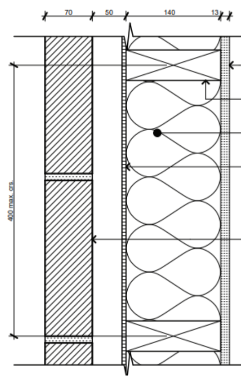
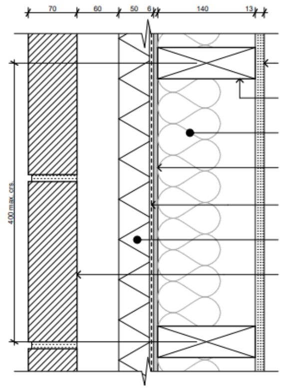
Type	Baseline Insulation	External Insulation
- EWT-01 - OT 92-01 - OA 43-01 - Horizontal Element		
R-Value	R-2.46	R-3.15

Table 17: Template of detail simulation, townhouse

Detail	Timber R-Value	Concrete R-Value	Steel R-Value
Insulated Roof to Outdoors	1.03	0.82	0.44

Table 18: Template of detail simulation, office building

The information under the type column will be identical to the classification information in the thermal modelling priority table. This enables easy navigation from the table to the results.

5.4. R-Values from Façade Heat Loss

The façade heat loss of the modelled details in section 5.3.1 is required to determine the overall R-Value of the building. The overall R-Value of the building is integral to the energy model in order to demonstrate the comparative benefits of different structural materials, and insulation types. Following the NZS4218 calculation method, heat loss through the building envelope can be calculated with the following equation:

$$Heat\ Loss = \frac{\text{Detail Area 1 (m}^2\text{)}}{\text{R} - \text{Value 1}} + \frac{\text{Detail Area 2 (m}^2\text{)}}{\text{R} - \text{Value 2}}$$

To work out the total R-Value, simply invert the equation:

$$R - Value = \frac{\text{Total Detail Area}}{\text{Total Heat Loss}}$$

From these equations, an overall R-Value is attained to apply to the thermal energy simulation.

5.5. Running Energy Simulations

When the R-Values from THERM have been applied to the energy simulations in honeybee, the total energy usage for the baseline building will be obtained. However, to ensure these results are accurate, quality assurance must be undertaken. The townhouse will be quality assured by the HEEP study, while the commercial office building will be quality assured by the BEES study and a previous energy model.

6. Application of Methodology – Case Study A

To assess external insulation's energy impact, the methodology as established in section 5 must be applied. The first step is by determining the most important details using the thermal modelling priority table. This table customised for the townhouse can be seen on page 34.

Figure 23: West elevation with detail areas, townhouse

Figure 24: North elevation with detail areas, townhouse

Figure 25: East elevation with detail areas, townhouse

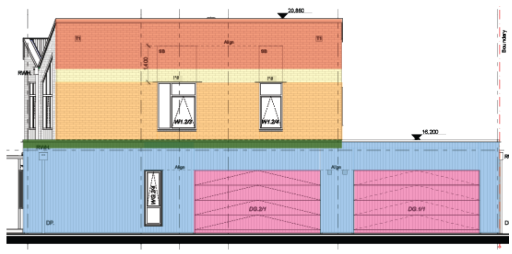


Figure 26: South elevation with detail areas, townhouse

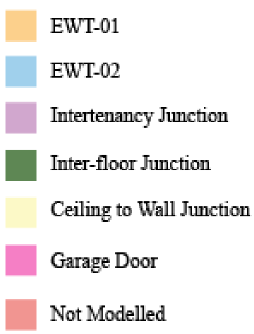


Figure 27: Elevation key, townhouse

Through the thermal modelling priority table on page 35, it is evident that five main details must be modelled as they represent 114m² (29%) of the façade surface area's thermal bridging. This area of thermal bridging of details to be modelled represents 82% of the thermal bridging elements, while the details not modelled represent 18%. These details are highlighted on the elevations in figures 23-26. Modelling these details will ensure the thermal performance of the building envelope will be representative of real-life heat transfer.

6.1. Thermal Modelling Priority Table – Townhouse

	Townhouse	Classification			Detail Analysis					Priority			
	Detail Number	**Construction Detail**	**Drawing Page**	**Vertical or Horizontal Element?**	**Facade Surface Area of Detail (m²)**	**Percentage of Total Facade Surface Area (%)**	**Thermal Bridging Element (TBE)**	**Surface Area of Thermal Bridging Element (m²)**	**Percentage of Thermal Bridging Elements from Total Facade Surface Area (%)**	**Thermal Modeling Importance**	**R-Value (THERM)**	**Heat Loss of Detail (W/m²K)**	**Thermal Resistance Importance of Detail**
Details Modelled (DM)	1	EWT-01	OT 92-01	Horizontal	183.6	46.6	140*45 Timber Stud	43.6	11.1	Very High	2.56	71.7	2
	2	Interfloor to Wall (Joist & Insulation)	OT 40-12	Vertical	44.8	11.4	235*45 Timber Joist, 140*45 Timber Blocking	32	8.1	High	0.5	89.6	1
	3	Ceiling to Wall	OT 40-16	Vertical	32.5	8.2	3x 235*45 Timber Blocking, 90*45 Timber Blocking	19.2	4.9	Medium	3.63	9	4
	4	Intertenancy to Wall	OT 40-12	Horizontal	13.5	3.4	140*45 Timber Stud	10.5	2.7	Low	0.91	14.8	3
	5	EWT-02	OT 92-01	Horizontal	36	9.1	140*45 Timber Stud	8.6	2.2	Low	2.49	14.5	4
		Details Modelled Totals			**DM Facade Surface Area: 310.7m²**	**DM Percentage: 78.9%**		**DM TBE Surface Area: 113.9m²**	**DM Thermal Bridging: 28.9%**				
Details Not Modelled (DNM)	6	Window Jamb to Wall	OT 40-10	Horizontal	14.3	3.6	2x 140*45 Timber Framing	6.3	1.6	Very Low	N/A	N/A	N/A
	7	Window Head to Wall	OT 40-09	Vertical	12.3	3.1	3x 140*45 Timber Framing	5.9	1.5	Very Low	N/A	N/A	N/A
	8	EWT-03	OT 92-01	Horizontal	23.1	5.9	140*45 Timber Stud	5.5	1.4	Very Low	N/A	N/A	N/A
	9	Corner Junction	OT 40-01	Horizontal	18.1	4.6	2x 140*45 Timber Stud	5.1	1.3	Very Low	N/A	N/A	N/A
	10	Window Sill to Wall	OT 40-12	Vertical	6.1	1.5	140*45 Timber Framing	3.9	1	Very low	N/A	N/A	N/A
	11	Window Sill to Foundation	OT 40-09	Vertical	6.6	1.7	3x 140*45 Timber Stud	1.9	0.5	Very low	N/A	N/A	N/A
	12	EWT-01 to Foundation	OT 40-05	Vertical	3.1	0.8	140*45 Timber Stud	0.74	0.2	Very low	N/A	N/A	N/A
		Details Not Modelled Totals			**DNM Facade Surface Area: 83.6m²**	**DNM Percentage: 21.1%**		**DNM TBE Surface Area: 29.3m²**	**DNM Thermal Bridging: 7.4%**				
		Total Facade Surface Area			**394**	**100**	**Total Thermal Bridging Surface Area**	**143.2**	**Total Thermal Bridging: 36.3%**				

Table 19: Thermal modelling priority table, townhouse

6.2. Detail Areas Modelled in THERM

The five details identified in the thermal modelling priority table will have the most impact on the building's heat loss. This is due to over 100m² of their façade surface area resulting in a thermal bridge. Therefore, in this section, external insulation design alternatives will be presented in comparison to the baseline insulation design. The baseline and external insulation thicknesses, R-Values and materials used for each design are shown in table 20. Appendix 2 and 4 specifies any extra parameters needed for the creation of these models in THERM, and the temperature changes through the detail.

	Internal Insulation	External Insulation	
Values	**Insulation Between Framing**	**Insulation Between Framing**	**External Insulation**
Thickness	140mm	90mm	50mm
R-Value	R-2.6	R-2.5	R-1.5
Thermal Conductivity	0.054 (Pfundstein, 2008)	0.036 (Pfundstein, 2008)	0.034 (Pfundstein, 2008)
Material	Polyester	Polyester	Mineral Rockwool
Product	Mammoth Wall Blanket	Autex Thermal Pads	Rockwool ThermalRockS

Table 20: Insulation properties townhouse

Note: Blue = Thermal Bridge

Pink = External Wall Insulation

Detail 1: EWT-01

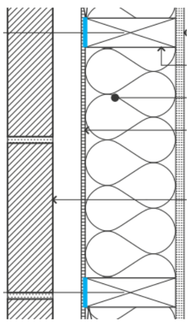
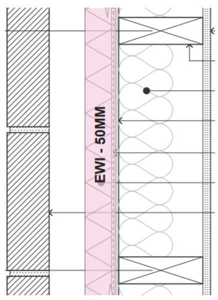
Type	Baseline Insulation	External Insulation
- EWT-01 - OT 92-01 - OA 43-01 - Horizontal Element		
R-Value	R-2.46	R-3.15

Table 21: EWT-01 design and simulation of external insulation

Detail 2: Inter-floor to Wall

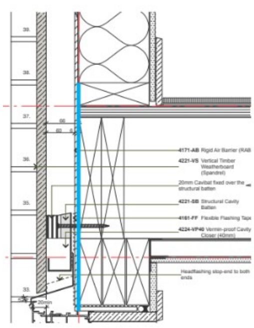
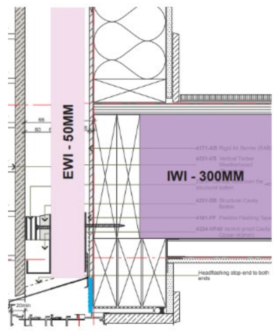
Type	Baseline Insulation	External Insulation
- Inter-floor to Wall - OT 40-12 - Vertical Element		
R-Value	R-0.5	R-2.77 (Average)

Table 22: Inter-floor to Wall design and simulation of external insulation

Detail 3: Ceiling to Wall

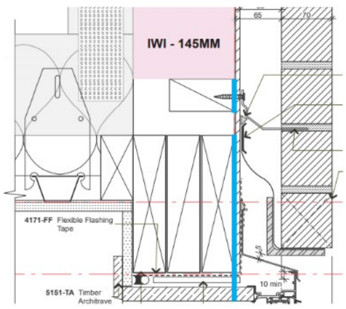
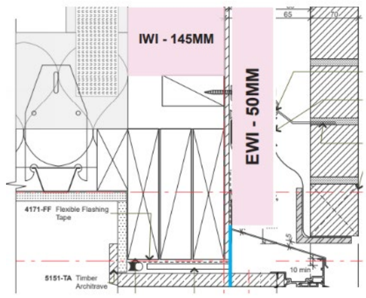
Type	Baseline Insulation	External Insulation
- Ceiling to Wall - OT 40-16 - Vertical Element		
R-Value	R-3.63	R-4.26

Table 23: Ceiling to Wall design and simulation of external insulation

Detail 4: Intertenancy to Wall

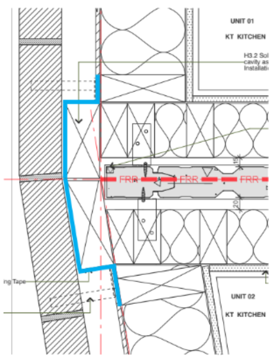
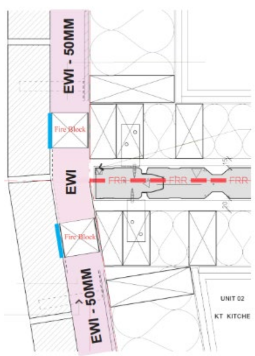
Type	Baseline Insulation	External Insulation
- Intertenancy to Wall - OT 40-12 - Horizontal Element		
R-Value	R-0.91	R-2.01

Table 24: Intertenancy to Wall design and simulation of external insulation

Note: For modelling purposes, the brick veneer wall and timber framing have been assumed to be straight instead of angled (see appendix 4)

Detail 5: EWT-02

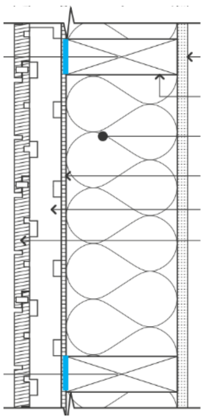
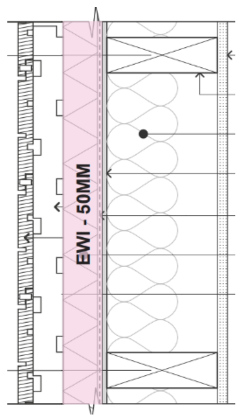
Type	Baseline Insulation	External Insulation
- EWT-02 - OT 92-01 - Horizontal Element		
R-Value	R-2.39	R-3.09

Table 25: EWT-02 design and simulation of external insulation

6.3. Total R-Values from Heat Loss

Through the design, modelling and testing of the five main detail areas, an overall R-Value can be obtained for the energy simulation. The calculation method as set out in NZS4214 and described in section 5.4 was used to calculate the heat loss and therefore R-Values.

Orientation	Façade Surface Area (m²)	Heat Loss (W/m-K)	Baseline Insulation R-Value	Heat Loss (W/m-K)	External Insulation R-Value
North	51.0	33.0	1.55	16.1	3.18
East	105.3	66.9	1.57	34.4	3.06
South	86.5	46.8	1.85	27.5	3.14
West	67.8	54.7	1.24	22.5	3.01
Total	310.4		R-1.52		R-3.10

Table 26: Heat loss through each façade, townhouse

The application of external insulation on the five detail areas resulted in the R-Values doubling from R-1.52 to R-3.10. In accordance with NZBC Clause H1, all wall elements must reach the minimum R-Value of 1.9 (see table 27). The baseline insulation does not meet these requirements; however, with the application of external insulation, the requirement is met.

Building Element	Climate Zone 1 (Auckland)
Wall	R-1.9

Table 27: NZBC Clause H1 Minimum R-Values for Zone 1 (NZS4218, 2009)

6.4. Energy Results

Baseline Insulation Results:

The baseline insulation energy simulation resulted in an annual energy usage of 38,055 kWh or 74.6 kWh/m².yr. This result includes the new baseline R-Values from the five detail areas identified in section 6.3. The HEEP study was used to quality assure these figures against dwelling averages. The HEEP (Housing Energy End-Use) study was a long-term project measuring and modelling the way energy is used in almost 400 New Zealand dwellings (BRANZ, 2013). This was chosen as the quality assurance because it is the most comprehensive study on dwellings, which are the closest to a townhouse unit. There are no studies recording the energy use on medium density housing; therefore, the HEEP study was used assuming that the units were individual houses. The category that was used to quality assure the baseline model was four or more bedrooms and a floor area larger than 201m² (see table 28). 257m² was used as the floor area figure as it is the average between 201m² and the highest floor area recorded (314m²) (BRANZ, 2013). As seen in table 28, the highest discrepancy between the HEEP study and the baseline mode was 3%; therefore, the baseline model can be trusted to produce accurate energy results.

Values	HEEP Values	Baseline Townhouse Model Values	Discrepancy
Bedrooms	4+	4	None
Floor Area	257m² (avg in category	255m² (One-unit size)	2m² (1%)
Total Energy Usage (kWh)	18,326 kWh	19,027 kWh (One-unit energy usage)	701 kWh (3%)
Total Energy Usage per floor area (kWh/m².yr)	71.8 kWh/m².yr	74.6 kWh/m².yr	2.8 kWh/m².yr (3%)

Table 28: Townhouse baseline model quality assurance

External Insulation Results:

The external insulation energy simulation resulted in an annual energy usage of 28,611 kWh or 56.1 kWh/m².yr. Therefore, this demonstrates that the application of external insulation reduced the overall energy use by 25%. A comparison of the energy distribution will be undertaken in section 6.4.1 to understand where this energy reduction is occurring.

6.4.1. Energy Results Comparison

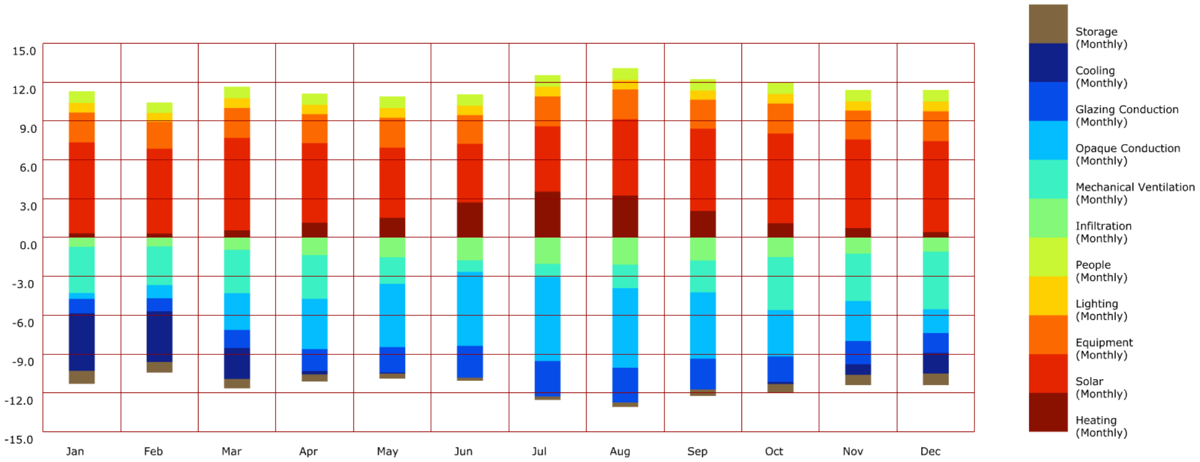


Figure 29: Energy balance graph, baseline insulation model

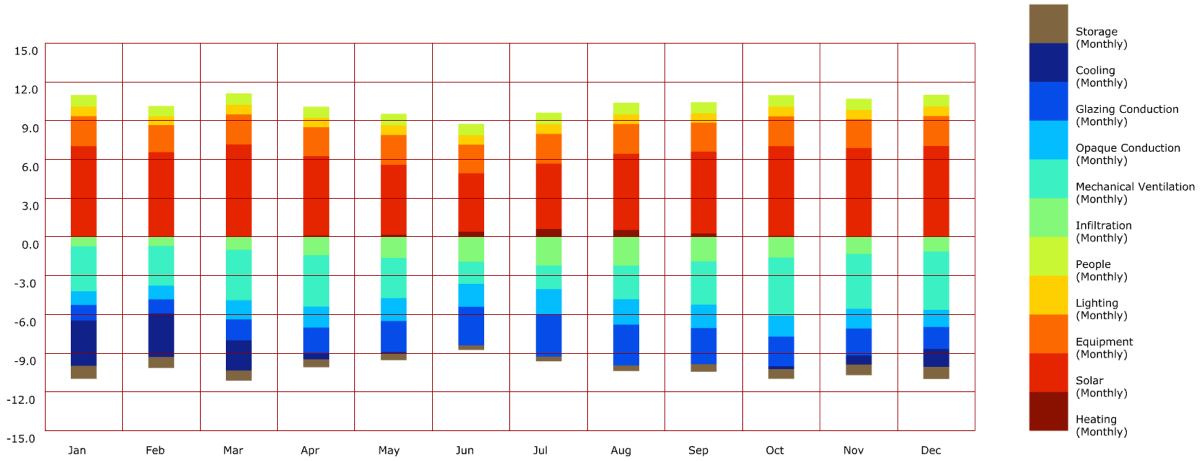


Figure 28: Energy balance graph, external insulation model

The baseline insulation energy balance graph in figure 29 shows that the opaque conduction is a large area of heat loss due to the low overall R-Value. Opaque conduction is defined as thermal conduction through an opaque (non-transparent) element such as a wall, roof, or slab. The external insulation energy balance graph in figure 28 shows a large reduction in opaque conduction due to the increased R-Value. Subsequently, this has resulted in a significant reduction of the heating energy in the external insulation model (see figure 30). However, it is evident that the cooling for the external insulation model has risen slightly (see figure 30). This indicates, then, a potential issue with increasing the R-Value of the façade so much that the cooling energy increase balances out the heating energy increase. Although this is not an issue with the current external insulation design of the townhouse, optimising thickness and R-Value of external insulation could be an area for further research.

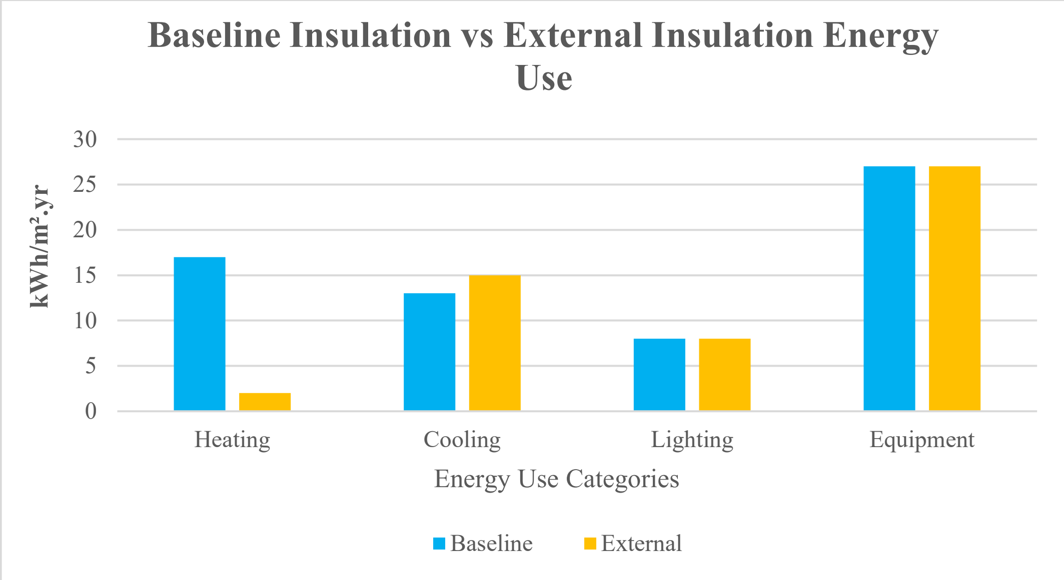


Figure 30: Baseline vs external insulation energy graph

6.4.2. Operational vs Capital Costs

The operational costs are calculated based on 2019 residential energy prices from the Ministry of Business, Innovation and Employment (MBIE, 2020). The price per kWh is $0.29.

Baseline Insulation Operational Costs: $5,533/unit per year or $461/month

External Insulation Operational Costs: $4,148/unit per year or $345/month

Total Saving: $1,384 annually per unit – 26% reduction in operational costs

The capital costs were calculated by another summer scholar who was specializing in costing. Recognition of this work has been included in the acknowledgements section.

Baseline: $1,356,090

External Insulation Design: $1,371,390

Total Increase: $12,805 more expensive – 1.47% increase in capital costs for external insulation

Payback Period: 9.2 years

Although it is 1.5% more expensive to build with external insulation, the benefits are incredible - 25% energy reduction, 26% less in operational costs, and only takes 9.2 years to pay back. Due to these findings, it can be concluded that external wall insulation is an applicable and energy efficient system that must be used on any medium density housing project.

7. Application of Methodology – Case Study B

To assess the energy impact of changing materials to timber, concrete and steel, the methodology as established in section 5 must be applied. The first step is by determining the most important details using the thermal modelling priority table. This table customised for the office building can be seen on page 43.

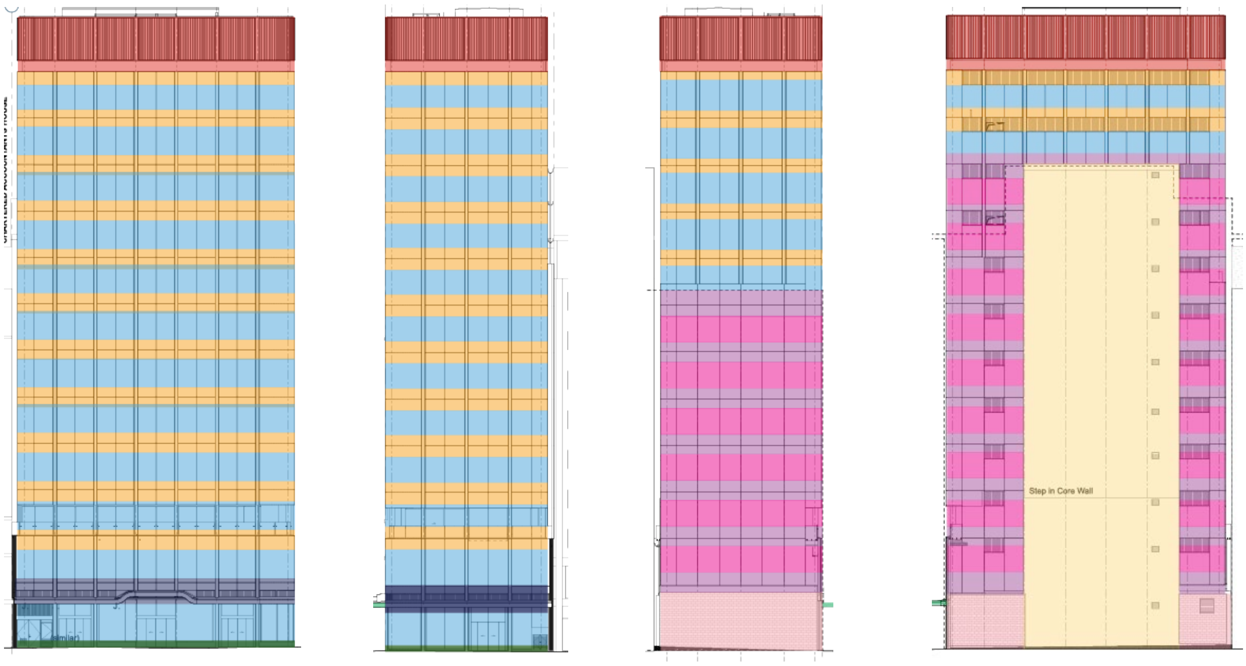


Figure 31: North, west, east and south elevations, highlighting each construction type

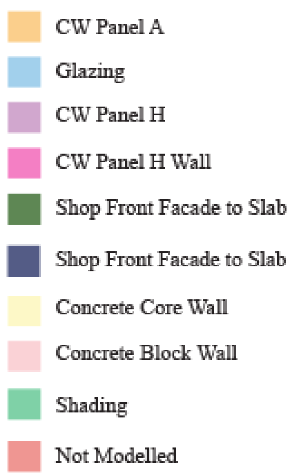


Figure 32: Key for office building construction types

Through the thermal modelling priority table on page 41, it is evident that seven main details must be modelled as they represent over 80% of the façade surface area. These details are highlighted on the elevations in figure 31. Modelling these details will ensure the thermal performance of the building envelope will be representative of real-life heat transfer.

7.1. Thermal Modelling Priority Table – Office Building

	Office Building	Classification					Detail Analysis				Priority	
	Detail Number	Construction Detail	Drawing Page	Vertical or Horizontal Element?	Floor Level	Detail Reccurence Per Floor	Façade Surface Area of Detail Per Floor (m²)	Percentage of Façade Surface Area Per Floor (%)	Total Façade Surface Area of Detail (m²)	Percentage of Façade Surface Area of Details on all Floors (%)	Comparative Analysis Benefit	Thermal Modeling Importance
Details Modelled	1	Non-Insulated Roof to Plant Room	31-03.	Vertical	Roof	1	157	50.8	157	50.8	Yes	Very High
	2	Curtain Wall Panel A	72-13	Vertical	Mid	7	174	56.3	1218	36.3	Yes	Very High
	3	Curtain Wall Panel A	72-14	Vertical	Top	4	254	82.2	1016	30.3	Yes	Very High
	4	Curtain Wall Panel H	72-21	Vertical	Mid	7	82	26.5	574	17.1	Yes	Very High
	5	Insulated Roof to Outdoors	74-10	Vertical	Roof	1	40	12.9	40	12.9	Yes	High
	6	Non-Insulated Roof to Outdoors	74-11	Vertical	Roof	1	37	12	37	12	Yes	Medium
	7	Shop Front Façade	71-04 & 05	Vertical	Ground	1	144	46.6	144	4.3	Yes	Low
		Details Modelled Ground Totals					**Ground: 144m²**	**Ground: 78.9%**	**Ground: 144m²**	**Ground: 4.3%**		
		Details Modelled Mid Totals					**Mid: 254m²**	**Mid: 59.2%**	**Mid: 1792m²**	**Mid: 53.4%**		
		Details Modelled Top Totals					**Top: 254m²**	**Top: 83.6%**	**Top: 1016m²**	**Top: 30.3%**		
		Details Modelled Ground, Mid and Top Floors Totals							**Total Surface Area: 2942m²**	**Total SA Percentage: 87.9%**		
		Details Modelled Roof Totals					**Total Surface Area: 234m²**	**Total SA Percentage: 51.6%**	**Total Surface Area: 234m²**	**Total Percentage: 76.7%**		
Details Not Modelled	8	Concrete Block Wall	S71-01	Horizontal	Ground	1	92	30.3	92	2.7	No	Very Low*
	9	Curtain Wall Panel H to Concrete Core	72-09	Horizontal	Mid	7	2	0.7	14	0.4	No	Very Low
	10	Concrete Block Wall to Concrete Core Wall	82-07	Horizontal	Ground	1	2	0.7	2	0.1	No	Very Low
		Details Not Modelled Ground Totals					**Ground: 94m²**	**Ground: 31%**	**Ground: 94m²**	**Ground: 2.8%**		
		Details Not Modelled Mid Totals					**Mid: 2m²**	**Mid: 0.7%**	**Mid: 14m²**	**Mid: 0.4%**		
		Details Not Modelled Totals					**Total Surface Area: 96m²**	**Total SA Percentage: 31.7%**	**Total SA: 108m²**	**Total SA Percentage: 3.2%**		
		Total Facade Surface Area					304		3355	91.1%*		
		Total Roof Surface Area					309		309	76.7%*		

Table 29: Thermal modelling priority table, office building

7.2. Detail Areas Modelled in THERM

The seven details identified in the thermal modelling priority table represent the majority façade (88%) and roof (76%) surface area. These detail areas have been tested with timber, concrete and steel structural elements. The R-Values of these different elements can be seen in table 31. Appendix 3 and 5 specifies any extra material properties needed for the creation of these models in THERM, and the temperature changes through the detail.

	Internal Insulation	**External Insulation**
Values	**Insulation Between Framing**	**External Insulation**
Thickness	90mm	75mm
R-Value	R-2.5	R-2.1
Thermal Conductivity	0.036 (Pfundstein, 2008)	0.034 (Pfundstein, 2008)
Material	Polyester	Mineral Rockwool
Product	Autex Greenstuf	Bradford Rockwool

Table 30: Insulation properties commercial office

Detail	Timber R-Value	Concrete R-Value	Steel R-Value
Non-Insulated Roof to Plant Room	1.03	0.82	0.44
Curtain Wall Panel A Floor	1.82	1.51	1.30
Curtain Wall Panel A Services	1.62	1.58	1.3
Curtain Wall Panel H Floor	2.01	N/A	N/A
Curtain Wall Panel H Services	1.95	1.89	1.85
Curtain Wall Panel H Wall	1.81	1.55	1.31
Insulated Roof to Outdoors	4.13	3.61	3.45
Non-Insulated Roof to Outdoors	1.86	1.59	1.32
Shop Front Façade Slab	0.33	N/A	N/A
Shop Front Façade Floor	1.37	1.16	1.02
Shop Front Façade Services	0.28	0.24	0.19

Table 31: Office building detail areas R-Value

7.3. Total R-Values from Heat Loss

Through the design, modelling and testing of the seven main detail areas, an overall R-Value can be obtained for the energy simulation. The calculation method as set out in NZS4214 and described in section 5.4 was used to calculate the heat loss and therefore R-Values.

Orientation	**Floor**	**Façade Surface Area (m²)**	**Timber R-Value**	**Concrete R-Value**	**Steel R-Value**
North	Ground	52.2	0.38	0.34	0.31
East	Ground	25.2	0.39	0.34	0.31
South*	Ground	N/A	Concrete Block Wall	Concrete Block Wall	Concrete Block Wall
West*	Ground	N/A	Concrete Block Wall	Concrete Block Wall	Concrete Block Wall
North	Mid	31.1	1.7	1.55	1.43
East	Mid	47.9	1.96	1.89	1.82
South	Mid	34	1.96	1.89	1.82
West	Mid	18.2	1.7	1.55	1.43
North	Top	31.1	1.7	1.55	1.43
East	Top	18.9	1.7	1.55	1.43
South	Top	12.9	1.7	1.55	1.43
West	Top	18.2	1.7	1.55	1.43
None	Roof	234	1.29	1.02	0.59

Table 32: R-Values in each orientation, office building:

*Note: The R-Value of the concrete block wall will be determined by Honeybee as there is no thermal bridging.

Floor	**Timber R-Value**	**Concrete R-Value**	**Steel R-Value**
Ground Façade	0.38	0.34	0.31
Mid Façade	1.83	1.72	1.63
Top Façade	1.7	1.55	1.43
Roof	1.29	1.02	0.59

Table 33: Total R-Value, office building

The application of different material properties in the same structural elements showed the R-Value decrease from timber to concrete, and more from concrete to steel. This is expected as the thermal conductivity of timber is the highest, followed by concrete and then steel. In accordance with NZBC Clause H1, all wall elements must reach the minimum R-Value of 1.2 (see table 34). This is met for the mid and top façade areas for all structural types, but not the ground façade. In addition, the roof must be at least R-1.9; however, it only reaches R-1.3 maximum. A further point of research could be detailing how the roof could comply with Clause H1.

Building Element	Climate Zone 3 (Wellington)
Roof	R-1.9
Wall	R-1.2

Table 34: NZBC Clause H1 Minimum R-Values Zone 3 (NZS4243, 2007)

7.4. Energy Results

Timber Energy Results:

The timber energy simulation of the office building resulted in an annual energy usage of 331,123 kWh/year or 122 kWh/m².yr. The base model of the office building was quality assured against the BEES study, and a previous model created of the building (see table 35). The BEES study has a vast range of values for a commercial office, which the office building model just fits within. Since there are no timber office buildings in New Zealand, the BEES report has only considered concrete and steel construction (BRANZ, 2014b). Due to this, it can be justified that the office base model for the timber construction is still accurate, albeit at the low end of the scale for energy consumption. The energy result for the base model can therefore be trusted as it just falls within the range – 0.7% over the lowest value. The concrete (147 kWh/m².yr) and steel energy usage (159 kWh/m².yr) also fall within the quality assurance bracket for BEES, but the values are much higher due to their typical constructions. The previous model's simulated energy was lower than the office base model at 114 kWh/m².yr, which is expected. This is because the office base model accounted for the retail space on the ground floor, while the previous model did not. However, it still falls within a sensible range (max 6.5%); therefore, the model for the commercial office building can be trusted.

Values	BEES Values	Baseline Office Building Model Values	Discrepancy
Total Energy Usage (kWh/year)	333,590-700,290 kWh/year	331,123 kWh/year (One-unit energy)	2,467 kWh/year (0.7%)
Total Energy Usage per floor area (kWh/m².yr)	121-251 kWh/m².yr (range)	122 kWh/m².yr	1 kWh/m².yr (0.7%)
Values	**Previous Model Values**	**Baseline Townhouse Model Values**	**Discrepancy**
Total Energy Usage (kWh)	312,657 kWh/year	331,123 kWh (One-unit energy)	18,466 (5.5%)
Total Energy Usage per floor area (kWh/m².yr)	114 kWh/m².yr	122 kWh/m².yr	8 kWh/m².yr (6.5%)

Table 35: Office building baseline model quality assurance

7.4.1. Energy Results Comparison

Timber

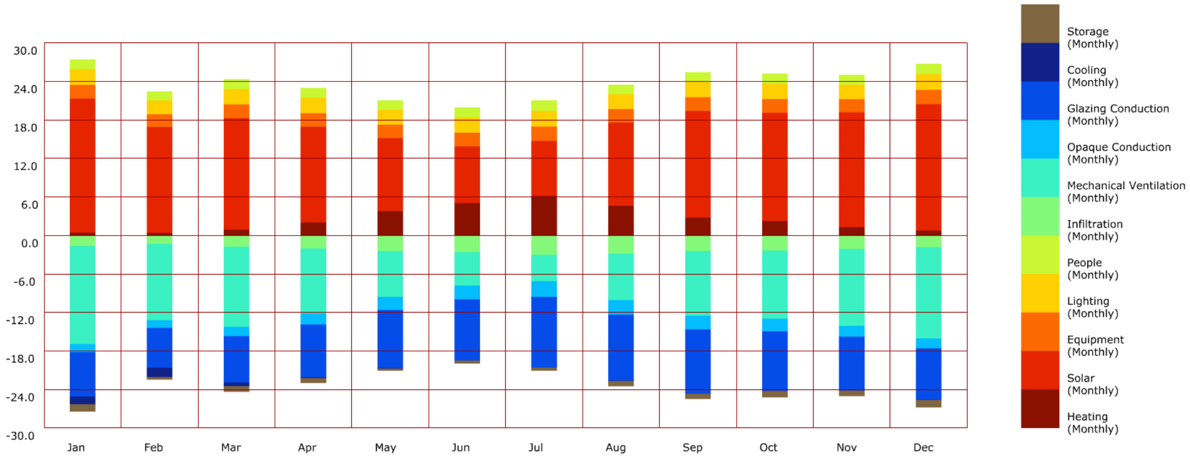


Figure 33: Timber baseline model energy balance, office building

Concrete:

The concrete energy simulation resulted in an annual energy usage of 397,347 kWh/year or 145 kWh/m².yr. This is a 16% increase in energy from the timber model.

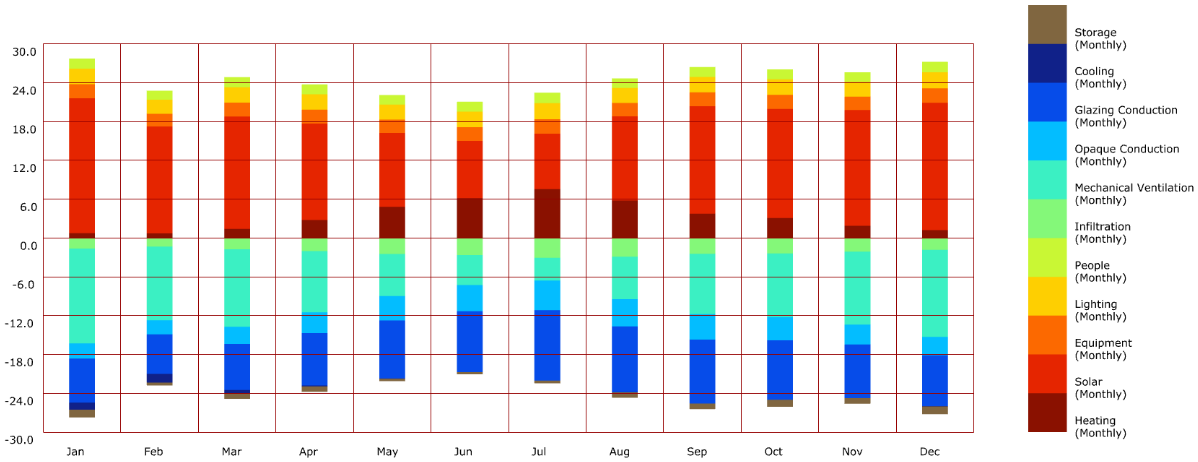


Figure 34: Concrete model energy balance, office building

Steel:

The steel energy simulation resulted in an annual energy usage of 437,082 kWh/year or 159 kWh/m².yr. This is a 26% increase in energy from the timber model.

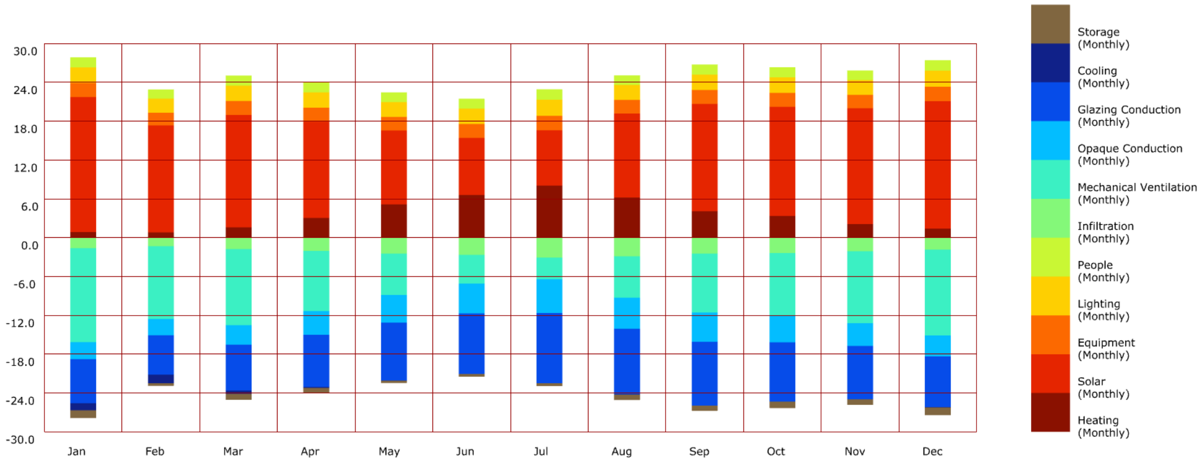


Figure 35: Steel model energy balance, office building

The comparison of energy balance graphs for different structural materials shows two things:

1. The opaque conduction – heat loss through building envelope – is increasing from timber to concrete, then again from concrete to steel.
2. Due to the increase in opaque conduction, the heating energy is also increasing.

As seen in figure 36, the heating energy for a steel construction is the highest of all structures. This is expected as steel has the highest thermal conductivity; therefore, the lowest R-Values in the THERM simulations. The cooling energy in the steel and concrete construction; however, is lower than the timber structure. This is because there is so much heat being lost through the building envelope that the cooling system does not need to cool down the zone.

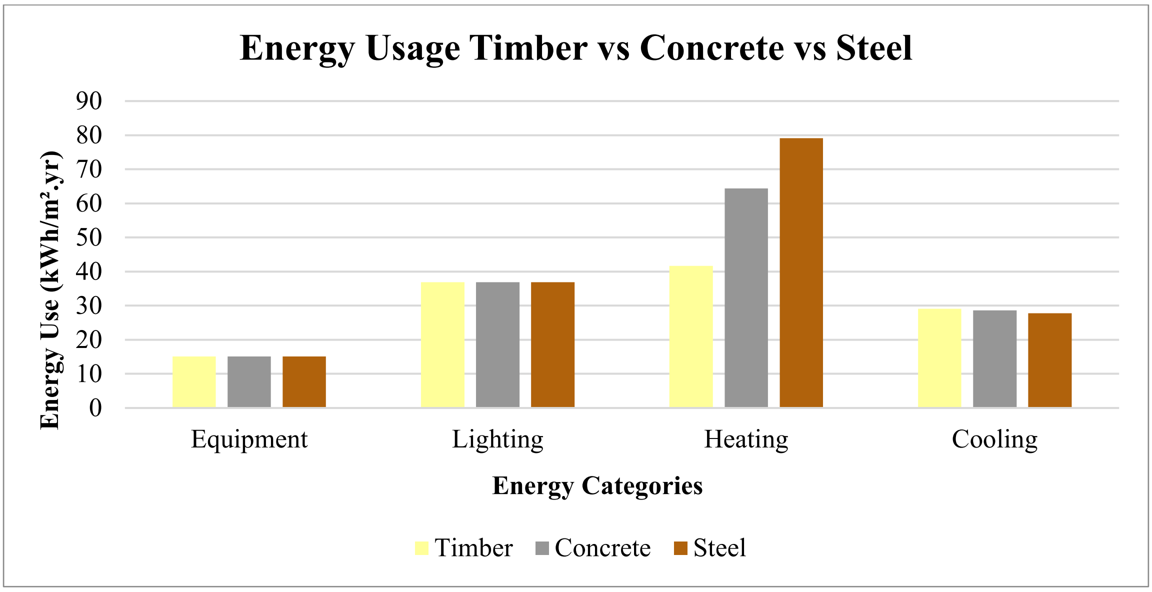


Figure 36: Timber, concrete and steel energy use graph

7.4.2. Operational vs Capital Costs

The operational costs are calculated based on 2019 commercial energy prices from the Ministry of Business, Innovation and Employment (MBIE, 2020). The price per kWh is $0.17.

Timber: $55,893

Concrete: $67,072 (16.7% increase from timber)

Steel: $73,799 (24.2% increase from timber)

Expenses: <u>Timber is 24% less expensive than steel and 17% less expensive than concrete</u>

The capital costs were calculated by another summer scholar who was specializing in costing. Recognition of this work has been included in the acknowledgements section.

Timber: $32,825,470

Concrete: $31,204,800 (5.2% decrease from timber)

Steel: $31,369,051 (4.6% decrease from timber)

Total: Timber is 5.2% more expensive than steel and 4.6% more expensive than concrete.

7.4.3. Embodied Energy

The embodied energy (EE) was calculated based on the volumes of the costed structural materials provided by the same summer scholar who did the costing. The values were obtained from a research paper into the EE of typical materials used in New Zealand construction (Alcorn, 2003). To obtain the EE values, Alcorn (2003) used the "cradle to gate" method. That is, including the energy it takes from the extraction of raw materials, to the transport to the manufacturing site, and the manufacturing itself. International transport of material ingredients is also included. Solar energy, human labour and transport to the construction site are not included in the EE values.

Timber

The value for the timber calculation was assumed to be glulam because there was no CLT embodied energy calculation in the reference.

Total Embodied Energy: <u>2,867,852 MJ</u>

Total Carbon Dioxide Emission: <u>-239,864 kg of CO_2</u>

Concrete

Total Embodied Energy: <u>8,416,191 MJ (65% increase from timber)</u>

Total Carbon Dioxide Emission: 1,392,479 CO2 kg of CO_2

Steel

Total Embodied Energy: 8,860,076 MJ (70% increase from timber)

Total Carbon Dioxide Emission: 1,185,362 kg of CO_2

Although building with timber at a commercial scale is between 4.5-5.5% more expensive than concrete and steel, the benefits are incredible – between 15-25% reduction in energy, 15-25% less in operational costs and 65-70% less embodied energy. In addition, the timber scheme sequesters almost 250,000 kg of CO_2, while the concrete and steel schemes emit over 1 million kg of CO_2. Due to these findings, it can be concluded that the commercial office building in this study should be designed and built in timber to achieve an energy efficient, sustainable and cheap to run building, even if it is potentially 5.2% more expensive.

8. Overall Findings and Conclusions

8.1. Case Study A – Townhouse

Assessing the thermal performance of external insulation in the building envelope of the townhouse has resulted in the following findings:

Finding 1: The R-Value of the building envelope increased by 50%, meaning there will be less heat loss.

Finding 2: The overall energy usage for the building reduced 25% due to the increase in R-Value. This heating energy was almost completely gone from the R-Value increase.

Finding 3: Operational costs have reduced 26% due to the significant drop in energy.

Finding 4: The capital cost of externally insulating is 1.5% more expensive than internally insulating.

With the addition of external insulation, capital costs increase 1.5%, however, the overall energy usage is reduced by 25% and the operational costs are 26% less. This is an immense saving that must be capitalized on with a measly 1.5% more in the build cost. Therefore, it can be concluded that external insulation should be used on case study A, and other low to medium density buildings in the Auckland climate.

8.2. Case Study B – Office Building

Assessing the thermal performance of different structural materials in the building envelope of the office building has resulted in the following findings:

Finding 1: The R-Value of the timber structure's building envelope was the highest, followed by concrete and then steel

Finding 2: The overall energy usage for the building was lowest for the timber structure. The concrete structure used 16% more energy than timber and the steel structure used 24% more than timber.

Finding 3: The operational costs are cheapest for the timber structure, then concrete at 17% more than timber and steel at 25% more than timber.

Finding 4: Timber is the most expensive structural material. Concrete is 4.6% less expensive than timber and steel is 5.2% less expensive than timber.

Finding 5: The embodied energy for the timber structure is the lowest of all three structures. The embodied energy for concrete is 65% more than timber and steel is 70% more than timber.

With the use of timber structural elements, the capital cost will be at maximum 5.2% more expensive; however, the energy usage is reduced by 15-25%, the operational costs are 15-25% less and timber uses at least 65% less embodied energy than concrete and steel. These findings show immense benefits in favour of the use of timber as a main structural element for this commercial office building. Therefore, it can be concluded that a timber structure should be used on case study B, and other office building must start using timber as their main structural elements.

8.3. Further Research

Further research into external insulation is needed to continue exploring ways in which we can apply it to buildings in New Zealand. The following items present future research into external insulation:

- Optimising external wall insulation thickness and conductivity for each main NZ climate
- Optimising all wall materials to create "the perfect wall" for each main NZ climate;
- Calculating the moisture, humidity and hence the mould risk for baseline and external insulation;
- Calculating the embodied energy difference between baseline and external insulation;

- Figuring out limitations of procurement and constructability of external insulation;
- Assessing the full building envelope – external roof insulation (warm roof), and external foundation insulation.

These areas of further research will fill in the blanks from the findings presented in section 8.1, ideally contributing to the argument for the use of external insulation on residential buildings.

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Appendices

Appendix 1: Modelling Priority Table Definitions

Definitions Townhouse

Classification

These columns allow easy reference of the details if desired.

- Detail Number: Numbering system for details.
- Construction Detail: Name of construction detail in architect's drawings.
- Drawing Page: Name of drawing page on architect's drawings.
- Vertical or Horizontal Element: The orientation of the detail – either vertical (section) or horizontal (plan).

Detail Analysis

These columns analyse the total façade surface area of each detail and the total façade surface area of thermal bridging elements.

- Façade Surface Area of Detail: The total facade surface area in square metres that the detail represents.
  - Details Modelled (DM) Surface Area: Total façade surface area of all details modelled.
  - Details Not Modelled (DNM) Surface Area: Total façade surface area of all details not modelled.
- Percentage of Total Façade Surface Area: The total percentage of facade surface area that the detail represents.
  - Details Modelled (DM) Percentage: Total percentage of façade surface area of details not modelled.
  - Details Not Modelled (DNM) Percentage: Total percentage of façade surface area of details not modelled.
- Thermal Bridging Elements: Building elements in the detail that have a significantly low thermal conductivity, e.g. non-insulated areas.
- Surface Area of Thermal Bridging Elements: The total façade surface area that the thermal bridging elements represent.
- Percentage of Thermal Bridging Elements from Total Façade Surface Area: The total percentage of façade surface area that the thermal bridging elements represent.

Priority

These columns have been added to establish which details are the most important to be modelled.

- Thermal Modelling Importance: The importance of modelling each detail dependent on the percentage of thermal bridging elements from total façade surface area.
- R-Value (THERM): The R-Value of the modelled details from THERM.
- Heat Loss of Detail: The total heat loss to outside from each detail in W/m²-K. This is calculated by dividing the total façade surface area of the detail by the R-Value.
- Thermal Resistance Importance of Detail: The importance of addressing this detail due to its lack of thermal resistance. This is dependent on the percentage of thermal bridging elements from total façade surface area and total heat loss.

Definitions Commercial Office Building

Classification

These columns allow easy reference of the details if desired.

- Detail Number: Numbering system for details.
- Construction Detail: Name of construction detail in architect's drawings.
- Drawing Page: Name of drawing page on architect's drawings.
- Vertical or Horizontal Element: The orientation of the detail – either vertical (section) or horizontal (plan).
- Floor Level: The floor level that the detail correlates to – ground, mid or top floors.
- Detail Recurrence per Floor: How many times this detail occurs through the different floor levels.

Detail Analysis

These columns analyse the total façade surface area of each detail and the total façade surface area of thermal bridging elements.

- Façade Surface Area of Detail per Floor: The total facade surface area in square metres that the detail represents for the ground, mid or top floors.
  - Details Modelled (DM) Surface Area: Total façade surface area of all details modelled for ground, mid and top floors.
  - Details Not Modelled (DNM) Surface Area: Total façade surface area of all details not modelled for ground, mid and top floors.
- Percentage of Façade Surface Area per Floor: The total percentage of facade surface area that the detail represents for the ground, mid or top floors.
  - Details Modelled (DM) Percentage: Total percentage of façade surface area of all details modelled for ground, mid and top floors.

- Details Not Modelled (DNM) Percentage: Total percentage of façade surface area of all details not modelled for ground, mid and top floors.

- Total Façade Surface Area of Detail: The total facade surface area in square metres that the detail represents across the whole building.
- Total Percentage of Façade Surface Area: The total percentage of facade surface area that the detail represents across the whole building.

Priority

These columns have been added to establish which details are the most important to be modelled.

- Comparative Analysis Benefit: The benefit these details will have to compare timber, concrete and steel structures. If there is no comparative analysis benefit, they will not be modelled.
- Thermal Modelling Importance: The importance of modelling each detail dependent on the total percentage of façade surface area.

Appendix 2: Case Study A Simulation Input Data

Schedules & Loads:

Townhouse Schedules	12am-8am	8am-11am	11am-6pm	6pm-10pm	10pm-12am	**Sources**
Occupancy (%)						NZS4218
Mon-Fri	100	60	60	100	100	
Sat	100	100	50	70	100	
Sun	100	100	50	70	100	
Metabolic Rate (W)	50	100	70	150	50	
Plug and Lighting (%)						
Mon-Fri	3	23	23	27	20	
Sat	3	23	23	27	20	
Sun	3	23	23	27	20	
Infiltration (%)	100	100	100	100	100	

Table 36: Townhouse schedules

Constructions and Material Properties:

Important Information:

- All material properties are from NZS4214
- Concrete material properties from "Thermal Conductivity of Concrete – A Review"
- All wall and roof insulation properties from "Insulating Materials: Principles, Materials, Applications" (see table 20)

- The thermal conductivity of materials is calculated by dividing the material thickness by the R-Value
- Thermal absorption is assumed as 0.9 and solar and visible absorption is assumed as 0.5
- Layer 1 is the outer most layer in constructions

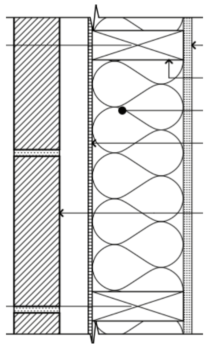
Layer	**Material**	**Thickness (mm)**	**Density (kg/m^3)**	**Specific Heat Capacity (J/kg-K)**	**Thermal Conductivity (W/m-K)**	
1	Brick Veneer	70	2240	790	0.89	
2	Air Barrier	50	0	0	0	
3	Rigid Air Barrier	6	1470	840	0.25	
4.1	Polyester Wall Insulation (R-2.6)	140	10	1500	0.054	
4.2	Timber Stud	140	450	1880	0.15	
6	Plasterboard	13	800	870	0.22	

Table 37: EWT-01 construction

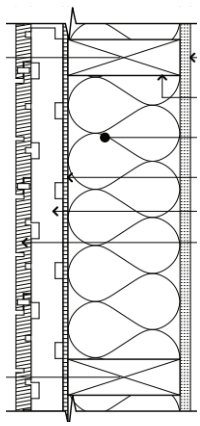
Layer	**Material**	**Thickness (mm)**	**Density (kg/m^3)**	**Specific Heat Capacity (J/kg-K)**	**Thermal Conductivity (W/m-K)**	
1	Vertical Timber Weatherboard	19	550	1880	0.13	
2.1	Air Barrier	40	0	0	0	
2.2	Structural Cavity Batten	40	450	1880	0.15	
3	Rigid Air Barrier	6	1470	840	0.25	
4.1	Polyester Wall Insulation (R-2.6)	140	10	1500	0.054	
4.2	Timber Stud	140	450	1880	0.15	
6	Plasterboard	13	800	870	0.22	

Table 38: EWT-02 construction

Layer	**Material**	**Thickness (mm)**	**Density (kg/m^3)**	**Specific Heat Capacity (J/kg-K)**	**Thermal Conductivity (W/m-K)**	
1	Plasterboard	13	800	870	0.22	
2.1	Polyester Wall Insulation (R-2.6)	90	10	1500	0.035	

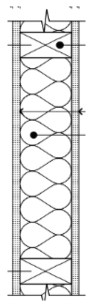
2.2	Timber Stud	140	450	1880	0.15	
3	Plasterboard	13	800	870	0.22	

Table 39: WT-01 Construction

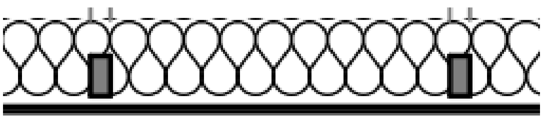
Layer	Material	Thickness (mm)	Density (kg/m^3)	Specific Heat Capacity (J/kg-K)	Thermal Conductivity (W/m-K)
1	Plasterboard	13	800	870	0.22
2.1	Polyester Roof Insulation (R-4)	200	10	1500	0.05
2.2	Timber Joist	140	450	1880	0.15
					

Table 40: Ceiling construction

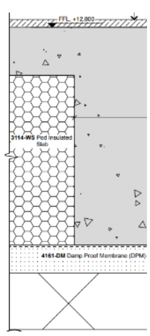
Layer	Material	Thickness (mm)	Density (kg/m^3)	Specific Heat Capacity (J/kg-K)	Thermal Conductivity (W/m-K)	
1	Timber Flooring	15	550	1500	0.13	
2	Concrete Slab	100	2300	840	1.6	
3	Pod Insulated Slab	300	450	1880	0.15	
4	Sand Blinding	50	0	0	0	
5	Compacted Hardcore Base	100	0	0	0	

Table 41: Slab construction

Note: Only the timber floor, concrete slab and pod insulated slab have been modelled – the sand binding and hardcore base do not provide any significant thermal resistance.

Construction Type	Boundary Condition
EWT-01	Outdoors

EWT-02	Outdoors
WT-01	Adiabatic
Ceiling	Outdoors
Slab	Ground

Table 42: Townhouse boundary conditions

Natural Ventilation:

Parameter	Description	Value
Construction	Low-E coated IGU at 4mm with 12mm argon gas. Aluminium framing. R-Value 0.3.	-
Open Area Fraction Schedule	The opening area (fraction) of a window.	0.3
Minimum Indoor Temperature	The indoor temperature below which the windows are closed.	20°C
Minimum Indoor Temperature Schedule	The indoor temperature schedule below which the windows are closed.	8am-6pm
Maximum Indoor Temperature	The indoor temperature above which the windows are opened.	24°C (NZS4218)
Maximum Indoor Temperature Schedule	The indoor temperature schedule above which the windows are opened.	8am-6pm
Maximum Indoor-Outdoor Temperature Difference	The difference between the indoor and outdoor temperatures below which the windows are closed.	3°C (Byrd, 2012)
Maximum Indoor-Outdoor Temperature Difference Schedule	The difference between the indoor and outdoor temperatures schedule below which the windows are closed.	8am-6pm
Minimum Outdoor Temperature	The outdoor temperature below which the windows are closed.	18°C
Minimum Outdoor Temperature Schedule	The outdoor temperature schedule below which the windows are closed.	8am-6pm
Maximum Outdoor Temperature	The outdoor temperature above which the windows are closed.	25°C
Maximum Outdoor Temperature Schedule	The outdoor temperature above which the windows are closed.	8am-6pm

Table 43: Natural ventilation parameters

Weather File:

https://www.ladybug.tools/epwmap/

Figure 37: Weather file location. Orange = Weather file. Blue = Townhouse location

This is the closest weather file to the townhouse location at 3.5km.

Appendix 3: Case Study B Simulation Input Data

Schedules:

Retail Schedules	12am-8am	8am-11am	11am-1pm	1pm-6pm	6pm-10pm	10pm-12am	Sources
Occupancy (%)							NZS4243
Mon-Fri	0	60	70	70	40	0	
Sat	0	60	80	80	20	0	
Sun	0	10	40	40	0	0	
Metabolic Rate (W)	0	150	300	150	70	0	
Plug and Lighting (%)							
Mon-Fri	5	90	90	90	50	5	
Sat	5	90	90	90	30	5	
Sun	5	40	40	40	5	5	
Infiltration (%)	100	100	100	100	100	100	

Table 44: Retail schedules, office building

Office Schedules	12am-8am	8am-11am	11am-1pm	1pm-6pm	6pm-10pm	10pm-12am	Sources

Occupancy (%)							NZS4243
Mon-Fri	0	95	95	95	5	0	
Sat	0	10	5	5	0	0	
Sun	0	5	5	5	0	0	
Metabolic Rate (W)	0	100	200	100	70	0	
Plug and Lighting (%)							
Mon-Fri	5	90	90	90	30	5	
Sat	5	30	15	15	5	5	
Sun	5	5	5	5	5	5	
Infiltration (%)	100	100	100	100	100	100	

Table 45: Office schedules, office building

<u>Construction and Material Properties:</u>

Important Information:

- All material properties are from NZS4214
- Concrete material properties from "Thermal Conductivity of Concrete – A Review"
- All wall and roof insulation properties from "Insulating Materials: Principles, Materials, Applications" (see table 20)
- The thermal conductivity of materials is calculated by dividing the material R-Value by thickness
- Thermal absorption is assumed as 0.9 and solar and visible absorption is assumed as 0.5.

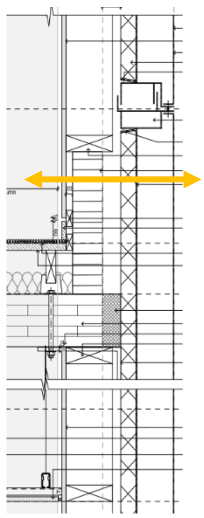
Layer	Material	Thickness (mm)	Density (kg/m^3)	Specific Heat Capacity (J/kg-K)	Thermal Conductivity (W/m-K)	
1	Aluminium Cladding	2	2800	910	230	
2	Rockwool External Insulation	50	10	1500	0.034	
3	Air Barrier	55	0	0	0	
4	Glulam Edge Beam	75	800	1500	0.142	
5	Air Barrier	20	0	0	0	
6	Plasterboard	13	800	870	0.22	

Table 46: Wall (spandrel panel) construction

Layer	Material	Thickness (mm)	Density (kg/m^3)	Specific Heat Capacity (J/kg-K)	Thermal Conductivity (W/m-K)
1	Concrete Slab	3000	2300	840	1.6

Table 47: Slab construction

Layer	Material	Thickness (mm)	Density (kg/m^3)	Specific Heat Capacity (J/kg-K)	Thermal Conductivity (W/m-K)
1	Timber Flooring	20	550	1500	0.13
2	Air Barrier	75	0	0	0
3	Acoustic Insulation	75	10	1500	0.028
4	CLT Floor Slab	150	800	1500	0.142
5	Air Barrier	900	0	0	0
6	Plasterboard	13	800	870	0.22

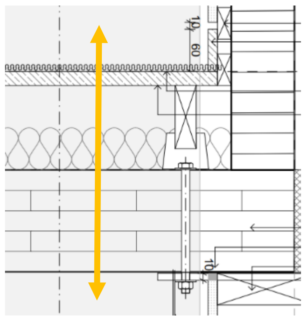


Table 48: Inter-floor construction

Layer	Material	Thickness (mm)	Density (kg/m^3)	Specific Heat Capacity (J/kg-K)	Thermal Conductivity (W/m-K)
1	Concrete Slab	150	2300	840	1.6
2	CLT Floor Slab	150	800	1500	0.142

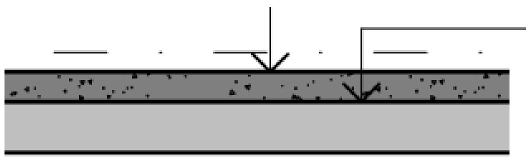


Table 49: Roof slab construction

Construction Type	Boundary Condition
Wall	Outdoors
Slab	Ground
Inter-floor	Adiabatic (To each floor above and below)
Roof	Adiabatic (To plant room)

Table 50: Boundary conditions

Weather File:

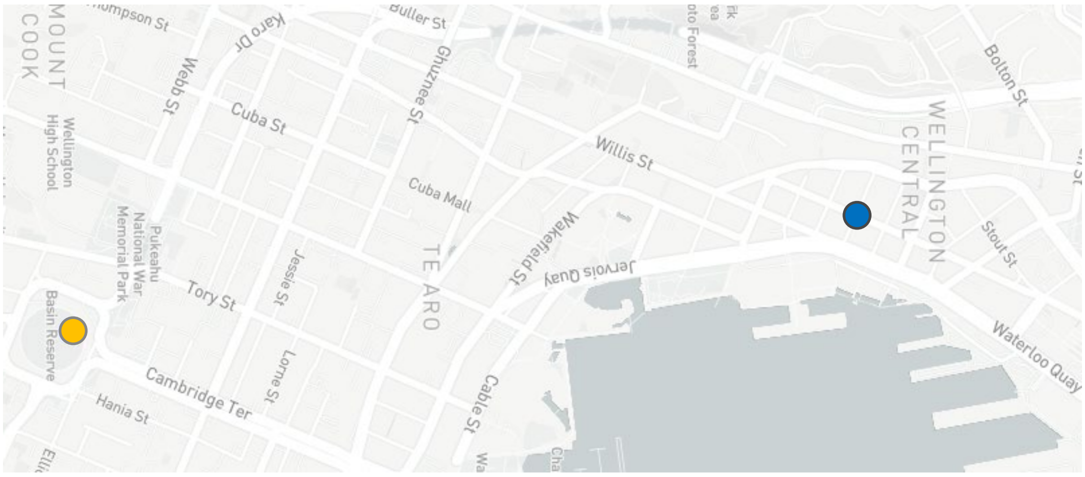


Figure 38: Weather file location. Orange = Weather file. Blue = Office building location

This is the closest weather file to the office building at 1.8km.

Appendix 4: Case Study A Results & Calculations

The following is the calculation processes for the overall R-Value from heat loss and operational costs for case study A.

	Detail #	1	2	3	4	5	
Façade Surface Area per Detail in m²	Orientation	EWT-01	Inter-floor to Wall	Ceiling to Wall	Intertenancy to Wall	EWT-02	Total
	North	36.6	8.4	6	0	0	51
	East	75.7	13.3	9.5	6.75	0	105.3
	South	42.8	7.7	5.5	0	30.4	86.5
	West	28.5	15.4	11.5	6.75	5.5	67.7
	Total	183.6	44.8	32.5	13.5	36	310.4

Table 51: Facade surface area of each detail in each orientation

	EWT-01	Inter-floor to Wall	Ceiling to Wall	Intertenancy to Wall	EWT-02
Baseline Insulation R-Value	R-2.46	R-0.51	R-3.63	R-0.91	R-2.39
External Insulation R-Value	R-3.15	R-2.77	R-4.26	R-2.01	R-3.09

Table 52: R-Value changes between baseline and external insulation

Orientation	Façade Surface Area (m²)	Heat Loss (W/m-K)	Baseline Insulation R-Value	Heat Loss (W/m-K)	External Insulation R-Value
North	51.0	33.0	1.55	16.1	3.18
East	105.3	66.9	1.57	34.4	3.06
South	86.5	46.8	1.85	27.5	3.14
West	67.7	54.7	1.24	22.5	3.01
Total	310.4		R-1.52		R-3.10

Table 53: Changed R-Values through heat loss calculation

THERM Simulations:

The following are images of the relevant details in case study A before and after application of external insulation when modelled in THERM.

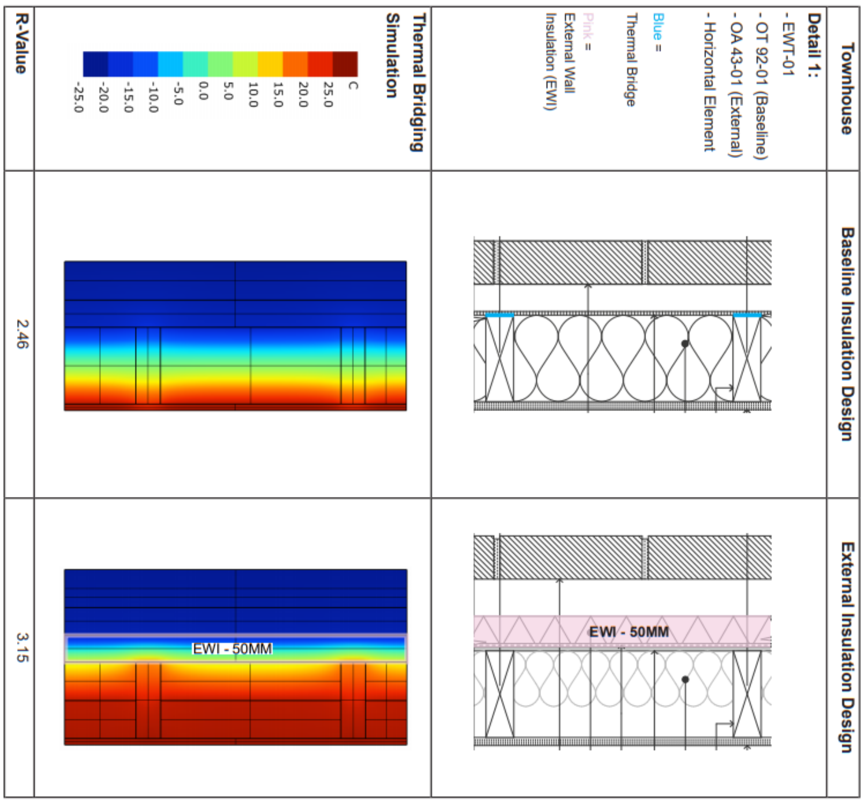


Figure 39: Detail 1 simulation, townhouse

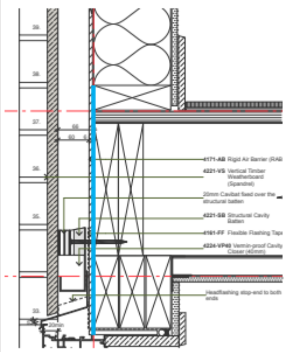
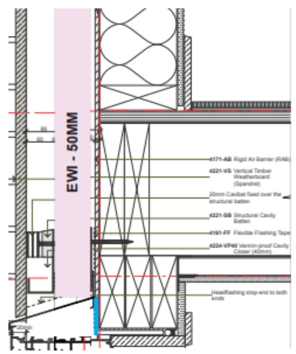
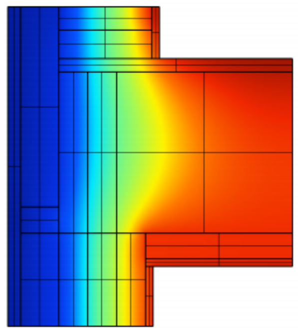
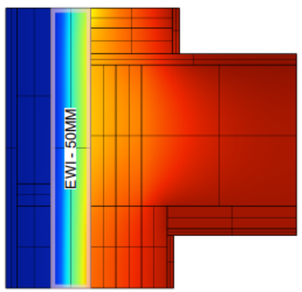
Townhouse	Baseline Insulation Design	External Insulation Design 1
Detail 2: - Interfloor to Wall - OT 40-12 - Vertical Element Blue = Thermal Bridge Pink = External Wall Insulation (EWI)		
Thermal Bridging Simulation C 25.0 20.0 15.0 10.0 5.0 0.0 -5.0 -10.0 -15.0 -20.0 -25.0		
R-Value	0.5	2.82 (EWI)

Figure 40: Detail 2 simulation, townhouse

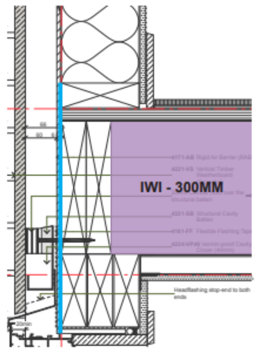
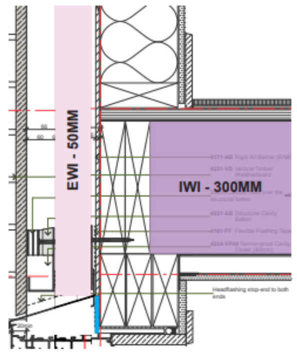
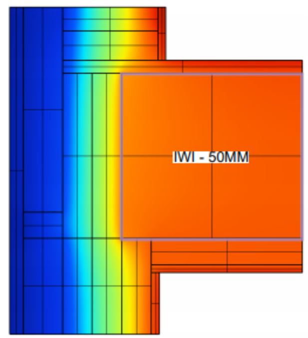
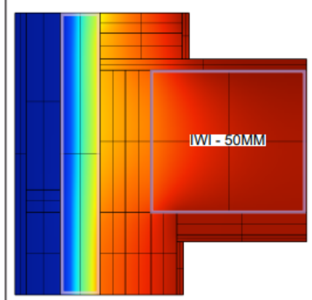
Townhouse	Insulation Design 2	External Insulation Design 3
Detail 2.1 & 2.2: - Interfloor to Wall - OT 40-12 - Vertical Element Blue Line = Thermal Bridge Pink = External Wall Insulation (EWI) Purple = Internal Wall Insulation (IWI)		
Thermal Bridging Simulation C 25.0 20.0 15.0 10.0 5.0 0.0 -5.0 -10.0 -15.0 -20.0 -25.0		
R-Value	1.08 (IWI)	3.09 (EWI & IWI)

Figure 41: Detail 2.1 & 2.2 simulation, townhouse

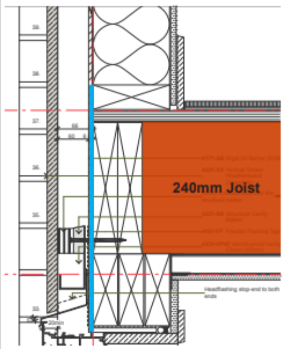
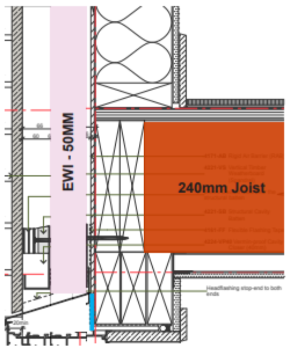
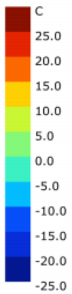
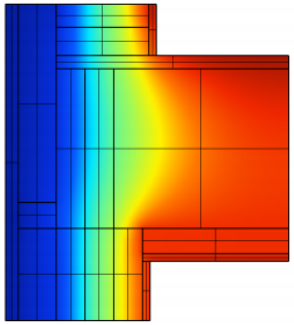
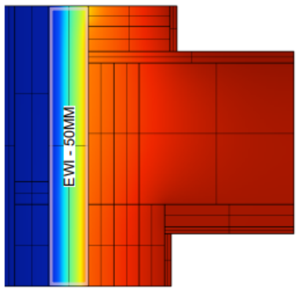
Townhouse	Baseline Insulation Design	External Insulation Design
Detail 2.3: - Interfloor to Wall, 240mm Joist - OT 40-12 - Vertical Element Blue = Thermal Bridge Pink = External Wall Insulation (EWI)		
Thermal Bridging Simulation 		
R-Value	0.56	2.42 (EWI)

Figure 42: Detail 2.3 simulation, townhouse

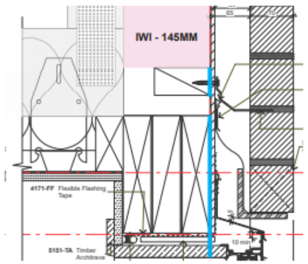
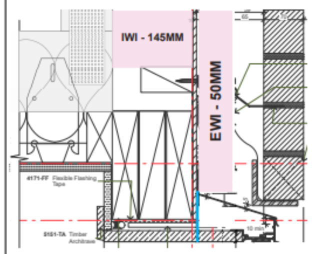
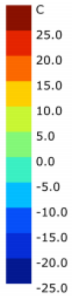
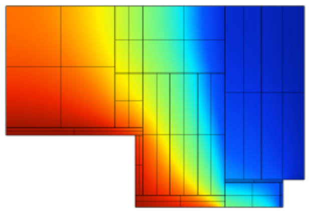
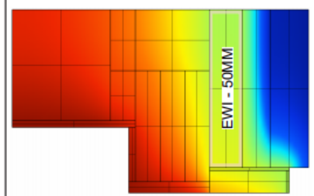
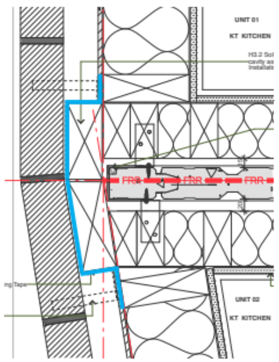
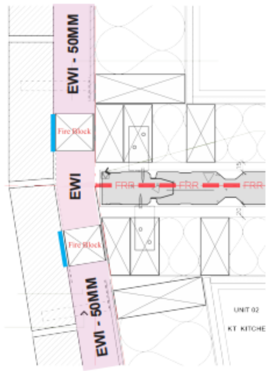
Townhouse	Baseline Insulation Design	External Insulation Design
Detail 3: - Ceiling to Wall - OT 40-16 - Vertical Element Blue = Thermal Bridge Pink = External Wall Insulation (EWI)		
Thermal Bridging Simulation 		
R-Value	3.63	4.26

Figure 43: Detail 3 simulation. townhouse

<table>
<tr><th>Townhouse</th><th>Baseline Insulation Design</th><th>External Insulation Design</th></tr>
<tr><td>Detail 4:
- Intertenancy to Wall
- OT 40-12
- Horizontal Element

Blue =
Thermal Bridge

Pink =
External Wall Insulation (EWI)</td><td></td><td></td></tr>
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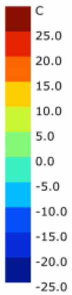
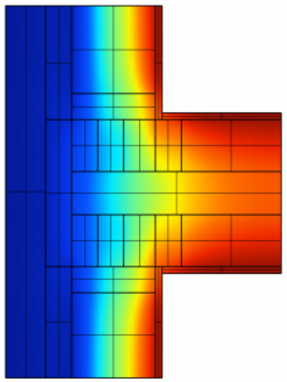
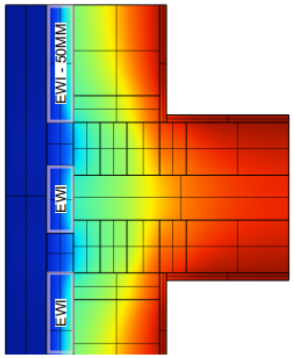
</td><td></td><td></td></tr>
<tr><td>R-Value</td><td>0.91</td><td>2.01</td></tr>
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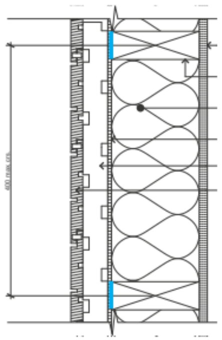
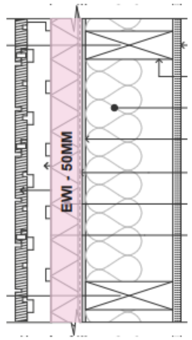
Figure 44: Detail 4 simulation, townhouse

<table>
<tr><th>Townhouse</th><th>Baseline Insulation Design</th><th>External Insulation Design</th></tr>
<tr><td>Detail 5:
- EWT-02
- OT 92-01
- Horizontal Element

Blue =
Thermal Bridge

Pink =
External Wall Insulation (EWI)</td><td></td><td></td></tr>
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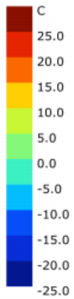
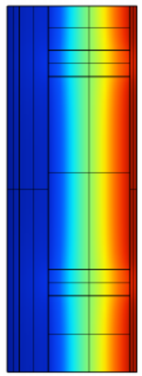
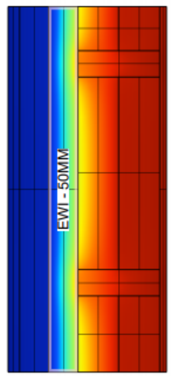
</td><td></td><td></td></tr>
<tr><td>R-Value</td><td>2.39</td><td>3.09</td></tr>
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Figure 45: Detail 5 simulation, townhouse

Appendix 5: Case Study B Results & Calculations

The following is the calculation processes for the overall R-Value from heat loss, embodied energy and operational costs for case study B.

R-Value Calculations from Heat Loss:

Orientation	Floor	Façade Surface Area (m²)	Heat Loss (W/m-k)	Timber R-Value
North	Ground	52.2	136.8	0.38
East	Ground	25.2	65	0.39
South	Ground	N/A	N/A	Concrete Block Wall
West	Ground	N/A	N/A	Concrete Block Wall
North	Mid	31.1	18.3	1.7
East	Mid	47.9	24.4	1.96
South	Mid	34	17.3	1.96
West	Mid	18.2	10.7	1.7
North	Top	31.1	18.3	1.7
East	Top	18.9	11.1	1.7
South	Top	12.9	7.6	1.7
West	Top	18.2	10.7	1.7
None	Roof	234	182.0	1.29

Table 54: R-Values in each orientation, Timber

Orientation	Floor	Façade Surface Area (m²)	Heat Loss (W/m-k)	Concrete R-Value
North	Ground	52.2	154.2	0.34
East	Ground	25.2	73.2	0.34
South*	Ground	N/A	N/A	Concrete Block Wall
West*	Ground	N/A	N/A	Concrete Block Wall
North	Mid	31.1	20.7	1.55
East	Mid	47.9	25.3	1.89
South	Mid	34	17.9	1.89
West	Mid	18.2	11.8	1.55
North	Top	31.1	20.1	1.55
East	Top	18.9	12.2	1.55

South	Top	12.9	8.3	1.55
West	Top	18.2	11.8	1.55
None	Roof	234	230.5	1.02

Table 55: R-Values in each orientation, Concrete

Orientation	Floor	Façade Surface Area (m²)	Heat Loss (W/m-k)	Steel R-Value
North	Ground	52.2	170.9	0.31
East	Ground	25.2	81.2	0.31
South*	Ground	N/A	N/A	Concrete Block Wall
West*	Ground	N/A	N/A	Concrete Block Wall
North	Mid	31.1	21.7	1.43
East	Mid	47.9	26.4	1.82
South	Mid	34	18.7	1.82
West	Mid	18.2	12.7	1.43
North	Top	31.1	21.7	1.43
East	Top	18.9	13.2	1.43
South	Top	12.9	9.0	1.43
West	Top	18.2	12.7	1.43
None	Roof	234	399.5	0.59

Table 56: R-Values in each orientation, Steel

Embodied Energy:

Timber (Glulam):

MJ/m^3: 5,727 * 500.76 = 2,867,852.52 MJ

CO_2/m^3: -479 *500.76 = -239,864 CO_2

Concrete:

MJ/m^3: 11,393*738.716 = 8,416,191 MJ

CO_2/m^3: 1,885*738.716 = 1,392,479 CO_2

Steel:

MJ/m^3: 245,757*9.076 = 2,230,490.2 MJ

MJ/m^3: 11,393*581.9 = 6,629,586.7 MJ

Total: 8,860,076 MJ

CO_2/m^3: 9,749*9.076 = 88,481

CO_2/m^3: 1,885*581.9 = 1,096,881.5

Total: 1,185,362 CO_2

Operational Costs:

Timber: 331,123 kWh.yr * $0.1688 = $55,893

Concrete: 3973,47 kWh.yr * $0.1688 = $67,072 (16.7% Increase from timber)

Steel: 437,082 kWh.yr * $0.1688 = $73,799 (24.2% Increase from timber)

THERM Simulations:

The following are images of the relevant details from case study B with timber, concrete and steel structural materials when modelled in THERM.

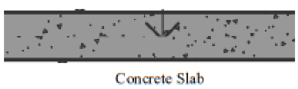
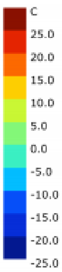
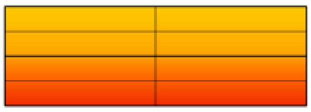
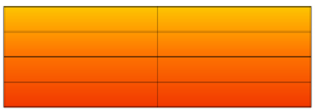
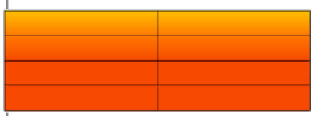
	Timber Design	Concrete Design	Steel Design
Detail 1: - Non-Insulated Roof to Plant Room - 31-03 - Vertical Element - Roof - Recurs 1 Floor			
Thermal Bridging Simulation 			
R-Value	1.03	0.82	0.44

Figure 46: Detail 1 simulation, office building

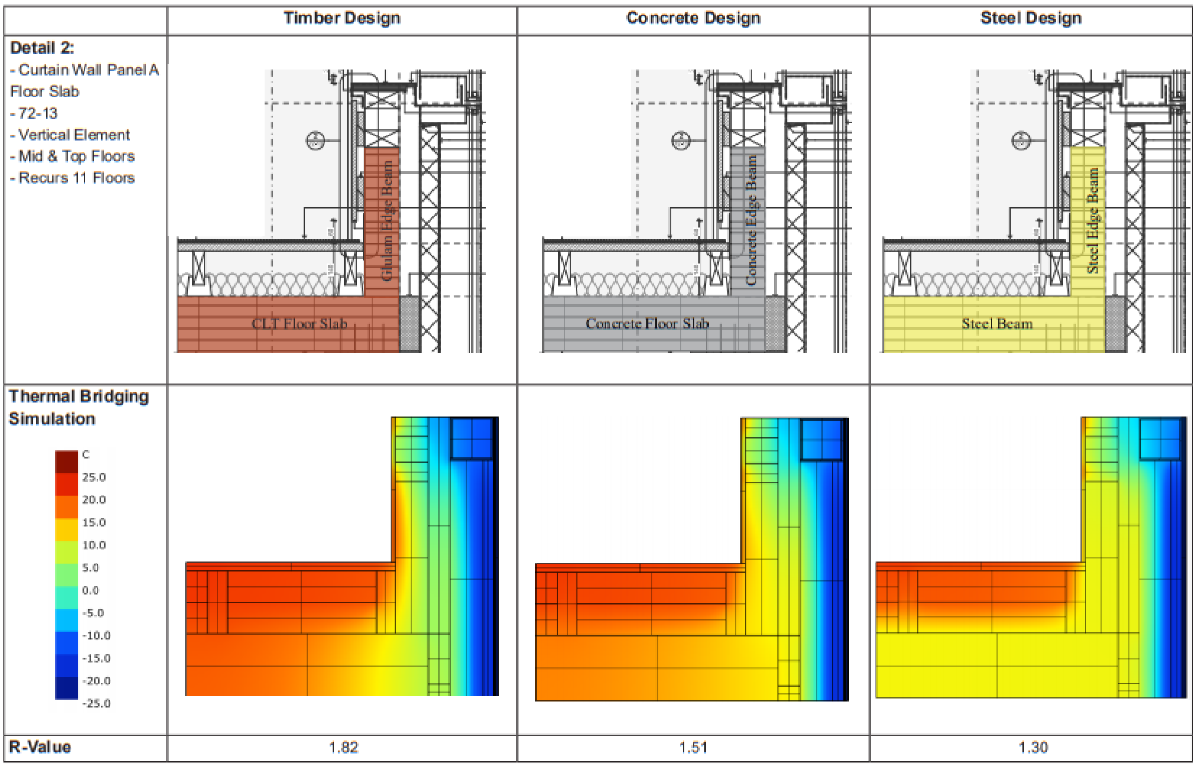


Figure 47: Detail 2 simulation, office building

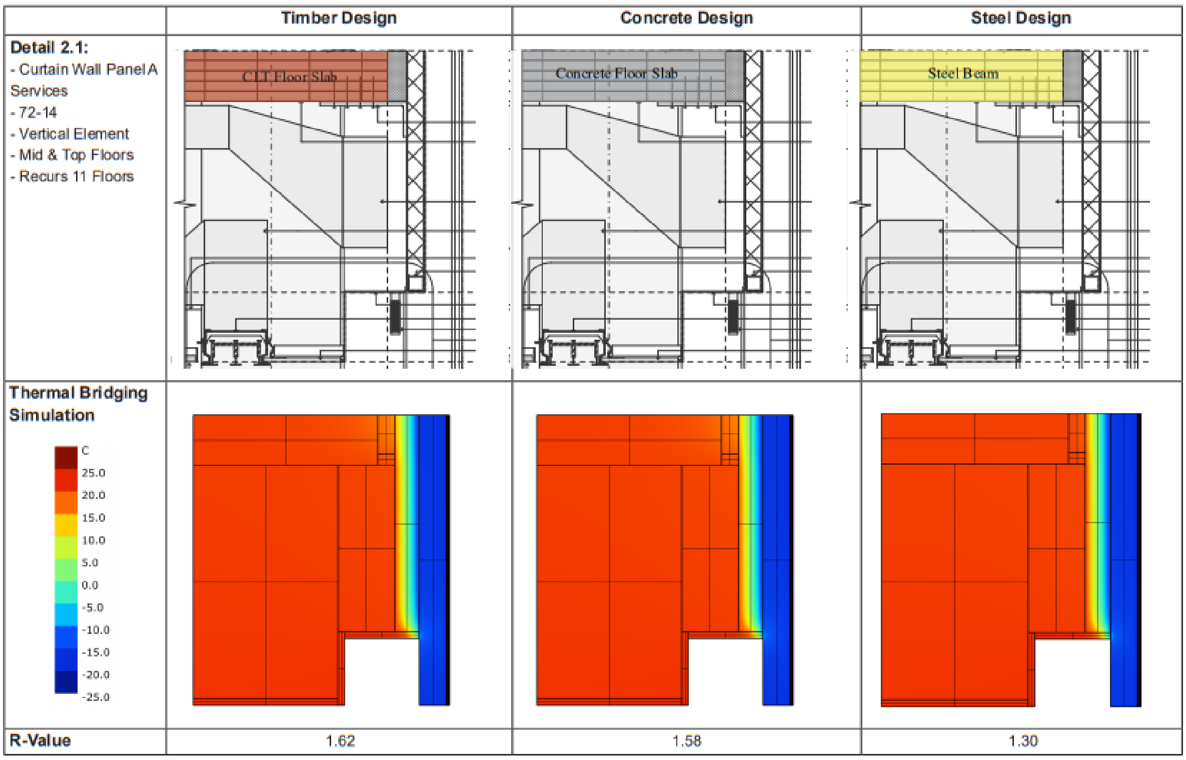


Figure 48: Detail 2.1 simulation, office building

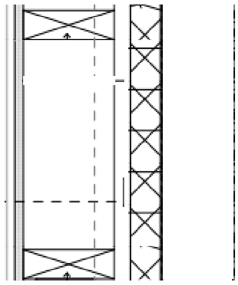
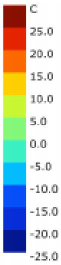
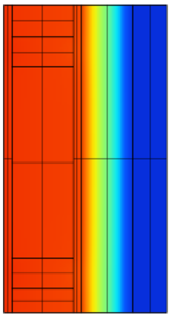
	Timber Design	Concrete Design	Steel Design
Detail 3: - Curtain Wall Panel H Wall - 72-21 - Vertical Element - Mid Floor - Recurs 7 Floors		N/A	N/A
Thermal Bridging Simulation 		N/A	N/A
R-Value	2.01		

Figure 49: Detail 3 simulation, office building

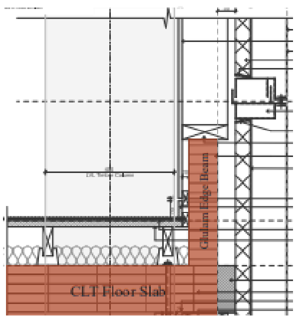
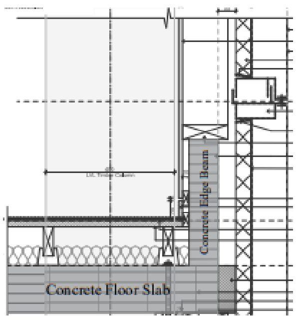
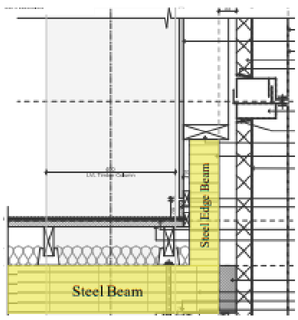
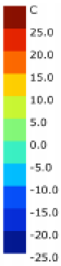
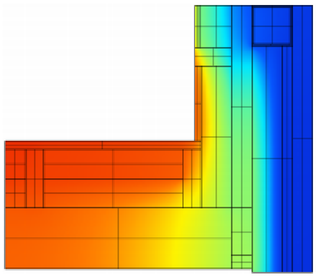
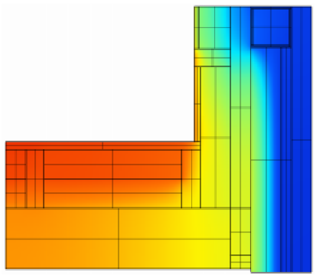
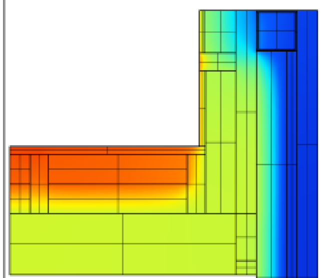
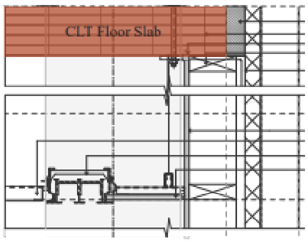
	Timber Design	Concrete Design	Steel Design
Detail 3.1: - Curtain Wall Panel H Floor Slab - 72-21 - Vertical Element - Mid Floor - Recurs 7 Floors			
Thermal Bridging Simulation 			
R-Value	1.81	1.55	1.31

Figure 50: Detail 3.1 simulation, office building

<table>
<tr><th></th><th>Timber Design</th><th>Concrete Design</th><th>Steel Design</th></tr>
<tr><td>Detail 3.2:
- Curtain Wall Panel H Services
- 72-21
- Vertical Element
- Mid Floor
- Recurs 7 Floors</td>
<td>
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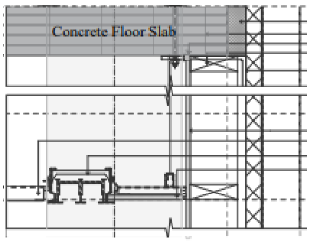
<td>
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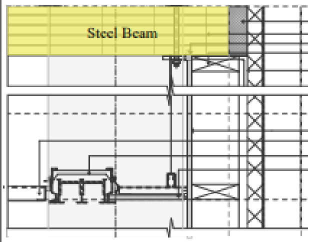
<td>
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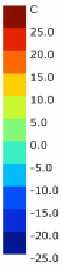
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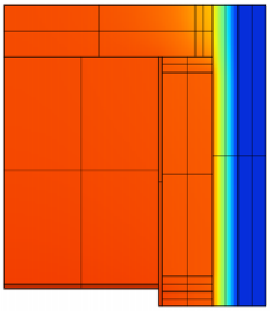
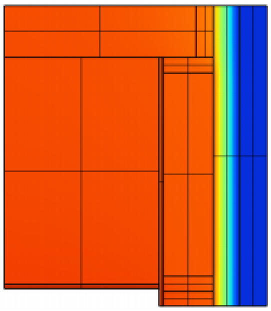
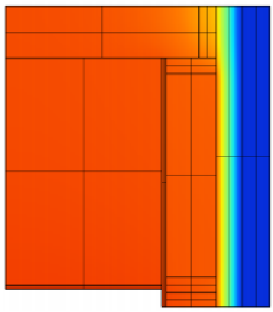
<td></td>
<td></td>
<td></td></tr>
<tr><td>R-Value</td><td>1.95</td><td>1.89</td><td>1.85</td></tr>
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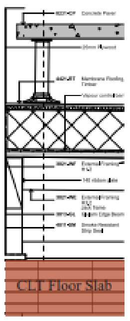
Figure 52: Detail 3.2 simulation, office building

<table>
<tr><th></th><th>Timber Design</th><th>Concrete Design</th><th>Steel Design</th></tr>
<tr><td>Detail 5:
- Insulated Roof to Outdoors
- 74-10
- Vertical Element
- Roof
- Recurs 1 Floor</td>
<td>
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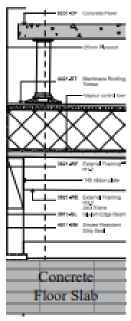
<td>
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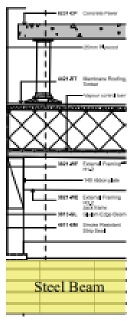
<td>
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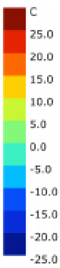
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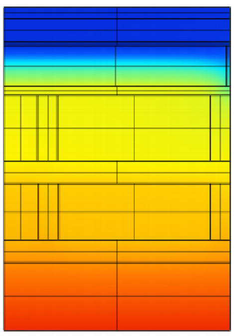
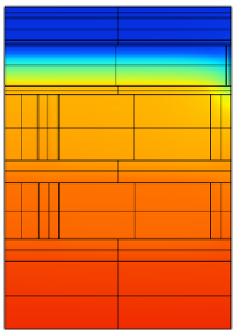
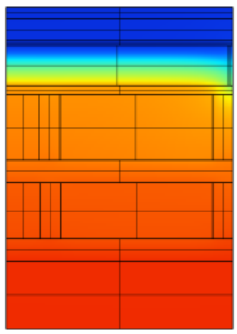
<td></td>
<td></td>
<td></td></tr>
<tr><td>R-Value</td><td>4.13</td><td>3.61</td><td>3.45</td></tr>
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Figure 51: Detail 5 simulation, office building

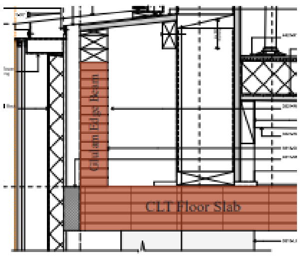
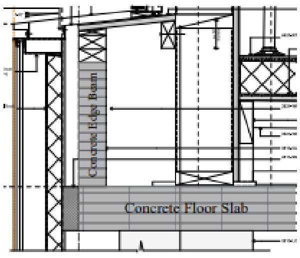
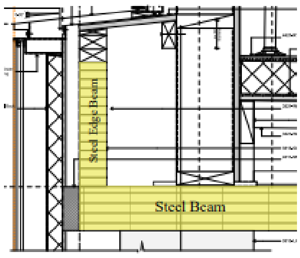
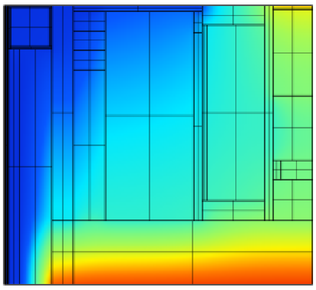
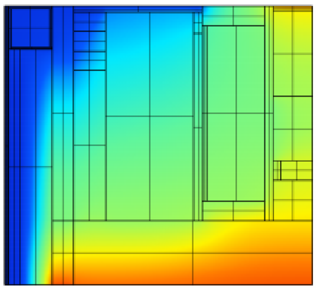
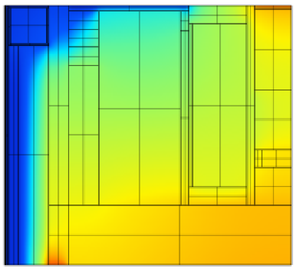
	Timber Design	Concrete Design	Steel Design
Detail 6: - Non-Insulated Roof to Outdoors - 74-11 - Vertical Element - Roof - Recurs 1 Floor			
Thermal Bridging Simulation C 25.0 20.0 15.0 10.0 5.0 0.0 -5.0 -10.0 -15.0 -20.0 -25.0			
R-Value	1.86	1.59	1.32

Figure 53: Detail 6 simulation, office building

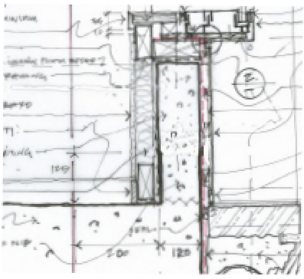
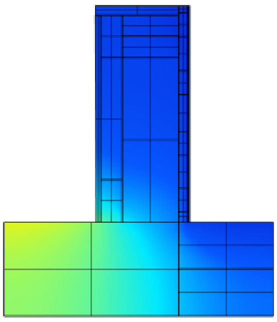
	Timber Design	Concrete Design	Steel Design
Detail 7: - Shop Front Facade to Concrete Slab - 74-04 - Vertical Element - Ground Floor - Recurs 1 Floor		N/A	N/A
Thermal Bridging Simulation C 25.0 20.0 15.0 10.0 5.0 0.0 -5.0 -10.0 -15.0 -20.0 -25.0		N/A	N/A
R-Value	0.33		

Figure 54: Detail 7 simulation, office building

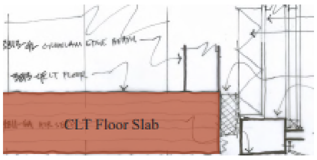
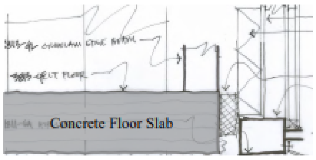
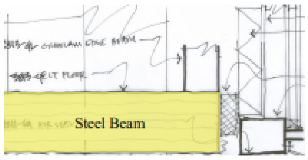
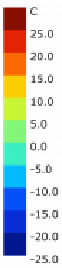
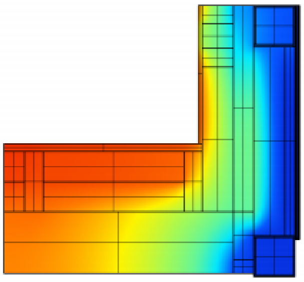
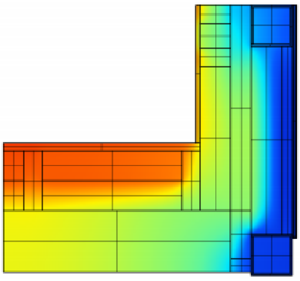
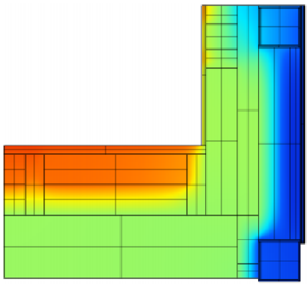
	Timber Design	Concrete Design	Steel Design
Detail 7.1: - Shop Front Facade to Floor Slab - 74-05 - Vertical Element - Ground Floor - Recurs 1 Floor			
Thermal Bridging Simulation 			
R-Value	1.37	1.16	1.02

Figure 55: Detail 7.1 simulation, office building

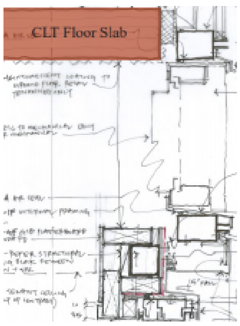
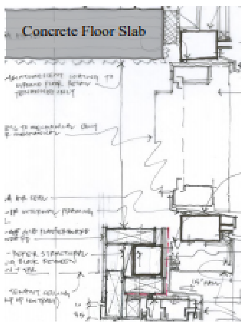
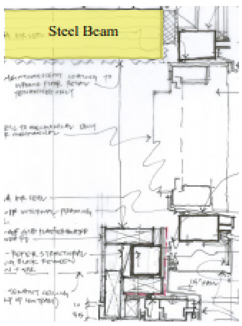
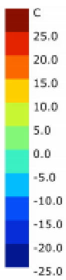
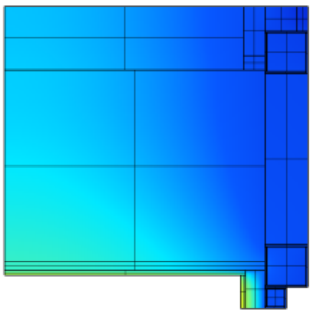
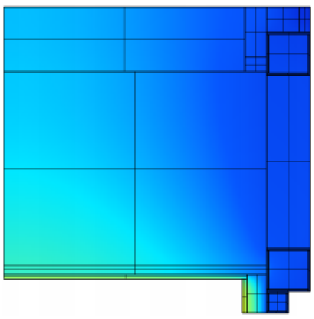
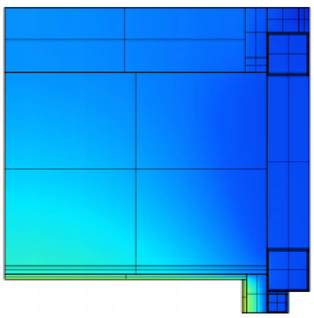
	Timber Design	Concrete Design	Steel Design
Detail 7.2: - Shop Front Facade to Floor Slab - 74-05 - Vertical Element - Ground Floor - Recurs 1 Floor			
Thermal Bridging Simulation 			
R-Value	0.28	0.24	0.19

Figure 56: Detail 7.2 simulation, office building