THERMAL PERFORMANCE OF BUILDINGS WITH POST-TENSIONED TIMBER STRUCTURE COMPARED WITH CONCRETE AND STEEL ALTERNATIVES

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Abstract

This thesis describes the influence of thermal mass on the space conditioning energy consumption and indoor comfort conditions of multi-storey buildings with concrete, steel and timber structural systems. The buildings studied were medium sized educational and commercial buildings. When calculating a building's life-cycle energy consumption, the construction materials have a direct effect on not only the building's embodied energy but also on the space conditioning energy. The latter depends, amongst other things, on the thermal characteristics of the building's materials; thermal mass can also be an influence on comfort conditions in the building.

A modelling comparison has been undertaken between three very similar medium-sized buildings, each designed using structural systems made primarily of timber, concrete and steel. The post-tensioned timber version of the building is a modelled representation of a real three-storey educational building that has been constructed recently in Nelson, New Zealand. The concrete- and steel-structured versions have been designed on paper to conform to the required structural codes and meet, as closely as possible, the same performance, internal space layout and external façade features as the real timber-structured building. Each of these three structurally-different buildings has been modelled with two different thermal envelopes (code-compliant and New Zealand best-practice) using a heating, ventilating and air conditioning (HVAC) system with heating only (educational scheme) and heating and cooling (commercial scheme). The commercial system (with cooling) was applied only to the buildings with the best-practice thermal envelope.

The analysis of each of these nine different construction and usage categories includes the modelling of operational energy use with an emphasis on HVAC energy consumption, and the assessment of indoor comfort conditions using predicted mean vote (PMV). From an operational energy use perspective, the modelling comparison between the different cases has shown that, within each category (code-compliant, low-energy and low-energy-commercial), the principal structural material has only a small effect on overall performance. The most significant differences are in the building with the best-practice thermal envelope with the commercial HVAC system, were the concrete building has slightly lower HVAC energy consumption, being 3 and 4% lower than in the steel and timber buildings respectively

The assessment of indoor comfort conditions during occupied periods through using PMV for each of the three categories shows that the timber structure consistently exhibited longer periods in the over-warm comfort zone, but this was much less pronounced in south-facing spaces. To examine the reasons for the less acceptable PMV in the timber-structure versions, an analysis of indoor timber and concrete surface temperatures was carried out in both buildings. It was found that, particularly in north-facing spaces, there were large diurnal swings in the temperatures of timber surfaces exposed to solar radiation. These swings were much less in the case of concrete surfaces so the environment was perceived to be more comfortable under such conditions because of the reduced influence of higher mean radiant temperatures.

To moderate this potential downside of solar-exposed internal timber surfaces, better results are achieved if, when timber is used for thermal mass, the timber is not exposed to direct solar radiation, for example locating it in the ceilings or on the south side of the building.

Two other approaches to combating the potential overheating problem in the timber-structured buildings were analysed in an illustrative mode; addition of external louvres to reduce direct solar gains at critical times of day and year; and use of phase change material (PCM) linings to act as light-mass energy buffers. Although external louvres increase comfort conditions significantly by reducing the periods of an overly warm environment, they produce an increase in heating energy consumption through reducing beneficial solar gains. The use of PCM linings shows little benefit to overall indoor comfort conditions for the building of this case-study.

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1 Introduction

Buildings have a significant impact on the environment, consuming 32% of the world's resources, including 12% of its water and up to 40% of its energy. Buildings are also responsible for 40% of the waste which ends up in landfills and 40% of global greenhouse gas emissions (WGBC, 2011). In the particular case of New Zealand's overall environmental impacts, represented by its greenhouse gas emissions profile, only 17% of total emissions can be attributed to the built environment, with agricultural (48%) and transportation (20%) being the sectors responsible for the largest impacts. However, both agriculture and transportation face considerable difficulties in reducing their share of emissions in comparison with the built environment where significant cost-effective reductions are possible (NZGBC, 2009).

A building goes through many stages throughout its useful life, none of which are particularly simple to analyse from an environmental point of view. These life-cycle stages of a building include: production of materials; transportation to site; site erection and construction; life time operations of building or structure; repairs; maintenance and refurbishment; demolition or dismantling at end of life; transportation for reuse; and recycling or disposal. A more simplistic way of summarising these stages for the sake of a more straightforward life-cycle energy analysis, for example, would be to subdivide life-cycle energy consumption into; initial and recurrent embodied energy (construction- and maintenance-associated energy consumption); operational energy consumption; and end-of-life energy (energy consumption associated with demolition and disposal or recycling processes). Strategies for reducing the environmental impacts in the construction and use of buildings include measurements associated with each of the building's life phases, but more significantly into the building's operational phase (Perez, Baird, & Buchanan, 2008).

1.1 Construction materials and operational energy

When calculating a building's life-cycle energy consumption, the construction materials have a direct effect on both the building's embodied energy and space conditioning energy. The latter depends, amongst other things, on the thermal characteristics of the building's materials; thermal mass can also be an influence on comfort conditions in the building. Most previous research into the environmental impacts of multi-storey buildings of different materials (e.g. concrete or steel structural systems) have made an emphasis on comparing the embodied energy in the construction, maintenance, and end-of-life phases of buildings but, in these comparisons, no significant emphasis has been placed on the buildings' operational environmental impacts.

This thesis is focussed on the operational phase of buildings, because the largest environmental impacts of a building's life-cycle are associated with its operation. Operational energy can range from 75% to 90% of a building's total life-cycle energy consumption (Cole & Kernan, 1996; John, Nebel, Perez, & Buchanan, 2008; Page, 2006; and Perez, et al., 2008). When comparing the capacity of buildings built using different structural materials (e.g. concrete, timber, steel) to reduce impacts during the operational phase of a building's life, a common approach is to simply refer to the presence of thermal mass in the respective structural system (Burgan & Sansom, 2006; and Gaimster & Munn, 2007). More recently hygrothermal mass has been proposed as an alternative to thermal mass in solid timber buildings (Bellamy and Mackenzie 2007), because the wood has not only thermal but also moisture buffering capacity, improving indoor comfort conditions and reducing space conditioning energy.

To reduce environmental impacts by effectively using the inherent thermal mass in structural materials, many design and operational parameters need to be taken into account (Balaras, 1996; Barnard, 1995; Barnard, Concannon, & Jaunzens, 2001; Braham, Barnard, & Jaunzens, 2001a; Burgan & Sansom, 2006; Gaimster & Munn, 2007; and Yang & Li, 2008). These parameters include the thermal mass material's thermal properties, its location and distribution within buildings, the thickness of thermal mass available, and the maximisation of the thermal linkage between indoor air and thermal mass. In the normal design of typical New Zealand buildings, consideration of most of these parameters is not common practice.

The aim of this research is to identify whether current structural systems in concrete, steel and timber, used in the construction of conventional multi-storey buildings, provide enough thermal mass to influence indoor thermal conditions and subsequently space-conditioning energy consumption. The study of how the thermal envelope of these buildings affects the performance of thermal mass has also been included.

1.2 Case study buildings used for comparison in this research

In this research, building energy and environmental modelling (BEEM), is used for the assessment and comparison of heating ventilation and air-conditioning (HVAC) energy consumption and indoor comfort conditions (using Predicted Mean Vote (PMV)) of case study buildings.

Buildings analysed in this research are three very similar medium-sized educational buildings, each designed using structural systems made primarily of timber, concrete or steel. The concrete and steel buildings have been designed (but not built) to replicate an actual three-storey 1980 m^2 gross floor area educational building (recently constructed in Nelson, New Zealand, and labelled in this thesis as the Arts building), which has a post-tensioned timber structure and timber concrete composite floors. For these types of buildings, the structural systems are normally prefabricated frames (columns and beams) with shear walls for earthquake and wind resistance, and cast-in-situ concrete topping on prefabricated floor systems. The different structures in the three buildings involve changes in the material of the beams and columns, and the structural shear walls in the timber and the concrete buildings (the steel building has a braced steel shear wall enclosed in gypsum plaster board). Although the floor system used in each of the three structures is very different from each other, all three systems involve relatively thick concrete toppings.

Because of the use of different floor systems, the visible ceiling in most of the rooms is the exposed underfloor of the structural systems in place. This exposed underfloor varies significantly between the timber building (exposed timber), the concrete building (the permanent timber formwork is visible between precast concrete floor joists), and in the steel building (exposed steel sheeting of the composite steel-concrete floor slab). Most of the interior lining materials are wood panelling in the timber building, and gypsum plasterboard in the steel and concrete buildings.

All the buildings have been modelled using two different insulation values in the thermal envelope (opaque walls and glazed areas), one sufficient to comply with the New Zealand building code and another with “best practice” insulation levels. The HVAC system in the actual Arts building includes hydronic radiant heating, mechanical ventilation with heat recovery, and cooling only in a computer room. This HVAC system has been labelled as “educational HVAC system”. An alternative HVAC system has also been modelled where cooling has been added into all rooms with directly supplied mechanical ventilation, and where most of the radiant heating has been replaced by convective heating. This HVAC system has been labelled as “Commercial HVAC system”. The buildings with the “code-compliant” thermal envelope have been modelled using the original HVAC system (Educational HVAC system). Buildings with the “best practice” thermal envelope have been modelled using both the educational and the commercial HVAC systems.

While, at the outset, the motivation for this research was entirely from the perspective of assessing the energy performance of timber-structured multi-storey buildings in comparison with their concrete- and steel-structured counterparts, the devastating consequences of the recent earthquakes in Christchurch have heightened an awareness of, and interest in timber as an alternative structural material in earthquake-vulnerable locations. In this consideration, the question of whether or not there are operational energy consequences in choosing timber ahead of its more widely adopted alternatives is bound to arise.

1.3 Objectives:

Following analysis of the literature review in Chapter 2, the following objectives were set. The overall objective of this research is to provide a benchmark identifying whether current structural systems in concrete, steel and timber, used with code-compliant and New Zealand best-practice thermal envelopes, provide enough thermal mass to influence indoor thermal conditions and subsequently space-conditioning energy consumption. This benchmark will be based on a comparison of concrete, steel, and timber structural systems.

To achieve these objectives the modelling and on-site work was carried out to answer the following specific research questions:

1. Does a concrete, steel, or timber multi-storey building, as currently built in New Zealand, contain enough thermal mass to have an effect on the space conditioning energy consumption?

2. For a concrete, steel, or timber multi-storey building, as currently built in New Zealand, does the thermal mass influence the indoor environmental conditions?

3. Are there optimal locations for thermal mass materials, and are those locations dependent on what those materials are?

4. In which way does the improvement of the thermal envelope from code-compliant to best-practice influence indoor environmental conditions and space energy consumption of buildings?

5. Are HVAC systems (which are almost always controlled by sensing dry-bulb indoor temperature), sensitive in any way to the thermal mass available in the three building structural types?

6. Does night-time ventilation improve indoor environmental conditions and subsequently the response of HVAC systems to the availability of thermal mass in the three building structural types?

7. Will good management of direct solar radiation have an impact on the building's indoor conditions when concrete or timber is used as thermal mass materials?

8. Will phase change material increase the effective thermal mass in a timber-framed building?

1.4 Thesis outline

A brief description of the motivation of this work has been given in this chapter.

In order to better understand the relevant background that presently exists in the literature, Chapter 2 provides a review and discussion on the environmental impacts of buildings, and a comparison of energy and carbon foot-printing. It also introduces thermal mass and hygrothermal materials as important aspects of building construction that can potentially influence the overall environmental impact of buildings. The parameters affecting the performance of thermal mass and hygrothermal materials are described. The chapter finally gives an explanation of the area of research where this thesis will be focused.

The bulk of the methodology used for the building energy and environmental modelling (BEEM) undertaken in this research is given in Chapter 3. The emphasis in this chapter is a description of the case-study buildings produced for this research. In addition to describing the general building geometry and construction used for modelling of each building, a description of the HVAC systems is given, and the way that these were modelled. Chapter 3 also includes the reasons for setting up metering of real buildings, a description of the chosen weather files, and the reasons for the choice of software are explained. The selection of a simplified “Test Building” is described, which is then modelled to assess the effectiveness of changes in the disposition and surface properties of concrete when used for thermal mass, with regard to energy use and building comfort.

Chapter 4 describes the Arts timber building, as constructed, and the Arts concrete and Arts steel buildings, as designed but not built. It also describes the low energy versions of all three buildings, and methods of modelling the thermal mass in the main structural elements. The choice of modelling software is described in more detail, together with techniques for modelling the various components of the entire HVAC system

Chapter 5 describes the structure and use of the reinforced concrete T-Block building, including the design and installation of metering equipment instrumentation, measurement data and thermal modelling of the building over a full year. The chapter includes a comparison of monitored and modelled indoor temperatures, and a discussion of differences. The primary purpose of this chapter is to calibrate the energy modelling software in an existing building (T-Block), before moving to modelling of many variations of the Arts building.

Chapter 6 describes a simplified calibration process undertaken in the Arts building, to be used as the primary case-study building, later the template for alternative case-study building models. A description of a monitoring system designed and installed in that building is given. The chapter includes a comparison of monitored and modelled indoor temperatures. In the case of energy consumption (for which meaningful monitored data was not available), a comparison with other broadly similar educational buildings is described, to give an order of accuracy for modelling in the remaining chapters.

Chapter 7 gives the results of the energy modelling assessment undertaken in all three sets of case-study buildings. The energy results are presented firstly by the categories in which the buildings were grouped initially, and secondly as a combined result for all case-study buildings with an emphasis on space conditioning energy. This describes the BEEM modelling analysis of the case study buildings by enhancing thermal mass performance.

Chapter 8 presents the results of the assessment of indoor environmental conditions in the case-study buildings. Initially it provides the results of comfort conditions determined by using Predicted Mean Vote (PMV) assessment, and secondly presents an analysis of the indoor air and selected surface temperatures in the concrete and the timber buildings. This analysis of surface temperatures was undertaken as a means of gaining a fuller understanding of the results produced in the PMV assessment and energy consumption.

Chapter 9 describes possible improvement of the energy performance and comfort conditions of the Arts Timber building by using three possible methods of improving overall indoor comfort conditions and subsequently reducing space conditioning energy consumption. These three methods are night-time ventilation, exterior louvres, and the use of Phase-Change-Materials (PCM).

Chapter 10 summarizes the conclusions and recommendations for further research.

The Appendices provide additional information to support the rationale, assumptions and findings of this research project. Finally, the architectural and structural design drawings of the Concrete, Timber and Steel buildings and the schedules of materials for each of them, are on an attached CD.

2 Background - literature review

This chapter provides a review and discussion on the environmental impacts of buildings, and a comparison of energy and carbon foot-printing. It also introduces thermal mass as an important aspect of building construction that can potentially influence the overall environmental impact of buildings. The parameters affecting the performance of thermal mass are described. The chapter also gives an explanation of the area of research where this thesis will be focused.

2.1 Environmental impacts of multi-storey buildings

A building goes through many stages throughout its useful life, none of which are particularly simple to analyse from an environmental point of view. From initial conception to final recycling, re-use or demolition, a whole range of processes must be taken into account. These include production of materials, transportation to site, site erection and construction, life time operations of building or structure, repairs, maintenance and refurbishment, demolition or dismantling at end of life, transportation for reuse, and recycling or disposal. In short, a full life cycle analysis (LCA) is required if one is to properly and thoroughly assess the environmental impact of a building (Perez, et al., 2008).

The following section reviews related literature about building construction materials and their contribution to sustainable development.

2.1.1 Multi-storey concrete and steel buildings' contribution to sustainable development

The claimed contribution of concrete to sustainable development is in areas such as durability, thermal mass (and subsequent reduction of space conditioning energy), recyclability, storm-water management, and easy deconstruction (Gaimster & Munn, 2007). Based on (Burgan & Sansom, 2006) the attributes of steel buildings to sustainable development are similar to those of concrete buildings, being reduced operational energy consumption via implementation of thermal mass, easy recyclability, and easy deconstruction. Other attributes of steel construction are efficient use of natural resources, minimizing waste, more efficient land use, and reducing the environmental impact on construction sites.

Both of these publications emphasize that environmental impacts produced during the lifetime operational phase of buildings overwhelm the environmental impacts associated with all other stages that buildings go through during their useful life. They emphasise that embodied energy for example, is much less important than operational energy consumption. Of total life-cycle energy consumption for an air-conditioned office building over a 60-year design life, operational energy represents about 90% of total energy use (Burgan & Sansom, 2006). Because of that, it is apparent that a focus must be given to the reduction of energy impacts associated with this stage of a building's total life.

Energy consumption during the operational phase of a building therefore becomes a good indicator of the overall environmental impact of that building. It is possible to say that from all operational energy end-uses in commercial buildings, structural systems and their corresponding secondary structural elements are likely to influence space conditioning energy consumption, more than other energy end-uses such as lighting or equipment energy consumption for example. This approach is taken in (Gaimster & Munn, 2007) where concrete buildings are credited with abundant thermal mass in floor systems and frames, which is generally recognized as having a positive effect in indoor environmental conditions and subsequently into reducing space conditioning energy. The same approach is taken in (Burgan & Sansom, 2006) to describe the attributes of steel framed buildings, which normally use cast in-situ medium weight concrete slabs as suspended floor systems. In (Burgan & Sansom, 2006) it is indicated that maximum performance of thermal mass over a daily cycle is achieved with only 75–100 mm thick concrete elements, such as in floor slabs. This suits the available thermal mass in suspended floor systems normally used in steel framed buildings e.g. the Comflor ® system which has about 150mm thick concrete in the slab (Corus New Zealand Ltd, 2002). Other than specifying thickness, neither (Gaimster & Munn, 2007) nor (Burgan & Sansom, 2006) elaborate further into other parameters that may affect the performance of thermal mass.

Other environmental advantages claimed for both concrete and steel structural systems, are that potentially these buildings can be deconstructed and reassembled elsewhere. Although this is at the moment fairly unusual, there is potential for recovery of the energy and material resources embedded in a building that can be derived from the reuse of the complete structure (Burgan & Sansom, 2006; Gaimster & Munn, 2007).

Apart from the recycling of concrete frames during deconstruction and reassembly, alternative scenarios for the end-of-life of concrete includes the crushing of concrete to be recycled as aggregate in new concrete, or the crushing of concrete to allow 'carbonization' used as a CO_2 re-absorption media (Gaimster & Munn, 2007). Problems both of these are related to the high energy (and therefore resulting CO_2 emissions) required to reprocess demolition concrete.

Recycling of steel is currently a common practice in many counties. In the UK, for example, all new steel has some recycled content, and this can vary between 10% and 100%, depending upon the availability and price of scrap, the specification of the steel, and the steel production route. But global demand for new steel exceeds the supply of scrap steel by a factor of around two and so it is not currently possible to meet the demand for all new steel entirely from scrap (Burgan & Sansom, 2006).

From all environmental credits of concrete or steel structural systems, this research is particularly interested in those happening during the operational phase of buildings and more specifically those inherent in structural systems that affect space conditioning energy, namely availability and potential performance of thermal mass.

2.1.2 Multi-storey timber buildings - structural systems

More recently, timber has been included as a construction material capable of being used as structural material for the construction of multi-storey buildings. Multi-storey timber building projects (mid-level high-rise) are currently emerging across Europe, mainly moved by the development of engineered timber structural systems, and the changing of fire safety regulations (Lowenstein, 2009). Examples of these timber buildings are a nine storey building in London (24 Murray Grove), a development of four eight-storey apartment blocks in the town of Vaxio in Sweden (Lowenstein, 2009). This new array of timber buildings has often been built using cross laminated timber (CLT) which is a timber material made of layers of solid timber glued together with alternating grain directions oriented at 90 degrees, similar to very thick plywood. CLT is widely used in residential buildings, mostly in non-seismic areas.

A new post-tensioned structural timber system has been developed at the University of Canterbury in New Zealand. This new system gives opportunities for the construction of mid-level high-rise, long-span buildings, enabling buildings with large open spaces (such as in commercial buildings), and resistance to hazards including earthquakes, and extreme weather events (Buchanan, Palermo, Carradine, & Pampanin, 2011).

2.1.2.1 Contribution of timber structures to sustainable development

Recent research has shown that the use of timber in construction contributes to sustainable development, by effectively affecting the carbon balance through four mechanisms: the relatively low fossil energy needed to manufacture wood products compared with alternative materials; the avoidance of industrial process CO_2 emissions from cement manufacture; the increased availability of biofuels from wood by-products that can be used to replace fossil fuels; and the physical storage of carbon i*n* wood building materials (Sathre, 2007; Sathre & Gustavsson, 2008).

These environmental advantages of using timber as structural materials in buildings are mostly related to benefits during the construction phase, more specifically associated with production of building materials. Other benefits of timber are associated with the end-of-life of timber, e.g. re-utilization of timber from demolition as a source of carbon-neutral biomass energy.

A good example of research that compares the environmental performance of buildings built using timber or reinforced concrete structural systems is given in (Sathre & Gustavsson, 2008). The case study building was a 4-storey 1190 m^2 building constructed in Sweden, originally built using a wooden structural frame and an alternative design was produced with a reinforced concrete frame. The focus was on the energy use and CO_2 emissions associated with the construction and demolition phases of the building life-cycle, because both buildings were designed to have virtually identical energy demands for heating and other energy uses during the operational phase. The results showed that the manufacture of materials for the wooden building uses 28% less primary energy and emits 45% less CO_2 than the manufacture of materials for the concrete building.

The assumption in (Sathre & Gustavsson, 2008) of the timber and the concrete buildings having the same operational energy consumption might work for residential buildings in Sweden where the only space conditioning energy used is for heating, and the occupancy is intermittent (normally only night-time occupancy). This is pointed out in (Simonson, Salonvaara, & Ojanen, 2001) where comfort conditions in timber buildings are studied in various Scandinavian countries.

Since it is during the operational phase where the highest environmental impacts occur in the life-cycle of buildings, closer attention needs to be given to comparisons of energy use in the operational phase, especially in more demanding conditions where complex heating ventilation and air-conditioning systems (HVAC) are utilized.

2.2 Comparison of energy and carbon footprint of buildings built in concrete, steel, or timber

A modelling comparison between of operational energy on a steel, timber and concrete framed buildings in New Zealand was undertaken in (Page, 2006), including assessment of energy and CO_2 emissions throughout the entire life-cycle of the buildings. Two typical government-funded buildings were designed with their main structural components predominantly in steel, timber or concrete. The building was a low-rise health building (1640 m^2 floor area). For the energy and CO_2 assessment, a lifetime of 50 years was used. The energy assessment showed a difference of 2% between the health building designs, with timber being the highest user. For CO_2 releases the three materials in the health building were within 3% of each other with steel and timber the lowest emitters.

2.2.1 Ratio of embodied to operational energy, and relative proportion of operational energy end-uses in total life-cycle energy consumption

A comparison of commercial buildings (with more complex HVAC systems) was undertaken in (Perez, 2008), where the assessment of 60-year life-cycle energy consumption and CO_2 emissions was studied in three similar medium-sized buildings, located in New Zealand - each designed with the structures and finishes being predominantly concrete, steel or wood. An additional fourth building was included in which all possible finishing elements were replaced by timber components; that building was labelled as “timber-plus” (basically a building built with solid wood for the structure and most finishing materials).

The results from (Perez, 2008) fed into (John, et al., 2008) which was a research report produced for the New Zealand Ministry of Agriculture and Forestry (MAF) with the same case-study buildings and the same operational energy analysis and results but with a more elaborate LCA model produced by SCION New Zealand. As described in (John, et al., 2008) two end-of-life scenarios were added to the assessment where deconstructed materials were either landfilled or re-utilized as building materials.

Modelling results in (Perez, 2008) and in (John, et al., 2008) are broadly similar, showing that operational energy consumption is about 75% of the total life-cycle energy use for all four buildings, which results in about 85% of total lifetime CO_2 emissions for the concrete and steel buildings, and almost 100% of total lifetime CO_2 emissions for the timber building. The proportion of operational energy in the total life-cycle energy consumption in (Perez, 2008) and in (John, et al., 2008) is lower than the 90% given in (Burgan & Sansom, 2006) earlier in this section, but is consistent with results found in (Cole & Kernan, 1996) for office buildings in Canada. Particularly in (Cole & Kernan, 1996), life-cycle energy consumption was studied in both a conventional and in a low-energy building. In the conventional building, after a 50 year life span, operational energy represented approximately 80% of the life-cycle energy consumption in Vancouver and 90% in Toronto (the latter having more severe climate).

When looking at the specific differences between life-cycle energy consumption of the concrete, steel, timber ,and timber-plus buildings in (Perez, 2008) and in (John, et al., 2008) it was found that the concrete building had the lowest life-cycle operational energy consumption, followed by the steel building (about 2% higher), then the timber-plus building (about 3% higher) and finally the timber building which had about 5% higher life-cycle operational energy consumption than the concrete building.

2.2.2 The aspects of structural systems that influence operational energy consumption of buildings

Based on (Perez, 2008) and (John, et al., 2008) it is possible to say that timber buildings may have low initial embodied energy and low embodied energy for maintenance but they have slightly higher operational energy. This is consistent with (Sathre & Gustavsson, 2008) where, although no operational energy was included in their assessment, timber buildings have lower embodied energy and embodied CO_2 emissions than concrete buildings. This is also consistent with (Page, 2006) where, although having the lower life cycle CO_2 emissions, timber buildings have the largest life-cycle energy consumption mainly because of poor insulation giving large space conditioning energy consumption.

When looking more closely at operational energy consumption in the case-study buildings in (Perez, 2008) and (John, et al., 2008), it was found that energy consumption in end-uses such as room electricity, lighting, system miscellaneous, and domestic hot water was about the same in all buildings. Space conditioning energy consumption is where differences are more evident. For example comparing the timber and the concrete buildings it was found that, although heating energy consumption was similar, cooling energy was significantly higher in the timber building compared with the concrete building.

Looking at aspects of a building that influence space conditioning energy consumption, thermal mass is the only significant difference when changing the primary structural systems e.g. from timber to reinforced concrete (including suspended floors). In other words, thermal mass is the only major aspect of the primary structural system that influences space conditioning and indoor environmental conditions. Other aspects such as R-value are an inherent part of a building's thermal envelope which is normally included as secondary structural elements or finishing in buildings.

2.2.2.1 Energy as the indicator chosen for operational environmental impacts

"*Energy has often been seen as a useful surrogate for overall environmental impact for many people, given the implied relationship between energy use and several other deleterious impacts, the multi-faceted nature of these impacts, and the absence of some other common factor or indicator. Particularly in the assessment of environmental impacts of buildings during the operational phase, energy has long been an appropriate indicator and the measurement of choice*" (Perez, et al., 2008).

In many cases it is feasible to calculate carbon dioxide emissions from energy data, though this tends to be country-specific, depending on the energy mix and industrial base of the region. This is not a simple matter when looking at embodied energy and embodied CO_2 emissions because aspects such as carbon sequestration in the case of wood materials, or recyclability in the case of steel-based material, needs to be accounted with a more complex approach (IFIAS, 1974; Nebel, Alcorn, & Wittstaock, 2009).

Although this literature review will look at both energy and CO_2 emissions during the operational phase of buildings, the assessment in this PhD research will be focused on operational energy consumption. Assuming that the building fabric mainly influences space conditioning energy consumption, the focus in this research will be on the influence that the thermal mass - inherent in structural systems using different structural materials – has on space conditioning energy and indoor environmental conditions, for both commercial buildings and educational buildings.

2.3 The focus on thermal mass

Thermal mass in buildings has been an increasing area of study due to its influence in reducing space conditioning energy of buildings, most dramatically in reducing energy consumption for cooling of buildings. This influence on cooling energy is gaining momentum due to, on the one hand the effects of climate change, which include warmer weather in which keeping cool will be important, and on the other hand, new buildings which must use less fossil fuel in a low or zero-carbon world (Roberts, 2008).

It is possible to say that homes, offices, schools and other buildings will need to maximise passive measures of more effective insulation, improved air-tightness and greater thermal mass (Roberts, 2008). Although the emphasis in this literature review is on the effect of thermal mass on space conditioning energy consumption and indoor environmental conditions of commercial and educational buildings, the next section introduces the topic of thermal mass in research into domestic buildings.

2.3.1 The effect of thermal mass on environmental impacts of domestic buildings

(Hacker, De Saulles, Minson, & Holmes, 2008) investigated the impact of a warming climate on operational energy and CO_2 emissions of light and heavy-weight houses in the UK. A 100 year life-cycle CO_2 emission analysis was reported for a two-bedroom, 65 m^2 floor area house in southeast England. The manner in which the balance between the embodied CO_2 (ECO_2) and operational CO_2 emissions of the building are affected by the inclusion of thermal mass and the impacts of climate change was quantified. The modelling of four different weights of thermal mass was considered for the single house, ranging from a timber framed with brick veneer house (light-weight), to a house built with-heavy weight block walls and hollow-core suspended floors.

Importantly, the house was modelled with continuous occupancy. The climate conditions used in the modelling were from a 100 year weather file constructed by sequentially adjusting a set of 20-year historic data sequences for climate change.

At the start of the life-cycle, the dwellings were passively cooled in summer, but air conditioning was installed when overheating reached a certain threshold. The inclusion of thermal mass delayed the year in the lifecycle when this occurred, due to the better passive control of summertime overheating. Operational heating and cooling energy needs were also found to decrease with increasing thermal mass due to the beneficial effects of fabric energy storage. The calculated initial ECO_2 was higher in the heavier weight houses, by up to 15% of the lightweight case value, but these differences were offset early in the lifecycle due to the savings in operational CO_2 emissions, with total savings of up to 17% in lifecycle CO_2 found for the heaviest weight case.

There are other LCA studies of houses available in this literature: (Mithraratne & Vale, 2004) is comparable to (Hacker, et al., 2008), carried out in New Zealand conditions. Based on the analysis of three house types (light, concrete, and super-insulated) under continuous operation (heating only), the research found that the reduction of life-cycle energy is not reliant on the use of thermal mass. However, if thermal mass is used in combination with passive solar design principles it could enhance performance. More than a low effect of thermal mass, it was found that it is difficult to activate thermal mass by applying passive solar design in small urban sites such as those commonly available in Auckland, New Zealand.

More significantly, by analysing total operating and embodied energy and CO_2 emissions of New Zealand houses, (Alcorn, 2010) found that, contrary to common perception, heating is not a major net emitter of CO_2 emissions for New Zealand houses as currently built. Indeed, it is the smallest emitter of all operating energy categories. Hot water is the largest CO_2 emitter. The next largest emitter is building materials - more than double the value for space heating.

Interestingly, (Hacker, et al., 2008) (Mithraratne & Vale, 2004) and (Alcorn, 2010) present a range of results from the importance of thermal mass in a warming environment in the UK, to the overview of the thermal mass influence into life-cycle energy and CO_2 emissions in New Zealand houses. The range of results in these three studies is an example of the influence of the context of the research into the outcome produced. In both of the studies in New Zealand (Mithraratne & Vale, 2004) and (Alcorn, 2010) space conditioning is limited to heating only, which together with an intermittent occupancy, made thermal mass not desirable. In (Alcorn, 2010) even space conditioning is downgraded as a secondary energy user. When modelling a warming climate - as a consequence of climate change – and using that “hypothetical” weather file for modelling, cooling is introduce as a means to keep comfort conditions at an acceptable level. Because of the inclusion of cooling, very heavy buildings tend to need cooling later on in time and subsequently use cooling for a shorter period of the life-cycle.

Differences between (Mithraratne & Vale, 2004) and (Alcorn, 2010) in New Zealand, and (Hacker, et al., 2008) is that the first two are mostly based on measured data and modelling of current buildings practices, while (Hacker, et al., 2008) is fully based on modelling of houses and to some extent an hypothetical climate. It seems that (Hacker, et al., 2008) put together all the conditions necessary to claim that heavy buildings with large amount of thermal mass, are in the long run the energy and CO_2 savers. It is still to seen if cooling will be ever introduced in New Zealand houses.

2.3.1.1 The influence of thermal mass on operational energy consumption of houses in New Zealand

Despite the importance of researches such as (Hacker, et al., 2008) and (Mithraratne & Vale, 2004), there are elements that have to be revisited to make them more meaningful to this current research. Basically, in both these earlier studies, the modelling of buildings was under conditions of continuous occupation. The manner in which the occupancy scheme (intermittent or continuous) affects the influence of thermal mass on heating energy consumption of heavy domestic buildings in New Zealand was studied in (Leslie, 1976). This work found that the effect of thermal mass is strongly coupled to the effect of the heating regime and the thermal insulation scheme. In the case of continuous heating, external insulation will reduce heating energy requirements, while in the case of intermittent heating, internal insulation will save energy. Since in New Zealand most homes are intermittently heated, the savings attributable to internal insulation as opposed to external insulation are worth having. In other words, in houses having intermittent occupancy, thermal mass can be neglected as a means of achieving energy savings

Regardless of its immediate location (rural or urban), and assuming that basic passive solar design principles can be applied to houses in New Zealand, the effect of thermal mass has been reported to achieve up to 20% saving in consumption of energy for heating (Leslie, 1976). It was found by (Bellamy & Mackenzie, 2003), that during one year of continuous occupancy, a heavy house (concrete or masonry) used 7% less heating energy than a light-weight timber house. It was also found that a heavy house does not overheat during the year and that on average these houses are approximately 1°C warmer than the light-weight timber houses during the night. In this study, day-time temperatures in a light-weight timber house reached a maximum of 30.9°C at a time when the ambient air temperature was 30.0°C; whereas the temperature in a concrete house peaked at 25.8°C in the same conditions. In a similar comparison (Leslie, 1976) found that the annual heating energy requirement in a heavy house are larger or smaller (depending on occupancy and insulation scheme) by up to 20% than for a light-weight house.

Based on studies by (Hacker, et al., 2008) (Mithraratne & Vale, 2004) and (Alcorn, 2010), it is possible to say that for houses with heating only, in the temperate climate of New Zealand, thermal mass is not necessarily a determining factor in life-cycle energy and CO_2 emissions. When cooling is included, and a warming climate (affected by climate change) is used for the modelling of the influence of thermal mass, this does became a determinant in the life-cycle environmental impact of a house. It is also significant that an intermittent or continuous occupancy scheme affects the performance of thermal mass when heating and/or cooling is applied.

2.4 The effect of thermal mass on the energy consumption of multi-storey commercial buildings

The present research is based on the analysis of multi-storey buildings with intermittent occupation e.g. educational or commercial buildings. In this research the differentiation between educational and commercial buildings will be confined to the inclusion of cooling in the HVAC system of the latter.

It is common knowledge amongst building designers that an increment of thermal mass, normally in the form of concrete, helps to mitigate extremes in indoor temperatures. There is substantial research which demonstrates that high mass buildings mitigate high interior air temperatures variations and sustain a steadier overall thermal environment (Balaras, 1996; Barnard, et al., 2001; Thompson, 2006). By increasing thermal mass it is also possible to gain advantages in the reduction of conditioning energy consumption while maintaining comfortable indoor environmental conditions (Yang & Li, 2008). These potential advantages of thermal mass on indoor environmental conditions and to space-conditioning energy performance are not a guaranteed outcome. For example, (Braham, et al., 2001a) pointed that the presence of thermal mass is not inevitably a good thing from an energy perspective because it may increase the daily warm-up period of buildings with subsequent energy penalty.

From (Bellamy & Mackenzie, 2001) and (Leslie, 1976) there can be extracted a list of the influential factors to increase the benefits of thermal mass in dwellings: climate severity, heating and cooling regimes, position of the thermal mass in relation to the wall insulation, and finally the R-value of the walls. While these were suggested for thermal mass in dwellings, they can also be taken as a point of reference for commercial buildings. The following section will analyse the influence of these factors on increasing the advantages of thermal mass for space-conditioning energy performance.

2.4.1 Influence of thermal mass on cooling energy consumption.

Although it is suggested that thermal mass has the potential to influence the performance of conditioning energy (Yang & Li, 2008), it has a more noticeable influence in reducing cooling energy consumption, predominantly in office buildings, particularly when it is integrated with night ventilation (Balaras, 1996; Barnard, et al., 2001; Thompson, 2006; Yang & Li, 2008). (Barnard, 1995) suggests that, as a cooling technology, “fabric energy storage systems” utilizing night cooling lie between natural ventilation and mechanical cooling in terms of performance and cost.

Effects of adding thermal mass in reducing cooling energy consumption of commercial buildings are reported to range from 18% in a commercial building in a hot and humid climate to 40% in a commercial buildings in a milder climate (Balaras, 1996). In (Yang & Li, 2008) it was demonstrated that thermal mass in a building, coupled with night-time ventilation, can reduce peak heating and cooling load by a factor that ranges from 18% to 50% for the warm climate of Hong Kong (with a peak temperature difference between day and night of 15°C). Since cooling equipment is sized to cope with peak loads, by reducing the peak load and subsequently operate with smaller cooling equipment, cooling energy consumption is reduced and capital cost of the plant is lower. (Balaras, 1996; Barnard, et al., 2001; and Yang & Li, 2008) have indicated that the effectiveness of thermal mass is enhanced in climates with marked diurnal variation of outdoor temperature. In those cases night-time ventilations can be utilized to remove the heat that has been stored by the thermal mass of the building during daily occupancy. These researchers also noted that intermittent occupancy improves the benefits of thermal mass because the stored heat is dissipated during any idle periods (when internal gains are minimized and there is no requirement for good comfort conditions).

In particular (Balaras, 1996), gives specific guidance on managing the factors that should govern night-time ventilation in heavy commercial buildings. He advises that the effectiveness of thermal mass is acceptable where the diurnal variation of ambient temperatures exceeds 10°C. Under such circumstances, with ample night-time ventilation and closing the building during the day, due to the thermal mass effect it is possible to achieve a temperature difference between the mean indoor and outdoor temperatures which is greater than 10°C in the negative direction, and an indoor temperature swing of 2.5°C. This is in some way re-emphasised by (Yang & Li, 2008) where it is noted that the daytime cooling load decreases as the outdoor temperature fluctuation between day and night increases. The amplitude of cooling load is proportional to the outdoor temperature swing; when the swing is larger the reduction of cooling load in buildings with thermal mass is larger than in buildings without thermal mass. (Yang & Li, 2008) specifically recommend a night ventilation rate of 90 $m^3/h*m^2$ of floor area. It is expected that a ventilation rate such as this will maximize the building thermal transmittance (heat flow into the material) during the night.

Minimizing transmittance during daytime is also recommended. Finally, (Balaras, 1996) suggests that when the climatic conditions do not permit the use of outdoor air, e.g. because of high humidity levels, it is still possible to pre-cool the building during off-peak hours, using an air-conditioning system. This, in fact, results in considerable savings to the user and to the electric utility[1].

2.4.2 Influence of thermal mass on heating energy consumption.

As was pointed earlier in this chapter, the presence of thermal mass is not inevitably a good thing from an energy perspective. Based in a modelling comparison between a light, medium, and heavy office building in the UK, (Barnard, et al., 2001) found that improvement of summer conditions with thermal mass is normally accompanied by an increase in heating demand. Thermal mass may act as a store for unwanted infiltration and conduction heat losses at night. Between a light-weight and a heavyweight version of the modelled case study building, there was an increase of 16% in the demand for delivered heat. Good insulation and air-tightness are important parameters for minimizing heating demand. This is similar to the findings of (Leslie, 1976) for heavy houses with intermittent heating in New Zealand, where internal insulation without thermal mass is the insulation option that saves most energy.

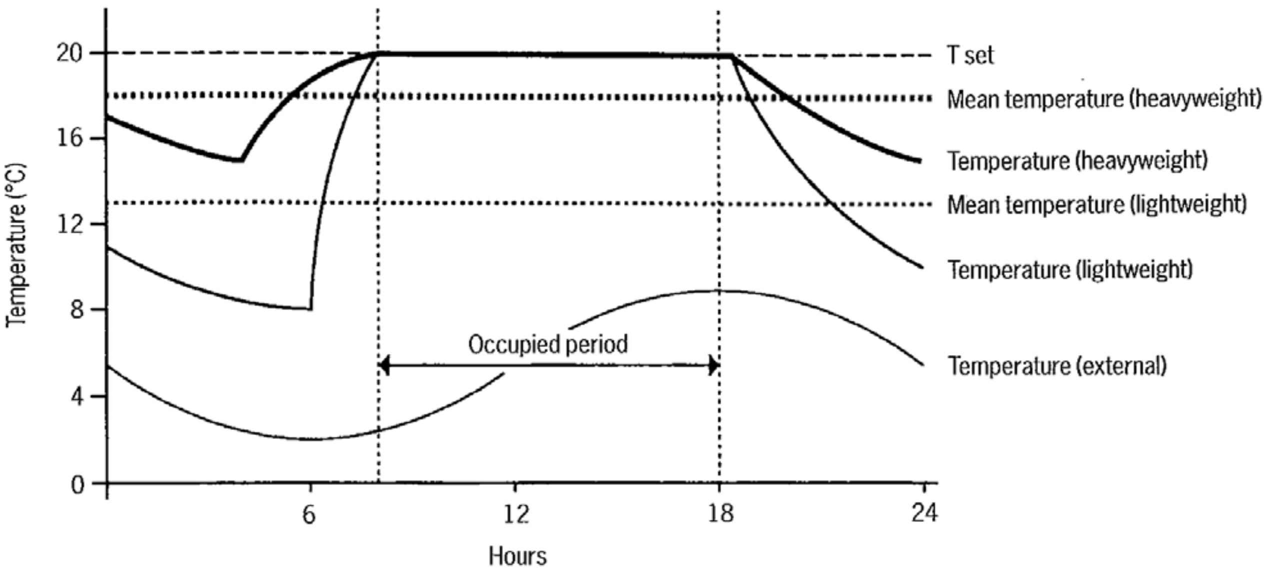

Figure 2-1: Heating curve for thermally lightweight and thermally heavyweight naturally ventilated buildings (from Barnard, et al., 2001).

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[1] Electric utilities usually charge much lower rates at night because demand drops considerably so such pricing inducement help flatten the utility's daily profile variation.

Figure 2-1 illustrates this effect of thermal mass on heating demand, by showing the heating curves for a thermally lightweight and a thermally heavyweight, naturally ventilated building heated for day-time occupancy (with the same level of insulation). It can be seen that because the 24-hour average temperature is higher for the heavier building, the area under the curve is greater, representing a greater required input from heating plant. However these penalties in heating demand only arise when intermittent heating is used. (Barnard, et al., 2001) have shown that for continuous 24 hours occupancy, a heavy-weight building shows less heating demand than a light-weight building. This is consistent with what was found in (Bellamy & Mackenzie, 2001) for heavy houses.

2.5 Thermal mass - parameters affecting the performance

The effectiveness of thermal mass depends on parameters such as the thermal properties of the mass material, its volume, location, and distribution.

2.5.1 Appropriate amount of thermal mass

The amount of thermal mass has also been discussed as an essential parameter in (Barnard, et al., 2001) where it is stated that the higher the available thermal mass of a building the more inherent cooling capacity it is able to store and the better it is able to keep temperatures down. The choice of the appropriate available thermal mass is a complex issue which is susceptible to occupancy. (Yang & Li, 2008) indicates that to achieve an appropriate amount of thermal mass, both thermal properties and convective heat transfer must be looked after carefully.

Increasing the amount of thermal mass available beyond 100 mm depth on a specific surface offers little benefit for diurnal operations (Braham, et al., 2001a). (Bellamy & Mackenzie, 2007) found that the energy performance of a solid wood wall greater than 40 mm thick outperforms that of a timber frame and plasterboard wall. Compared with light-weight timber frame construction, the heating and cooling energy savings due to solid wood's thermal mass ranged from 4% to 24%. (Balaras, 1996) indicates that beyond a certain material thickness, the heat flow into the indoor air does not take place during the night hours, but it is delayed till the following daytime hours. (Barnard, 1995) agrees in that increases of thickness of a concrete slab, above 100mm will offer little benefit in performance. The thicker a concrete slab (up to 100 mm thick), the smaller will be its diurnal temperature variation. This improves performance by maximising the temperature difference between the slab and the air. On the other hand a large temperature fluctuation in sympathy with the air significantly reduces the temperature differential between the slab and the air, that differential driving the heat transfer.

(Balaras, 1996) provides the only benchmark available in the literature, as far as the author is aware, suggesting (with diurnal temperature variation above 10°C), an increase of thermal mass from 21 to 201 kg/m^2 of floor area, in closed and in ventilated buildings, can reduce the peak indoor temperature by approximately 1°C and 2°C, respectively.

2.5.1.1 Increase of thermal linkage

It is suggested in (Barnard, et al., 2001) that because of the ineffectiveness of a high thickness of thermal mass, achieving an appropriate amount of effective thermal mass was more an issue of having an increased surface of thermal mass exposed to indoor spaces. This was well explained earlier by the same author in (Barnard, 1995) where it was indicated that one of the prime factors influencing the performance of thermal mass is the magnitude of the 'Thermal Linking' which is determined by the values of the surface heat transfer coefficients and the area of contact between the fabric and the air. This same author stated that it is desirable to increase the surface area available for convective heat transfer e.g. by utilizing concrete floor systems with ribs, or any shape that increases the surface of the exposed thermal mass.

Heat exchange between the air and exposed concrete can be thought of as a flow through two resistances in series which limit the heat exchange. Because of the relatively large thermal conductivity of dense concrete, the resistance of the concrete itself normally is small when compared with the surface resistance. It is therefore the surface resistance which governs the rate of heat flow. The surface resistance is primarily determined by the values of the radiative and convective heat transfer coefficients. Since the scope for improving radiative heat transfer is extremely limited, convective heating must therefore be enhanced to provide a significant reduction in surface resistance (Barnard, 1995). One method of achieving this is by using systems such as a false floor void (underfloor air distribution systems), and convective heat transfer with the thermal mass is increased by introducing turbulence into the air flow within the false floor.

2.5.2 Thermal mass materials

For a material to effectively store heat, it must exhibit a proper density, high thermal capacity, and a high thermal conductivity value (Balaras, 1996).

Figure 2-2 illustrates the relationship between the relative storage ability of concrete, aerated concrete and wood over a range of thicknesses, assuming a 5W/m^{2}K heat transfer coefficient. Based on a 24 hour period it shows that temperature variations penetrate up to about 100 mm into wall material, depending on the material type and the rate of heat transfer.

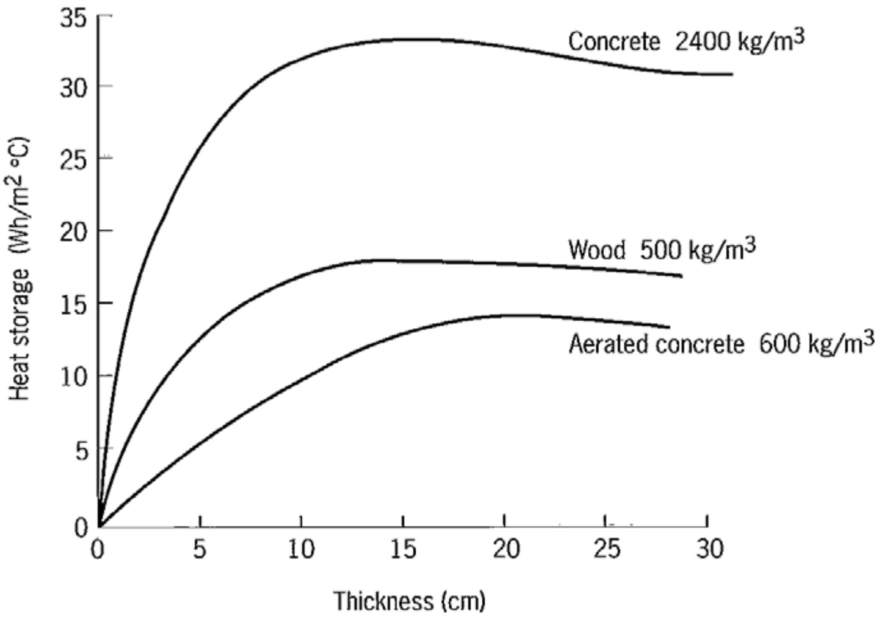

Figure 2-2: Relative thermal storage capacities (from Braham, et al., 2001a)

2.5.3 Thermal mass location and distribution

Location and distribution of thermal mass is an important parameter affecting its performance. In houses for example, (Leslie, 1976) estimates that the effect of thermal mass in a slab-on-ground floor is much greater than that of the walls and roof. In multi-storey buildings, location and distribution of thermal mass is a more complex issue. (Balaras, 1996) suggests that it is possible to distinguish between two types of thermal mass regarding its location, based on whether the heat storage material receives energy by solar radiation (direct) or by irradiation and room air convection (indirect). Direct heat gains are experienced by the interior surfaces which may absorb solar radiation as it enters through the building’s openings. Indirect heat gains are experienced by opaque elements inside the building from the energy which is transferred indoors from direct gain surfaces. Direct locations are much more effective for placing heat storage mass than indirect locations.

The interior finishing of a building may insulate thermal mass; for example (Barnard, et al., 2001) note that the use of a solid false ceiling limits heat transfer by effectively insulating the thermal mass available in the soffit of a suspended concrete slab from the space below. They suggest that opening areas within the ceilings (as low as 15% of the ceiling) can be sufficient to allow significant air circulation and subsequent heat transfer. However it is estimated that significant heat transfer can still be achieved if the ceiling material is made of a conductive material rather than an insulative material. Further in this area (Braham, et al., 2001a) indicates that the type of structural frame (e.g. steel or concrete) has little effect on the performance of thermal mass since the mass of the frame is relatively small compared to that of structural floor slabs – although the structural frame can affect the performance of thermal mass if an in-situ floor is an integrated frame component.

2.6 Summary of thermal mass

As was explained in the first part of this literature review, from Sections 2.1 to 2.3, most of the energy consumption of building's life-cycle happens during the operational phase. In this literature review, operational energy consumption ranges from 75% to 90% of the life-cycle energy consumption of buildings; this percentage variation depends mostly on the life-span of the building, the type of building and the climate conditions in its location (Cole & Kernan, 1996; John, et al., 2008; Perez, 2008).

When looking at building construction materials and their respective structural systems (the focus in this research is on concrete, steel and timber structural systems) and their influences on life-cycle energy consumption of buildings, two approaches taken by industry to enhance the attributes of each material to reduce life-cycle energy consumption can be recognized. One is related to the initial embodied energy of the materials and the other with alternative end-of-life scenarios.

During the second part of this literature review (more specifically in Sections 2.3 and 2.4) a series of examples was given of the effects of thermal mass on space conditioning energy consumption in dwellings, and in multi-storey buildings. Particularly in multi-storey buildings, the benefits of thermal mass were identified in the reduction of cooling energy consumption and also in the improvement of indoor comfort conditions, provided that thermal mass is accessible and occupancy conditions are controlled to enhance the performance of the thermal mass e.g. (Balaras, 1996; Barnard, et al., 2001; Bellamy & Mackenzie, 2003; Hacker, et al., 2008; and Yang & Li, 2008).

Finally, in Section 2.5, the most significant parameters affecting the performance of thermal mass were described, including thermal properties, location and distribution in buildings, thickness of thermal mass available, and maximisation of the thermal linkage between indoor air and thermal mass. Increasing the surface area of exposed thermal mass is desirable and, to achieve this, concrete floor systems with ribs or any other shapes that increase the surface area are recommended (Balaras, 1996; Barnard, 1995; Barnard, et al., 2001; Braham, Barnard, & Jaunzens, 2001b; and Yang & Li, 2008).

Although there is sufficient previous research about the performance of buildings with thermal mass which meet the specific conditions for the enhanced performance of thermal mass, it is still difficult to identify the type of building and its structural system and layout that can meet those criteria. For example, one big unanswered question is "Will any structural system with concrete suspended floors have enough exposed thermal mass to influence space conditioning energy performance and indoor comfort conditions?" Research is necessary to provide a benchmark which identifies if conventional structural systems used in conventional multi-storey buildings will, in themselves, meet the criteria necessary for their thermal mass to influence indoor thermal conditions and subsequently have an impact on space-conditioning energy consumption.

Since it has been demonstrated that timber material can be used as thermal mass in buildings, and that there are structural systems made of timber that can be used in the construction of multi-storey long-span commercial buildings, a comparative analysis is necessary to assess the impact of thermal mass available in concrete and timber structural systems (and in the subsequent buildings constructed using those systems) on indoor environmental performance and space energy consumption.

2.6.1 Conclusions from the literature review – What is the gap in existing literature that this research is going to fill?

A body of research literature has been described, looking at the influence of thermal mass on life-cycle energy consumption of houses, with emphasis on reducing space conditioning energy. There are two authors whose research is based on the comparison of energy consumption of houses with different levels of available thermal mass (Hacker, et al., 2008; Mithraratne & Vale, 2004) and one author looking at the influence of insulation placement and schedules of occupancy on the energy performance of heavy houses (Leslie, 1976).

In multi-storey buildings most of the research into the influence of thermal mass on life-cycle energy consumption is on the specification of the aspects that enhance the influence of concrete as thermal mass in a building's fabric, e.g. placement, influence of finishing, occupancy scheduling, etc. There is almost no mention of multi-storey buildings having different types of materials or different amounts of materials as exposed thermal mass. It is said for example that the type of structural frame (e.g. steel or concrete) has little effect on the performance of thermal mass because most of the thermal mass is made available in structural concrete floor slabs (Braham, et al., 2001a). It is also noted that beyond 100 mm depth, the concrete in a floor slab offers little benefit for diurnal operations (Braham, et al., 2001a).

Since most of the structural systems for multi-storey buildings - regardless of the structural material of the frame - use concrete floor slabs, it can be argued that available thermal mass will be by default very similar, and if the buildings are designed with a similar thermal envelope, they will have a similar space conditioning energy consumption and indoor environmental conditions.

However, there is no literature looking at the influence of thermal mass of timber on operational energy consumption of multi-storey buildings.

Because the primary interest of this research was founded on the development of a new post-tensioned structural timber system designed to be used in the construction of mid-level high-rise, long-span buildings (such as commercial and educational buildings), this research will compare the influence of thermal mass of timber, steel and concrete structural components on the operational energy consumption of multi-storey buildings built using the different structural materials.

2.6.1.1 Additional literature

Additional literature will be described in Chapter 3 where specific literature on the characteristics of the tool for energy modelling used in this thesis, and on the calibration of energy models is given.

3 Methodology: Overview and Justification

This chapter displays the background research that justifies the modelling exercise undertaken in Chapter 4, which describes the bulk of the methodology used for the building energy and environmental modelling (BEEM). In order to test the BEEM software capabilities and to justify the methodology used in Chapter 4 this chapter considers that methodology but applied to a simplified case study named “Test building”. The selection of the simplified Test building is described, which is then modelled to assess the effectiveness of changes in the geometry and surface properties of concrete when used for thermal mass, with regard to energy use and building comfort. In addition to describing the general building geometry and construction used for modelling of the Test building an overview of the modelling of the various building components is given. This chapter also includes the reasons for setting up metering of real buildings, a description of the chosen weather files, and the relevant characteristics of the software chosen for the modelling.

3.1 Introduction

This research was intended to be grounded in the reality of actual building construction, rather than being a pure modelling exercise. Because the primary interest was founded on the evolving timber-structured, medium-size multi-storey buildings, such a building type needed to be the focus of this study.

Currently, examples of such buildings are extremely limited, so the then-proposed Arts and Media complex at Nelson Marlborough Institute of Technology in Nelson, New Zealand (NMIT) represented a unique opportunity as a case study. The Arts building (described in more detail in Section 4.1.2) is a three-storey 1980 m^2 gross floor area educational building, built to provide facilities for the School of Arts and Media at NMIT.

The use of this building represents the opportunity to:

1. Have detailed information on all aspects of its design and construction to incorporate into a simulation model.
2. Install an appropriate set of measurement equipment to monitor its actual performance.
3. Compare monitored and modelled data to provide confidence that the model captured realistically the essential thermal and energy characteristics of the actual building.

With the behaviour and characteristics of this timber-structured building model thus established, variations on this original model could then be developed:

1. Alternative structures, namely concrete or steel.

2. Superior insulative performance (beyond the as-constructed, code-compliant) version of each structural type.
3. Operational change from an educational usage to more general commercial usage (for which a more complex summer-cooling HVAC system would be necessary).

These modelling variations on one “base case” building, and comparisons between them from both energy and thermal comfort perspectives, would thus have the potential to allow wider conclusions to be drawn. Because the Arts building did not exist – and indeed, its design was not complete at the commencement of this study – an adjacent new NMIT building (the T-Block, with similar orientation, footprint, and floor area) provided an ideal initial opportunity to establish a reliable approach to building modelling because it, too, was able to have monitoring equipment installed.

3.2 Methodology outline:

This methodology section is a representation of the rationale of the research.

Table 3-1: Visual picture of the modelling parts of the thesis.

Aspects			Section (s) in the thesis in which this aspect will be covered
1	Operational energy emphasis		Chapter 2 - Section 2.2
2	Merits of Modelling Vs Real buildings		Chapter 3 - Section 3.2
3	Extension of the Arts building model to other hypothetical buildings		Chapter 3 - Section 3.5
4	Choice of Case study buildings:	1.Arts Building	Chapter 4 - Section 4.1
		1.T-Block	Chapter 5 - Section 5.1
5	Variation to models of Arts building:	1. Material 2. Insulation 3. HVAC	Chapter 4 - Sections 4.2 to 4.4
6	Software requirements	1. Choice of Software	Chapter 4 - Section 4.5.1
7	Addition of cooling capability to commercial buildings		Chapter 4 - Section 4.6
8	Validation of Models	1. T-Block	Chapter 5
		1.Arts Building	Chapter 6
9	Accuracy of model Vs actual comparison	1. T-Block	Chapter 5
		1.Arts Building	Chapter 6
10	Interpreting data comparison between buildings variants		Chapters 7,8 and 9
11	Drawing of conclusions - Extend this to other buildings		Chapter 10

Table 3-1 is a summarising outline of the modelling parts of the thesis, showing the main aspects, and identifying the corresponding chapters/sections within the thesis.

3.3 Merits of modelling vs real buildings

It is difficult to argue against the validity of energy-related data obtained from the monitoring of real buildings (provided that monitored data has been obtained from reliable instruments that have been properly installed, calibrated and maintained). However, any building energy investigation that is based exclusively on such an approach is necessarily limited in the number and variety of building types that can be studied. Furthermore, meaningful comparisons between the results obtained from the different buildings are constrained by the fact that there may be significant differences between the manner in which the buildings are managed and operated (either by their control systems or by the occupants). Finally there is the obvious limitation that only existing buildings can be investigated in this way, precluding the possibility of exploring the energy and thermal comfort consequences of making changes to the design and operation of the buildings.

These limitations of real building comparisons make the outwardly simpler alternative of confining a comparative study to an exclusively modelling approach appear to be attractive. Certainly such an approach levels the playing field to the extent of ensuring that the building variants are subjected to exactly the same external drivers (primarily climatic), internal gains, and operational regimes. However, any quantitative conclusions that are drawn from such modelling comparisons can only be extended reliably into the "real world" if there is confidence that the modelled buildings are reliable representations of their equivalent real buildings.

Such confidence often is misplaced because differences between modelled and measured energy consumption can be very large, causing uncertainty in the validity of the modelled results. That difference can range from being 22% lower to 48% higher (Egan, 2009). There is, however, a mixed approach which has the potential to restore reasonable confidence to an investigation which is primarily modelling. Some authors suggest that by having real measured data on a building which has also been modelled, models can be calibrated, reducing differences between modelled and measured energy consumption down to less than 1% (Pan, Huang, & Wu, 2007; Pedrini, Westphal, & Lamberts, 2002; Srinivasan, Lakshmanan, & Srivastav, 2011).

The results in this research are produced over a set of case studies which are variations of a single case study building. Those variations were modelled. The modelling methodology used on those case studies was to be calibrated initially in the model of a real building similar to the base case study building. This real building was to be instrumented to a sufficient extent to allow comparison with the predictions from its equivalent model.

3.4 Choice of case study buildings

There are two case-study buildings that are used in this research: the Arts and Media building (known as the Arts building), and the T-Block building (known as T-Block).

Although most of the modelling and analysis in this research is based on the Arts building, because of the time of construction the validation of the modelling methodology used in this research was carried out in the T-Block. The T-Block was built three years earlier than the Arts building and was already occupied when this present research started in August 2008. The Arts building, on the other hand, was under construction at that time and only opened in February 2011.

Both buildings are located at the Nelson campus of the Nelson Marlborough Institute of Technology. Both buildings share many similarities such as similar size, placement, orientation, and usage. Because the T-Block was occupied at the beginning of this research, it provided an opportunity to establish the most appropriated modelling method, and because of the availability of energy metering equipment installed in that building, to calibrate that methodology before the modelling exercises began in the Arts building.

The Arts building is a three-storey 1980 m^2 gross floor area building, which has been built using a post-tensioned timber structure, with timber concrete composite floors and – mostly – a light weight insulated envelope. Since the focus of this research was on post-tensioned timber structured buildings and the Arts building was the first, and at that time, only building being built using the post-tensioned timber structural system, it was selected to be used as the case study. The earlier T-Block is a three storey reinforced concrete building of about 2,070 m^2 gross floor area, which was built using precast concrete columns and beams structural system, concrete precast floor system and – mostly – a light weight insulated thermal envelope. The detailed description of the Arts building is given in Section 4.1.1 and of the T-Block in Section 5.2.

3.5 Variation to the models

To achieve the specific objectives of this research established in Section 1.3, the buildings modelled and analysed in this research are three replicas of the actual Arts building, each designed using structural systems made of timber, concrete or steel. Thus the labels:

- The Arts Timber building
- The Arts Concrete building
- The Arts Steel building

Although the actual Arts building has been built using a timber structure, it has attached to the ground floor level (Level 1) a large workshop building and a performance space. Because multi-storey buildings were the focus of this research, when modelling the Arts Timber building – and the concrete and steel versions of it - the workshop and the performance spaces were not included. The exclusion of these spaces was taken into account in determining appropriate locations for the installation of energy monitoring devices in the real building.

Each of the three buildings mentioned above was modelled using two different thermal envelopes (including walls, floor slab, roof and glazing). The first was a code-compliant thermal envelope, used initially in the actual Arts building and sufficient to comply with the New Zealand building code. In the second thermal envelope, the R-values of walls, floors and roof, and U-Value of windows were upgraded to “best practice” levels. The aim of this highly insulated thermal envelope was to produce simulations in which the influence of heat losses is minimized so the influence of the indoor fabric’s thermal mass would become clearer. The list of replicas of the Arts building and its variation of thermal envelope can be seen as follow:

- The Arts Timber building with a code-compliant thermal envelope
- The Arts Concrete building with a code-compliant thermal envelope
- The Arts Steel building with a code-compliant thermal envelope
- The Arts Timber building with a highly insulated thermal envelope
- The Arts Concrete building with a highly insulated thermal envelope
- The Arts Steel building with a highly insulated thermal envelope

There are two HVAC systems that were used for modelling the Arts building and its replicas (each with two thermal envelopes). One is the actual HVAC system used in the Arts building (excluding the part of the HVAC serving the workshop and the performance space), which is more representative of the HVAC system in an educational building because of the absence of cooling. The second HVAC system is a variation of the actual HVAC system but with cooling included to some areas. The inclusion of cooling improves environmental conditions throughout summer and makes this system more representative of a commercial building’s HVAC system.

- Actual HVAC (representative of HVAC used in educational buildings)
- Actual HVAC with cooling (representative of HVAC used in commercial buildings)

Section 3.5.1 will expand on the difference between these two HVAC systems; subsequently in Section 4.6 these HVAC systems and the way they were modelled will be described in detail.

Only the building with the upgraded highly insulated thermal envelope will be modelled using both the actual HVAC, and the actual HVAC with cooling. The buildings with the actual thermal envelope will be modelled only with the actual HVAC system. Putting together the variations outlined above, the full list of models used as cases-studies in this research is:

- The Arts Timber building with code-compliant thermal envelope and actual HVAC system.
- The Arts Concrete building with code-compliant thermal envelope and actual HVAC system.
- The Arts Steel building with code-compliant thermal envelope and actual HVAC system.
- The Arts Timber building with highly insulated thermal envelope and actual HVAC system.
- The Arts Concrete building with highly insulated thermal envelope and actual HVAC system.
- The Arts Steel building with highly insulated thermal envelope and actual HVAC system.
- The Arts Timber building with highly insulated thermal envelope and actual HVAC system with cooling added.
- The Arts Concrete building with highly insulated thermal envelope and actual HVAC system with cooling added.
- The Arts Steel building with highly insulated thermal envelope and actual HVAC system with cooling added.

3.5.1 Addition of cooling capability to extend to commercial applications

As just explained, two different HVAC systems were used to run simulations on the Arts timber building, Arts steel building and Arts concrete building using the actual and the highly insulated thermal envelope. These two HVAC systems were defined earlier as the actual HVAC system (representative of an HVAC system in an educational building) and the Actual HVAC system with cooling (representative of an HVAC system in a commercial building).

The actual HVAC system was designed initially for the Arts building by Aurecon, a service engineering company (Aurecon New Zealand Ltd, 2009). That HVAC system includes mechanical ventilation provided by a centralized air handling unit (AHU) combining supply and return of air. There is a heating coil to warm incoming outdoor air, if necessary, and a heat exchanger recovering heat from the return air. Local heating is provided mostly by a heated slab on Level 1 and radiators on Levels 2 and 3. There are single fan coil unit providing heating and cooling to the computer room in Level 1. The air from the AHU is supplied to rooms on the south side of the building and migrates by pressure difference to the atrium on the north side of the building. The mechanical air return is centralized in a single duct taking air from the top of the atrium on the north side of the building.

Being an educational building, no mechanical cooling was included in the original HVAC system design other than in the computer room. This is a common practice in New Zealand and is due to the very low building occupancy expected during summer months. Regardless of the expected low occupancy of the actual Arts building during summer, for the modelling exercises in this research the case-studies are simulated with a year-round occupancy. This approach helps to identify whether the inclusion of natural ventilation during summer is sufficient to maintain comfortable environmental conditions, and if the building's available thermal mass is enough to produce a difference in each of the case-study buildings modelled.

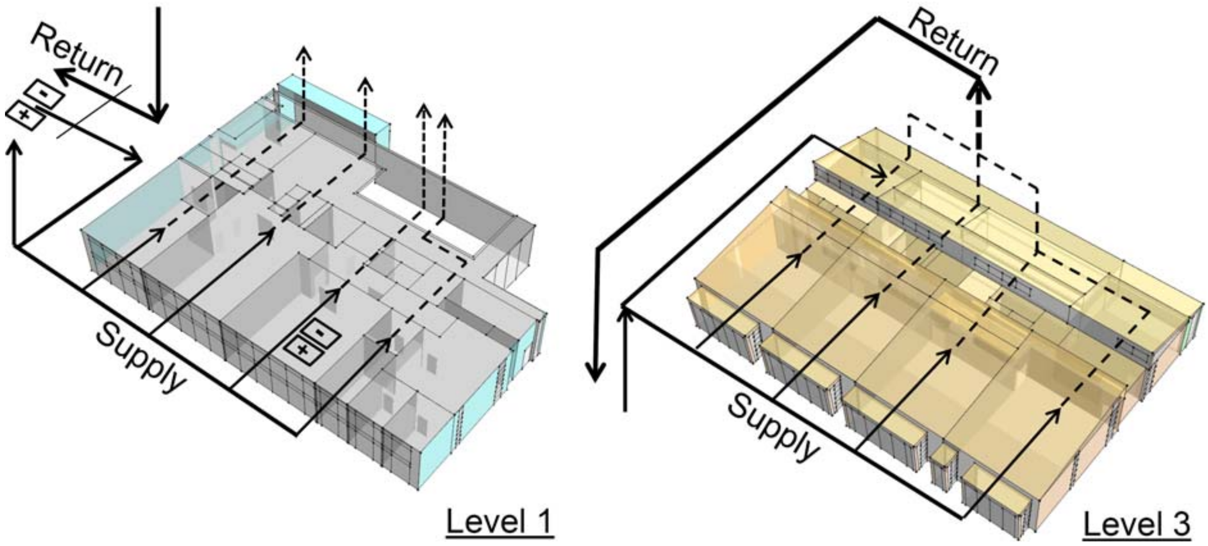

Figure 3-1: Schematic of the actual HVAC system in the Arts building.

Figure 3-1 shows a schematic of the flow of air which is mechanically supplied and extracted in the Arts building. It illustrates how the mechanically supplied air from the AHU is ducted (continuous line) to rooms in the south side of the building and then migrates via open grilles from the north to the south part of the building (segmented line). The return air return is ducted from the top of the atrium space.

For the design and subsequent modelling of the HVAC system with added cooling capability, design meetings were carried out between the author of this research and the designers of the actual HVAC system in the Arts building (Aurecon). It was decided that the best approach was to adapt the actual HVAC system to include cooling in some areas rather than re-designing it. The suggestion from Aurecon was to introduce induced air systems (with both cooling and heating coils) locally to rooms where mechanically air is first supplied (mostly in the south part of the building). That way, the now-cooled air will follow the same path as in the actual HVAC system illustrated in Figure 3-1. This means that no cooling is directly supplied to most of the rooms and spaces in the north part of the building, and that cool air in that area is only made available when derived from rooms in the south part of the building.

The introduced - passively induced air - cooling and heating system is by a commercially available standardized module called Parasol Comfort Modules ® (Parasol units). The Parasol units are used as the cooling and heating system of choice for all the offices located in the workshop area on Level 1 of the actual Arts building (not in the model of the Arts building). Since these induced air systems recirculate the rate of supplied air from the AHU, no additional fans or fan power was necessary in the models. Because Parasol units include a heating coil, all the radiant heating (heated slab and radiators) was replaced in the rooms where these modules were placed.

The sizing of the heating and cooling capacity installed in each room was determined by the default heating and cooling capacity of each of these standardized Parasol units (see Section 4.6.1.2 for details). The rationale used was to determine the number of units necessary to meet the heating capacity of each room (by the Aurecon design), thus automatically fixing the available cooling capability which is an inherent capacity built into the chosen Parasol unit. The approach is based on the premise that rooms must be comfortable in winter during all occupied hours while, during summer, rooms will be comfortable most of the time but not for all the occupied hours due to the fact that no specific cooling load is given to each room.

In a smaller room, such as most of the offices in the south part of the building, one Parasol module was usually enough to overcome the heating and the cooling load of such a space during an entire year. In bigger rooms such as the Studio on Level 2, four Parasol units were necessary to meet the heating load for that room.

3.6 Extension of the Arts building model to other hypothetical buildings

There are limiting factors of the case study buildings in this research that determine how far the results may be extended to other buildings. The limiting factors – which are cumulative in their consequences, and expanded on in more detail below - are:

- Lightness of all structural systems used
- The size of the buildings - multi-storey medium-size buildings.
- The location of buildings - extendable to other buildings in a temperate climate.
- The usage of buildings determined by the HVAC system in place - extendable to other educational and commercial buildings.

The Arts building and its replicas modelled with variations in thermal envelope and in HVAC systems are representative of a range of buildings in New Zealand conditions. In Section 4.4 of this document, a detailed description of the structural systems used in the replica buildings is given. In the design of the replicas of the Arts building, the same architectural and structural design team as in the actual Arts building was involved. The design criteria for the replica building was the same as for the actual Arts building; in that way the choice of structural components, regardless of their material, was driven to meet a pre-defined criterion used in the specific building design of the Arts building. Since in the actual Arts building, because of being built using a timber structure and a timber concrete composite floor, structural lightness was determinant in the design of the structural system of the alternative buildings. The fact that the structural system in the actual building was prefabricated also determines the choice of structural elements and subsequently the structural system used in the replica buildings. All of the above means that none of the case study buildings was exceptionally heavy - not even the concrete building - making the detailed results in this research extendable to medium weight prefabricated buildings, but not to truly “heavy” buildings.

The size of the building also determines the representativeness of the results in this thesis. The actual Arts building is a three storey high building. Higher buildings will have bigger structural elements with subsequent influence of mass into indoor environments. The height of the building will also influence aspects such as air circulation and systems such as HVAC.

The location of buildings - more specifically the weather conditions used for the modelling of case study in this research - is also a determinant in the extendability of the results produced. The Arts building, and subsequently all modelled case study buildings, are located in Nelson, New Zealand (latitude 41°18'S, longitude 173°16'E). The description of Nelson weather conditions, and how this compares with weather conditions in other New Zealand locations, can be seen in Section 5.4 Although New Zealand is subdivided into three climatic zones (NZS, 2007), it is - in a macro-climatic classification - a temperate climate.

Finally there is the factor of building usage. The buildings analysed in this research have an intermittent occupancy which starts at 8am and finishes at 6pm from Monday to Saturday. All models were simulated using a year round occupancy, regardless of the inclusion of cooling for the improvement of environmental conditions during summer.

For all the reasons listed above, it can be said that the results produced in this research can be extended to multi-storey, medium size, medium-weight, prefabricated commercial and educational buildings in a temperate climate.

3.7 Operational energy emphasis

In Section 2.2.1 the ratio between embodied and operational energy in life-cycle energy consumption of multi-storey medium sized commercial buildings, was given. The responsiveness of this ratio to changes in the climate conditions in which buildings are located, and to the building’s life span, was also mentioned. From Section 2.2.1 it can be said:

- Operational energy consumption is more than 75% of the total life-cycle energy use of buildings with intermittent operation, with a life span of 60 years, and the building is located in a temperate climate. This is equivalent to about 85% of total life-cycle CO_2 emissions.
- If operation is continuous throughout 24 hours a day, the relevance of operational energy consumption, into life-cycle energy consumption will increase even further.
- If the building is located in an area with more severe climate conditions, the relevance of operational energy consumption into life-cycle energy consumption increases (can be up to 90%).
- If life-span of buildings increases, the relevance of operational energy consumption into the life-cycle energy consumption also increases.

Due to the relevance of environmental impacts during the operational phase of multi-storey medium size commercial buildings, a low embodied energy will have a relatively low impact on the building's life-cycle environmental impacts. This is particularly significant in timber buildings, because, as stated on Section 2.2, timber buildings may have low embodied energy (and CO_2 emissions) but they still have high operational energy consumption mainly because of a relatively high space conditioning energy consumption.

Particularly in the assessment of environmental impacts of buildings during the operational phase, energy has long been an appropriate indicator and the measurement of choice for overall environmental impact (See Section 2.2.2.1). In contrast to looking at environmental impacts embodied in building's materials and construction processes, when assessing environmental impacts produced during operations of building, these are mostly materialized in the form of energy consumption (thermal and electric). From these data it is feasible and relatively easy to calculate carbon dioxide emissions with the use of specific coefficients for conversion. This differs from calculations of embodied energy consumption and embodied CO_2 emissions where, due to carbon sequestration or recyclability of materials, the balance between energy and CO_2 is affected.

Based on the arguments above, it can be concluded that to improve the environmental performance of timber buildings, primary attention must be given to reducing space conditioning energy consumption.

3.8 Validation of models

Because the usage of the then-new T-Block coincided with the start of this research at a time when the Arts building was still in its early design phase, modelling and measurement of energy consumption took place initially in the T-Block building. This building presented an opportunity to learn how to use the modelling software of choice, and at the same time calibrate those models against measured data.

A detailed geometry comparison between the T-Block and the Arts building can be seen in Section 5.2. This is to justify the use of the T-Block for the validation of the method used for the modelling of the T-Block and subsequently the Arts building that is used in this thesis. The calibration of the modelling of the T-Block is presented in Chapter 5 while the validation of the modelling results of the Arts building is presented in Chapter 6.

As a prelude to those later details, this section will elaborate on two important underlying and essential preliminary aspects of the validation process:

- The metering requirements in the T-Block and the Arts building
- The creation of a weather file with real meteorological data

3.8.1 Metering requirements

Metering equipment was installed first in the T-Block and secondly on the Arts building. The aim of using metering equipment was to calibrate the energy models of the T-block, and subsequently to validate the modelling methodology that would later be used on the Arts building. The aim of the metering on the Arts building was to validate results from modelling.

In May 2009 energy monitoring equipment was adapted to the existing electrical services design of the T-Block. The installed Building Management System (BMS) had temperature sensors in 6 rooms in that building; data from those was included for calibration of models. The monitoring of the T-Block is explained in detailed in Section 5.5, and the metering equipment installed in the T-Block is listed below:

- Total electricity
- Kitchen electricity
- Hot water cylinder electricity
- Total heating energy (thermal energy)
- Indoor temperatures in 6 rooms (2 in each level, one south facing, another north facing).

T-Block was designed to provide facilities for teaching the careers of catering and well-being at NMIT. Because of that it has some unusual energy end-uses such as a very large kitchen as a teaching facility, and very large domestic hot water (DHW) calorifier to meet demands in the kitchen and other teaching facilities. The electricity consumption of the kitchen and the DHW system was isolated with meters (75% of the main board installed capacity) and the remaining consumption was assumed to correspond to all other end uses such as lighting and equipment combined. Thermal energy was also isolated (used on heating only). Calibration was undertaken by comparing total measured electricity and heating energy consumption against modelled data. The temperature from six rooms was also used for comparison.

Metering equipment was also installed in the Arts building (see detailed explanation of the system on Section 6.2). The Arts building is part of a group of three buildings at NMIT, called the Arts and Media complex configured by:

- The Arts building (three storey main building)
- Performance space
- Workshop

Thermal and electric energy are supplied to the Arts and Media complex as a whole. To extract meaningful data for the three storey Arts building alone, this had to be isolated from main electric energy consumption (total Arts and Media complex); the metering equipment was designed to achieve that goal. The same approach had to be taken to individualize the thermal energy consumption in the Arts building. As for the T-Block, temperature monitoring equipment had been installed previously to feed into the BMS. The metering equipment installed in the Arts and Media complex to allow separation of the data of the Arts building alone consisted of:

- Main heat energy (thermal energy)
- Workshop heat energy (thermal energy)
- Performance space heat energy (thermal energy)
- Main electricity
- Workshop electricity
- Performance space electricity

Sensors of indoor temperatures where located in 11 rooms (5 rooms in Level 1, 2 in Level 2, and 4 in Level 3). For this research, thermal energy from the campus heating system was the most significant energy being monitored because it represents virtually all of the heating energy input[2].

3.8.2 Climatic data – Actual vs TMY

To properly compare and subsequently calibrate the models of the T-Block and the Arts building, the modelled energy consumption and indoor temperature needed to be compared against the

[2] As will be explained later, there were problems in the monitoring of the hot water energy and the commissioning of that system is still on-going.

measured energy consumption and indoor air temperature in both the T-Block and the Arts building. To do this, a real time weather file would be required for running the simulation with the same climatic conditions as when the real data was recorded.

Normally when performing energy modelling alone, the input of weather data is in the form of a weather file with weather data from a ***typical meteorological year*** (TMY). Because the validation approach required that the modelled buildings be subjected to the same climatic conditions as those experienced by the real buildings, a TMY file would be inappropriate unless it corresponded closely to the actual climatic data file. Even close correspondence on a macro time scale between a TMY file and an actual climatic data file (e.g. for average weekly or monthly temperatures and solar radiation) would not ensure similar correspondence if there was an interest in a model's representation of a building's dynamic response to hour-by-hour climatic changes. Hence a weather file using real weather data was created by taking Nelson's 2010 specific meteorological data and converting this into an input file for simulations. The source of the 2010 real meteorological data was NIWA's CliFlo database (NIWA National Institute of Water & Atmospheric Research, 2011). Details of the tool used for converting the raw climatic data into a weather file are explained in Section 5.4.

Also in Section 5.4 a whole year comparison between both, the weekly average dry-bulb temperature and global radiation in the TMY and in the custom 2010 weather files is provided. Basically that comparison shows that the custom 2010 weather file is not unusual, with temperature and global radiation not differing significantly in the TMY when compared with conditions in 2010.

3.9 Accuracy of model vs actual comparison, and implications this will have on the validity of results

"Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful." (Box & Draper, 1987).

Results from energy simulations are normally different than results from the measured energy consumption of real buildings. As an illustration of this difference, (Egan, 2009) presents a comparison of modelled energy performance (using only the information available at the design stage), and measured energy consumption of three commercial buildings located in Canberra, Australia. The building sizes ranged from a single storey 2950 m² to a fifteen storey 21,400 m² building (Total analysed area was about 42,800 m^2).

Although the models were produced using a weather file with real meteorological data, the difference between the measured and the modelled total electricity consumption (including HVAC electricity together with power and lighting electricity), ranged from being 22% lower to 48% higher. The difference between the measured and the modelled total gas consumption (HVAC natural gas consumption) ranged from being -80% to +45%. Differences between modelled and measured energy consumption, were mostly driven by less-than-expected occupancy, and differences in scheduling of after-hours and non-working days.

3.9.1 Calibration methods used in literature

"Despite widespread interest in the professional community, no consensus guidelines have been published on how to perform a calibration using detailed simulation programs" (Reddy, Maor, & Panjapornpon, 2007).

This section introduces different calibration methodologies that were found in the literature review, where acceptable tolerances are suggested. The first publication found where calibration of modelling has been applied, is (Pedrini, et al., 2002) where a calibration method organized in three steps was used:

1. Simulation from building plans and documentation (this first step includes the tuning of schedules and the use of a weather file with real meteorological data).
2. Walk-through and energy audit.
3. End-use energy measurements.

This methodology was first tested in a 30,000 m^2, five storey commercial building located in the south of Brazil. The building was fully conditioned and was built in 1978.

The annual difference between simulated and actual energy consumption was 114%, with a peak monthly difference of 159%, in January. After intensive schedule adjustment and the use of a weather file for simulations with real meteorological data, the annual difference between simulated and actual energy consumption was only 5.6%, with a peak monthly difference of 19.1% in June. The second step of the calibration was a "Walk-through and audit phase" in which a tuning of inputs such as equipment power density, cooling set point and schedules took place. After that step, the annual difference between simulated and actual energy consumption was 0.1%, with a peak monthly difference of 13.3% in February. After the final step "End-use energy measurements" in which the results were used for tuning the schedule and internal power density of equipment and artificial lighting, the annual difference between simulated and actual energy consumption was 0.2%, with a peak monthly difference of 9.2% in December. The issue of comparing total modelled and measured consumption broken down into energy end-uses is also studied in (Raftery, Keane,

& Costa, 2009) where it was suggested that once total consumption is broken down into lighting and equipment loads, very significant differences can be seen between the initial and updated models.

There are four additional cases from (Pedrini, et al., 2002) where the calibration method was tested in commercial buildings. Fully conditioned buildings, located in Brazil (between 12.5° and 27.5° South latitude), and totalling approximately 53,000 m^2 of area, were compared. The annual differences between simulated and actual energy consumption ranged from -11.9% to 7.6%. The peak differences ranged from -1.3% (March) to 17.5% (October).

(Pan, et al., 2007) used a calibration method which is practically subdivided in two steps:

1. Simulation from building plans and documentation.
2. The use of a real meteorological year data instead of the TMY weather file; the tuning of internal loads and schedules of operations of the HVAC system, and the reset of infiltration.

The main difference compared with (Pedrini, et al., 2002) is that in (Pan, et al., 2007) the calibration was all consolidated in one step and, significantly, the reset of infiltration was added to the calibration process. The method was tested in an 88 storey tall building located in Shanghai, with a total building area of about 300,000 m^2. Floors 3 - 50 contained office space and floors 53 - 87 were a hotel. This building was constructed in 1999.

The simulation results of the calibrated model matched well with the real 2004 energy usages. The average monthly electricity consumption between model and metered data before and after calibration is represented by a monthly difference of 39% Vs 7%. The same differences for Gas are 82% Vs 13% after calibration (Pan, et al., 2007).

3.9.1.1 The influence of schedules only

(Srinivasan, et al., 2011) discusses the calibrated simulation procedure based on the development of building operating schedules according to an event calendar. The case study building was an 111,480 m^2 convention centre, located in San Francisco, California, which was built during different time-periods, between 1970 and 2000.

The first model was based on input data obtained from as-built drawings but a weather file with real meteorological data was used in this first simulation. The calibration was based on transformation of the event calendar into a detailed operating schedule, including occupancy, lighting and general equipment. Measured energy use data for the 2007 year was used for calibration.

The building Energy Use Intensity (EUI) for the Benchmark Baseline model was computed by converting all annual energy use types into a common energy unit and then dividing by the building area. The building EUI as determined by simulation was 654 MJ/ m^2 while the actual EUI was 651 MJ/m^2 (equal to just 1.5% difference).

3.9.1.2 The influence of infiltration only

(Eagan, 2011) investigated the impact of air tightness assumptions on the accuracy of modelled energy performance predictions of Australian office buildings. Six Canberra office buildings were tested with the blower fan apparatus. Based on these results an air leakage range (with plant operating) of 0.25 to 1.5 air changes per hour (ACH) was chosen for the simulation part of this study. The air leakage level without plant operating was assumed to be 0.12 ACH to 0.75 ACH which is half that of the air leakage with plant operating.

These models all indicated that halving the air leakage relative to the datum case reduced the energy consumption to approximately 85-95% of its previous value, depending on the climate. For example, with the increment of the air leakage range from 0.25 ACH to 0.5 ACH, there was a decrease in cooling requirement which was offset by a sharp increase in heating needed.

These results imply that the consequences of inaccurate air leakage assumptions on modelled energy performance may be unpredictable. The results in (Eagan, 2011) are similar to those in (Hand, Kim, & Woo, 2011) where it was found that infiltration proved to be the most difficult issue for measurements, and changes in assumptions had the greatest impact on overall performance.

3.9.2 Temperature differences

(Pereira & Ghisi, 2011) is the only research, as far as the author is aware, that takes into account indoor air temperature comparison between modelled and measured buildings, but this research was confined to houses only. The indoor temperature of a naturally ventilated residential building (124 m^2) in the south of Brazil, was monitored. Two seven-day monitoring periods were selected: between 15 and 21 August 2007 (without natural ventilation) and between 7 and 13 January 2008 (with natural ventilation).

Calibration showed that simulations with natural ventilation did not reveal rates as precise as those without any ventilation. Temperature curves obtained by simulation showed peak differences were about 2.0°C higher than those obtained by measurements. Nevertheless, mean differences were small (about 0.4°C) and, when temperature ranges during the period are analysed, measurements increased by 2.8°C and simulations were higher about 4.1°C. Therefore, a greater influence of ventilation occurred in the simulated model than that reported in the monitored house.

3.9.3 Summary of a benchmark for the accuracy of building models

The two most comprehensive calibration methods studied in this literature review compare only total energy consumption, but no calibration of energy end-uses is documented (Pan, et al., 2007; Pedrini, et al., 2002). A summary is given in Table 3-2.

Table 3-2: Summary of differences between model and measured total energy consumption

Phases	Items tuned	Difference between model and measurements	%
(Pedrini, et al. 2002)			
1. Model from building design		Annual:	114
		Peak monthly (January):	159
2. Scheduling and actual weather file	1.1 Real meteorological data. 1.2 Tuning of schedules	Annual: Peak monthly (June):	5.6 19.1
3. Walk-through and audit.	3.1 Equipment power density 3.2 Cooling set point 3.3 Schedules	Annual: Peak monthly (February):	0.1 13.3
4. End-use energy	4.1 Schedule of equipment 4.2 Schedule of artificial lighting 4.3 Power density of equipment 4.4 Power density of lighting	Annual: Peak monthly	0.2 9.2
(Pan, et al., 2007)			
1. Model from building design		Electricity - Monthly:	39
		Gas - Monthly:	82
2. Calibration	2.1 Real meteorological data. 2.2 Internal loads 2.3 Schedules of occupancy 2.4 Schedules of operations of HVAC 2.5 Reset of infiltration.	Electricity - Monthly: Gas - Monthly:	7 13

From Table 3-2 it can be seen that a difference in annual electricity consumption from a calibrated model to real measurement range from 5.6 % to 0.1%.

Both (Pedrini, et al., 2002) and (Pan, et al., 2007) have a second step of the calibration process (see steps on Table 3-2) that imply the use of a weather file with real meteorological data, and tunning of schedules of occupancy, particularly in (Pan, et al., 2007) tunning of internal loads and infiltration is added to second step of the calibration process. Results for this second calibration step in both (Pedrini, et al., 2002) and (Pan, et al., 2007) can be seen in Table 3-2, where differences between modelled and measured annual electricity consumption is 5.6%, and monthly differences range from 7% to 19%. Other applications of the second step of the calibration method suggested used in (Pedrini, et al., 2002) found annual differences between simulated and actual electricity consumption that ranges from -11.9% to 7.6%.

More extensive work of calibration, after a walk-through and audit were mostly equipment power density and cooling set-points were tuned, bringing differences down to 0.1% and peak of 9% in a summer month (Pedrini, et al., 2002).

Aspects that cause significant disagreement between model and measurements in buildings were differences in scheduling (Egan, 2009), inaccuracy of infiltration in models (Eagan, 2011), where it was found not only that infiltration values in Australia should be higher, but also that increasing infiltration, dramatically increases the energy consumption in space conditioning of commercial buildings. There is no calibration of models based in comparison of modelled and measured indoor air temperature. The only research that compares modelled and measured indoor air temperature was undertaken in naturally ventilated houses, and found that indoor temperature peak differences were about 2.0°C higher in the model than those obtained by measurements (Pereira & Ghisi, 2011).

3.10 Modelling software requirement – Choice of Software

Section 4.5.1 introduces Virtual Environment (VE), the software used for the modelling of the case-study buildings in this research. The Apache (Applications Program for Air-Conditioning and Heating Engineers) is the simulation engine in VE where the thermal analysis is performed. To model the dynamic thermal performance characteristics of different building materials with different masses, Apache adopts a finite difference approach to the solution of the heat diffusion equation. This involves first replacing the element with a finite number of discrete nodes at which the temperature will be calculated. Nodes are distributed within the layers in such a way as to ensure accurate modelling of the heat transfer and storage characteristics for the chosen time-step (IES Ltd, 2011).

Because investigating the influence of thermal mass is central to this current research, in addition to the above brief comment on Apache's fundamental approach to solving the heat diffusion equation within building components (including thermal mass elements), it is appropriate to overview the manner in which VE/Apache resolves the influence of solar radiation intercepted by building surfaces. This is outlined in Section 3.10.1 following.

Subsequently, Section 3.10.2 is a discussion on previous work which has evaluated the effectiveness of VE's Apache engine as a building energy simulation tool.

3.10.1 Modelling direct solar radiation

Shading of the beam component of solar radiation is modelled in two ways in Apache:

- Shading and solar tracking calculations performed by SunCast[3].
- Shading calculation performed by Apache for construction-based shading devices (only applied to glazing).

The SunCast shading file is generated from data for the 15th day of every month. The data for a given month comprises hourly data describing the exposure of both exterior and interior surfaces to beam solar radiation. Apache reads the data from the SunCast file and uses it to modify the beam component of solar radiation, and when the beam enters the building through gazing, to assign it to interior surfaces. The shading file also contains diffuse shading factor indicators, for each exposed surface of the building, the degree of shading for the sky vault.

The data on the SunCast shading file records a shading factor for each exterior building surface receiving beam solar radiation. In the case of glazed elements, the file also records which interior surfaces are irradiated by the beam after it passes through the glazing, and to what extent (expressed in terms of sun-patch areas projected perpendicular to the beam). If a receiving surface is itself glazed or is a hole, the radiation is traced on through this element to other receiving surfaces beyond, and so on.

When local shading devices such as louvres are set to be installed in exterior glazing, these elements are set when the specific construction (in this case exterior windows) are configured in Apache Construction Data Base. These louvered exterior windows shade both direct and diffuse solar radiation. They also shade long-wave sky radiation. The calculations performed by these shading devices are carried out in Apache at run-time. The results of these calculations are combined with any SunCast shading calculation.

The method used by Apache to track solar intensity value across internal walls is by considering that single entity as experiencing each hour the average solar intensity value uniformly over the entire component. By having an average solar intensity value uniformly over the entire component at any instant there would be no variation of temperature across the exposed surface of the component. In Apache, when it is combined with the shading file produced by SunCast, each

[3] SunCast is the module that interacts with the Apache interface to perform shading and solar insolation studies.

surface will be treated as a single entity with the solar intensity averaged uniformly across the component, thus each surface will have a single surface temperature (IES Ltd, 2011).

Within the SunCast module images can be generated which illustrate which elements are shaded and which are directly insolated at any given time, and also output the percentage of a surface receiving direct solar gains at a given time. In the subsequent Apache analysis, however, these gains are averaged across the surface in question. Appendix B provides an illustration of the format of the software-generated tables that represent this insolation data for two specific surfaces.

3.10.2 Methods for testing whole-building energy simulation programs applied to VE

ANSI/ASHRAE Standard 140-2001, “Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs”, defines a series of tests for building energy simulation programs (ASHRAE, 2001). This standard method of test (SMOT), which has its origin in the IEA ‘BESTEST[4]’ diagnostic tests, requires the simulation of a number of variants of a test building. The aim of the tests is to provide a valuable benchmark by which the predictions of a simulation program may be compared with those of its peers, as a means for establishing a degree of confidence in the correctness of its algorithms and their implementation.

(Gough & Rees, 2004) presents the results of this test applied to the simulation program Virtual Environment’s Apache simulation engine. The Apache results were in good agreement with those from the reference programs (e.g. TRNSYS, Energy-Plus). Out of 326 tests, Apache predicted a value outside the range set by the other programs in only 13. In each of these cases a satisfactory explanation has been found for the difference.

Heating loads: The annual heating loads calculated by Apache lie within the range of values calculated by the other 9 programs. There is a tendency for Apache’s heating loads to lie towards the upper end of the distribution of predicted values, and in three instances Apache’s annual heating load exceeds that of the other programs. There are three possible reasons for this that can be identified: The first reason is that Apache models the participation of the room air in radiant exchanges (referred to as air emissivity). This is a small but significant effect which is ignored by the other programs for which results are presented in the Standard. One of the consequences of

[4] The Building Energy Simulation Test (BESTEST) is a project conducted by the International Energy Agency (IEA), which purpose was the development of a method for systematically testing whole-building energy simulation programs and diagnosing the sources of predictive disagreement (Neymark & Judkoff, 2002).

this mechanism is an increase in the thermal coupling between the room air and the internal surfaces of the room, and this tends to increase the heating load. A second possible reason for higher than average heating loads is the algorithm used by Apache for the calculation of long-wave radiation from the sky. Apache uses the CIBSE Guide A[5] algorithm for this process, which gives somewhat cooler sky temperatures than some other methods. Finally - as a third possible reason - Apache, unlike most of the programs involved in the study, performs a calculation of the obscuration of both short-wave and long-wave sky radiation by shading objects. The inclusion of diffuse shading will have reduced the solar gain, causing an increase in heating load.

Cooling loads: In all cases analysed, Apache's predictions of both annual and peak cooling loads fall within the range of values calculated by the other programs. In only 5 cases representative of low-mass buildings, Apache shows a small reduction in peak heating load that occurs when the shading device is added, again, this can be attributed to long-wave sky shading. In cases representative of high mass buildings, Apache's predictions lie within the spread of values from the other programs.

There are two instances where Apache predicts, a simultaneous lowest increase in peak heating load and the largest increase in annual cooling load. This result can be attributed to somewhat artificial circumstances that arise in relation to Apache's air emissivity modelling.

Because of a high infiltration rate in these two cases (higher than 1 ACH) the room moisture content for this case followed the external air moisture content. Room moisture content is one of the variables affecting the calculation of air emissivity in Apache: higher humidity is linked to higher air emissivity. At the time of the peak heating loads (January 4) the external moisture content, and consequently the room moisture content is low with a consequently lower air emissivity. This translates to less thermal coupling between the air and the room surfaces, with a subsequent result in a small reduction in annual heating load. During the summer when most cooling demand occurs, external moisture content (and therefore room moisture content) tends to be high. This strengthens air surface coupling by the air emissivity effect, and this in turn increases conduction gain and solar heat transfer to the air point, with the subsequent result that there is a small increase in annual cooling load.

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[5] CIBSE guide A: Environmental design (CIBSE, 2006).

3.11 Interpreting data comparison between building variants (energy, and comfort conditions) and checking sensitivity of the comparison to the assumptions made

To support the presumption that VE would be an adequate simulation tool to perform the modelling necessary to achieve the objectives of this research, a series of modelling exercises was carried out on a test building (named the Test building). It was also important to test the method by which thermal mass was being modelled in this research. Hence the aim of the modelling on this Test building is to carry out a sensitivity analysis to clearly identify the capability of VE to appropriately represent the influence of building's thermal mass on the calculation of space conditioning energy consumption and indoor environmental conditions.

The Test building was designed as a simplified Arts building, smaller in floor area and with fewer partitions (and subsequently fewer thermal zones), and with reduced finishing materials such as ceilings. It is in fact a simplified version of the Arts Concrete building, the Concrete building having been chosen because it is the case study in which thermal mass can be increased most readily. In the modelling of the Test building the schedule of occupancy is the same as in the Arts building (described on Section 4.5.3); also the internal gains, lighting and infiltration in the Test building are defined in the thermal templates designed initially for the modelling of the Arts building. Thermal templates used in the modelling of the Test building were: classrooms, gallery space, and circulation (specified for the Arts Building on Sections 4.5.4 to 4.5.6). Finally, as in the Arts Building, the Test building is modelled using the TMY weather file of Nelson, New Zealand (Section 3.11.1). The two main aspects tested in the Test building are:

- The suitability of VE for evaluating the influence of thermal storage in building fabric elements on energy consumption and comfort conditions of buildings.
- The method of modelling structural thermal mass by using stand-alone walls.

At the same time a number of other sub-tasks were able to be explored and found to be complementary to these two main aspects. These sub-tasks are:

- To include a benchmark of the influence of significantly increased thermal mass in the Test building on space conditioning energy consumption and indoor comfort condition.
- To study the influence of increasing the surface heat transfer coefficient as a way of representing massive surfaces having complex surface profiles as a simple flat construction instead.
- To identify the incidence of direct solar radiation on thermal mass surfaces.

- By increasing the surface area available, to check that the abstraction of frame mass elements into stand-alone-walls is an adequate representation of the influence of real structural elements.

3.11.1 Modelling of the Test building and its comparison with the Arts building:

Figure 3-2 is a view of the models of both the Test building and the Arts building. Other than some geometrical simplifications in the Test building, exterior wall and glazed areas are equivalent. A plan view of Level 1 in both the Test and the Arts buildings is given in Appendix A.

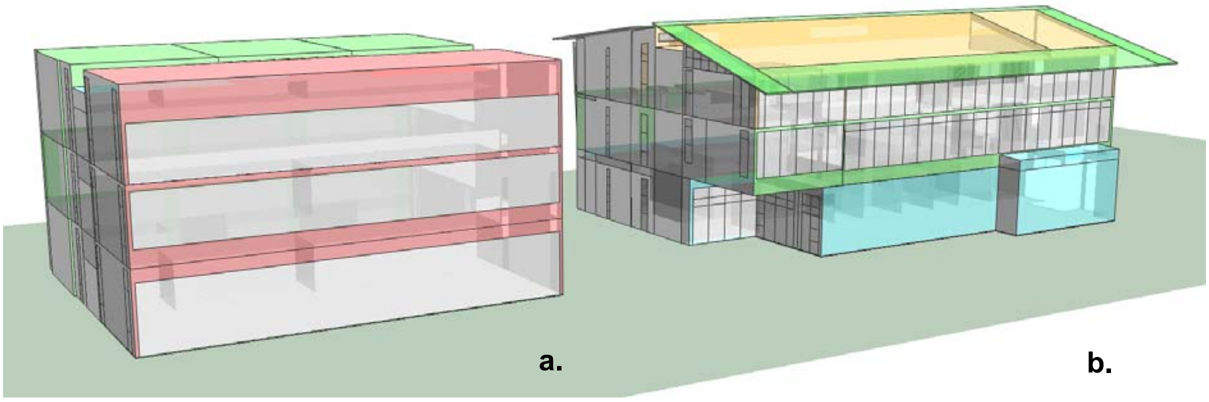


Figure 3-2: North façade of the Test building (a) and the Arts building (b)

Basically the Test building is the minimum building that includes the spaces necessary to represent all the scenarios and configurations of spaces present in the Arts building, such as studio room exposed to the East and to the West, Atrium space exposed to the north, studios exposed to the south, and so on.

Table 3-3: Comparison of floor area in the Arts and in the Test building.

Level name	Actual Arts building Gross floor area (m^2)	Test building Gross floor area (m^2)
Level 1	629	533
Level 2	676	490
Level 3	676	502
Total	1981	1525

Table 3-3 is a comparison of the total gross floor area and gross floor area of the Arts and the Test buildings, subdivided by levels; overall the Test building is about 30% smaller than the Arts building.

Table 3-4 shows the total R-values used on the thermal envelope of both the Arts and the Test buildings. Structurally, the Test building uses the same structural system as the Arts building, with great care being taken in the modelling of all structural elements contributing to thermal mass as described on Section 4.4. In the Arts concrete building, as in the Arts timber building, thermal mass is located mostly in structural elements and floor systems. Constructions contributing thermal mass are:

- Structural Shear walls.
- Suspended floors
- Structural frame

Table 3-4: Construction of the Test building (same values as in the Arts building).

External walls		External glazing	Roof	Slab-on-ground
External light wall	Shear wall Concrete			
∑R	∑R	∑R	∑R	∑R
4.6	2.9	0.5	9.4	3.4

R: m^2K/W

3.11.1.1 How representative of the Arts building, is the Test building?

As explained, the Test building is a simplified version of the Arts concrete building. The sizes of the spaces and their exposure to thermal mass are of the same nature as in the Arts building. A list of similarities between the models of the Arts concrete building and the Test building is given below:

- Both models are located in the same place.
- Both buildings have equivalent HVAC systems.
- The height of each level is the same in both models.
- The width of the rooms facing south, the central corridor, and the rooms facing north is the same in both models.
- The length of the studio rooms on Level 3 of the Arts building is the length used for every studio room in the Test building – except for the Studio on Level 2 which is single space.
- Both models have an atrium of the same height exposed to the north.
- Both models have the same construction details.
- Both models have the same thermal envelope components and resistances.
- Both models use the same weather file, profile/schedule(s) (occupied hours, set-point temperatures, and internal gains, and infiltration values.

Differences between the Arts and the Test building are:

- No finishing materials such as carpets or false ceilings are included in the model of the Test building; this was done to maximize the heat transfer between the air and the storage elements.
- The total length of the Test building is 25% shorter than the Arts building; this is equivalent to having one less studio room on Level 3 of the Arts building.

3.11.1.2 HVAC in the Test building

A simplified version – simpler in the sense that the HVAC serves a smaller building with fewer rooms - of the actual HVAC system with cooling was used to model the Test building. A schematic comparison between the HVAC system in the Arts concrete building and the Test building can be seen in Appendix A. The main similarities are listed below:

- Both models uses convective cooling and heating – from Parasol units - in the rooms directly supplied with air from the AHU.
- Both models have under-floor heating on Level 1 of the atrium space and radiators on Level 2 and 3 of that same space.
- Both models have the return of air from the top of the atrium space.
- The path of supplied air and return is the same in both buildings.
- In both buildings, the same rationale is used for the sizing of Parasol units allocated in each room.
- Both models have heat recovery.

3.11.2 The responsiveness of VE to the increment of thermal mass in buildings

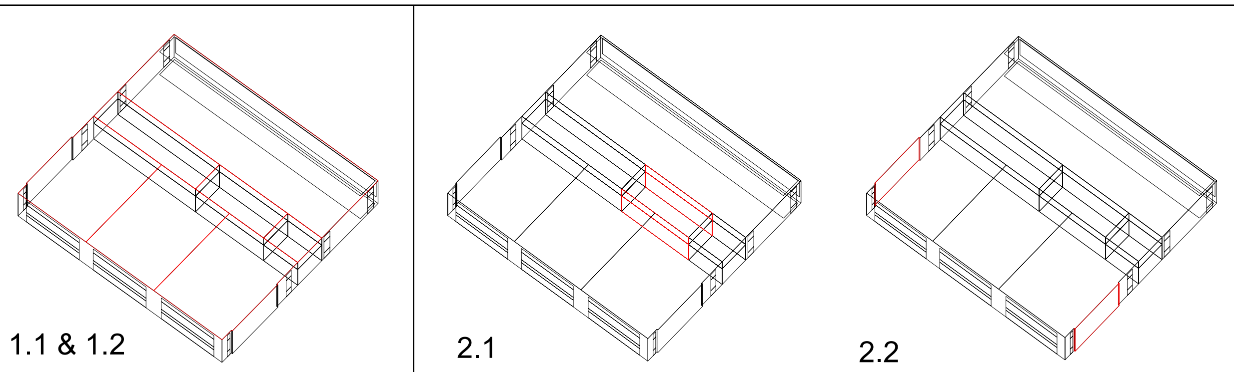
This section introduces the results of the models of the Test building, which were created to gradually introduce thermal mass – from very light weight to very heavy weight in three steps - and evaluate its effect on space conditioning energy consumption and indoor comfort conditions.

The form in which thermal mass was introduced was by gradually including the massive structural elements into the model.

1. The first model is a light-weight model without structural walls and with the actual floor system in the Arts concrete building (Interspan floor, modelled as a 25mm thick concrete slab, plus a 40mm layer of timber, and a final 75mm of concrete topping), which has a relatively low amount of concrete incorporated (Details of the modelling of the Interspan floor system can be seen in Section 4.4.2).
2. Subsequently, massive internal and external structural shear walls are included in the model.

3. Finally, in the model with the Interspan floor and the structural shear walls, the floor system is replaced by the heaviest precast concrete floor system used in New Zealand, the Hollowcore floor (modelled as a 165mm thick concrete slab plus a 100 of concrete topping, see details of the Hollowcore floor on Table 3-4.

Table 3-3 illustrates the steps by which thermal mass is added to the model of the Test building. Firstly it can be seen - for Level 2 - floor system highlighted in red, which initially is the Inter-span floor system (1.1) and later on is replaced by the Hollowcore floor system (1.2). Secondly, the inclusion of internal concrete shear walls (2.1) and the external concrete Shear walls (2.2) are shown. Simulations were performed with both internal and external shear walls included simultaneously.



1. Floor system	2. Structural shear walls	
1.1 Interspan floor 1.2 Hollow-core floor	2.1 Internal shear walls	2.2 External shear walls

Figure 3-3: Gradual introduction of thermal mass into the BEEM - models.

Also in this section a comparison will be undertaken in the Test building to test if the use of heavier floor system with profiled shapes (which increase the surface area of the thermal mass exposed to indoor environment) will have an effect on space conditioning energy and indoor comfort conditions. The comparison will be carried out between four case-studies, namely:

1. The actual Test building (with the Interspan floor and the structural shear walls).
2. The actual Test building with a Double-Tee floor system.
3. The Test building with the Double-Tee floor and a reduction of under-floor surface resistance to a relatively low resistance.
4. The Test building with the Double-Tee floor and a reduction of under-floor surface resistance to a very low resistance.

The reduction of surface resistance is for the purpose of increasing the heat transfer between the air and the concrete slab. Due to the profiled shape of the Double-Tee floor, the increment of the surface resistance was undertaken by a factor of the increment of surface area. This was suggested in (Barnard, 2002) where, to represent complex surfaces, the surface resistance may be adjusted to give an appropriate representation of the heat transfer between the air and the thermal storage element. The actual Test building is included in the comparison to benchmark the results against the base scenario.

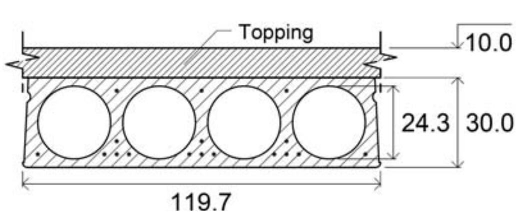
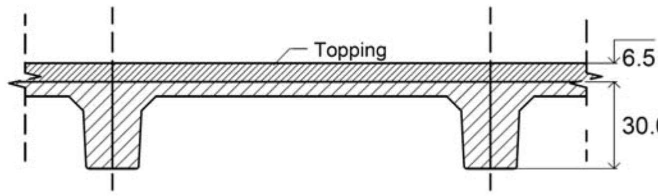
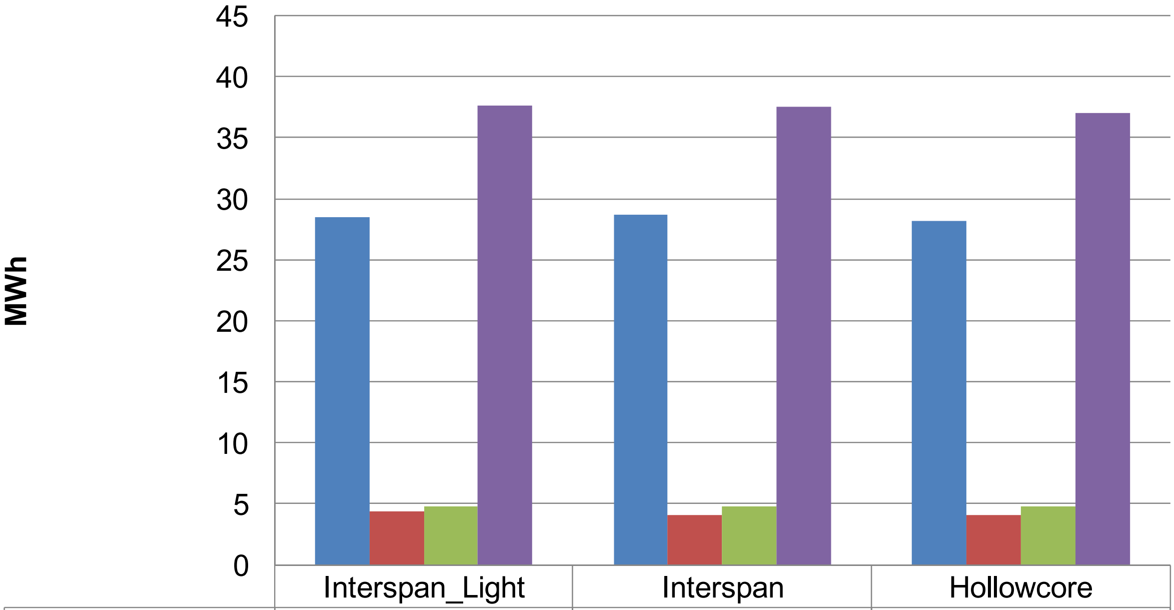
<table>
<tr><th>Hollow-core floor 300 mm deep</th><th>Double-Tee floor 300 mm deep</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Modelled as a 265mm deep concrete slab (including a 100mm concrete topping). It has a flat underlay surface where 1m of floor = 1m of exposed surface.</td><td>Modelled as a 165mm deep concrete slab (including a 65mm concrete topping). It has a profiled underlay surface where 1m of floor = 1.6m of exposed underlay surface.</td></tr>
<tr><td>Inside surface resistance set by default to 0.1 m^2K/W.</td><td>Inside surface resistance is set consecutively as 0.01 and 0.001 m^2K/W.</td></tr>
</table>

Figure 3-4: A comparison between the Hollowcore and the Double-Tee floor systems.

Figure 3-4 shows detailing of the Hollowcore and the Double-Tee floor systems and the way these were modelled. The way the Double-Tee floor was modelled was by increasing the surface resistance of the bottom surface which is exposed to indoor environments. The surface area is about 60% higher in the real profiled floor systems than in the modelled flat slab.

3.11.2.1 Thermal mass in the floor system and the inclusion of shear walls

Figure 3-5 shows the simulation model results for annual space conditioning energy consumption in the Test building with the Interspan floor; the Test building with the Interspan floor and the structural shear walls; and the Test building with the Hollowcore floor and structural shear walls. It can be seen that the pattern of energy consumption in any of the space conditioning energy end-uses is almost without variation between the three versions of the Test buildings.



	Interspan_Light	Interspan	Hollowcore
Heating (Comb.)	28.4	28.7	28.2
Chillers (Elec.)	4.4	4.1	4.1
Fans (Elec.)	4.8	4.8	4.8
Total (Comb.)	37.6	37.6	37.0

Figure 3-5: Space conditioning energy consumption (annual), modelled in the Test building with thermal storage in the floor only (labelled Interspan_light); thermal storage in the floor and in the shear walls (Interspan); and thermal storage in the very heavy floor and in the shear walls (Hollowcore).

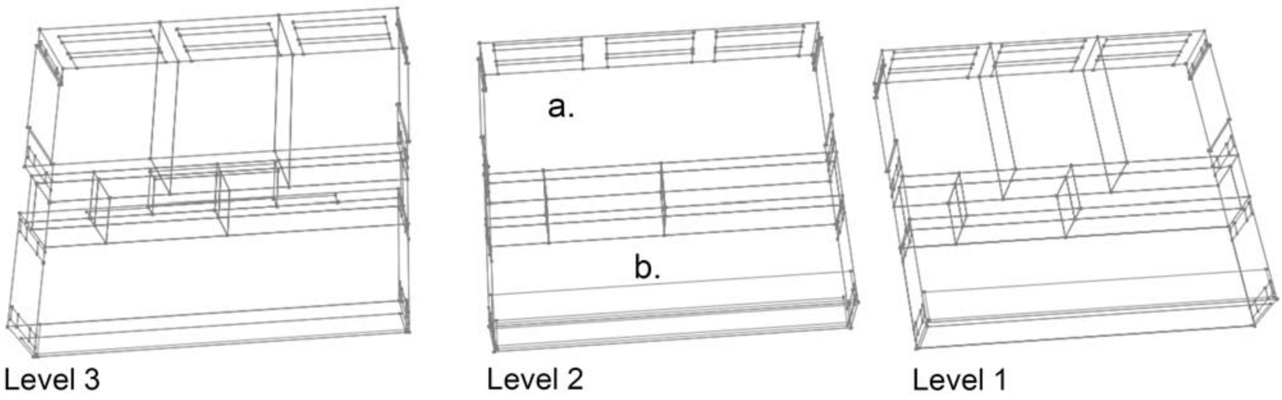
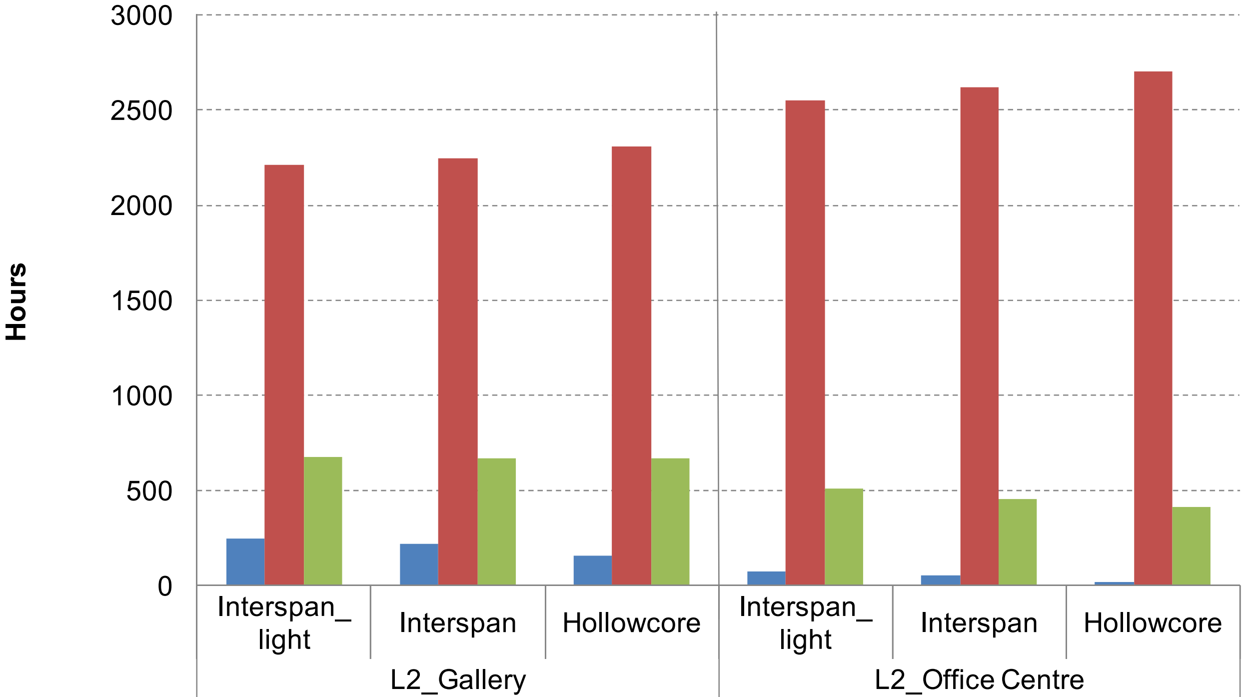


Figure 3-6: View of the three levels on the Test building and the specific location where PMV has been assessed in this research.

Methodology for the assessment of indoor comfort conditions used in this research is the Predicted Mean Vote (PMV) (ASHRAE, 2004). Details on the method of assessment of PMV can be seen in Section 8.2; basically, indoor comfort conditions are graded in accordance with a thermal sensation scale developed by the ASHRAE Standard 55-2004 where it is suggested that a acceptable thermal environment for general comfort in the range of PMV from -0.5 PMV to +0.5 PMV (ASHRAE, 2004).

Figure 3-7 shows the results of Predicted Mean Vote analysis in room located on Level 2 in each of the three versions of the Test building analysed in this section. Rooms on Level 2 were chosen because of the influence of the floor system used not only in the floor but also as a ceiling. The specific rooms where the PMV was carried out is on Office Centre on Level 2 (a.) facing South, and the Gallery space on level 2 (b.) facing North. By looking at the PMV of occupied hours, it is possible to see the influence that the building's fabric thermal mass, in combination with the active HVAC system, has on indoor comfort conditions of the three versions of the Test building analysed in this section.



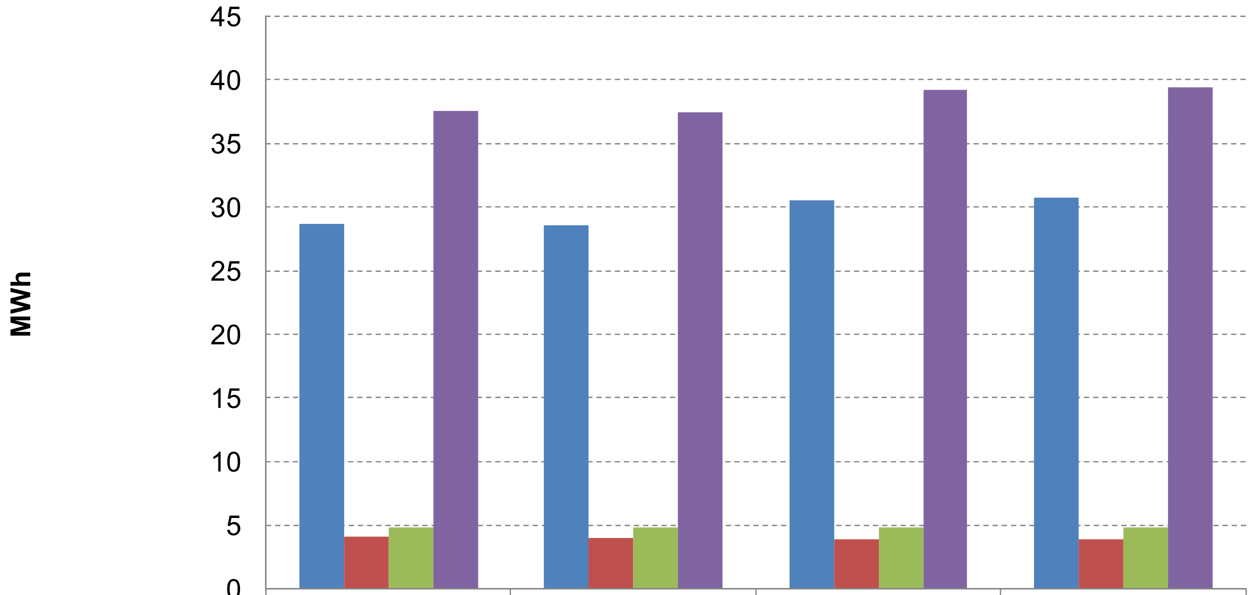
	L2_Gallery Interspan_light	L2_Gallery Interspan	L2_Gallery Hollowcore	L2_Office Centre Interspan_light	L2_Office Centre Interspan	L2_Office Centre Hollowcore
< -0.50	245	218	154	72	54	17.5
-0.50 to 0.50	2209	2247	2309	2548	2619	2701.5
> 0.50	677	666	667	511	457	411

Figure 3-7: Predicted mean vote (PMV) of Level 2 Galley space (North facing) and Office space (South facing) in the Test building with thermal storage in the floor only (Interspan_light), thermal storage in the floor and in the shear walls (Interspan), and thermal storage in very heavy floor and in the shear walls (Hollowcore).

Unlike its effect on space conditioning energy consumption modelled in VE, thermal mass does have a perceptible influence on indoor comfort conditions. There is a small increment of hours (from 2209 to 2247 hours, or 3% for L2_Gallery) within comfortable environmental conditions when the structural shear walls are added to the model of the Test building with the Interspan floor. An even greater level of comfort improvement results when the Hollowcore floor system is used. Similar trends are apparent for the L2_Office Centre location.

Although, there is some variation in the results of PMV, neither the results of space conditioning energy nor the PMV assessment vary dramatically if thermal mass is added to the Test building's fabric to a level of very high available thermal mass. A few alternatives can be tested to see why the VE software seemingly is not responsive to changes in the amount of thermal mass. The following section will explore the influence that reducing surface resistance has on the performance of thermal mass.

3.11.2.2 The influence of increasing heat transfer coefficient of the massive concrete slab by reducing surface resistance

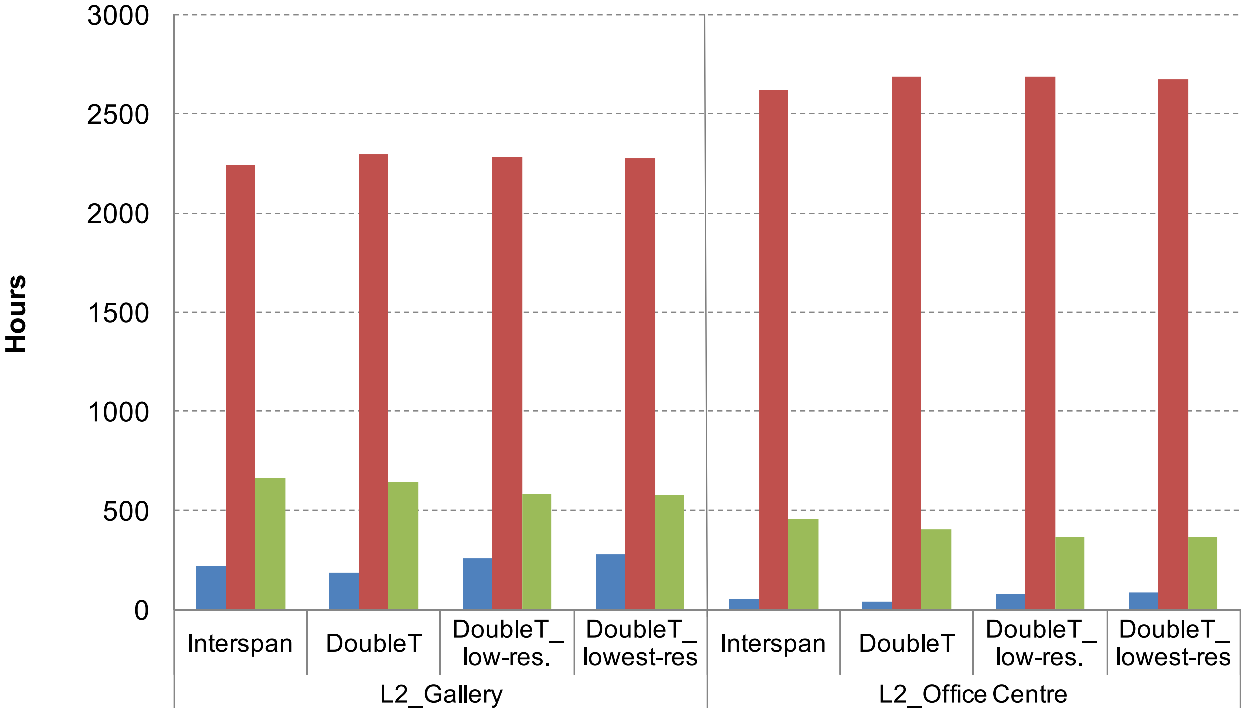


	Interspan	DoubleT	DoubleT_ low-resis.	DoubleT_ lowest-resis.
Heating (Comb.)	28.7	28.6	30.6	30.8
Chillers (Elec.)	4.1	4.0	3.9	3.9
Fans (Elec.)	4.8	4.8	4.8	4.8
Total (Comb.)	37.6	37.4	39.2	39.4

Figure 3-8: Space conditioning energy consumption (annual), in the actual Test building (Interspan), and the Test building using the Double-Tee floor system modeled with three different surface resistances for the bottom surface of the slab.

Figure 3-8 shows the modelled results for annual space conditioning energy consumption in the actual Test building (Interspan), compared against three versions of the Test building using the Double-Tee floor system. These three variations correspond to the changes in the surface resistance of the bottom surface of the Double-Tee floor slab. Because the Double-Tee floor has a profiled shape exposed to occupied space below, surface resistance was proportionally changed in accordance with a method suggested for representing the actual thermal interaction across complex surfaces when the software is constrained to representing only surfaces which are flat.

Details of the Double-Tee slab have been given in Figure 3-4. In the Test building with the Double-Tee floor (“DoubleT” in Figure 3-7) resistance is given by default and is set to 0.1 m^2K/W. In the Test building with the Double-Tee floor with low-resistance (DoubleT_low-resis.), this surface resistance is set to 0.01 m^2K/W; and in the Test building with the Double-Tee floor and the lowest resistance (DoubleT_lowestr-resis.) surface resistance is set to 0.001 m^2K/W. These drastic reductions in surface resistance – which are thermally equivalent to increasing the area available for heat transfer between the surface and the air – were for the purpose of testing the sensitivity of the software to changes in this particular parameter. All three models include the structural shear walls.



	L2_Gallery Interspan	L2_Gallery DoubleT	L2_Gallery DoubleT_ low-res.	L2_Gallery DoubleT_ lowest-res	L2_Office Centre Interspan	L2_Office Centre DoubleT	L2_Office Centre DoubleT_ low-res.	L2_Office Centre DoubleT_ lowest-res
< -0.50	218	189	260.5	281	54	39	78	87
-0.50 to 0.50	2247	2294	2283	2273.5	2619	2688.5	2686	2675.5
> 0.50	666	647	586.5	575.5	457	402.5	366	367.5

Figure 3-9: Predicted mean vote (PMV) of the Level 2 Galley space (North facing) and Office space (South facing) in the actual Test building (Interspan), and the Test building using the Double-Tee floor system modeled with three different surface resistances for the bottom surface of the slab.

Figure 3-8 shows that by modeling with the default values for surface resistance, the space conditioning energy consumption of the Test building with the Interspan floor system and the

Double-Tee (heavier) floor system is almost the same. When reducing the surface resistance of the bottom surface of the Double-Tee floor from 0.10 m^2K/W to 0.01 m^2K/W there is a more significant increment of heating which increases the total space conditioning energy consumption by about 5%. There is no significant increment of space conditioning energy consumption when the surface resistance of the bottom surface of the Double-Tee floor is increased from 0.01 m^2K/W to 0.001 m^2K/W which suggests that at such low surface resistance values it was the internal conductive resistance within the floor mass that had become the dominating constraint on heat transfer into and out of the thermal mass.

For each of the two spaces there is no significant difference between the number of hours within comfortable conditions in any of the case studies in Figure 3-9. There is a small increment of about 2% more hours within comfortable environmental conditions when the floor system changes from the Interspan to the Double-Tee. This is mainly because the Interspan has been modelled as a flat slab consisting of a 25mm thick concrete slab, plus a 40mm layer of timber, and a final 75mm of concrete topping compared with the Double-Tee floor system modelled as a flat slab of 165mm of concrete, including topping. Differences between the number of hours within comfortable conditions in the Test building with the Double-Tee floor with default and low surface resistance is very low, and is almost imperceptible. The reduction from a low to the lowest surface resistance of the bottom surface of the Double-Tee floor reduces by 2% the number of hours within a comfortable environment.

3.11.3 The method of modelling thermal mass of structural frame elements by using stand-alone walls

Figure 3-10 illustrates how stand-alone walls were introduced to represent structural columns and beams. Stand-alone wall dimensions were calculated based on quantities of materials in the structural frame provided by a quantity surveyor. The rationale and the method of calculating the volumes of materials allocated in frame elements such as columns and beams in the Arts building and its replica buildings is explained in detail in Section 4.4.3 and the same concept is being used here in this current exercise of exploring the sensitivity that the VE modelling predictions have to some aspects of the building representations.

The dimensions of stand-alone walls in the Test building were taken from the sizes used in rooms in the Arts building. Particularly the size of the stand-alone walls in the studio rooms on Level 3 of the Arts building was used for rooms on the south part of the Test building. Subsequently, the dimensions of stand-alone walls in the gallery space of the Arts building, were used for the gallery space of the Test building.

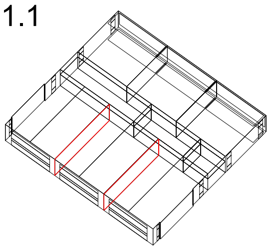
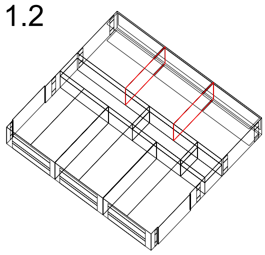
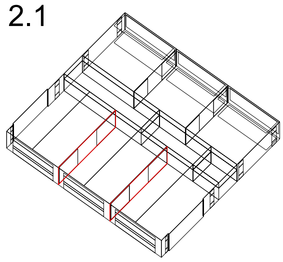
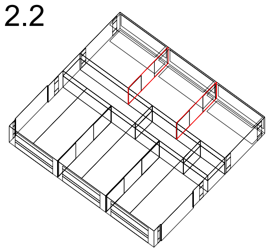
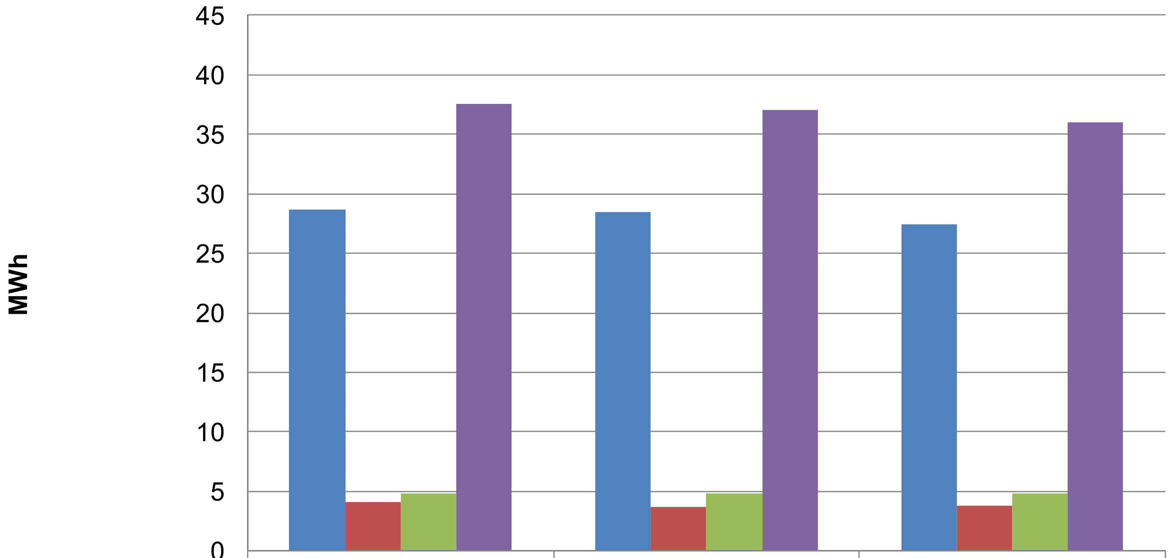
1.1	1.2	2.1	2.2
			
1. Stand-alone walls – long across room		2. Stand-alone walls – short across room	
Concrete wall_0.2 m Whole room's length	Concrete wall_0.1 m Whole room's length	Concrete wall_0.6 m 1/3 of room's length	Concrete wall_0.3 m 1/3 of room's length

Figure 3-10: Stand-alone walls (in red) type and placement in Level 2 of the Test building.

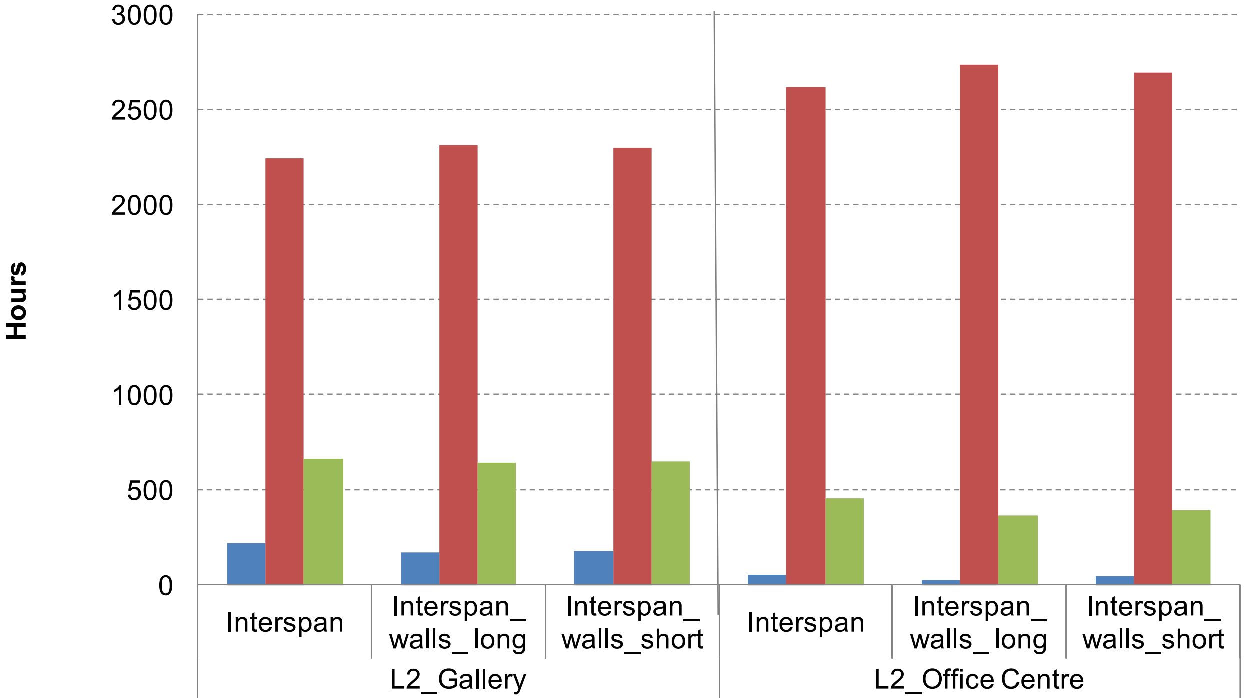


	Interspan	Interspan_Stand Alone Walls_Long	Interspan_Stand Alone Walls_Short
Heating (Comb.)	28.7	28.5	27.4
Chillers (Elec.)	4.1	3.7	3.8
Fans (Elec.)	4.8	4.8	4.8
Total (Comb.)	37.6	37.0	36.0

Figure 3-11: Space conditioning energy consumption (annual), modelled in the Test building using the Interspan floor system (as built), compared with the same building but with two different methods of modelling stand-alone walls (as representations of structural columns and beams).

Figure 3-11 shows the modelled results of annual space conditioning energy consumption of the Test building (including shear walls) using the Interspan floor system (as built), and compared with the same building but with two different methods of modelling stand-alone walls (as representations of structural columns and beams). The so-called Stand-alone walls_Long have walls as long as the complete width of the spaces in which they are placed, while the so-called Stand-alone walls_Short have walls as long as 1/3 of the complete width of the spaces in which they are placed. Because the volume of concrete in columns and beams calculated for each room is to be maintained, when the length of the wall increases, the thickness decreases; thus the short stand-alone walls are about three times thicker than the long stand-alone walls.

Figure 3-11 shows that there is a consecutive small reduction of 2% in total space conditioning energy between the three case studies. The most significant variation in space conditioning energy used is in the reduction of 4% of the heating energy consumption in the model with Interspan floor and short stand-alone walls compared with the model without any stand-alone walls.



	Interspan (L2_Gallery)	Interspan_ walls_ long (L2_Gallery)	Interspan_ walls_short (L2_Gallery)	Interspan (L2_Office Centre)	Interspan_ walls_ long (L2_Office Centre)	Interspan_ walls_short (L2_Office Centre)
< -0.50	217.5	174	179	54	28.5	45.5
-0.50 to 0.50	2246.5	2310	2299	2619	2735.5	2692
> 0.50	666	646	652	457	366	392.5

Figure 3-12: The results of the analysis of PMV for the Gallery space (North facing) and the Office space (South facing) on Level 2 of the Test building (including shear walls) using the Interspan floor system (as built), compared with the same building but with two different methods of modelling stand-alone walls.

The results of the analysis of PMV for the Gallery space (North facing) and the Office space (South facing) on Level 2 of the Test building - in each of the case studies analyzed for energy in Figure 3-11 - is presented in Figure 3-9. As in most of the tests carried out in this section, differences between comfort conditions between all case studies in this figure are very low. Peak difference in the number of hours within comfortable environmental conditions (4%) occurs between the Interspan building without stand-alone walls and the Interspan building with long stand-alone walls. This is predictable because of the influence of a large area of concrete added to the space which acts as thermal mass. The number of hours within the comfortable environment range for the Interspan building with long and short stand-alone walls differ by about 1%.

3.11.4 Drawing conclusions from modelling capabilities of VE and the influence of these in further modelling

It has been shown that there is almost no impact on space conditioning energy consumption when thermal mass is added to the base Test building model, first in the form of shear walls and subsequently in the form of a heavier floor system. Introducing long stand-alone walls to the base building reduces space conditioning energy consumption by about 2%, whereas introducing short (but thicker) stand-alone walls to the base building reduces space conditioning energy consumption by about 4%. In both cases, the reductions are of heating energy.

There is a peak 5% space conditioning energy increment (mostly in heating) when the surface resistance of the bottom surface in the Double-Tee floor system is reduced from its default value (0.10 m^2K/W) to a lower value of 0.01 m^2K/W. Reducing surface resistance beyond that value does not have an significant impact on space conditioning energy consumption.

In terms of thermal comfort, when thermal mass is added to the base model in the form of shear walls, there is a small increment of hours (3%) within comfortable environmental conditions. When, subsequently, a heavier floor slab is added, the increment of hours within comfortable environmental conditions when compared with the base building is 6%. There is no significant change in PMV results when the surface resistance of the bottom surface in the Double-Tee floor system is reduced from its default value (0.10 m^2K/W) to a lower value of 0.01 m^2K/W. Introducing long stand-alone walls to the base building, increases the number of hours within comfortable environmental conditions by 4%, whereas introducing short stand-alone walls to the base building only increases the number of hours within comfortable environmental conditions by 2%.

The most significant situation is the effect that a reduced surface resistance has, increasing heating energy consumption, while adding short stand-alone walls reduces heating energy consumption. It appears that lowering the surface resistance has made thermal mass more accessible and, contrary to results where thermal mass is made available by increasing the available volume, heating energy increases. When adding internal stand-alone walls, indoor space volume is reduced; subsequently because of the reduction of the space that needs conditioning, space conditioning to that room is also reduced.

The fact that there is an *increase* in annual energy consumption when the floor thermal mass is effectively made more accessible through this artificial lowering of surface resistance may seem contrary to conventional wisdom which encourages accessible thermal mass as an energy-saving measure. The most likely explanation for this outcome in this situation is that, unlike residential buildings, this building has an operational schedule in which the space conditioning system operates to achieve comfort conditions only during occupied hours. In this scenario, most of the energy transferred from the air into thermal mass elements (such as the Double-Tee floor) will be an energy penalty on the HVAC system but the later outflow from the thermal mass back into the air will be outside operational hours and will therefore be largely lost as a possible energy credit. This was pointed earlier on Section 2.5 where (Braham, et al., 2001a) suggested that the presence of thermal mass is not inevitably a good thing from an energy perspective because it may increase the daily warm-up period of buildings with subsequent energy penalty. Having said that, there would seem to be little doubt that the energy flow back from the accessible thermal mass would have a tempering effect on space temperatures during unoccupied hours and hence bring some reduction in the load on the HVAC plant during initial start-up the next day.

Despite the generally low sensitivity of modelling predictions of energy consumption to the amount of thermal mass, in terms of thermal comfort, however, VE does appear to have sufficient sensitivity to identify that the higher accessible thermal mass in concrete buildings is beneficial in reducing the temperature variations during occupied hours, leading to a more favourable PMV. This benefit in thermal comfort is not necessarily inconsistent with the comment made above that there may be an energy penalty associated with high, very accessible thermal mass for buildings having limited operational hours. The energy usage being assessed is that associated primarily with operation of the HVAC system (during operational hours) as it tries to meet its design objective of achieving comfort conditions.

The fact that this modelling of variations on the Test building has shown only minimal sensitivity of annual energy usage to changes in thermal mass (except for the most extreme variation of a comparatively massive floor system with artificially enhanced surface heat transfer) is an early pointer to the possibility of only modest changes in the predicted energy consumption of the planned variations on the structure of the Arts case study building that were listed in Section 3.2. This possibly anticipated outcome does not mean that there is now little point in carrying out that comparative modelling study. In particular, none of the modelling in this chapter is for a situation that corresponds to the real timber-structured Arts building from which actual monitoring data is able to be obtained for model validation purposes. Additionally, it cannot be concluded in advance that dominantly timber-based buildings will behave thermally in a manner which is very similar to the concrete-only versions of the Test building. Finally, the Test building has included a number of simplifications in comparison with the actual Arts building and the planned variations on it. It would be presumptuous to postulate – without putting the postulate to any test – that those simplifications would have no thermal consequences.

4 Modelling of case-study buildings

This chapter describes the bulk of the methodology used for the building energy and environmental modelling (BEEM). It also describes the Arts timber building, as constructed, and the Arts concrete and Arts steel buildings, as designed. It also describes the low energy versions of all three buildings, and methods of modelling the thermal mass in the main structural elements of all three buildings. The choice of modelling software is described, together with techniques for modelling various components of the entire HVAC system.

4.1 Building model introduction

In this research, building energy and environmental modelling (BEEM), is used for the assessment and comparison of HVAC energy consumption and indoor comfort conditions (using Predicted Mean Vote (PMV)) of case study buildings.

Buildings analysed in this research are three very similar medium-sized educational buildings, each designed using structural systems made primarily of timber, concrete or steel. The concrete and steel buildings have been designed (but not built) to replicate an actual three-storey 1980 m^2 gross floor area educational building, which has a timber structure and timber concrete composite floors. The actual three storey building was built to provide generic space and facilities for the School of Arts and Media in a tertiary education institution located in Nelson, New Zealand. It is a new building constructed during 2010 and operative from February 2011. In this thesis, the Arts and Media building is labelled as the Arts building.

The buildings were modelled using two different insulation values in the thermal envelope (opaque walls and glazed areas), one sufficient to comply with the New Zealand building code and another with “best practice” insulation levels. In the modelling process, the thermal mass in the structural material was added to each room as a stand-alone internal wall. Each building using the “code-compliant” thermal envelope is named after the material in their structural systems (i.e. Concrete). Buildings using the “best practice” thermal envelope are labelled as a “low” (i.e. Concrete–low) because each of these represents the low energy version of the buildings.

The original HVAC system (in the actual Arts building) includes hydronic heating using a heated floor slab and radiators, mechanical ventilation with heat recovery, and cooling in a computer room only. An alternative HVAC system was modelled where cooling was added into all rooms with directly supplied mechanical ventilation, and where most of the underfloor heated slab was replaced by convective heating. Because of the lack of cooling in office spaces, the original HVAC system in this research is representative of HVAC systems used in educational buildings. With the further addition of cooling to office spaces, the alternative HVAC system in this research is representative of HVAC systems used in commercial buildings.

The buildings with the "code-compliant" thermal envelope were modelled using the original HVAC system (educational HVAC system). Buildings modelled in this condition are labelled specifying the structural material only (i.e. Concrete). Buildings with the "best practice" thermal envelope were modelled using both the educational and the commercial HVAC system. Labelling of these buildings includes the structural material, the version of thermal envelope, and HVAC system used (i.e. Concrete–low–commercial).

4.1.1 Timber structural system in the actual Arts building

The actual Arts building has been built using a state-of-the-art timber structural system made primarily of an engineering wood material called Laminated Veneer Lumber (LVL). LVL is produced by peeling logs into 3mm veneers and gluing into billets, 1.2m wide and 40-100mm thickness, in a mechanised continuous process which allows delivery of very long lengths, limited only by transportation (Buchanan, et al., 2011).

Structural columns and beams are prefabricated using layers of LVL glued into larger sizes, and are connected to each other using bolted connections. For earthquake resistance, LVL post-tensioned shear walls are used in the transverse and longitudinal directions. The floor system includes a 75mm concrete topping over an LVL board horizontally placed as permanent formwork and glued to LVL joists to make a timber Tee-beam. The exterior building envelope is mostly light-weight insulated walls, although thick structural shear walls made of LVL are embedded in portions of the external walls in the east and west facades, reducing the external wall cavity space and subsequently the insulation values. There is a double-glazed curtain wall on most of the north façade, and a large double-glazed window area on the south façade. All external glazing is installed in standard aluminium frames which do not have thermal breaks incorporated into them.

4.1.2 Arts building space layout description

The Arts building has a total gross floor area of 1981 m^2, and a total usable area of 1693 m^2. The building is arranged in three storeys occupied mostly by large studio rooms, performance spaces, administration offices, and a full-height gallery space in the north façade. Although there are some changes, mostly in room sizes, the internal layout is consistent through all three storeys: There is a long glazed area of the north wall (appropriately shaded by the roof overhang) that draws natural light into the main building through a full height gallery atrium. The gallery is three storeys tall and combines a series of enclosed rooms and open circulation spaces orientated and exposed to the gallery voids.

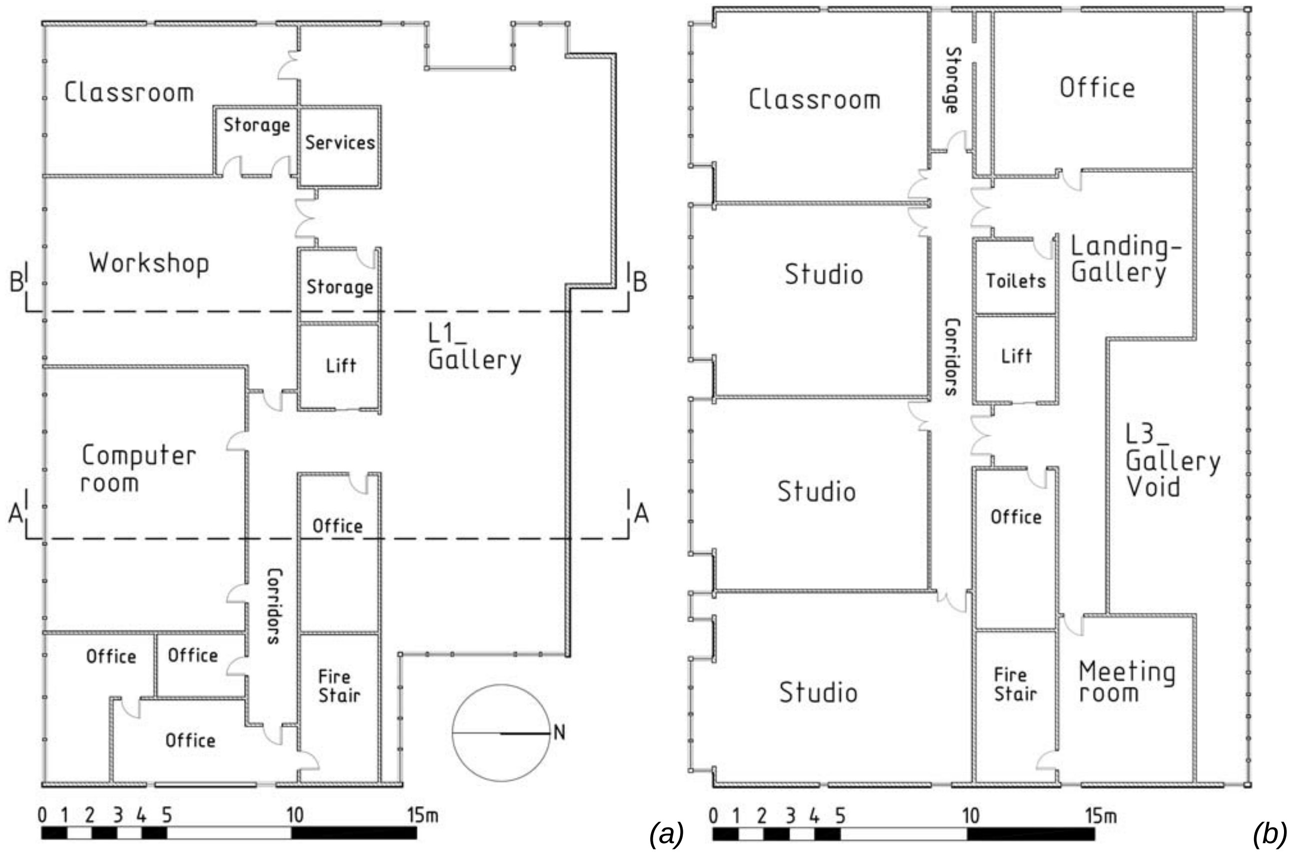


Figure 4-1: Plan views of the Arts building. (a) Level 1). (b) Level 3.

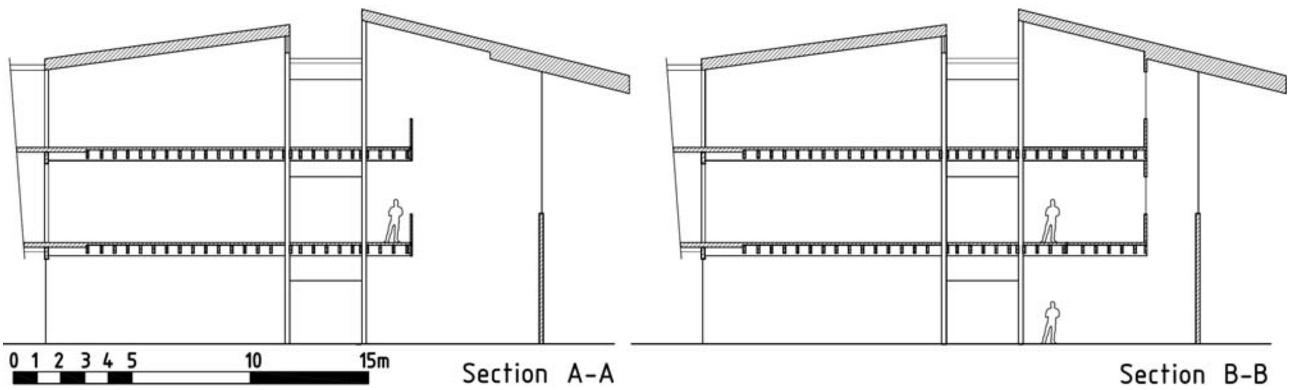


Figure 4-2: Cross sections of the Arts building.

The internal layout of the Arts building can be appreciated in Figure 4-1 where a plan section of level 1 and level 2 is given, providing an idea of the layout across the three levels of the building. It can be seen in Figure 4-1 (a), that the gallery is flanked by a narrow structural core containing relatively small rooms aligned together continuously from the east to the west façade of the building. This narrow service space is penetrated with linkages between the gallery and flexible multi-use seminar and studio spaces exposed to the south wall. A series of relatively large enclosed rooms exposed to the south façade normally are occupied as studio or teaching areas and some offices, especially in the Level 1. The south wall is conceived as a large glass area for drawing natural light into the studios. The upper level glazing leans out to become a "public gallery wall". The use of clear glass is used to reveal the wooden multi-storey structure of floor/ceilings and walls.

The size of gallery space can be appreciated in Figure 4-2 where a transverse cross section of the Arts building shows the full height of the north facing gallery across the three levels. A large portion of Level 1 corresponds to the base of the, three storey tall atrium/gallery space. Compared with Level 1, the area occupied by the gallery void is less in Level 2 and 3 of the building.

4.1.2.1 Arts building space floor area and external facades description

Table 4-1 shows a comparison between gross floor area and the usable floor area for each level of the Arts building respectively; total values are also included.

Table 4-1: Arts building comparison between gross floor area and usable floor area.

Level name	Gross floor area (m^2)	Usable floor area (m^2)	Usable to gross area (%)
Level 1	629	594	94
Level 2	676	560	83
Level 3	676	540	80
Total	**1981**	**1693**	**85**

There is only a 6% difference between gross floor area and usable floor area in Level 1. Due to the space occupied by the gallery void this difference increases to 17% in Level 2 and to 20% in Level 3. In this report, the usable floor area calculation does not account for the area occupied by internal walls and void spaces.

The height between structural floors in the Arts building is 4.4m, 4.0m, and about 4.7m in Levels 1, 2, and 3 respectively. The external wall area of the building is 493 m^2 for Level 1, 460 m^2 for Level 2, and 567 m^2 for Level 3. The total wall area and the corresponding external glazed area, organized by façade, are given in Table 4-2.

Table 4-2: Arts building's external walls and glazing area.

Façade	External wall area (m^2)	External glazed area (m^2)	External glazed to wall area (%)
North Façade	391	192	49
South Façade	475	323	68
East Façade	272	54	20
West Façade	381	74	20
Total	**1520**	**643**	**42**

Glazed surface is smaller in the north façade compare with the south façade. Although there is a curtain wall in the north façade this is only available on Levels 2 and 3 but not on Level 1. On the south façade Level 1 is completely glazed; on Level 2 and 3 of the same façade, glazed “bow windows” placed in the leaned section of the façade, increase the external surface area of the façade, adding significant external glazed area. The layout and extension of the glazed area in the south (a) and east (b) façade can be seen in Figure 4-3.

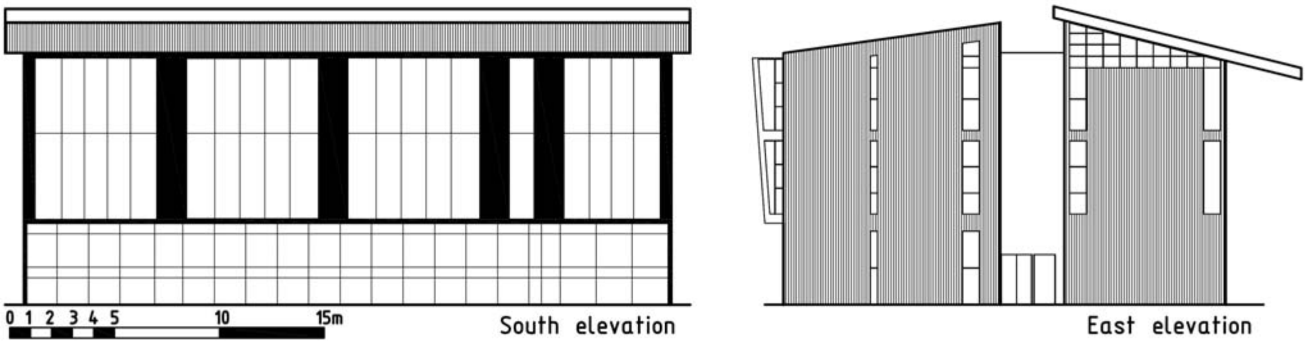


Figure 4-3: Arts building’s south (a) and east (b) elevations.

From Table 4-3 can be seen that the area of glass in the total envelope wall is relatively large (42%). Due to a low R-value, glazed areas have significantly higher heat losses than those opaque areas of external walls which, in the Arts building, are normally light-weight insulated wall. Particularly in the south façade, because of the large glazed area (68%), it may be expected that overall heating energy consumption will be relatively high and comfort conditions relatively low (due to a low mean radiant temperature) in the zones exposed to that façade.

Due to an overall high glazed area on the external walls of the Arts building, it might be expected that the large heat losses will not only penalize the energy performance of this building, but will also temper the differences in the energy performance and indoor comfort conditions in the concrete, steel and timber buildings, particularly when these will be modelled with the “code-compliant” thermal envelope.

4.2 Construction of the case study buildings

As it was explained in Section 4.1 there are three alternative versions of the Arts building:

- Timber building - Arts building with a timber structural system (actual).
- Concrete building - Arts building with a concrete structural system.
- Steel building - Arts building with a steel structural system.

The three buildings were modelled with two different thermal envelopes: The ‘code-compliant’ and the ‘best-practice’ thermal envelope (low-energy buildings). Simulations of buildings with the code-compliant thermal envelope were undertaken using the Arts building actual HVAC system (HVAC representative of educational buildings). Buildings with the best-practice thermal envelope were modelled with the actual HVAC system, and an alternative HVAC system for which the main difference was that cooling has been included (HVAC representative of commercial buildings).

A comprehensive list of the nine resulting case study buildings modelled in this research is given in Table 4-3. The names in Table 4-3 are used across the entire thesis.

Table 4-3: summary of the case study buildings and their respective names in this thesis.

Thermal envelope	HVAC System	
	Educational	Commercial
Code-compliant	Timber	
	Concrete	
	Steel	
Best-practice	Timber-low	Timber-low-commercial
	Concrete-low	Concrete-low-commercial
	Steel-low	Steel-low-commercial

4.2.1 Construction categories and attributes

There are nine different construction and usage categories in this research that are common to all six buildings studied (three buildings with the code-compliant and the best-practice thermal envelope[6]). The construction categories as follow:

1. Windows: This category is subdivided into external windows (part of the building's thermal envelope), and internal windows (not part of the building's thermal envelope).
2. External wall: Corresponds to all external wall construction that is part of the building's thermal envelope.
3. Internal wall: Corresponds to all the internal partitions (not part of the building's thermal envelope).
4. Structural suspended floors: Corresponds to all suspended floor systems that are part of the primary structural system of the building. This construction varies significantly between all three buildings construction type (Concrete, Timber and Steel buildings) in this research.

[6] The definition of thermal envelope in this section is taken from NZS 4243.1 (NZS, 2007).

5. Suspended ceilings: Suspended ceiling height defines the heights of inhabitable spaces inside the buildings thermal envelope. In the modelling of thermal zones in this thesis, inhabitable spaces below suspended ceiling and unoccupied spaces above the suspended ceilings and below suspended floors were modelled as two separated thermal zones.
6. External overhang floor: Corresponds to all suspended floor constructions existing in the building that are part of the building's thermal envelope (e.g. ceiling/floor above the main access area of the east façade of the Arts building).
7. Roof: Corresponds to all roof construction (part of the building's thermal envelope).
8. Slab-on-ground: Corresponds to the concrete slab on ground (part of building's thermal envelope).
9. Heated Slab: Corresponds to the concrete slab-on-ground with embedded hydronic heating system (part of building's thermal envelope).

Windows have very different thermal parameters than the other eight categories of envelope construction. All eight categories other than windows are considered to be opaque, so thermal capacitance (as defined by density, specific heat capacity, and thickness) is used as rough measure of the capacity of the material to store heat. Because the manner in which a mass element will respond thermally – both within itself and in its interactions with its surroundings – is very dependent on the geometric configuration of that mass, thermal capacitance alone is rarely used if a realistic model of the transient thermal behaviour is required. Window constructions, by contrast, are – to a good approximation - mass-less, but they require properties characterising their solar transmission properties. The difference suggested between windows and opaque construction is predetermined by the users' guides of the simulation tool used in this research (IES Ltd, 2009).

There are more approximated methods than simple thermal capacitcance for quantifying the "potential" thermal mass of any type of construction. The author is aware of the 'admittance method' presented in CIBSE Guide A3, which is a measure of the rate of heat flow into and out of a construction element under dynamic sinusoidal temperature variation (CIBSE, 1986). In this research the aspects of the dynamics of heat flows into and out of the constructions are left to be generated by the BEEM software which uses a finite difference representation of layers of construction materials in its solution of the heat diffusion equation (as was mentioned in Section 3.9). This approach achieves a realistic thermal representation of thermal mass elements because it does take the actual geometric configuration of each mass into account.

4.2.2 Attributes of construction and their disaggregation into materials

Each construction is characterized thermally by its resistance R and, for thermal mass calculations, both the density and the specific heat of all constituent materials are also required. For all nine construction categories introduced in Section 4.2.1, the resistance R was calculated. For materials with thermal conductivity of k, and thickness L, the thermal resistance R (units of m^2K/W) was calculated according to:

$$R=L/k$$

The New Zealand specific data for the thermal conductivity of each material was taken from NZS 4214:2006, together with air cavity resistance and outside and inside surface resistance values (NZS, 2006). To determine the total thermal resistance of a construction built as the assembly of various different materials, the calculation methodology was taken from NZS 4214 (NZS, 2006).

Table 4-4: Example of an external wall construction layer's total R values

	R	R	R	R	R	R	R	∑R
External Light Wall	0.04 Outside surface	0.00 Profiled steel	0.01 Air cavity	2.44 R2.8 Bridged insulatio	0.09 Timber (Pine)	0.07 Gypsum board	0.13 Inside surface	2.81

R: m^2K/W

Table 4-4 shows an example of the construction of an external wall which has been disaggregated into different materials combined with a ventilated air cavity and the outside and inside surfaces conditions. It is not only possible to see the resistance R values for each component of the construction but also to see the total resistance R of the construction.

4.3 Construction of the Timber-low, Concrete-low, and Steel-low buildings

The architectural design of the actual Arts building was produced by a Nelson based Architectural consultant (Irving, Smith Jack Architects Ltd). The structural design of the building was produced by the local branch office of a global engineering consultancy firm (Aurecon). For the design of the alternative Concrete and Steel buildings the same architects and structural engineers were appointed to develop both the architectural and structural designs. Most of the changes in the Concrete and Steel buildings compared to the actual Timber building were in the replacement of the primary structural system and some secondary structural elements such as roof structure. Most of the external and internal walls, all of the windows, suspended ceilings, external overhang floors, heated slab, and slab-on-ground are the same for the Timber, Concrete, and Steel buildings.

4.3.1 Thermal envelope description

In the case of the three buildings with the best practice thermal envelope, no structural or major architectural modifications were undertaken in comparison with the buildings with the code-compliant thermal envelope. In these buildings the insulation values of the thermal envelope were significantly increased to a level of best possible practice in New Zealand, without undertaking re-design of construction such as external walls. All external windows where changed from standard double gazing in aluminium frames without thermal breaks to double glazing windows with Argon gas between glass panels, and thermally-broken PVC frames. These changes to buildings with the best-practice thermal envelope were produced within the models by the author of this research.

Particularly in the design of the roof structure, the designers option in the code-compliant Concrete and Steel buildings, was to use steel purlins (C section steel profiles). In the actual Timber building, LVL purlins were used. The method of determining the total thermal resistance of parts of buildings in NZS 4214 differs between timber and steel framed roofs. Particularly in the case of steel framed roofs, due to high thermal conductivity the steel C section profile is accounted for as uninsulated steel box profile acting as a significant thermal bridge (Standards New Zealand, 2006a). The R value of the roof with steel purlins (R 4.0) is lower than the R value of the roof construction with LVL purlins (R 5.1). Due to potential differences in the energy performance of buildings with LVL or steel purlins, a set of code-compliant buildings with LVL purlins only was produce in parallel for assessment using BEEM software. All case study buildings with the best-practice thermal envelope were modelled with LVL purlins in the roof structure. The added insulation in those cases increased the R value of the roof to a much higher R 9.4.

A detailed table specifying the total R values of each of the nine construction categories in Section 4.2.1 in the Timber, Concrete, and Steel code-compliant and best-practice buildings is included in Appendix C. A variation of R values of each of the constructions implicated in the thermal envelope of the Timber, Concrete, and Steel code-compliant and best-practice buildings can be seen in Table 4-5.

Table 4-5: Building's thermal envelope R values.

	Slab-on-ground	External walls			External glazing	Roof	
		External light wall	Shear wall	Shear wall LVL		LVL purlins	Steel purlins
	∑R	∑R	∑R	∑R	∑R	∑R	∑R
Code-Compliant	3.4	2.8	1.4	2.7	0.3	5.1	4.0
Best-Practice	3.4	4.6	2.9	4.2	0.5	9.4	N/A

R: m^2K/W

In Table 4-5 there are significant variations of the R value of the components of the building's code-compliant and best-practice thermal envelopes in the Timber, Concrete, and Steel buildings.

4.4 Structural elements contributing thermal mass

The main objective of this research is to quantify the effect of the thermal mass in the structural materials (concrete, steel or timber) on the space conditioning energy consumption. To achieve this it is necessary to identify and categorize the potential thermal mass elements available in each structural system.

Despite the earlier comments (Section 4.2.1) about the severe limitations of thermal capacitance, C (which is the product of volume, density and specific heat) as a realistic measure of the effectiveness of thermal mass elements, it has been numerically evaluated in this section. This has been done purely for the purpose of identifying where *potential* significant elements of effective thermal mass may or may not be present. In these evaluations there is no implication that these numerical values for capacitance are anything other than very rough pointers to the situations in which there is likely to be a relative abundance or deficiency of effective thermal mass. The true quantitative evaluation of the thermal mass effectiveness is entrusted to the much more sophisticated unsteady state thermal modelling algorithms built into the BEEM software.

For all of the nine construction categories in which the fabric of all case study buildings in this research has been subdivided (see Section 4.2.1), the total R and C values we're calculated. These values are specified for the Timber, Concrete and Steel buildings in Tables A-1 and Table A-2 of Appendix C and for the Timber-low, Concrete-low and Steel-low buildings in Tables A-3, and Table A-4 of the same appendix.

Table 4-6: Timber, Concrete, and Steel and buildings, massive construction's R – C values.

	Suspended floor		Shear walls				Stand-alone walls	
			External		Internal			
	∑R	∑C	∑R	∑C	∑R	∑C	∑R	∑C
Timber	0.8	250	2.7	175	1.5	175	0.5 - 6.2	50 - 700
Concrete	0.4	250	1.4	450	0.1	450	0.1 - 0.8	200 - 2800
Steel	0.1	300	N/A	N/A	2.7	30	N/A	N/A

R: m^2K/W C: KJ/m^2K

Three structural elements we're identify as being the most significant source of thermal mass in the Timber, Concrete and Steel buildings regardless of their thermal envelope; these are suspended floors, shear walls, and stand-alone-wall (a simplifying method of modelling the complex surfaces of structural frame). Table 4-6 lists the R and C values of those three constructions in the Timber, Concrete, and Steel buildings.

The following section will explain the way in which thermal mass is available in shear walls, suspended floor, and stand-alone-walls in the Timber, Concrete, and Steel buildings.

4.4.1 Shear walls

As explained in Section 4.1.1, in the actual Arts building shear walls are included for earthquake resistance of the timber structural system. Shear walls were re-designed in concrete and steel for the structural design of the Concrete and Steel buildings respectively. Structurally, shear walls work in pairs; there are four pairs of these walls in each building (8 in total). Figure 4-4 identifies specific locations of the structural walls in the structural layout of the timber building (a). It can be seen that shear walls in the longitudinal direction (1 and 2) are embedded as internal walls, and the shear walls in the transverse direction are embedded in a portion of the external walls in the west (3) and east (4) facades of the buildings.

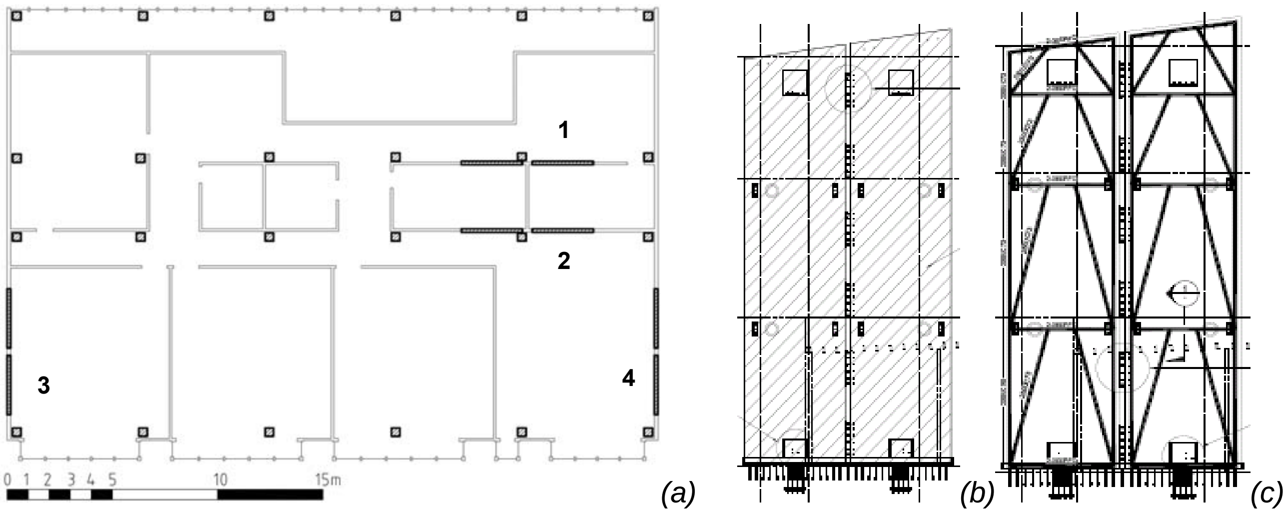


Figure 4-4: Arts building structural layout with shear wall highlighted (a), and elevation of shear walls; massive (b), and light-weight (c).

Under ‘shear walls’ construction in Table 4-6, the R and C values for the internal and external shear walls of the Timber and Concrete buildings are given, however, no shear wall (external or internal) is specified for the Steel building. For the purpose of this research, the concrete and the LVL shear walls are considered to have high thermal mass, but the shear wall in the Steel building, which is made of steel profiles in a reticulated fashion, is considered to have negligible thermal mass. This is graphically presented in Figure 4-4 where it is possible to see an elevation view of a massive shear wall (b) (made of concrete or LVL) and the reticulated steel shear walls used in the

Steel building (c). By default the construction assigned for all external walls in the Steel building is ‘external light wall’.

Compared with ‘external light walls’, the C value of massive external shear wall such as in the Timber and Concrete buildings is significantly bigger (see Table 4-5). Although the thickness of the LVL shear wall (189 mm) and the concrete shear wall (200 mm) is similar, due to higher density and specific heat capacity, the C value of the concrete shear wall is significantly bigger than the C value of the LVL shear wall (see Table 4-6).

4.4.2 Structural suspended floors

As well as the shear walls, the constructions of ‘structural suspended floors’ in Table 4-6 are also significantly different between the Timber, Concrete, and Steel buildings, and represent another important component of the primary structural system that, depending in the level of exposure to the habitable space, can contribute to the thermal mass. In the Timber building, the floor system used is called Potius ® flooring system (Figure 4-5 (a)). The system is a prefabricated stressed skin composite floor system made of long-span vertically-oriented LVL joists glued together to a horizontally-oriented LVL board that act jointly as a permanent formwork which works in composite action with a cast in-situ mesh reinforced concrete topping. In the Potius ® system, the volume of concrete is 0.08 m^3/m^2 and the volume of LVL is 0.10 m^3/m^2 (joist included).

(a) Potius ®	(b) Interspan ®	(c) ComFlor ®

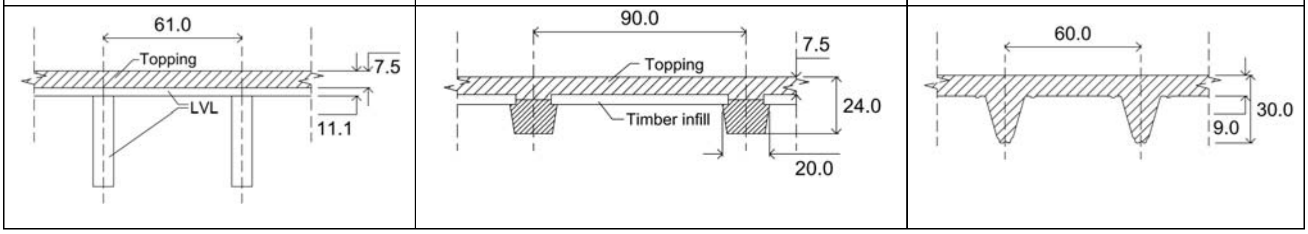


Figure 4-5: Section of the Potius ® (a), Interspan ® (b), and Comflor ® (c) floors systems

In the Concrete building the floor system used is called Interspan® flooring system and consists of 200mm wide precast prestressed concrete ribs spaced generally at 900mm centres with timber infills placed between them. This multi-piece system is tied together with a 75mm in-situ concrete topping and mesh reinforcing (Figure 4-5 (b)). In the Interspan® system, the volume of concrete is 0.10 m^3/m^2 and the volume of timber is 0.04 m^3/m^2.

In the Steel building the suspended floor system used is a steel-concrete composite floor system called ComFlor® decking system. It is a lightweight galvanized steel trapezoidal profile which works in composite action with an in-situ cast mesh reinforced concrete topping. The Comflor®

system has a volume of Concrete of 0.13 m^3/m^2 which is greater that the Potius® (0.08 m^3/m^2) and the Interspan® (0.10 m^3/m^2) systems and the volume of steel is only 0.001 m^3/m^2.

Suspended structural floor systems have a large C value mostly because of the concrete in the systems. The R values in the suspended floor systems are not significant, mostly because these are uninsulated construction elements which are not part of a building's thermal envelope. The Potius® system in the Timber building and the Interspan® system in the Concrete building both have C values of about 250 kJ/m^2K, and the Comflor® system in the Steel building is slightly more at 300 kJ/m^2K.

4.4.2.1 Modelling of suspended floor systems

The complex shapes of the floor systems were modelled as flat layers. A layer of timber was added below the concrete topping in the Potius® and in the Interspan® systems; this timber layer had a volume equivalent to that of the complex shape given by the timber joist and permanent formwork of the Potius® system, for example. The same approach was taken in the Interspan® system, and for the inclusion of the steel sheet in the Comflor® system.

Some literature suggests that increasing the heat transfer coefficient between the flattened complex surfaces and the air may help to give a more appropriate representation of the heat transfer between the air and the complex shape of the real thermal mass (Barnard, et al., 2001). This was analysed earlier on the Test building on Section 3.11.2.2 and it was found that decreasing surface resistance of complex surfaces to increase heat transfer, does have a small effect on space conditioning energy consumption and no effect on comfort conditions.

No concrete floor surfaces were left exposed in the actual Arts building, being covered with either carpet or vinyl flooring films. This research recognises that thermal mass has to be modelled to reflect common practices of building finishing in New Zealand and, because of that, floor systems were modelled with each of these coverings. The specific R and C values of floor systems with either carpet or vinyl covering can be seen in Tables C-1 and Table C-2 of Appendix C.

4.4.3 Modelling of the structural frame

Regardless of one specific research suggesting that the type of structural frame (i.e. timber, concrete or steel) has little effect on the performance of thermal mass (Braham, et al., 2001a), this research considers that, because of being exposed to indoor spaces, frame elements may provide significant thermal mass and are therefore worth of assessment with the BEEM modelling.

In the architectural design of the Arts building there has been an intentional design approach of leaving timber structural elements exposed to the indoor spaces (rather than being embedded into external or internal walls) and free of finishing of any kinds; this can be appreciated in Figure 4-6. The rationale behind this is well explained by the architect's own words: '*An early decision was taken to design a very transparent building which strongly expresses its multi-storey timber structure from within. As you look inside and move through the building, its entire character is set by the demonstration of a complete structural timber system of walls, floor/ceilings and their connections' (Irving Smith Jack Architects Ltd, 2008)*. When re-designing the Concrete and the Steel buildings, the same architectural design concept was applied. Since a detailed structural design was available for the Timber, Concrete, and Steel buildings, the calculation of total mass in the exposed structural fames could be undertaken.

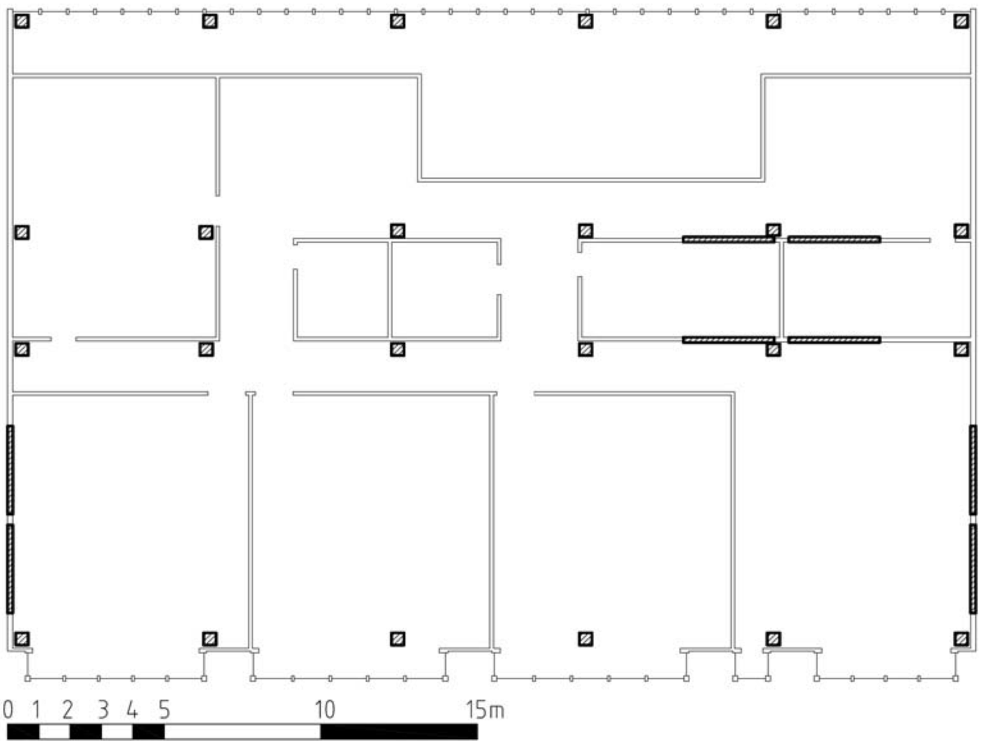


Figure 4-6: Plan section level 3 of the Timber building (structural columns).

Thermal modelling of the structural frames was a particularly difficult task because the space geometry modelling interface in the BEEM software used for this research, did not allow the inclusion of geometries other than thermal zones; in other words, added geometries had to be either an occupied or an unoccupied room. To model the frame, an internal partition was added to all conditioned rooms, as a stand-alone-wall with a volume equivalent to the added volume of all structural members exposed to that particular room. No frame elements were included in unconditioned spaces such as ceiling voids. The frame elements accounted for were columns, beams and roof rafters. Rafters were available in some of the rooms in level 3 only, and beams were taken into account in all conditioned spaces without a suspended ceiling.

4.4.3.1 Specific volumes of stand-alone-walls

The structural and architectural designs of the Timber, Concrete, Steel buildings were assessed for materials quantity calculation by a quantity surveyor (QS) consultant (Davis Langdon). The QS provided the quantities of materials in the Timber, Concrete, and Steel buildings in a schedule organized by structural elements and their respective material masses (tonnes). From that schedule of materials, the volume and mass of all frame elements (columns, beams, and rafters) of the Timber, Concrete and Steel buildings were easily obtained. For instance, this was used for thermal mass volume calculation of shear walls and in the floor systems.

In the same way as for structural shear walls, only the LVL and concrete used in frame elements were considered to have significant thermal mass, but in the case of the steel building where all structural elements are made of steel, these were considered to have negligible thermal mass.

Table 4-7: Timber, and Concrete building's material quantities in structural components.

LVL in			
Structural element	Dimensions (mm)	Section (m^2)	Number of elements
Columns			
C1	405 x 300	0.12	30
C2	405 x 400	0.16	38
Beams			
B1	2 / 750 x 171	0.26	8
B2	2 / 460 x 171	0.16	13
B3	396 x 189	0.07	6
B4	660 x 189	0.12	6
B5	460 x 171	0.08	2
B6	300 x 171	0.05	6
B7	400 x 171	0.07	6
Rafters			
R1	2 / 550 x 171	0.19	6
R2	2 / 400 x 171	0.14	4
R3	400 x 189	0.08	4
R4	400 x 189	0.08	4

Concrete in			
Structural element	Dimensions (mm)	Section (m^2)	Number of elements
Columns			
C1	450 x 450	0.20	30
C2	450 x 450	0.20	38
Beams			
B1	850 x 450	0.38	8
B2	600 x 450	0.27	13
B3	450 x 350	0.16	6
B4	600 x 450	0.27	6

Data in Table 4-7 has been extracted from the schedule of materials produced by the QS and show the general dimensions and final section of all structural columns, beams and roof rafters made of LVL used in the Timber building. Also in Table 4-7 are the concrete structural frame elements used in the Concrete building. Roof rafters in the Concrete building were made of steel and were subsequently not included in Table 4-7. For the timber and concrete structural elements in Table 4-7 the total number of elements such as columns, beams, and rafters is given. It can be seen that the cross-sections of columns and beams made of concrete, are in all cases larger than those made of LVL.

Table 4-8: Summary of total thermal mass of exposed structural frames in each of the conditioned rooms in the Arts Timber and Arts Concrete buildings.

Room names and level	Stand-alone walls						
	general information			Timber building		Concrete building	
	Height (m)	Area (m^2)	Number of walls	Thickness (m)	Volume (m^3)	Thickness (m)	Volume (m^3)
1st level							
Seminar	2.8	7.8	1	0.10	0.8	0.14	1.1
Textiles	4.4	13.9	1	0.70	9.7	1.00	13.9
Computers	3.8	9.7	1	0.06	0.6	0.08	0.8
Gallery 1st Floor	4.4	31.6	1	0.60	19.0	0.60	19.0
Link	2.8	8.0	1	0.10	0.8	0.14	1.1
Interview	3.8	6.6	1	0.10	0.7	0.14	0.9
Head of Sch-Prg leader	3.8	6.6	1	0.10	0.7	0.14	0.9
Staff-Program leader	3.8	6.6	1	0.10	0.7	0.14	0.9
2nd level							
Studio	4.0	12.8	3	0.80	30.6	1.20	46.0
Gallery/Display	4.0	6.7	2	0.24	3.2	0.60	8.0
Landing	4.0	9.5	1	0.60	5.7	0.60	5.7
Staff (6)	4.0	9.5	1	0.30	2.9	0.60	5.7
3rd level							
Studio seminar	4.7	12.8	1	0.30	3.8	0.20	2.6
Studio Drawing West	4.7	12.8	1	0.30	3.8	0.14	1.8
Studio Drawing Central	4.7	12.8	1	0.30	3.8	0.14	1.8
Studio Drawing East	4.7	13.0	1	0.60	7.8	0.30	3.9
Staff meet / small group	3.0	7.5	1	0.50	3.7	0.40	3.0
Gallery	4.6	7.5	2	0.50	7.5	0.40	6.0
Staff	3.0	7.5	1	0.10	0.8	0.14	1.1

Table 4-8 is a list all the conditioned rooms in the Timber and Concrete buildings; for every room the room's habitable space height is given. As it was stated in Section 4.2.1, suspended ceilings normally define the height of habitable spaces; however, there are many rooms without suspended ceilings where structural beams thermal mass is accounted for in the volume of stand-alone walls in Table 4-8.

Also included in Table 4-8 is the area of all stand-alone walls and the number of walls included per room. For instance in the studio room on level 2, due to its large area with and no suspended ceiling or internal partitions, most of the building's structure is exposed. The subsequent large volume of structural material exposed to the indoor environment is such that three stand-alone walls were used in the model to represent the equivalent volume of material. Figure 4-7 is an internal view of the model representation of the three stand-alone walls allocated to the studio room in Level 2 of the Timber building.

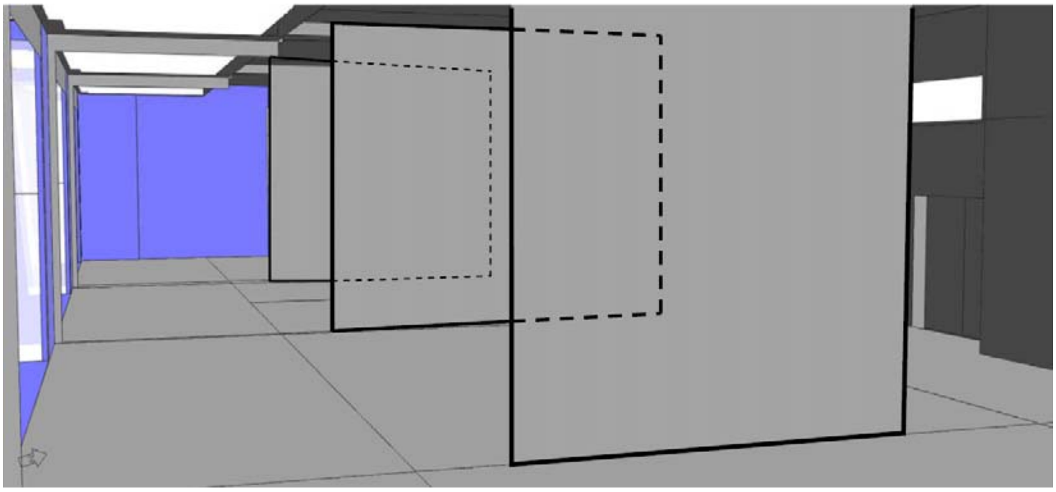


Figure 4-7: Second level Studio, view of the three massive stands alone walls – view from the south wall.

Together with area and the number of walls per room, the thickness of timber and concrete stand-alone walls is given in Table 4-8. The thickness multiplied by the area and the number of walls gives the total volume of thermal mass in each room. Total volume of both timber and concrete in Table 4-8 is equivalent to total volume of structural material exposed to habitable spaces from the schedule of material produce by the QS.

Table 4-9: Timber and Concrete Building's internal stand-alone walls representing thermal mass in structural components.

Timber stand-alone walls		
Name in model	∑R	∑C
LVL_0.06	0.46	50
LVL_0.10	0.77	100
LVL_0.24	1.85	200
LVL_0.30	2.31	300
LVL_0.50	3.85	500
LVL_0.60	4.62	500
LVL_0.70	5.38	600
LVL_0.80	6.15	700

Concrete stand-alone walls		
Name in model	∑R	∑C
Concrete_0.08	0.05	200
Concrete_0.14	0.09	300
Concrete_0.20	0.13	500
Concrete_0.30	0.19	700
Concrete_0.40	0.25	1000
Concrete_0.60	0.38	1500
Concrete_1.00	0.63	2500
Concrete_1.20	0.75	3000

R: m^2K/W C: kJ/m^2K

Finally Table 4-9 lists the eight standardised stand-alone walls introduced into the BEEM modelling of the Timber and Concrete buildings. In some cases, a stand-alone wall of the same thickness is used in different rooms; for instance, the 0.10 m thick LVL wall is used in five different rooms in level one (Seminar, Link, Interview, Head of School and Program leader, Staff room and Program leaders). This is because standardised stand-alone walls work as an approximation of the original volume of thermal mass available in frames, thereby simplifying the modelling process.

Stand-alone walls in table in Table 4-9 are categorized based on thickness. For every wall in Table 4-9 the total thermal resistance R and approximate capacitance C are given. Most important in Table 4-9 is the C value showing the total heat storage capacity of the walls. In comparison with the Timber building, the concrete building has much larger C values in the internal stand-alone walls. Although, as already explained, quantitative capacitance values are not used in any of the modelling, the very substantial difference between these values is a pointer to an expectation of differing thermal behaviour when the modelling analysis is carried out. The results from the Test building modelling, however, have foreshadowed the possibility that the influence of thermal mass on operational energy requirements may be reduced in the circumstances of the daytime-only occupied schedule of the NMIT case study building.

4.5 Thermal conditions in the modelling of buildings

4.5.1 Software used

Using a currently available software tool for building energy and environmental modelling, this research studied the effect of the thermal mass in the structural materials of timber, concrete, and steel framed buildings, on the space conditioning energy consumption and indoor comfort conditions of multi-storey, medium sized educational and commercial buildings in New Zealand.

BEEM modelling has been performed using Virtual Environment (VE) which is an interconnected set of building performance-modelling tools from Integrated Environmental Solutions (IES). As far as the author is aware, the only guidelines for BEEM software selection are in the CIBSE application manual AM11 ‘Building Energy And Environmental Modelling’ (CIBSE, 1998). VE software has a standard core modelling interface which can be linked to many functions independently from the core program. The core program of VE is the building modeller (ModelIT) used to create an integrated data model (IDM). The IDM captures every aspect of building geometry, construction, climate and equipment. The central IDM is then connected to a variety of different interconnected modules with capabilities such as energy consumption and carbon emissions, lighting, day-lighting and solar design, CFD, and many others. As suggested (CIBSE, 1998) a graphical user interface, such as ModelIT, permits accuracy in the modelling of the buildings in a time effective way.

The Apache (Applications Program for Air-Conditioning and Heating Engineers) interface is the module where the thermal analysis is performed. Apache interacts with three modules which simulate different aspect of thermal performance:

- Solar shading and penetration (SunCast).
- HVAC systems and control (Apache HVAC).
- Natural ventilation and mixed mode systems (MacroFlo).

Detailed modelling of the HVAC system of the actual Arts building was carried out using the Apache HVAC module. Apache HVAC is used to create an HVAC system schematic model, subsequent to creating a building model using the IES building modeller ModelIT. The building models, together with the HVAC system schematics, are used to estimate the expected energy consumption of the building's space heating and cooling systems. It is used to examine in detail the expected performance of an HVAC system and controls under a range of operating conditions (U.S. Department of Energy, 2010). There is another comprehensive study on dynamic energy storage in building fabric (Barnard, 1995) that uses the Apache thermal analysis program as a modelling tool to assess the energy and thermal performance of systems using thermal mass in conjunction with mechanical HVAC systems.

Finally, other characteristics such as a graphical output interface, the provision of good user manuals combined with quick on-line user support, and an educational discount on cost influence the selection of the BEEM software.

4.5.2 Location and weather data

The weather data used in BEEM are typical meteorological values generated from a data bank much longer than a year in duration; this devised data set is known as a typical meteorological year (TMY). The actual Arts building is located in Nelson, in the north of New Zealand’s South Island. All comparisons were carried out using the TMY file of Nelson.

The Nelson region (Nelson-Marlborough) is the sunniest region in New Zealand, with warm, dry and settled weather predominating during summer, and usually overall mild winter days (NIWA, 2011).

Table 4-10: Summary climate information for Nelson, Christchurch, Wellington, and Auckland.

Location	Rainfall	Wet-days	Sunshine	Temperature			Ground frost	Wind	Gale days
	mm	>= 1.0 mm	hours	Mean °C	Extreme maximum °C	Extreme minimum °C	days	mean speed km/h	mean speed at least 63Km/h
AUCKLAND	1240	137	2060	15.1	30.5	-2.5	10	17	2
WELLINGTON	1249	123	2065	12.8	31.1	-1.9	10	22	22
CHRISTCHURCH	648	85	2100	12.1	41.6	-7.1	70	15	3
NELSON	970	94	2405	12.6	36.3	-6.6	88	12	2

Typical summer daytime maximum air temperatures in Nelson range from 20°C to 26°C, but occasionally rise above 30°C. Typical winter daytime maximum air temperatures range from 10°C to 15°C. The mean annual temperature in Nelson is 12.6°C, with maximum extreme temperature of 36.6°C and a minimum extreme of -6.6°C.

Table 4-10 summarises the climate information for Nelson, Wellington, Christchurch, and Auckland. Since NZS 4243 subdivides New Zealand into three climatic zones based not only on climatic data but also taking into consideration territorial boundaries, in Table 4-10 the comparison is between Nelson, and one city representative of each of the climatic zones suggested in NZS 4243 (NZS, 2007), zones and its representative city as follow:

- Zone 1 comprises the Coromandel District, Franklin District and districts north of these (represented in Table 4-10 by Auckland).
- Zone 2 comprises the remainder of the North Island excluding Taupo, Ruapehu District and northern part of the Rangitikei District (represented in Table 4-10 by Wellington).
- Zone 3 comprises the remainder of the country, i.e. Taupo District, Ruapehu District, northern part of Rangitikei District, South Island and all other islands not in zone 1 (represented in Table 4-10 by Nelson and Christchurch).

As it has been mentioned, the Nelson-Marlborough region is the sunniest region in New Zealand; this is reflected in Table 4-10 where annual hours of sunshine average at least 2400 hours for Nelson, compare with 2100 in Christchurch and approximately 2060 for both Wellington and Auckland. Nelson has less wind than many other urban centres and its temperatures are often moderated by sea breezes. Regardless of the amount of sunshine hours, it is significant in Table 4-10, that the annual mean temperature is very similar in Nelson (12.6°C), Christchurch (12.1°C), and Wellington (12.8°C), and there is a significant 20% increment in the mean annual temperature of Auckland (15.1°C) compared with Nelson.

4.5.3 Occupancy and operation (Profiles)

Since the actual Arts building is an educational building, all four buildings were simulated using schedules of occupancy, lighting, equipment, and HVAC operation, based in schedules developed for school buildings recommended in NZS 4243 (NZS, 2007).

Table 4-11: Weekly schedules used in BEEM controlling most of the operations (a), and for the operation of hydronic heated slab only (b).

Occupancy, lighting, equipment, and HVAC plant operations (a)			
	12am-8am	8am-6pm	6pm-12am
Monday to Saturday	0%	100%	0%
Sunday	0%	0%	0%

HVAC radiant slab heating (b)			
	12am-7am	7am-6pm	6pm-12am
Monday to Saturday	0%	100%	0%
Sunday	0%	0%	0%

Two main daily schedules were developed in this research to be used in BEEM, Table 4-11 shows a schedule for building occupancy, lighting, equipment, and HVAC plant operation (a), and a second schedule which is produced for the hydronic heated slab operation only (b). Schedule (b) is a variation of schedule (a) and is used to turn on the heated slab one hour earlier than all applications in schedule (b).

A daily profile covers only a period of one day, which is used as blocks to create time variation patterns over longer periods (i.e. weekly profiles). In Table 4-11 it can be seen that the daily schedules for week days includes Saturday and that only Sunday is unoccupied. Educational buildings in New Zealand are not expected to operate during most of the summer period. Because of this, cooling is normally not required for most of the teaching facilities and offices, and is only made available in lecture theatres or computer laboratories because of large internal gains produced by high occupancy and/or equipment. Despite the actual operations of educational buildings, in this research BEEM models operate all year round.

Table 4-12: Schedules used in Virtual Environment to define annual operations.

Annual schedules	Start		End	
	Day	Month	Day	Month
All aplications other than heating (c)	1	Jan.	31	Dec.
Heating - boiler operation (d)	1	May	31	Oct.

Table 4-12 shows the annual schedules produced when daily schedules in Table 4-11 are organized in annual patterns. It can be seen that occupancy, lighting, equipment and HVAC plant operates year round, but the campus boiler operate only during 6 months (1st of May until 31st of

October); this is due to a management scheme in which central boilers are "off" during the warmest six months of the year, meaning that no thermal heating is available outside of this period.

4.5.4 Room thermal templates

BEEM in this research combines room thermal conditions in all the spaces in the model and a HVAC system operating in conditioned spaces only. Thermal conditions in the spaces were prearranged in thermal templates which were subsequently applied to all conditioned and unconditioned spaces in the building. Spaces inside the building thermal envelope where a thermal template has been assigned became a thermal zone; the thermal templates hold specific data for: heat gains, lighting density, and infiltration.

The HVAC system designed for the actual Arts building was reproduced in the Apache HVAC tool and was superimposed on conditioned spaces in the models (mechanically ventilated spaces are included into the conditioned spaces category). There are seven different thermal templates used in the modelling off all three buildings in this research (regardless of the thermal envelope used); these are presented in Table 4-13 along with their respective internal gains associated with people and equipment.

Table 4-13: Internal gains assigned to thermal templates used in simulation

Building thermal templates	Internal Gains			
	People			Equipment
	Occupant density (m^2/Person)	Sensible gain (W/Person)	Latent gain (W/Person)	Sensible gain (W/m^2)
Classroom	6.5	63	54	0.0
Computer room	6.5	63	54	8.1
Gallery	23.3	63	54	0.0
Office	23.3	63	54	8.1
Storage & Circulation	0.0	0	0	0.0
Toilets	0.0	0	0	0.0
Unoccupied & Voids & Mass	0.0	0	0	0.0

It can be seen in Table 4-13 that internal gains are produced mainly by people and, on a smaller scale, by equipment and lighting (further in Table 4-14). People's internal gains are either latent or sensible; sensible gains correspond to a 55 % and Latent gains to a 45 % of the occupant space gain component. Occupancy is approximately 170 people in total: 50 people on the first floor, 57 people on the second, and 63 on the third floor. Regularly occupied space per person is 10 m^2 which, inversely, corresponds to an average density of 0.1 people per m^2.

Table 4-13 also show that ‘storage & circulation’, and ‘toilets’ thermal zones have no internal gains apart from lighting (further explained in Table 4-14). Furthermore, ‘unoccupied & voids & mass’ thermal zones have no internal gains at all, and the thermal template used in such thermal zones reflects that their conditions are completely derived from adjacent thermal zones and, in some cases, these act as a thermal “buffer”, i.e. thermal zones between suspended ceiling and structural suspended floors.

Infiltration is set to be 0.25 air changes per hours (ac/hr) in all rooms located adjacent to the building thermal envelope, and is 0 ac/hr in fully internal rooms (Standards New Zealand, 2006b). Internal gains associated with equipment only exist in the computer room and in all office spaces.

4.5.5 Lighting Data

It can be seen in Table 4-14 that a specific illuminance value (lux) per square metre of floor area was assigned to each thermal template; illuminace values were set in accordance with NZS 4243: Part 2: Lighting (Standards New Zealand, 2007). A dimming profile was created in VE to allow for external natural light to be allowed for into the illuminance per square metre calculation. When enough natural light was available inside a thermal zone, VE was able to cap the total illuminace value by diming electric lighting; in these circumstances the electric consumption associated with lighting was not constant and fluctuated during the day.

Table 4-14: Thermal template’s illuminance and lighting power density.

Building Thermal templates	Lighting	
	Total illuminance Natural + Electric (Lux)	Sensible gain (W/m^2)
Classroom	400	19
Computer room	400	19
Gallery	150	6
Office	400	19
Storage & Circulation	150	6
Toilets	150	6
Unoccupied & Voids & Mass	0	0
Installed power density	3.8 W/m^2/(100 lux)	

The installed power density in Table 4-14 was used to calculate the total sensible gains (total sensible gains are the result of the installed power density multiplied by total illuminance).

4.5.6 Conditioned and unconditioned thermal zones

All spaces in the BEEM models of the Timber, Concrete, and Steel buildings were set-up as thermal zones with their respective thermal templates assigned. All conditioned thermal zones were subsequently superimposed with an HVAC system modelled in an Apache HVAC tool.

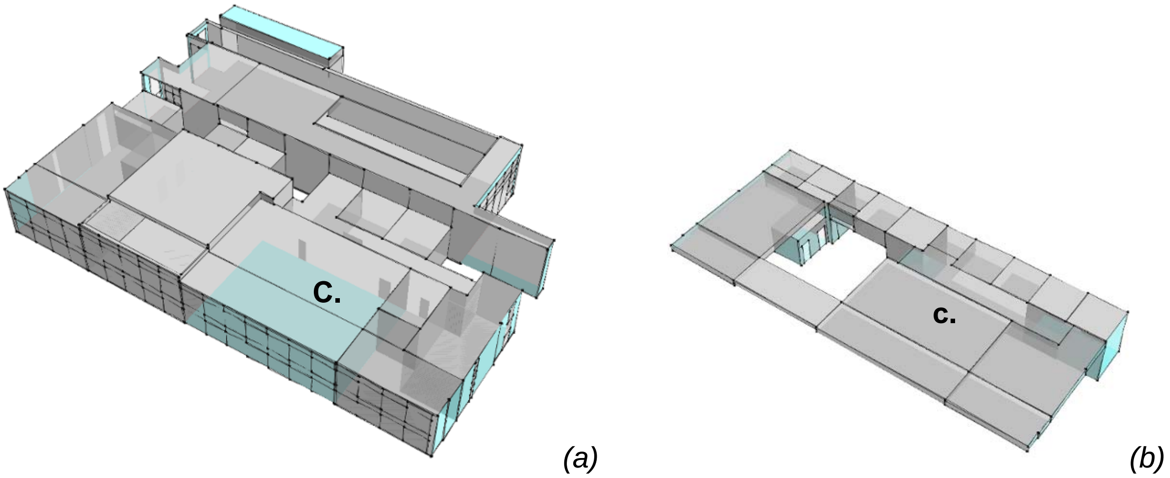


Figure 4-8: level 1 - conditioned (a) and unconditioned (b) thermal zones.

Figure 4-8 clarifies for level 1 the extent of conditioned thermal zones (a), compared with unconditioned thermal zones (b). For instance if mechanical ventilation is supplied to the computer room (C) with a inter-structural floor height of 4.3m but a suspended ceiling at 3.75m, the 0.55m height space in between the suspended ceiling and the structural floor (c) has been modelled as a unconditioned thermal zone.

Table 4-15: Level 1 thermal zones area and volume.

Level 1 - Conditioned thermal zones	Area (m^2)	Volume (m^3)
Computer room	84	315
Office_Core	37	108
Office_Perimeter	42	158
Classroom_Perimeter	141	530
Gallery	211	863
∑	516	1,975

Level 1 - Unconditioned thermal zones	Area (m^2)	Volume (m^3)
Storage & circulation_Core	53	137
Storage & circulation_Perimeter	18	76
Unoccupied & Voids & Mass	300	282
∑	371	495

	Area (m^2)	Volume (m^3)
Level 1 totals	887	2,470

Table 4-15 shows two parallel columns with area and volume data for conditioned and unconditioned thermal zones in level 1 in the BEEM model of the Arts building. Both conditioned and unconditioned thermal zones have been organized by thermal templates. Some of the thermal templates include either Core or Perimeter sub-classification; for instance 'office core' and 'office perimeter' specify the location of the office in relationship to the building thermal envelope. 'Perimeter' indicates that rooms are adjacent to the building thermal envelope and 'core' indicates fully internal rooms; subsequently this differentiation allows the specification of the infiltration as explained in Section 4.5.4.

Table 4-15 also shows area and volume data for the level 1 conditioned and unconditioned spaces. The floor area of conditioned thermal zones in Level 1, corresponds to 82 % of Level 1 gross floor area, total gross floor area in leve1 is 629 m^2 but the sum of the floor area of all conditioned and unconditioned thermal zones in level 1 is 887 m^2. This difference is because most of unconditioned spaces in the BEEM model correspond to upper ceiling spaces not accounted for in the gross floor area calculations.

The space volume (or air volume) of the conditioned thermal zones in level 1, corresponds to 80 % of the total volume of Level 1. The relative proportion between the space volumes of each of the different conditioned thermal zones is 16 % computer, 13% offices, 27 % classrooms, and 44 % gallery. The relative proportion between the space volumes of each of the different unconditioned thermal zones is 43% storage & circulations, and 57% unoccupied & voids & mass.

Table 4-16 and Table 4-17 contain the corresponding area and volume data for the conditioned and unconditioned spaces on Levels 2 and 3.

Table 4-16: Level 2 thermal zones area and volume.

Level 2 - Conditioned thermal zones	Area (m^2)	Volume (m^3)	Level 2 - Unconditioned thermal zones	Area (m^2)	Volume (m^3)
Gallery	108	728	Storage & circulation_Core	12	30
Office_Perimeter	47	180	Storage & circulation_Perimeter	24	94
Classroom_Perimeter	328	1,264	Unoccupied & Voids & Mass	64	96
Toilets	29	74	∑	100	220
∑	511	2,246			
Level 2 totals				611	2,466

Table 4-17: Level 3 thermal zones area and volume.

Level 3 - Conditioned thermal zones	Area (m^2)	Volume (m^3)	Level 3 - Unconditioned thermal zones	Area (m^2)	Volume (m^3)
Office_Perimeter	84	242	Storage & circulation_Core	31	105
Classroom_Perimeter	329	1,294	Storage & circulation_Perimeter	32	83
Gallery	201	752	Unoccupied & Voids & Mass	70	91
Toilets	29	74	∑	133	279
∑	643	2,362			
Level 3 totals				776	2,641

A detailed breakdown into each room under each of the thermal templates (conditioned and unconditioned) in Table 4-15, Table 4-16, and Table 4-17 is given in Appendix D (Table D-1, D-2 and D-3). The level of detail included in these appendix tables is what is required as input to the BEEM models of the Timber, Concrete and Steel buildings.

4.6 Modelling of the HVAC System in the Virtual Environment's Apache HVAC tool

As explained in Section 4.5.1 a high level of detailing was use to carefully model the HVAC system of the actual Arts building using the Apache HVAC tool, to enable the expected performance of the HVAC system to be examined when this was coupled together with a building model created using the VE building modeller ModelIT. In this research there are technically six building models created in ModelIT representing each of the three case study buildings (Timber, Concrete, and Steel), modelled with two different thermal envelopes (code-compliant and best practice).

Within the introduction to BEEM models in Section 4.1 it was highlighted that two different HVAC systems were modelled in the Apache HVAC tool, one representative of educational buildings (heating + mechanical ventilation) and another representative of commercial buildings (heating + mechanical ventilation +air conditioning). The buildings with the code-compliant thermal envelope were modelled using the educational HVAC system. Buildings with the best practice thermal envelope were modelled using both the educational and the commercial HVAC system (See case study buildings summary in Table 4-3, Section 4.2)

4.6.1 Overview of the HVAC system (educational and commercial)

This section introduces the two HVAC systems used for the modelling, specifying the most significant direct characteristics of each system itself and all indirect components associated with the operation of the systems, i.e. heat and cooling sources.

4.6.1.1 Educational HVAC system

The HVAC system in the actual Arts building includes mechanical ventilation provided by a centralized air handling unit (AHU) combining supply (2060 l/s) and return of air (2060 l/s). During the low temperature winter period, introduced external air can be warmed up to 27°C by a hydronic heating coil (45 kW capacity). A heat exchange unit operates in winter conditions, recovering heat from warm exhaust air.

Heating in level 1 is provided mostly by a hydronic heated slab (total capacity 26 kW). Heating in the level 2 and level 3 is provided by hot water radiators (total heating capacity in level 2 is 44 kW, and in level 3 43 kW). There is an air-conditioning unit in the computer room providing both convective heating and cooling. Heating coil capacity is 12.6 kW and cooling coil capacity is 10.3 kW. The computer room is 85 m^2 and is located in level; it is the only room with cooling in this HVAC system. Hot water is sourced from a diesel boiler with a capacity to deliver up to 200 kW at 80% efficiency while cooling in the computer room is sourced from an electric air cooled chiller with a cooling capacity of 30 kW. For the educational HVAC system, the detailed mechanical ventilation local air volumes and all radiant heating data are summarized in Table E-1 of Appendix E.

4.6.1.2 Commercial HVAC system

This alternative HVAC system is based in the educational HVAC system but considerable modifications were carried out when cooling was including. The mechanical air distribution system is basically the same as in the educational HVAC system with only one significant modification, being a relatively large cooling coil (45 kW capacity) which pre-conditions the air during summer conditions or warmer periods; this cooling coil is sized to being able to deliver 18°C if necessary to maintain a room temperature of about 24°C during the peak cooling day.

In addition to a cooling coil in the AHU, in this alternative HVAC system local convective cooling and heating has been added into all rooms which have directly supplied mechanical ventilation from the AHU (rooms in south side of the building, mostly). The systems used are ‘Parasol ® comfort modules’ which are water-based induced air systems with both a cooling and a heating coil. This system operates in a similar manner to chilled beams, but in the Parasol ® system the air is distributed in four directions instead of two.

Because of both convective heating and cooling being provided by the induced air units, most of the radiant heating systems in the conditioned rooms facing south were eliminated (radiant heating systems on rooms facing north remain the same as in the educational HVAC system). The most significant replacement of radiant heating systems on conditioned rooms facing south were the underfloor heated slab on Level 1, and the hot water radiators on Levels 2 and 3. Night-time mechanical ventilation was set to run during summer conditions whenever a specific outdoor temperature range is met.

For level 1 the convective heating capacity is 21 kW and convective cooling capacity is 21 kW as well. The radiant heated slab on the gallery’s ground floor (level 1) has a capacity of 12 kW. For level 2, convective heating capacity is 16 kW and convective cooling capacity is 12 kW (south side). Radiant heating capacity, on the north side of level 2 is about 8 kW. For level 3 south side, convective heating capacity is 16 kW and convective cooling capacity is 12 kW, radiant heating capacity is about 5 kW in the north side. The air-conditioning unit in the computer room remains the same as in the educational HVAC system. The hot water source is also the same as in the educational HVAC system, and the hydronic cooling is sourced from an electric air cooled chiller with a cooling capacity of 100 kW. The detailed mechanical ventilation local air volumes and all radiant and convective heating data for the commercial HVAC system, is summarized in Table E-2 of Appendix E.

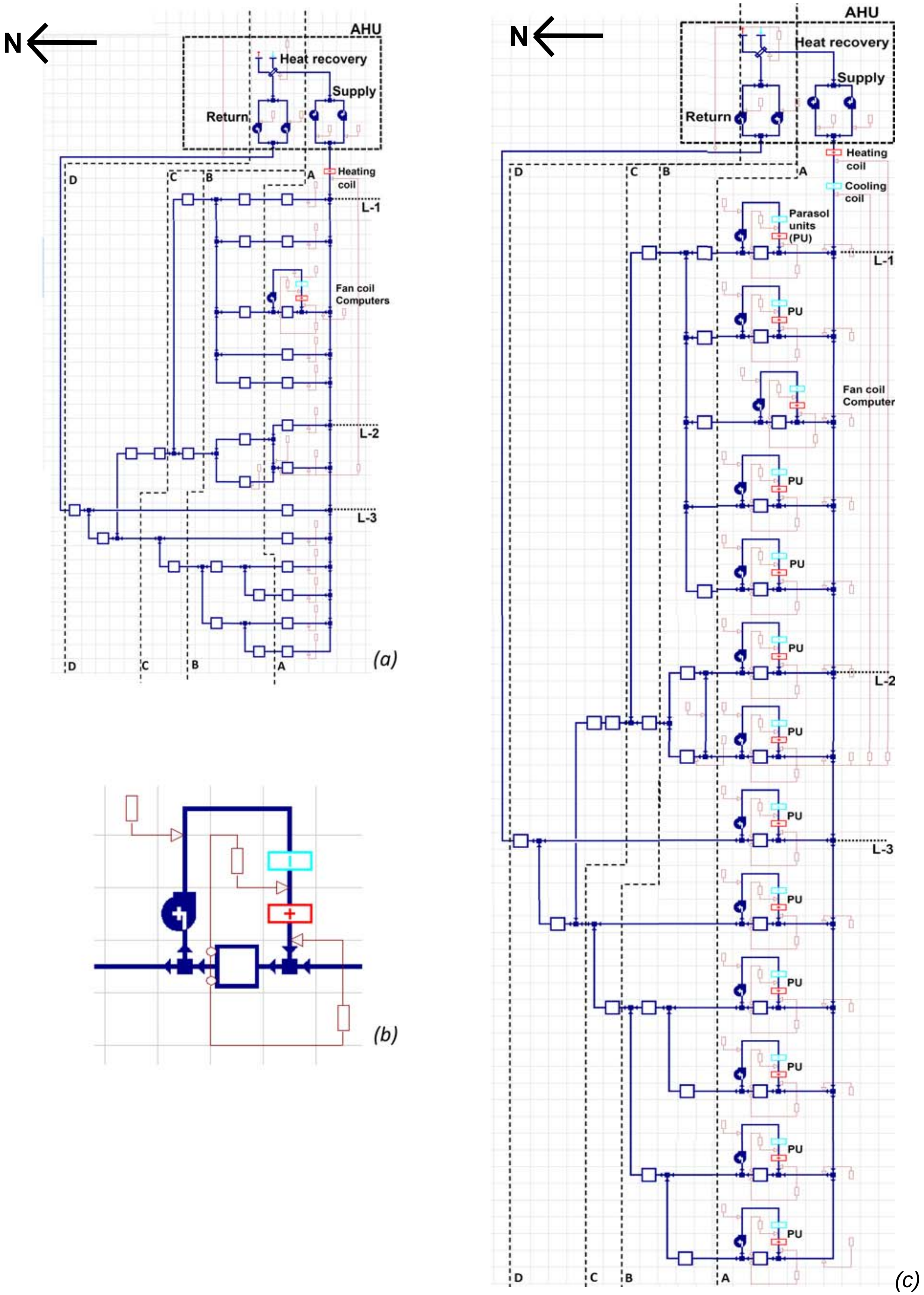


Figure 4-9: Schematic network of the HVAC system - educational (a) and commercial (c) - in Virtual Environment's Apache HVAC tool, and schematic of an induced air (Parasol ®) unit in (b).

Figure 4-9 shows the schematics of the mechanical ventilation network produced in the Apache HVAC tool, for the educational HVAC system (a), and the commercial HVAC system (c). Also in Figure 4-9 is a detail of the model in Apache HVAC tool of a Parasol ® unit (b), used repeatedly in the commercial HVAC system model (c). It can be seen in both HVAC systems, that the air handling unit supply air through a network integrated mainly by rooms and air connectors. Despite the apparent differences in both networks (a) and (c), mechanically supplied air flows through the network of connectors in the same networks equally.

Total mechanically extracted air is 2060 L/s and takes place in level 3; mechanically supplied air is 560 L/s in Level 1, and 750 L/s in levels 2 and 3.

4.6.2 Ventilation (mechanical and natural)

For a better understanding of the path that mechanically supplied and extracted air follows inside the building, it is worth remembering the building's layout explanation given previously in Section 4.1.2. As explained in that section the Arts building internal layout can be simply subdivided into three areas, being: the full height gallery space adjacent to the north wall; the flexible multi-use seminar and studio spaces adjacent to the south wall; and the narrow structural core in between the gallery spaces and the spaces towards the south wall. The narrow structural core has a suspended ceiling above the occupied space that creates a built-in 'plenum space' between the suspended ceiling and the structural floor above. That plenum is used as an air connector creating a path for mechanically supplied air to migrate from the rooms in the south part of the building to rooms in the north part of the building. The air finally flows through the gallery void up to the third floor of the galley where it is extracted. There is a single return air duct, which extracts air from the top of the gallery and directs it through the heat recovery unit, placed in the AHU, before the air is exhausted to the exterior.

Supply fans directly supply air to rooms in the south façade of each level. In Figure 4-9 each level is subdivided into segments (A, B, C, and D), representing the flow of mechanically-supplied air through the building. Rooms in segment A, correspond to rooms directly supplied with a mechanically-provided external air flow; normally these rooms are located adjacent to the south façade of the building. Rooms in segment B correspond to 'plenum spaces' used as air connectors of the narrow structural core. Segment C represents habitable and conditioned rooms north of the narrow structural core but south of the gallery void. Air migrating from the rooms in segment A is indirectly supply through the 'plenum spaces' (Segment B) to rooms in segment C. Air supplied to Segment C, carries all internal heat gains and relative humidity generated by occupancy in Segment A. Finally, segment D corresponds to unoccupied spaces such as gallery voids were the air flow is at that point driven by the return fan extracting the air from the top of the gallery.

Although thermal zones in segment D are catalogued as unoccupied these are indirectly conditioned.

Together with mechanical ventilation, most of the rooms exposed to the south, east and west walls can incorporate natural ventilation for cooling purposes (CO_2 concentration is kept to an acceptable level by the mechanically supplied air) by opening specifically placed openable windows. Natural ventilation in the gallery space is limited to openable windows in the east and west ends of Level 1 of the gallery, and openable windows placed at the top of the gallery (above the suspended ceilings of Level 3), not only in the east and west walls but also in a portion of the external wall of the gallery that, at that height, face south. The main entrance to the building is located in Level 1 at the west end of the gallery and there is a secondary entrance in the same level but at the east end of the gallery; both entrances combine doors and openable windows. There are no openable windows in the north façade.

4.6.2.1 Night-time ventilation

As initially suggested in Section 2.4 although thermal mass has the potential to reduce space conditioning energy consumption, it has a more noticeable influence in reducing cooling energy consumption, particularly in buildings with intermittent occupancy where night time ventilation can be integrated. To enhance effectiveness of night-time ventilation, a marked diurnal variation of outdoor temperature is necessary, in that regard diurnal outdoor temperature variation of 10 to 15°C were suggested as most favourable (Balaras, 1996; Barnard, et al., 2001; Thompson, 2006; Yang & Li, 2008).

Based in data from the TMY weather file from Nelson, New Zealand, average diurnal outdoor temperature fluctuation is in 7.4°C in November, 9.4°C in December, 7.7°C in January, and 8.2°C in February. Although average values are not particularly high the maximum values are closest to what is suggested as optimum in Section 0, being about 14°C in December and November, 12°C in January and 15°C in February.

Because it has been established that Nelson has appropriate conditions for the application of night-time ventilation, and because night-time ventilation is able to enhance the influence of thermal mass not only in reducing cooling energy consumption but also into improving indoor environmental conditions during buildings occupied time, night-time ventilation has been included in the commercial HVAC system (with cooling) modelled in Apache HVAC tool. In parallel, to assess the influence that night-time has over thermal mass performance, a commercial HVAC system was modelled without night-time ventilation, and this was used to carry out a comparison.

Night-time ventilation is set to operate from November 1st, across the summer, until the end of April of the following year. The specific daily profile used to control night-time ventilation established that from 8:00 until 18:00 (building's occupied hours) the AHU will have a constant supply of air at full capacity (200 l/s supply and 200 l/s return). At any other time, the AHU will supply and return air at full capacity, when outdoor temperature is below 22°C.

4.6.3 Heating and cooling

Table 4-18 and Table 4-19 show the heating and cooling capacities of the educational and commercial HVAC system respectively. Only hydronic systems are used for heating and cooling in both HVAC systems modelled in this research.

4.6.3.1 Heating and cooling in the educational HVAC system

In Table 4-18 both heating and cooling are subdivided by systems, i.e. radiators for heating, or air-conditioning for cooling.

Table 4-18: Educational HVAC system's heating and cooling capacities

	Educational HVAC system (Heating)						
	AHU	Radiators			Heated slab (kW)	Air-conditioning	
	Heating (kW)	R - 1 (4.6 kW)	R - 2 (3.8 kW)	R - 3 (2.7 kW)		Heating (kW)	Cooling (kW)
Level 1	45	0	0	0	26	13	10
Level 2		9	27	8	0	0	0
Level 3		18	19	5	0	0	0
∑	45	28	46	14	26	13	10

Total heating (kW)	171
Total cooling (kW)	10

Although hot water is used mostly for radiant heating systems such as heated slab, and radiators, there is also convective heating using hydronic heating coils to warm outdoor incoming air in the AHU (45 kW), or in the heating coil in the air-conditioning unit (13 kW) unit in the computer room (85 m^2). Radiators represent the most-used heating system with the highest heating capacity corresponding to about 50% of the total heating capacity. Convective heating from the AHU and the air-conditioning unit (mostly from the heating coil in the AHU) represents the second highest heating system used (about 35% of the total heating capacity) and the heated slab represent the remaining 15 % of the total heating capacity. Both heating coils in the AHU and air-conditioning unit are also present in the commercial HVAC system.

Cooling capacity is only 10 kW and is from the cooling coil of the air-conditioning unit in the computer room. Due to no occupancy during summer, the cooling coil is designed mostly to overcome large internal gains produce by high occupancy, computers and other equipment such as printers and photocopiers operating during any occupied period.

4.6.3.2 Heating and cooling in the commercial HVAC system

In Table 4-19 the most significant changes compared with the educational HVAC system is the inclusion of convective cooling and heating via induced air systems, and the inclusion of a cooling coil in the AHU for the conditioning of incoming air during summer conditions. Most of the heating systems in place on rooms located at the north side of the building are left as they are in the educational HVAC system.

Table 4-19: Commercial HVAC system's heating and cooling capacities

	Commercial HVAC system (Heating + Cooling)								
	AHU		Parasol Units		Radiators		Heated slab (kW)	Air-conditioning	
	Heating (kW)	Cooling (kW)	Heating (kW)	Cooling (kW)	R - 1 (4.6 kW)	R - 2 (3.8 kW)		Heating (kW)	Cooling (kW)
Level 1	45	45	21	21	0	0	12	13	10
Level 2			16	12	5	4	0	0	0
Level 3			16	12	5	0	0	0	0
∑	45	45	53	45	9	4	12	13	10

Total heating (kW)	136
Total cooling (kW)	100

The convective heating from the coils in the AHU and in the air-conditioning unit (computer room) represent about a 40% of total heating capacity available; convective heating from the Parasol ® units represent another 40%; the heated slab still remaining on the ground floor of the gallery accounts for 10% and the radiators on the north side of level 2 and 3 represents the remaining 10%.

Total heating capacity in the educational HVAC system is higher (171 kW) than in the commercial HVAC system (136 kW). This difference arises largely because of the modular nature of the standard heating component used in the two systems. The radiator modules used in the educational HVAC system seemingly are over-sided in comparison with the modular Parasol ® units in the commercial HVAC system. If in the educational HVAC system radiant heat represent about 65 % of the system total heating capacity, in the commercial HVAC system this represent only a 20% of the total heating capacity of the system.

Cooling capacity is relatively large in the commercial HVAC system (larger than the heating capacity). Most of the heating capacity is allocated to the cooling coil in the AHU (45 % of the total cooling capacity) and the cooling capacity of the Parasol © units represents 45 % of the system's total cooling capacity, with the remaining 10% of the total cooling capacity allocate to the cooling coil in the fan-coil unit.

4.7 Modelling method of the heating and cooling equipment

4.7.1 AHU heating and cooling coil

All external air is heated by a hydronic heating coil placed in the AHU before entering the indoor spaces in both the educational and in the commercial HVAC system. That heating coil is able to deliver off-coil air temperatures of up to 27°C when outside temperature is 0°C, for example. Due to a large air volume of incoming outside air (2060 l/s), the heating coil capacity is relatively large (45 kW). In the Apache HVAC model, off-coil temperature is controlled in the largest studio space in the building, being the studio room on level 2 (328 m^2). Depending on the outdoor conditions, off-coil temperature will be warmed up to 27°C to maintain an minimum indoor dry-bulb temperature in the studio on level 2, of 20°C with a proportional band-width of 2 K.

Particularly in the commercial HVAC system, a cooling coil is added to condition the incoming air when dry-bulb temperature in the studio room on level 2 increases above 24°C. Depending on the outdoor conditions, the off-coil temperature will be cooled down to a minimum of 18°C. In both HVAC systems in this research, the conditions in the studio room determine the dry-bulb temperatures of the air delivered to all other rooms with mechanical air supply from the AHU. In the case of the commercial HVAC system, off-cooling-coil temperature is controlled at 24°C with a proportional band-width of 2 K.

4.7.2 Fan-coil unit – computer room

The air-conditioning unit (fan-coil unit) in the computer room in both the educational and in the commercial HVAC system, recirculates a flow of air of approximately 700 l/s (no outdoor air added). There is a flow of air (250 l/s) directly supplied from the AHU to the computer room, but there is no mechanical extraction of air, only passive extraction via air connectors from the computer room to rooms in the north part of the building.

In the fan-coil unit, the heating coil is capable of delivering up to 35°C off-coil temperature, and the cooling coil is capable of delivering a minimum of 13°C off-coil temperature. Room temperature is proportionally controlled to have a mid-band temperature of 22°C and a proportional bandwidth of 4 K.

4.7.3 Hydronic heating and cooling induced air systems

The Parasol ® unit are modelled similar to a conventional fan-coil unit. Although the rate of air induction in the Parasol ® units vary depending on pressure and flow, this lies generally in the range of 3-5 times the volume of air supplied to a room by the AHU (Swegon, 2010). Each Parasol ® unit was modelled as a fan-coil unit recirculating the room air volume at four time the rate of the air supplied to the room by the AHU (normally about 125 L/s in small rooms); heating coil capacity is 2.7 kW and cooling coil capacity is 2.1 kW. Most of the rooms have only one Parasol ® unit installed, but in the case of the large studio space on level 2 a unit with five times the capacity of a single Parasol ® unit was modelled.

In Parasol ® unit, heating coil is capable of delivering up to 35°C off-coil temperature, and cooling coil is capable of delivering a minimum of 13°C off-coil temperature. Room dry-bulb temperature is locally controlled to have a mid-band temperature of 21°C and a proportional bandwidth of 4 K.

4.7.4 Hot water Radiators

As can be seen in Table 4-20 there are three different radiators used in the educational HVAC system (Table 4-18) being R-1 (4.6 kW), R-2 (3.8 kW) and R-3 (2.7 kW), and from those, two were subsequently used in the modelling of the commercial HVAC system (Table 4-19), being R-1 and R-2. Detail modelling data for the set-up of radiators in Apache HVAC tool includes not only the information in Table 4-20 but also the radiator's radiant fraction of the heat emitted (0.3), the referenced temperature difference (60°C) to specify the expected heat output of the radiator, and finally the radiators material which, in all three radiator types in the model, is steel. All data for the modelling of radiators is specific data from the manufacturer (Aquatherm, 2011).

Table 4-20: Radiator's input data as required in Virtual Environment's Apache HVAC tool.

	R-1	R-2	R-3
Heat Output At Ref. Temp. Difference (kW):	4.60	3.84	2.70
Distribution Pump Consumption (kW): [7]	0.01	0.02	0.01
Total Weight (kg)	71.0	81.7	39.8
Water Capacity (l):	17.0	30.4	9.50

[7] Total pump power consumption is divided by radiators and heated slab circuits.

Water in the radiators is distributed by two electric pumps (P-2 and P-3) placed on level 1 and Levels 2 and 3, are served by one pump each (Aurecon New Zealand Ltd, 2009). Motor power consumption in P-2 and in P-3 is 0.2 kW. Water distribution energy in Table 4-20 is simply the total water distribution energy divided by the proportion of the each radiator's water capacity to total system water capacity. No external heat losses of distributed water where assumed in the modelling, this is reflected in the model by having a heat output equal to the output from the heat source (Diesel Boiler). Total heat output for radiators in level 2 is 44 kW and in Level 3, output is 43 kW.

Controlling the performance of radiators involved the modelling of the behaviour of thermostatic radiators valves sensing room's dry-bulb temperature and controlling the flow of hot water (l/s) entering the radiator at 80°C. Thermostatic radiator valves where modelled with a set-point of 22°C and a dead-band of 2 K.

4.7.5 Hydronic Heated Slab

Table 4-21 shows, on a thermal zone basis, detailed heated slab specifications giving heat output together with room's area, water capacity of the room's heated slab, and room's heated slab water distribution energy. Data in Table 4-21 is input data for the modelling of the heated slab system in the Apache HVAC tool.

Table 4-21: Heated slab system main characteristics for modelling the Level 1 thermal zones in the Apache HVAC tool.

Level 1 - Thermal templates	Room Area (m^2)	Heated slab		
		Heat Output (kW)	Water Capacity (Lt)	Water Dist. Energy (kWh)[3]
Office_Core	28.2	2.80	20.6	0.03
Office_Perimeter	42.3	2.56	29.7	0.04
Classroom_Perimeter	141	8.36	115	0.16
Gallery	211	12.3	153	0.22
∑	**423**	**26.0**	**318**	**0.5**

The design and specification of the layout of the underfloor heating systems was produced by Aurecon and was made available for the modelling in this research (Halliday, 2010). The water capacity of the slab was calculated by initially calculating linear metres of hydronic tubing (PEX) per circuit serving each of the rooms grouped in the thermal zones in Table 4-21. Water capacity of a lineal metre of PEX was easily obtained based on tubing internal diameter found in the product specification (Kembla, 2011). Water capacity in the slab is the result of the linear metres of hydronic tubing used in the room, by water content of a linear metre of PEX. Water in the heated slab is distributed by a specially allocated electric pump placed in the first floor (Aurecon New Zealand Ltd, 2009). Motor power consumption of the pump is 0.45 kW and flow rate is 3.6 l/s. Water distribution power in Table 4-21 is simply the total water distribution power divided by the proportion of the room's heated slab water capacity to total system water capacity.

The dry-bulb temperature in rooms with underfloor heated slab in Level 1 is controlled in a similar way as heating radiators, i.e. by sensing the room's dry-bulb temperature and controlling the flow of hot water (l/s) entering the hydronic tubing embedded in the slab at 40°C. A thermostat was modelled with a set-point of 22°C and a dead-band of 2 K, meaning that dry-bulb temperature in rooms with underfloor heating will fluctuate, in winter conditions, between 21 and 23°C.

4.7.5.1 Heated slab modelling in the Apache HVAC tool

Heated slabs are modelled as separate thermal zones in Apache HVAC. By design, hydronic tubing is positioned 50 mm from the top surface and 100 mm from the bottom slab surfaces of the slab on ground (there is a 100 mm expanded polystyrene (EPS) layer below the concrete slab). Slab surface is thermally active. Floor surfaces are covered with vinyl in most of the rooms, and with carpet in some areas.

The modelling method used for this situation was suggested in (Moore, 2008). The internal volume of the slab zone was minimized to 0.1 litres per m^2 floor area, or an internal height of just 0.1 mm; this essentially eliminates the air volume without having a volume of zero. The Radiator component provided within Apache HVAC was then located within the minimized volume of the heated slab thermal zone. As explained in Section 4.7.4, modelled radiators requires values for thermal capacity, flow, mass, and pump power. The thermal capacity of this hydronic heating component was then set to be 100% convective to force its interaction with the slab materials to be similar to that of the water inside of the hydronic heating loop without the tubing material (which is accounted for in the finite-element modelling of slab conductivity, as described below).

The slabs are cast concrete at 2300 kg/m^3 with a specific heat capacity of 920 J/kg-K. The conductivity of the concrete was adjusted from 1.60 W/m-K down to 0.55 W/m-K for the layer of concrete above the hydronic tubing, to account for the size, material, and spacing of the hydronic tubing (Halliday, 2010; Kembla, 2011). This adjustment was made using THERM—a simple two-dimensional finite element heat transfer model from Lawrence Berkeley National Laboratory. Air-film resistance and emissivity for the inside surfaces of the slab zones were set to values approaching zero and 1.0, respectively. Because actual zero values are not permitted, a value approaching zero was used to represent these surfaces as if they were in direct contact with the heating water. The detailed analysis undertaken in Therm software to estimate the conductivity of the upper layer of the concrete heated slab, can be seen in Appendix F.

4.7.6 Heating and cooling sources

4.7.6.1 Boilers - heating sources

There is one boiler supplying both HVAC systems in this research. Table 4-22 shows the modelling data for this diesel boiler. It has a capacity to deliver up to 200 kW of heating at 80% efficiency; the total heating capacity of the system in place (including radiant and convective heating) is approximately 170 kW and 140 kW in the educational and commercial HVAC systems respectively. Electric water pumps were included in the model to distribute hot water inside the buildings to the heated slab in Level 1 and radiators in Levels 2 and 3.

Table 4-22: Boiler specification

Boiler	Fuel	Load performance		
		Load (kW)	Efficiency (%)	Distribution loses (%)
Boiler_Heating	Oil	200	80	0

In the Apache HVAC model the boiler was considered to be external to the building thermal envelope, therefore excluding any internal gains from boiler losses. Likewise, any energy input to the pump which externally supplies heating water to the building is considered to be external to the building model.

4.7.6.2 Chillers:

Two chillers were modelled, each serving one HVAC system. Table 4-23 gives the specification for each chiller. Both chillers are electric air-cooled units and these capacities are 31 kW and 100 kW for the educational and commercial HVAC systems respectively.

Table 4-23: Chiller specifications

HVAC system	Chiller type	Capacity (kW)	COP	Fuel	Distribution loses (%)	Oversizing factor
Educational	Air cooled chiller	31	2.3	Electricity	0.0	1.15
Commercial	Air cooled chiller	100	3.0	Electricity	0.0	1.15

Following the same approach as was taken with the boilers, chillers were placed adjacent to the building but outside its thermal envelope so no internal gains produced by the chillers have been incorporated in the modelling. As can be seen in Table 4-23 no distribution losses were included in the system. There is a primary water circuit incorporated in the chiller, driven by a pump consuming 6.2 W/(l/s), and a secondary circuit distributing chilled water from the chiller to the air-conditioning unit in the computer room. The consumption for the secondary pump is approximately 25 W/(l/s). Both pumps are included in the system modelling carried in the Apache HVAC tool.

5 Calibration of energy modelling

This chapter describes the structure and use of the reinforced concrete T-block building, including the design and installation of metering equipment instrumentation, measurement data and thermal modelling of the building over a full year. The chapter includes a comparison of monitored and modelled indoor temperatures, and a discussion of differences. The primary purpose of this chapter is to calibrate the energy modelling software in an existing building (T-Block), before moving to modelling of many variations of the Arts building.

5.1 The T-Block building

Three years before usage of the Arts building at the Nelson Marlborough Institute of Technology (NMIT) began in February 2011, the construction of another educational building of overall similar characteristics as the Arts building was completed.

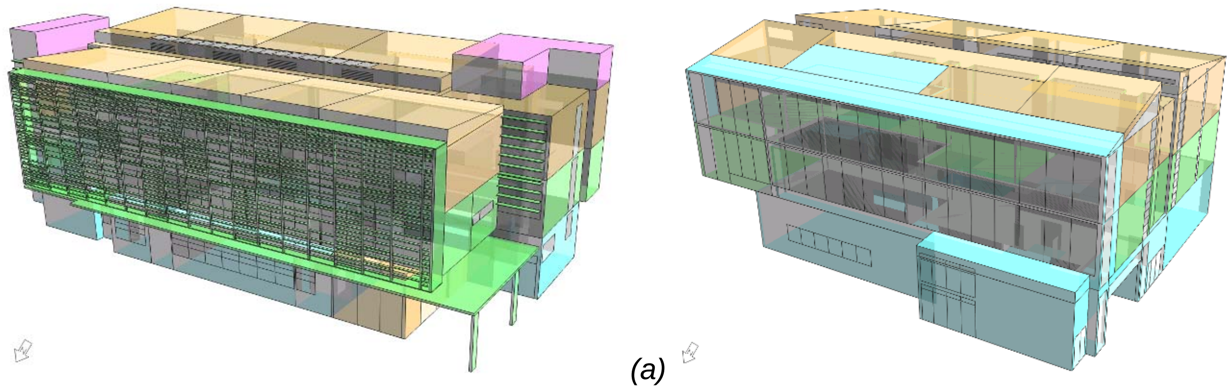
That adjacent building is called the T-Block and was built to host the school of Tourism, Hospitality and Wellbeing at NMIT. Figure 5-1 shows the relative positions of the T-Block and the Arts buildings when the latter building was under construction.


(a) (b)

Figure 5-1: (a) south façade of T-Block with the Arts building under construction to the left, and (b) the corresponding north façades.

When this current research commenced in August 2008 the construction of the T-Block was almost completed and by February 2009 the building was fully operational. Since both the T-Block and the Arts buildings have similarities in size, shape, occupancy, location and orientation it was decided that the first energy analysis of this research would be on the T-Block building and, later on, the experience gained in the energy modelling of the T-Block would be transferred to the Arts building's energy modelling.

Not only energy modelling was undertaken in the T-Block. Additionally a complete energy end-usage and indoor air temperatures monitoring system was designed and retrofitted into the building. The aim of installing metering equipment was to subsequently use the metered data to calibrate the energy model. In other words, real data from metering would allow a calibration of the energy modelling of T-Block and later on, by using a similar energy modelling methodology, validate the simulations in the Arts building. Also the work in the T-Block was an opportunity to become familiar with the BEEM methodology using IES Virtual Environment software (VE). The energy metering system was retrofitted to T-Block between May and July 2009, allowing energy end-usage data to be recorded from August 2009. The indoor temperature monitoring system already existed as part of the building management system (BMS) which controlled the building's air processing components.



(a) *(b)*

Figure 5-2: Comparison of the models produced in VE software for the T-Block building (a) and the Arts building (b), both displayed to same scale.

Figure 5-2 shows the model view in VE, of the north façade of both the T-Block and the Arts buildings. The level of detail of both building geometries applied to the outside geometry modelling is apparent. These images also show the approximates dimensions and overall shape similarities of the two buildings. Because the BEEM modelling of both buildings was not done simultaneously, there are a few refinements in the way geometry was model in the Arts building compared with the T-Block building, as will be detailed later.

This chapter explains the work undertaken in the T-Block to implement the metering system, process the data, and in parallel, calibrate the BEEM model. The emphasis here is very dominantly on T-Block, with only Section 5.2 including any comparisons with the Arts building which is the principal subject of this thesis research.

5.2 Geometry and construction of T-Bock and comparison with the Arts building

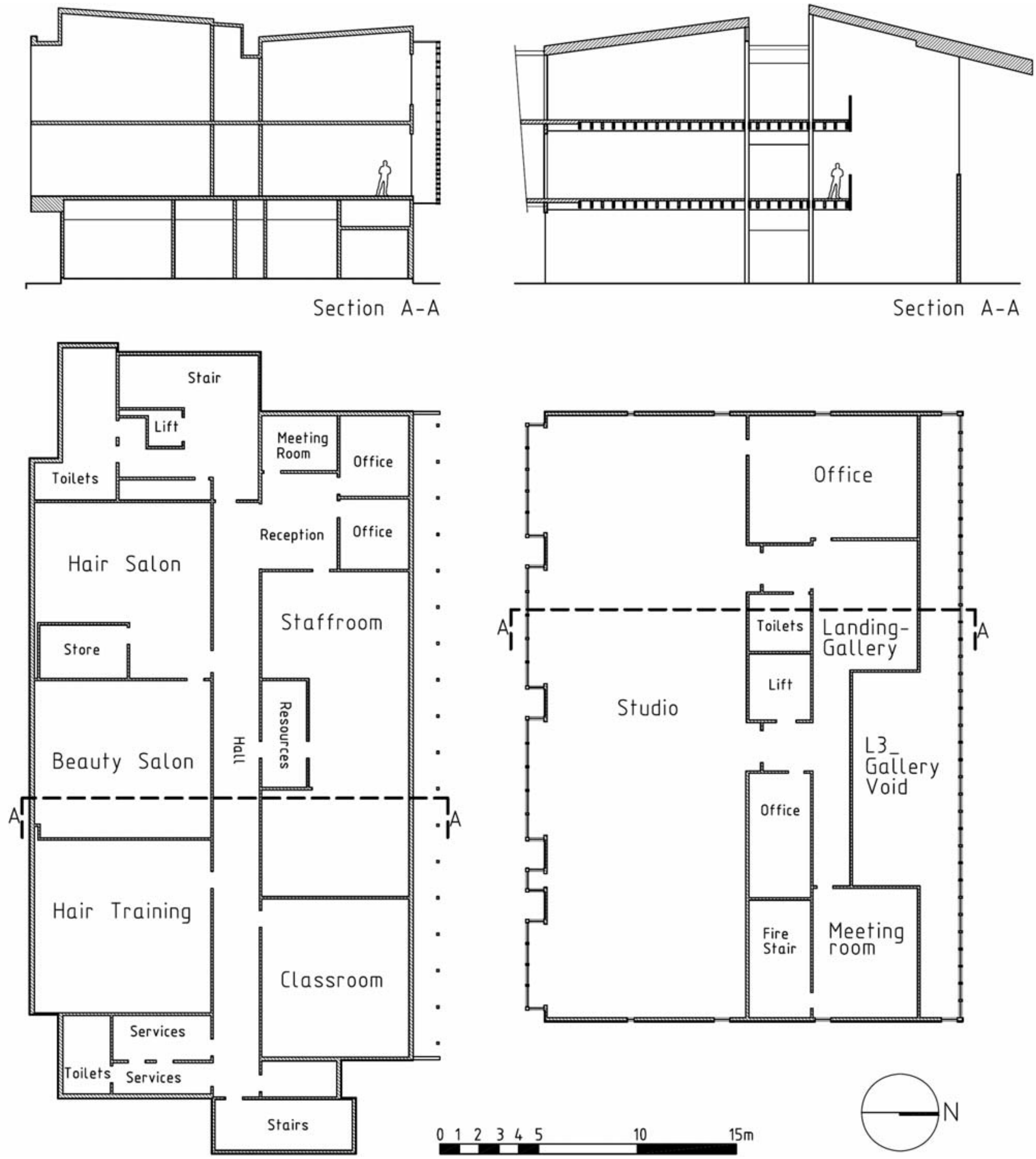


Figure 5-3: Comparison of the plan section in level 2 of the T-Block (left) and the Arts buildings (right).

T-Block is a three storey educational building of about 2,070 m^2 (gross floor area), combining not only spaces normally available in tertiary educational buildings such as classrooms, lecture theatres, computer room, academic and staff facilities, and administration offices, but also the sort of ‘unconventional’ spaces needed to teach the careers of catering and well being. In Level 1 of T-Block for example, there is a large training kitchen, a dessert kitchens (or cold kitchen), a coffee lab, a restaurant with a bar included, changing rooms, laundry and storage spaces (including a cold storage room). In Level 2 there is a beauty salon, a hair salon, and a hair training room in addition to conventional staff and administration facilities and class rooms. Level 3 is mostly class rooms, a lecture theatre and a computer room. There is a plant room above Level 3, where the Air Handling Unit and all fans supplying air to the kitchen area, and a large 2000 Lt domestic hot water calorifier are located; this plant room is referred to subsequently as Level 4.

Figure 5-3 is a comparison between the plan section of Level 2 in both the T-Block on the left and the Arts building on the right. In both buildings Level 1 is not representative of the layout in Levels 2 and 3 which are occupied by classrooms or studios, offices, and circulation spaces. In Level 1 of the Arts building a large area is allocated to circulations in the base of the atrium space whereas Level 1 of the T-Block is occupied by a large kitchen space and catering-related training areas.

In Levels 2 and 3 of T-Block, rooms are either exposed to the north or to the south façade leaving the circulation in the centre of the plan. The circulation space in the centre of the plan is configured as a continuous two storey hall because it is connected by large openings in the suspended floor of Level 3 allowing the air to flow between Level 2 and Level 3, and also visually connects both levels. The roof of the hall space is glazed, allowing natural light into Levels 3 and 2 of the hall space. There are also openable louvered windows at the side of the glassed roof of the hall space. These louvers are exposed to the outside and are controlled by the BMS to open and close depending on indoor air temperatures.

(a) (b) (c)

Figure 5-4: Pictures of the T-Block’s central hall space on Level 2 (a), Level 3 (c), and roof (b).

Figure 5-4 illustrates how the natural light is admitted into Level 2 through an opening in the floor slab of Level 3 (a). Also in (a) the glazed roof in Level 3 (containing louvred windows) can be seen.

Picture (b) shows an outside view of the operable louvred windows for natural ventilation into the hall. Finally in (c) the internal windows in Level 3 connecting rooms in the north façade with the internal hall are open for the circulation of air; this air is subsequently exhausted to the exterior through the louvred windows in the roof of the hall on Level 3.

5.2.1 Ventilation

Apart from being the main circulation space in Levels 2 and 3, and allowing natural ventilation, the hall permits space mechanical ventilation. This is because the hall in Level 2 contains the supply and returns ducts of the mechanical ventilation system to the classrooms, workshops and the hall in Level 2. This "centralized" layout of circulation spaces and mechanical air distribution, is essentially the opposite of the corresponding layout in the Arts building. As explained in section 4.6.2 , in the Arts building the mechanical ventilation is supplied to rooms in the south side of the building and extraction is located at the top of the gallery in the north side of the building. Also the main circulation space in the Arts building is located close to the gallery space in the north side of the building. In other words, in T-Block the mechanical supply and return of air is centralized in the central hall, whereas in the Arts building mechanical supply and return of air are widely separated with the air forced to migrate across each level from the south side to the north side of the building.

5.2.2 Comparison of T-Block and Arts building sizes

Table 5-1 and Table 5-2 are self explanatory; they present the data of floor area subdivided by levels and also the external wall area and the openings areas within these. This comparison shows the strong similarities between buildings. There is a difference of 87 m^2 (4%) between total gross floor areas of both buildings and this difference increases when looking at floor usable area where T-Block is almost 300 m^2 bigger than the Arts building. Although 300 m^2 seems to be a big difference, it represent a 15% increment of floor usable area and can be attributed to the fact that T-Block has two relatively large stairs areas, one at the east and the other at the west end of the building.

Table 5-1: T-Block and Arts buildings comparison of gross floor area and usable floor area.

Building	Levels	Gross floor area (m^2)	Floor usable area (m^2)	Lettable to usable (%)
T-Block	Level 1	646	600	93
	Level 2	711	667	94
	Level 3	711	724	102
	Total	2,068	1,991	96
Arts building	Level 1	629	594	94
	Level 2	676	560	83
	Level 3	676	540	80
	Total	1,981	1,693	85

Table 5-2 shows differences of 7% bigger total external wall surface in T-Block compared with Arts; this is not consistent with the size of external glazed area which is 5% bigger in Arts building compared with T- Block. Particularly in the south façade Arts building has 20% more glazing area than T-Block but on the other hand, the glass area in the north façade 12% smaller in Arts building compared with T-Block. The ratio of external wall to glazed surface is similar in both buildings when this is analysed by façades. Both buildings have a relatively large glazed area in the south façade which is inefficient because of large heat losses through windows, especially when these are facing south. The apparent architectural justification for this is that for both buildings both street frontage and primary access is on the south side.

Table 5-2: T-Block and Arts buildings external walls area and openings areas organized by building facades.

Building	Façade	External wall area (m^2)	External glazed area (m^2)	Glazed to wall (%)
T-Block	North	535	219	41
	South	467	269	58
	East	235	40	17
	West	297	71	24
	Total	1,534	599	39
Arts building	North	391	192	49
	South	475	323	68
	East	272	54	20
	West	284	58	21
	Total	1,423	627	42

5.2.3 Construction

T-Block is structured in precast reinforced concrete column and beams (in the first two levels) supporting an Interspan ® flooring system in the suspended floor of Levels 2 and 3 (the same floor system as in the Arts Concrete building); above the suspended floor in Level 3 the building is structured in steel columns and roof beams and purlins. The thermal envelope is mostly light-weight insulated walls but some uninsulated concrete structural walls are located in the stairs wells on the west and east side of the building.

As explained earlier in Section 4.2.2, each construction is characterized by its resistance R as an indication of the thermal resistance, and a capacitance C as a very approximate indicator of the capacity of the construction to store thermal energy. Table 5-3 lists the R and the C values for each component of building's thermal envelope in this comparison.

Table 5-3: Comparison of the material R and C values in the thermal envelope of the two buildings.

T-Block	∑R	∑C
Thermal envelope		
Slab on Ground_Vinyl	5.4	2,800
Roof - Steel sheet	2.5	40
Roof - Asfalt Membrane	2.5	40
External light envelope Wall	2.4	30
External Concrete Insulated W	2.3	400
External double glazing	0.4	20
Suspended floor		
Interspan floor - Vinyl	0.4	300
Interspan floor - Carpet	0.7	300

Arts and Media	∑R	∑C
Thermal envelope		
Slab on Ground_Vinyl	3.4	1,600
Roof - Steel sheet	5.1	60
External light envelope Wall	2.8	30
Insulated LVL shear wall	2.7	200
External double glazing	0.3	20
Suspended floor		
Potius - Vinyl	0.8	300
Potius - Carpet	1.1	300

Although most of the constructions listed in Table 5-3 form part of the thermal envelope of the buildings, the suspended floor systems are included as well because of their high C value and hence high thermal mass potential. Most of the thermal envelope in T-Block is the 'external light envelope wall' having R and C values similar to those for the same envelope component in the Arts building. The 'Roof' construction used in T-Block has much lower R value than that in the Arts, conversely, for the 'slab-on-ground' construction, T-Block building has a higher R value than that in the Arts building because of a thicker insulation layer below the 'slab-on-ground' of the T-block.

The geometry of both buildings was modelled into VE using the Model IT interface. For both buildings all architectural, structural, and mechanical services design drawings where provided by the designers. A high level of detail was taken to produce both models, although several lessons were learned in modelling T-Block that were implemented later in the modelling of the Arts buildings.

5.3 Thermal conditions in T-Block

This section describes the methodology used for the modelling of thermal conditions inside T-Block. This Section can be compared against Section 4.5 where in detail description of the modelling of internal gains, infiltration, occupancy, lighting, and thermal zoning of the Arts Building are given.

The interface used for the dynamic energy simulation of T-Block is Apache-Sim which is a simplified building and system performance simulation tool that modelled mechanical systems energy for idealised heating and cooling plant. Apache-Sim can also use input data from the Apache HVAC tool, where more specific HVAC system can be modelled (as was used in modelling the Arts building). Apache-Sim is used for calculations of conditioning energy consumption in idealized HVAC system (using predefined HVAC systems), it can also work coupled with Apache HVAC tool for the input of specific HVAC systems.

5.3.1 Profiles in the T-Block building

The rationale behind the use and production of operation profiles in VE has been given earlier in Section 4.5.3. The occupancy profile in T-Block is given in Table 5-4.

Table 5-4: Schedules used in VE to define daily and weekly operations.

	12am-8am	8am-6pm	6pm-12am
Monday to Saturday	0%	100%	0%
Sunday	0%	0%	0%

Weekly profiles used as blocks create the time variation pattern of a monthly or an annual profile. Table 5-5 shows the annual profile which was produced based in the NMIT 2010 academic year. The schedule is subdivided in four study block with study breaks of about two weeks in between and a long summer break at the end of semester two.

Table 5-5: Schedules used in Virtual Environment to define annual operations.

Annual schedules	Sart - End		Sart - End		Sart - End		Sart - End	
	Day Mth.	Day Mth.	Day Mth.	Day Mth.	Day Mth.	Day Mth.	Day Mth.	Day Mth.
Occupancy	7 Feb.	1 Apr.	18 Apr.	2 Jul.	18 Jul.	24 Sep.	10 Oct.	26 Nov.
Heating	6 May	29 Oct.						

Table 5-5 also includes the annual heating profile which starts on the May6 and runs continuously until October 29. Outside this period, the only heating available is from an electric coil in the Air Handling Unit (AHU) which, if necessary, pre-heats cold incoming air to 20°C during occupied hours.

5.3.2 Thermal templates in the T-Block building

All the spaces in T-Block have thermal conditions pre-arranged and grouped in thermal templates. Thermal templates were superimposed on all occupied spaces inside the builidng's thermal envelope. In T-Block thermal templates only contain specific data for internal gains, lighting and infiltration.

Table 5-6 lists the four thermal templates used in T-Block and also includes the usable floor area associated with each of these thermal templates. Only “unheated” spaces have no conditioning energy associated with them and represent 22 % of the usable floor area in Level 1, 12 % in Level 2 and 28 % in Level 3 (20 % of the total building usable area).

Table 5-6: Thermal templates and their respective extension (Lettable area) in the T-Block building.

Thermal templates	Level 1 (m^2)	Level 2 (m^2)	Level 3 (m^2)	∑
Heated	186	219	498	902
Heated + Mechanical Ventilation	195	235	0	430
Unheated + Mechanical Ventilation	90	131	24	244
Unheated	130	83	202	415
∑	600	667	724	
Total usable area (m^2):	1,991			

As shown in Table 5-7, all four thermal templates have the same internal gains associated with people and lighting. Particularly in lighting, a dimming profile was created in VE to allow for external natural light to be equated into the illuminance per square metre calculation (500 Lux). In some specific rooms in Level 1 such as the training kitchen and all catering related areas, the beauty salon, and the hair training room in Level 2, an "equipment" internal gain was added to the thermal template. This gain added to the space a sensible gain of 80 W/m^2 and an electricity consumption of 80 W/m^2. Later on during the calibration process, an electricity consumption of 40 W/m^2 was added to all conditioned spaces in the model, this was done to artificially increase total electricity consumption to match what has been monitored for that building. Infiltration in T-Block was set to 0.5 ac/hr in all rooms located adjacent to the thermal envelope and 0 ac/hr in all fully internal rooms.

Table 5-7: Thermal templates used in T-Block

	Internal Gains				
	People			Lighting	
	Occupant Density (m^2/Person)	Sensible Gain (W/Person)	Latent Gain (W/Person)	Total illuminance. Natural + Electric (Lux)	Sensible gain (W/m^2)
Heated	10	90	60	500	18.8
Unheated					
Heated + Mech. Vent.					
Unheated + Mech. Vent.					
Installed power density					3.75 W/m^2/(100 lux)

As already mentioned, the interface for the dynamic energy simulation used in T-Block is a simplified system performance simulation called Apache-Sim. A "System" tab dialog within Apache-Sim allows the creation of HVAC systems by setting their properties. Table 5-8 summarizes the principal characteristics of the HVAC system assigned to the rooms grouped as a block under each thermal template organized in each level in T-Block.

Table 5-8: HVAC system in T-Block (summary)

Level	Thermal Templeate	Floor lettable (m^2)	Heating capacity (kW)	Total Supply and Extraction		
				Supplied (L/s)	Extracted (L/s)	Supply - Extract (L/s)
Level 1	Heated	186	13.0	0	0	0
	Heated + Mech. Vent.	195	13.4	5,640	6,622	-982
	Unheated + Mech. Vent.	89.5	0	591	1,264	-673
Level 2	Heated	219	17.6	0	0	0
	Heated + Mech. Vent.	235	15.8	830	1,000	-170
	Unheated + Mech. Vent.	60.2	0	30.0	300	-270
	Hall	70.6	0	270	0	270
Level 3	Heated	498	34.4	0	0	0
	Unheated + Mech. Vent.	23.8	0	0	200	-200

For each thermal template, the total heating capacity assigned is given in Table 5-8, which also details the way that mechanical ventilation is simplified in Apache-Sim as a flow of air which is the result of the differences between mechanically supplied and returned air. The mechanical ventilation data, organized under "Total Supply and Extraction" present the data of every thermal template that has mechanical supply or extraction. Using the 'Heated + Mechanical Ventilation' thermal template in Level 1 as an example: This has 5,640 l/s supplied and 6,622 l/s extracted.

- This creates a deficit of 982 l/s which is supplied in VE as external air.
- The 5,640 l/s is supplied in VE as temperature from a created profile, were external air will be supplied into the room unless its temperature is lower than 20°C, in that case, air at 20°C will be supplied.

In the case of the negative flow of 982 l/s this is proportionally set up for each room individually. If the room is adjacent to the thermal envelope of the building, the proportional flow of air created for the negative pressure will be supplied from the exterior environment, in the case of being a fully interior room, the air is supplied from an adjacent room.

For the purpose of this exercise, there is no cooling supplied to any room in T-Block, although there is convective heating produce by the heating coil in the Air Handling Unit (22 kW), the effect of this is modelled by applying the profiled temperature to the flow of supplied air, all other heating source is model as radiant by setting a heating source's radiant fraction of 0.5.

5.4 Real time Weather File production

The weather data normally used in BEEM simulations are typical meteorological year (TMY). Metered data, on the other hand, shows the performance of a building under real conditions, with real meteorological data. The difference between a TMY and the real meteorological data during any monitoring period will be one contribution to the inevitable differences between the results produced in the simulations, and energy/temperature data from the actual buildings.

To allow a more meaningful check of the simulation model, a weather file using real weather data was created by taking Nelson's 2010 specific meteorological data and converting this into an input file for simulations. Actual data was retrieved from NIWA's CliFlo database (NIWA National Institute of Water & Atmospheric Research, 2011). The data retrieved was: dry-bulb temperature, dew point temperature, relative humidity, atmospheric pressure, global horizontal radiation, wind direction, wind speed, and total sky cover

This data was recorded at Nelson airport weather station. If there were any gaps in the hourly data, this missing data was retrieved from Blenheim airport. Total sky cover data was given in eighths and then converted to tenths which was the required format. The total sky cover was given in three altitude layers, with separate cover given for each layer. When there were different covering percentages for each layer, the greatest amount of coverage was chosen to represent the total sky cover. This method would most likely tend to underestimate the cloud cover. The opaque cloud cover was then simply a copy of the total sky cover which would help to correct this underestimate. Diffuse and direct beam radiation was calculated from global horizontal radiation using NIWA's solar view algorithms; this data was provided by NIWA (Liley, 2011).

To convert the data retrieved as an Excel file, from NIWA's CliFlo database to an EPW file (EnergyPlus Weather Data) that can be used for simulations in VE, the Weather-Converter program from EnergyPlus energy simulation software was used (US Department of Energy, 2010). The Weather-Converter program can process raw weather data in several formats into an epw. format (EnergyPlus, 2010).

Table 5-9: Composition of the Nelson TMY weather file. The year from which the meteorological data of that specific month was taken to build the TMY file is also specified.

Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Weeks	1 - 4	5 - 8	9 - 13	14 - 17	18 - 22	23 - 26	27 - 30	31 - 35	36 - 39	40 - 43	44 - 48	49 - 52
Year	2005	2000	1995	2007	1995	1997	2006	1998	2000	2006	2002	2002

Figure 5-5 is a whole year comparison between both, the weekly average dry-bulb temperature in the TMY and in the custom 2010 weather files, and the weekly average global radiation in the TMY and in the custom 2010 weather files. Both, dry-bulb temperature and global radiation data in the custom 2010 weather file is data retrieved from NIWA's CliFlo database, and are parameters having the greatest influence on buildings conditioning energy performance than any other data type in the weather file.

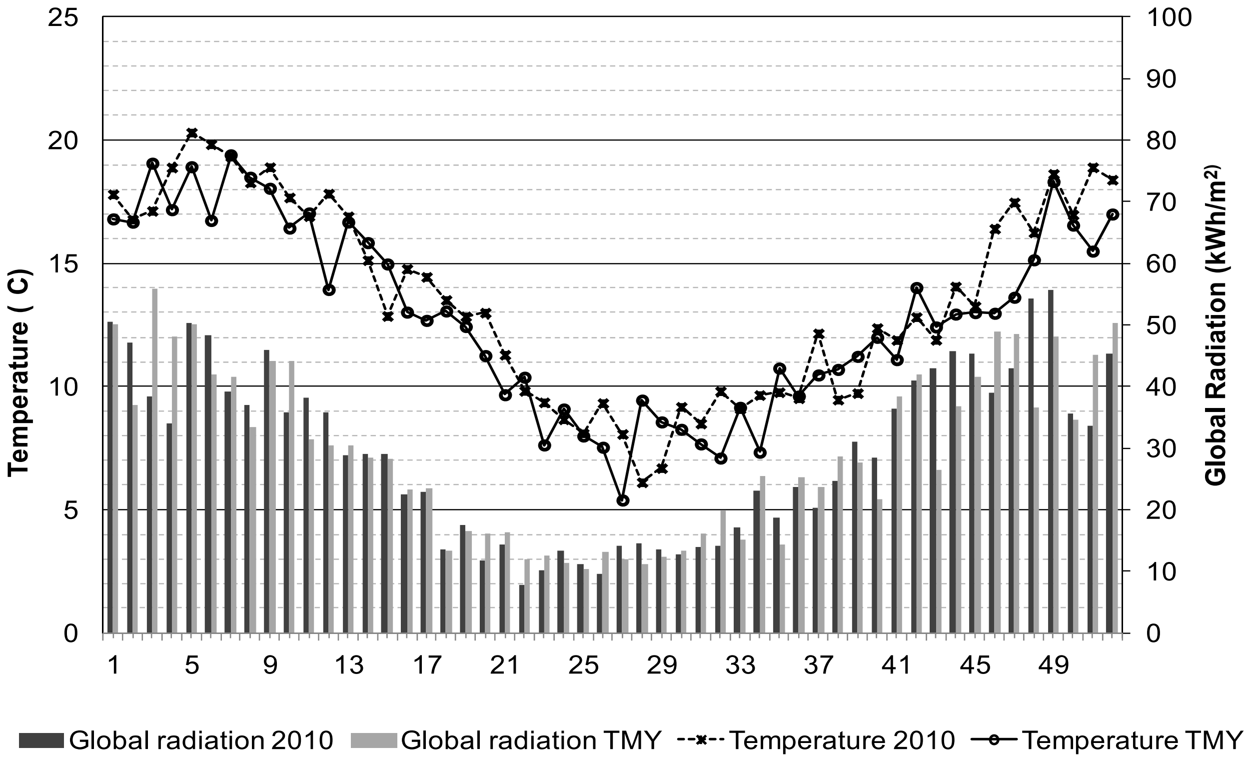


Figure 5-5: Whole year, average weekly, comparison between outdoor dry-bulb temperature and global radiation in the custom 2010 and the TMY Weather files.

Figure 5-5 shows that the weekly average temperature does not differ significantly in the TMY when compared with conditions in 2010. Although the 2010 temperatures were slightly lower in the first half of the year than corresponding temperatures in the TMY. The peak difference is about 4°C in Week 12 and in Week 47. Figure 5-5 shows a similar trend for global radiation, with is no significant difference between both weather files but some isolated peak differences occurring in the warmest weeks of the year (about 20 kW/m^2 in Week 4 and about 18 kW/m^2 in Week 49).

Table 5-10: Comparison of outdoor dry-bulb temperature and global radiation in the custom weather file and the TMY weather file.

	Dry-bulb temperature (°C)		Global radiation (W/m²)	
	2010	TMY	2010	TMY
Average	13.6	12.9	175	175
Max	28.0	29.0	1,066	1,109
Min	-2.0	-1.7	0	0
Median	14.0	13.0	0	3.0
Standar Dev.	5.2	4.9	263	263

Table 5-10 is a summarising comparison of relevant statistics for 2011 and the TMY dry-bulb temperature and global radiation. These statistics confirm that the custom 2010 weather file is not unusual.

5.5 Metering layout and equipment

The monitoring of the T-Block building includes total electricity, total heating energy, and various energy end-uses together with indoor temperatures in 6 rooms. The system was designed and installed by a company specialising in energy management (Schneider Electric, 2011). Because the monitoring equipment was retrofitted on May 2009, energy monitoring was adapted to the existing electrical services design. Temperature monitoring equipment has been installed previously to feed data to the BMS, to control incoming air temperature in the air handling unit and schedule the opening of windows located in the thermal envelope for natural ventilation. The energy and temperature monitoring points are summarized in Table 5-11.

Table 5-11: List of meters for energy and temperature in T-Block.

Energy	
Thermal Energy:	
1	Water Energy (Heating)
Electric Energy (Distribution boards):	
2	Mains
3	Kitchen
4	Hot Water Storage

Temperature		
Room Air Temperature:		
1	Level 1	1A - South
2		1B - South / West
3	Level 2	2A - North
4		2B - South
5	Level 3	3A - North
6		3B - South
Other Temperatures:		
7		AHU Supply Air
8		Outside Air

5.5.1 Thermal Energy Monitoring

Thermal energy refers to low pressure hot water (LPHW) provided by the NMIT's central boiler and used for hydronic heating by radiant slabs and radiators inside the building. LPHW is the only source of heat for heating, except for an electric coil (23 kW) in the AHU operating on demand when the boiler is "Off". The monitoring equipment for LPHW consists of a flow meter and temperature sensors in the LPHW supply and return pipes at entry to and exit from the building (see Figure 5-6 (a)). The monitoring provides heating energy in kWh by accounting for water flow, and temperature difference in and out of the building. A picture of the flow meter and the temperature sensor in the LPHW supplying pipe can be seen in Figure 5-7 (a).

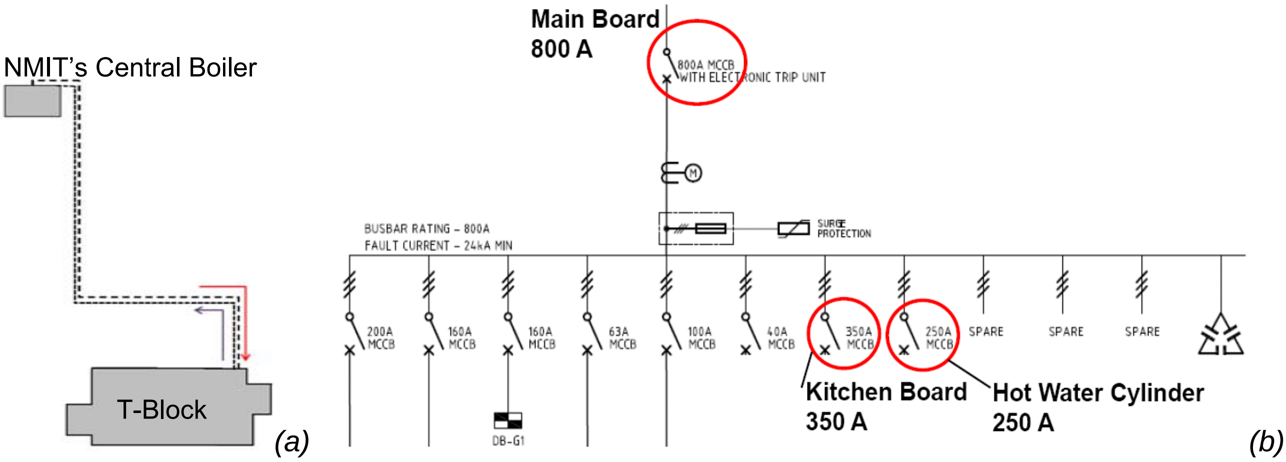


Figure 5-6: Illustration (a) is the layout of LPHW distribution to the T-Block building, and (b) is the electric services single diagram.

5.5.2 Electric Energy Monitoring

For electric energy monitoring, monitoring equipment was installed in three distribution boards in T-Block, being the main electricity distribution board, the kitchen and the hot water calorifier electricity distribution boards.

Figure 5-6 (b) shows the electrical services of the building. The circuit breaker on the main distribution board has a capacity of 800 ampere while the capacities for the kitchen and for the hot water calorifier are 350 and 250 ampere respectively. Totalling 600 A, these two sub-circuits represent 75 % of the total distributed electricity by the main electricity board so that identifying these two biggest energy end uses provides a rough idea of the electricity consumption of the rest of the building without the unusual energy end-uses necessary to run mostly the spaces allocated for the teaching of cooking and catering in Level 1.

As mentioned in Section 5.2 in T-Block there are "unconventional" spaces needed to teach the careers of catering and well-being. In Level 1 there is a large Training kitchen, a dessert kitchen (or cold kitchen), a coffee lab, and storage space including two large cold storage rooms. The electricity consumption of such spaces is distributed from the kitchen distribution board. In the plant room on Level 4, a 2000 Lt hot water calorifier is installed, and supplies the large demand of domestic hot water (DHW) of not only of the kitchen and catering areas on Level 1, but also the toilets in Level 1, Level 2 and Level 3, and the hair washing equipment in the beauty salon on Level 2. Thus by subtracting from main electricity consumption, the electricity consumption of the kitchen area on Level 1 and the hot water calorifier on Level 4 a rough approximation of the building's lighting, equipment, and mechanical ventilation electricity consumption can be obtained. Figure 5-7 (b) shows three current transformers (CT), installed (clipped) in each of the three phases feeding the main distribution board.

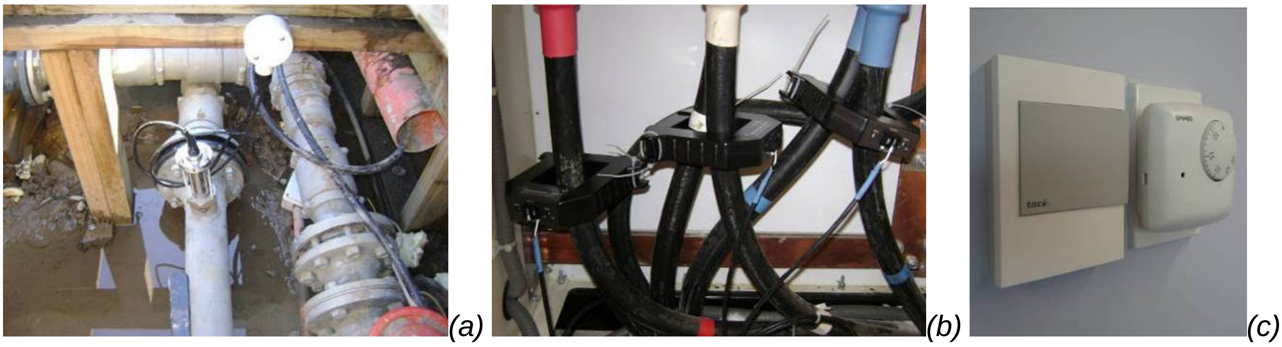


Figure 5-7: (a) Heating energy meter (hot water flow meter plus water temperature meter), (b) Current transformer installed in each phase of the main electric board, (c) Temperature meter.

5.5.3 Temperature monitoring

Figure 5-7 (c) illustrates one of the air temperature monitoring devices. These sensors are located in six rooms in T-Block: two rooms on each floor - normally one facing north and a second one facing south – as detailed in Figure 5-8.

Figure 5-8: Room temperatures – location of the 6 rooms being monitored in the T-Block building. From left to right the monitored rooms located in Level 1, Level 2, and Level 3.

Figure 5-9 (a) illustrates the specific location of one of the temperature sensors is shown, circled, in the staff office (labelled 2A in Figure 5-8). Generally the sensors were located on an interior partition, as far as possible from the thermal envelope of the building.

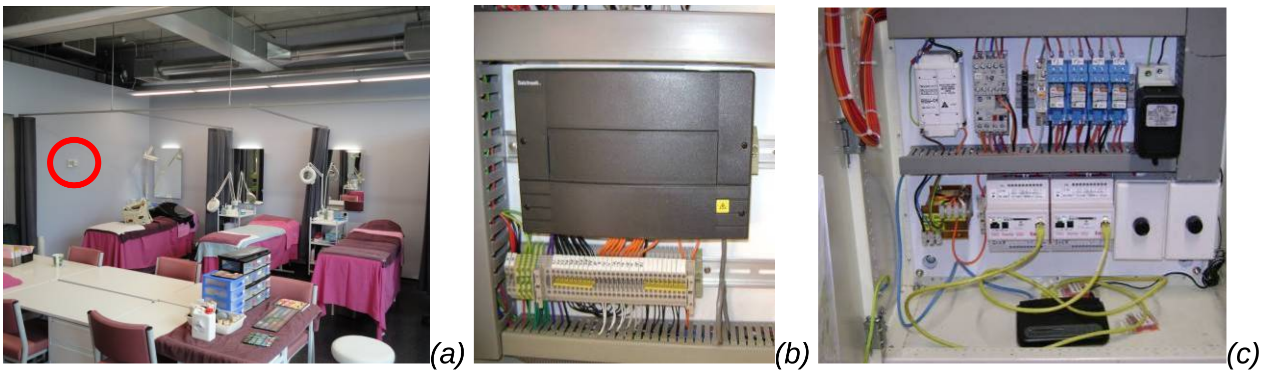


Figure 5-9: (a) detail of the location of the temperature meter in the beauty salon, (b) controller, (c) embedded web server.

The monitoring system is designed for small and medium sized buildings and is web-based, allowing remote monitoring. Figure 5-9 (b) shows the programmable controller and in (c) two embedded web server are visible at bottom centre. Programmable controllers receive data mostly from air temperature and manage the operations of the Air Handling Unit. The web servers collected the data every hour (energy), and half hour (air temperature), into a one day file in a text format, which was automatically sent to the author by email daily. On receipt these files were copied into an Excel file for the creation of weekly, monthly and finally year files of monitored data and graphs.

5.6 Monitoring results and comparison with modelled data

The emphasis of this thesis is into indoor space conditioning energy consumption which, in the case of T-Block and also in the Arts building, is mostly thermal energy (because of the almost total absence of refrigeration). In this research, DHW is assumed to contribute negligibly to the internal space heating. In T-Block although DHW is relevant in total electricity consumption, has very little internal gains associated with it. This is mainly because not only the hot water calorifier is installed on the plant room outside the building's thermal envelope, but also because most of hot water goes down the drain and does not remain within the occupied spaces. This is consistent with one modelling study comparing slab-integrated radiant cooling to more conventional alternatives in a set of different climate conditions (Moore, 2008). In that study, DHW was taken out of the study due to its low contribution to internal loads.

Other than lighting the modelling of T-Block, did not attempt initially to quantify the distribution of electrical input via plugged in equipment – just the total heat input. By visiting the building, a rough estimation of room equipment energy consumption was obtained; these values were then input into the thermal templates of each room as direct heat gains. Lighting energy consumption can be modelled with more accuracy by defining illuminance values per room and the type of lighting equipment used. For the objective of this research, the results of monitored heating thermal energy consumption and the resulted indoor air temperatures are the most significant data to be compared against modelled results. Since there is not a monitoring system in place that is able to break down total electricity consumption into electricity end-uses, total monitored electric energy consumption in T-Block is used as a benchmark for the estimations of internal gains in the model.

5.6.1 Electric energy consumption comparison

Table 5-12 shows the electrical energy consumption in DHW, kitchen area, and 'others', together with thermal energy consumption obtained from monitoring data in T-Block.

Table 5-12: Total monitored energy in T-Block during 2010.

	Electric energy (MWh/yr)			Thermal energy (MWh/yr)
	DHW	Kitchen	Others	Heating
	111	14	198	59
Total electricity (MWh/yr)	322			
Total energy (MWh/yr)	381			

'Others' electric energy consumption is the result of total electric energy less DHW and kitchen electric energy consumption (as explained in Section 5.5.1) which is a rough estimate of the electric energy consumption of conventional electric energy end-uses such as lighting, equipment and mechanical ventilation for areas of the building not included in the kitchen electric distribution board. Figure 5-10 is a comparison between monitored and modelled total electric energy, also included is the monitored and modelled total electric energy with DHW and kitchen area electricity subtracted out ('Others' in Table 5-12). It is this net electric energy consumption that was used for the estimation of internal gains for modelling of thermal energy consumption.

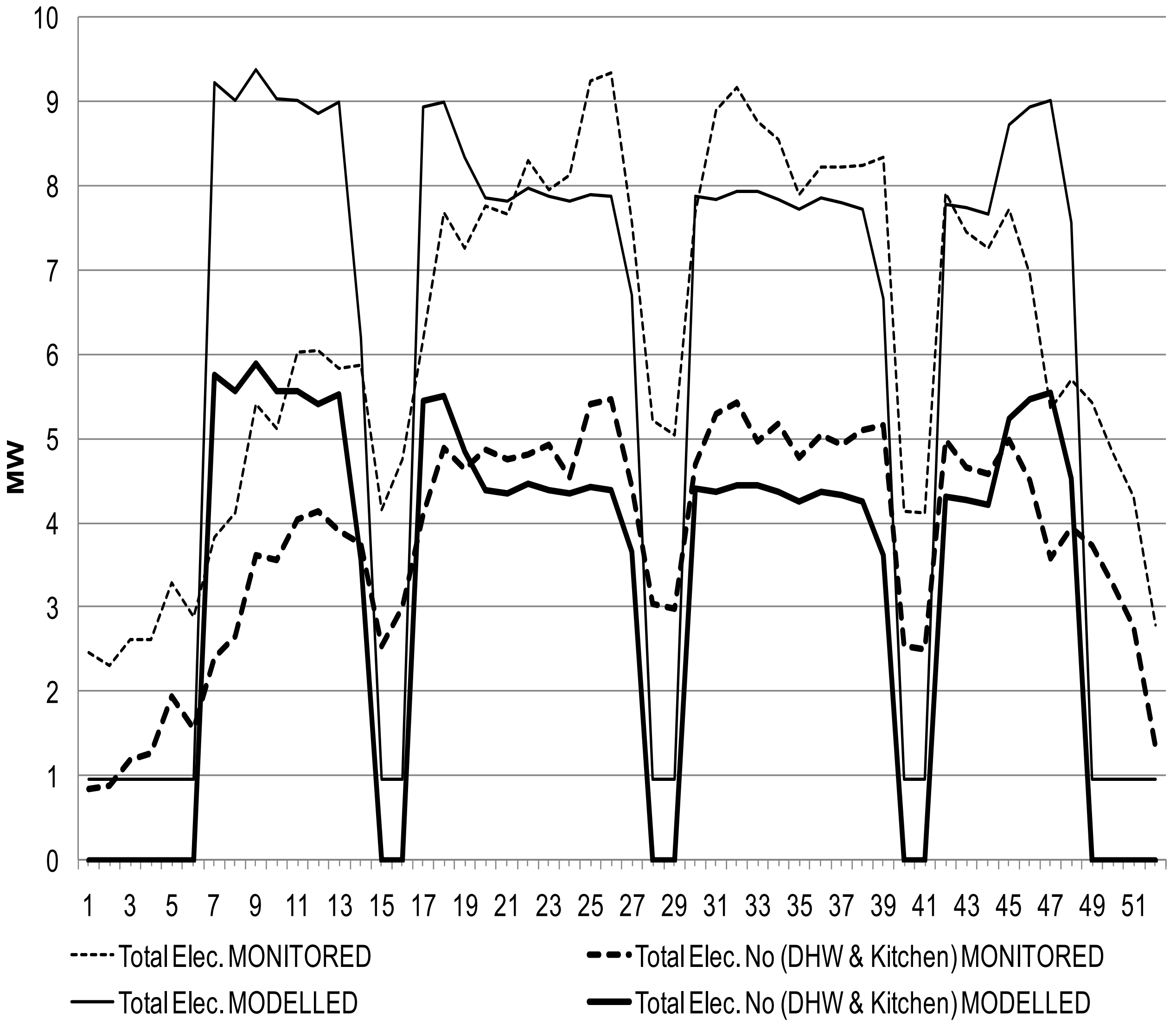


Figure 5-10: Total Electricity consumption + DHW Energy consumption

The actual values of monitored and modelled total electric energy consumption compared with 'Others' electric energy consumption is given in Table 5-13. To achieve the similarity between monitored and modelled values in Table 5-13, modelled electric energy consumption had to be increased by adding extra equipment electricity consumption (about 20 W/m^2) to all spaces which subsequently increased internal gains. This is a very simplified approach to deal with the uncertainty of real internal gains generated by conventional electric energy end-uses.

Table 5-13: Summary comparison between metered and modelled data

	Total Elec.	Total Elec. No (DHW & Kitchen)	Total Elec.	Total Elec. No (DHW & Kitchen)
	MONITORED	MONITORED	MODELLED	MODELLED
Average (kW)	6.2	3.8	5.9	3.3
Max (kW)	9.3	5.5	9.4	5.9
Total (MWh)	322	198	308	169

5.6.2 Thermal energy consumption comparison

A comparison between monitored and modelled weekly heating thermal energy consumption, can be seen in Figure 5-11. Weekly average outdoor air temperature is also included to identify the influence of climate conditions on heating energy consumption.

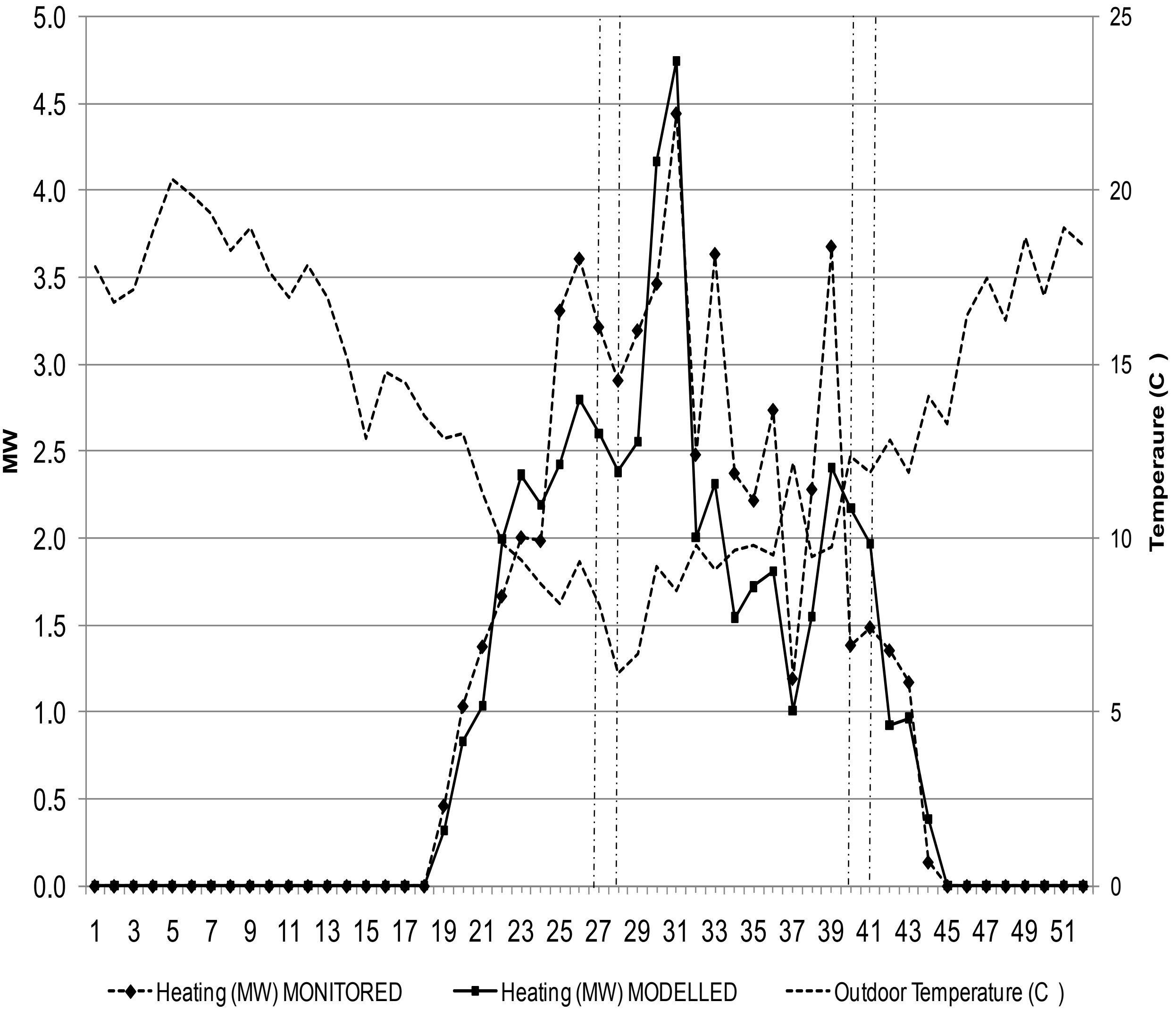


Figure 5-11: Heating thermal energy consumption - comparison between monitored and modelled data.

In Section 5.3.1 (Table 5-5) the annual templates used for the energy modelling of T-block were given. Heating thermal energy is provided by a centralized boiler operating during winter only, from the May 6 until October 29, which is evident in Figure 5-11 where heating started on week 18 (May 03 – 09) and ended on week 44 (October 25 – 31). Two of NMIT's four study breaks lie within this heating period (there are 3 study break of two weeks each, and one long summer break of about 14 weeks). The two study breaks during the heating season were on Weeks 27 and 28 and Weeks 40 and 41; these weeks are highlighted with a vertical segmented line in Figure 5-11. The influence of the two study breaks into the heating consumption is also evident as a reduction in heating consumption in both monitored and modelled heating energy consumption patterns. Since values in Figure 5-11 are weekly averages, these show a reduction of heating consumption in both weeks of both of the study breaks where, although internal gains were reduced by low occupancy, none of the openable windows were operable during these periods in both the monitored and modelled building.

There is a peak of heating energy consumption in Week 31, two weeks after the first study break, this occurred simultaneously with low outdoor dry-bulb air temperature (peak low on Week 28). The cooling down of the thermal mass of the building during the study breaks also might have an influenced in the heating peak on Figure 5-11; this will be discussed further when weekly average indoor temperatures in T-Block are analysed in the next section.

In summary the analysis of heating thermal energy some key values are informative. The average weekly monitored thermal energy consumption is 1.1 MWh compared with the model in which the value is 1.0 MWh. The maximum weekly monitored thermal energy consumption is 4.4 MWh compared with modelled values of 4.7 MWh. Finally the total thermal energy consumption in heating is 58.7 MWh in the monitored data compared with a 51.1 MWh in the modelled building.

5.6.3 Air Temperature comparison in T-Block

Each of the six rooms in T-Block which have air temperature monitoring equipment installed can be seen in Section 5.5 (Figure 5-9) where Level 1, Level 2, and Level 3 are presented, each level with two rooms highlighted in grey, one room facing north and the second one facing south (exception of room 1B in Level 1 which face south west). By monitoring thermal conditions in rooms exposed to north compared to rooms facing south, the monitoring system is giving a range of indoor air temperature across each floor.

For each of the rooms in Figure 5-9, a comparison between monitored and modelled average, maximum, and minimum temperature is given in Table 5-14. Also included are the monitored and modelled values of median temperature, and their respective standard deviations.

Table 5-14: Summary of T-Block room's temperature data analysis.

	Training Kitchen (1A)		Restaurant (1B)		Staff Room (2A)		Beauty Salon (2B)		Classroom (3A)		Classroom (3B)	
	L 1 - North		L1 - South		L 2 - North		L2 - South		L 3 - North		L3 - South	
	Monit.	Mod.	Monit.	Mod.	Monit.	Mod.	Monit.	Mod.	Monit.	Mod.	Monit.	Mod.
Average	21.6	22.2	22.5	19.8	22.5	21.7	21.8	19.9	21.3	21.7	21.4	20.3
Max	28.9	30.2	27.8	29.2	28.0	31.3	28.2	27.1	29.8	32.6	32.2	30.9
Min	13.4	13.4	15.3	9.4	17.0	12.1	14.5	11.5	13.3	10.2	11.0	8.3
Median	21.8	22.3	22.5	20.6	22.6	21.7	21.6	20.0	21.3	21.7	21.1	21.0
Standard Dev.	2.3	2.8	2.0	3.4	1.7	3.3	2.3	2.7	2.4	3.7	3.5	3.9

There is no consistent pattern when the monitored and modelled maximum temperatures are compared: in four of the rooms the modelled maximum exceeds the monitored maximum while in two rooms (both south-facing) the modelled maximum is less than the monitored maximum. For the minimum temperatures, however, the modelled minimum never exceeds the monitored minimum (they are equal for the training kitchen) with the greatest extreme case arising in the restaurant (15.3°C monitored minimum compared with 9.4°C modelled minimum). When combined, these observations imply that, in general, the model is predicting larger diurnal temperature swings than have been recorded by the monitoring equipment. Of relevance to this, as noted in Section 3.9.2, (Pereira & Ghisi, 2011) reported simulation peak temperature differences exceeded measured values (by about 2°C) in their investigations.

Because, by definition, maximum and minimum temperatures are extreme and short-duration occurrences, any significant differences between monitored and modelled values of these temperatures will not automatically translate into significant differences between the monitored and modelled energy consumption figures, nor indeed into significant differences in thermal comfort (particularly since minimum temperatures occur outside occupied hours).

Hence a more meaningful basis for comparing the model's temperature predictions with the monitored values is to observe the average temperatures (first line of Table 5-14) since, to a first approximation, it is the average indoor-outdoor temperature difference which primarily governs the rate of energy loss from a building having a given thermal envelope. Here the modelled/monitored values compare more favourably, the modelled value being higher for two rooms (0.6°C for the kitchen) and lower for four rooms (2.7°C for the restaurant is the most extreme difference). It is possibly not a coincidence that the restaurant is the same room for which the discrepancy on the minimum temperature was greatest.

The degree of agreement of the monitored and modelled median temperatures (fourth line of Table) is the most encouraging and arguably the most meaningful because, by effectively raising the statistical influence of the most commonly encountered temperatures, it lessens the influence of the most extreme excursions (i.e. maxima and minima). As already noted above, these extremes – particularly the minima – do not appear to have been well represented in the model. From the median temperature perspective, four of the rooms have monitored/modelling agreement within 1°C (two with monitored higher than modelled – Classroom 3B by only 0.1°C - and two with it being lower) while, again, it is the restaurant showing the largest discrepancy (monitored temperature 1.9°C higher than modelled). As an approximate single value indicator of the degree of agreement between monitored and modelled temperatures, when the differences for the six monitored rooms are averaged, the resulting value of 0.6°C is not too dissimilar from the mean difference of 0.4°C reported by (Pereira & Ghisi, 2011) in their measured/simulated comparison.

Indoor air temperature fluctuation about the average values can also be observed by looking at whole year hourly temperature's standard deviation in Table 5-14. Modelled indoor air temperature has, in all rooms, a higher standard deviation than monitored air temperatures regardless of the orientation of the room. This is consistent with the observation above that the model is predicting larger diurnal temperature swings than have been recorded by the monitoring equipment. Differences in standard deviation between monitored and modelled north-facing room's indoor temperature range from 0.5°C in Level 1 to 1.6°C in Level 2. In south-facing rooms, differences on standard deviation between monitored and modelled south-facing room temperatures range from about 0.4°C in Level 3 to 1.3°C in Level 1.

5.6.4 Indoor air temperature in Level 1, Level 2, and Level 3

In the energy modelling of T-Block, emphasis was given to modelling rooms in Level 2 to the best possible accuracy. Since the emphasis of this thesis is into the influence of thermal mass into space conditioning energy consumption, by focussing on the analysis of air temperatures in Level 2 the influence of the particular structural fabric of T-Block will be most evident. This is because Level 2 is a space supported within concrete suspended floors enclosed by a light weight insulated envelope, compared with Level 1 where the indoor environment might be highly influenced by the massive concrete slab on ground, or in Level 3 where the there is a lightweight roof and thermal envelope in general, without any consistent source of thermal mass other than the suspended floor below. Also, because Level 2 has a lower area of the building's thermal envelope than Level 1 and Level 3, heat losses can be expected to have a smaller influence on the results that this research is looking for. Nevertheless, it is appropriate that the monitored and modelled temperatures from Levels 1 and 3 be considered as well, and these will be commented on first.

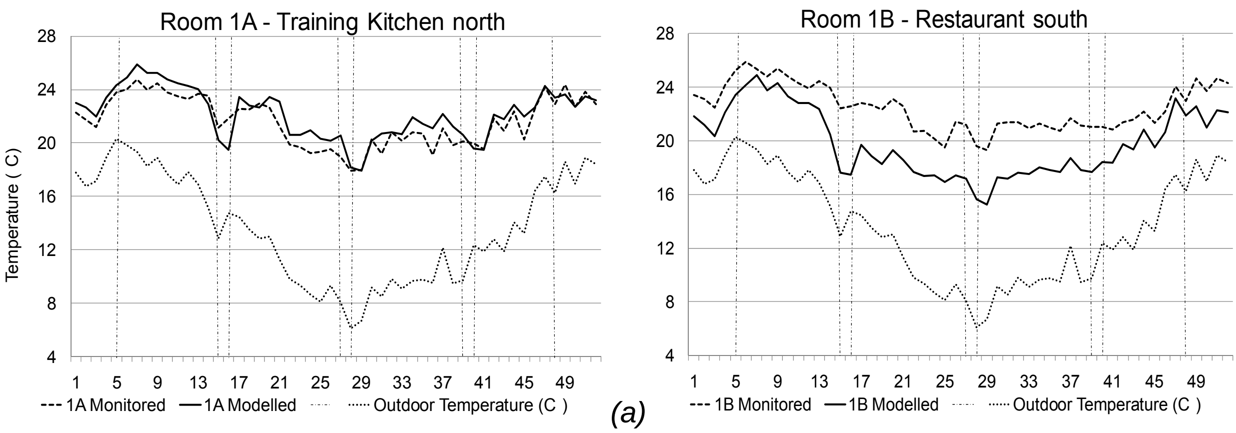
Figure 5-12 shows the two rooms fitted with air temperature sensors in Level 1 (the training kitchen in (a) and the restaurant in (b)), and in Level 3, a picture of the general classroom facing north (c).

The training kitchen is a large open space (no internal partitions) equipped with cooking equipment, lighting and mechanical air supply and extraction systems via kitchen hoods. Occupancy in this room is not constant and varies between periods of low and very high occupancy.


(a) (b) (c)

Figure 5-12: Rooms with air temperature monitoring equipment in the training kitchen (a), and restaurant (b) in Level 1, and in a general classroom (c) in Level 3.

The restaurant (Picture (b)) is a room heavily exposed to the building's thermal envelope where mostly large panes of single glazing is used; it has low occupancy during the day and very high during afternoons and evenings. The general classroom in picture (c) is exposed to the north façade, and the other Level 3 room with an air temperature sensor is visually similar. Level 3 has a light weight construction structured in steel columns and beams, with the only significant source of thermal mass being in the concrete suspended floor system which, in both rooms, is covered with carpet. There are no differences between insulation values in the external walls and in the roof, both being about R 2.5.



(a) (b)

Figure 5-13: Weekly averaged room air temperature in rooms on Level 1 - the training kitchen (a) and restaurant (b).

The weekly average monitored and modelled air temperatures for the training kitchen and for the restaurant are labelled as (a) and (b) in Figure 5-13, (which is consistent with what's been done in other figures). The three short study breaks and also the long summer break are again indicated with vertical segmented lines located at the beginning and at the end of each study break. (For the long summer break, the line at Week 48 indicates the beginning of the break in November and the line at Week 5 indicate the end of the summer break in February).

Monitored and modelled air temperatures in the training kitchen show generally good agreement with the modelled average weekly temperature almost consistently being slightly below the monitored equivalent. When the magnitude of this discrepancy is compared with the overall inside-outside temperature difference in Figure 5-13 (a), however, it can be deduced that the overall impact on the accuracy of modelling predictions of the energy required to maintain that inside-outside temperature difference should be small. For the restaurant a much larger gap exists between the monitored and modelled temperature profiles, with the monitored temperatures being consistently higher. Contributing to this is the already noted fact that for this room the model predicted a much lower minimum temperature than that which was monitored. Two software-related constraints may explain the apparently poor modelling of the restaurant: Firstly the software was unable to vary occupancy density during one given day and instead used one constant low occupancy density. Secondly, the restaurant has thick curtains installed but these were not thermally modelled because of the complexity of their intermittent use). These curtains would reduce the heat losses through the large single glazed windows, particularly at night time when the minimum temperatures would occur.

The weekly average monitored and modelled air temperatures of the general classroom facing north and general classroom facing south on Level 3 are shown in Figure 5-14.

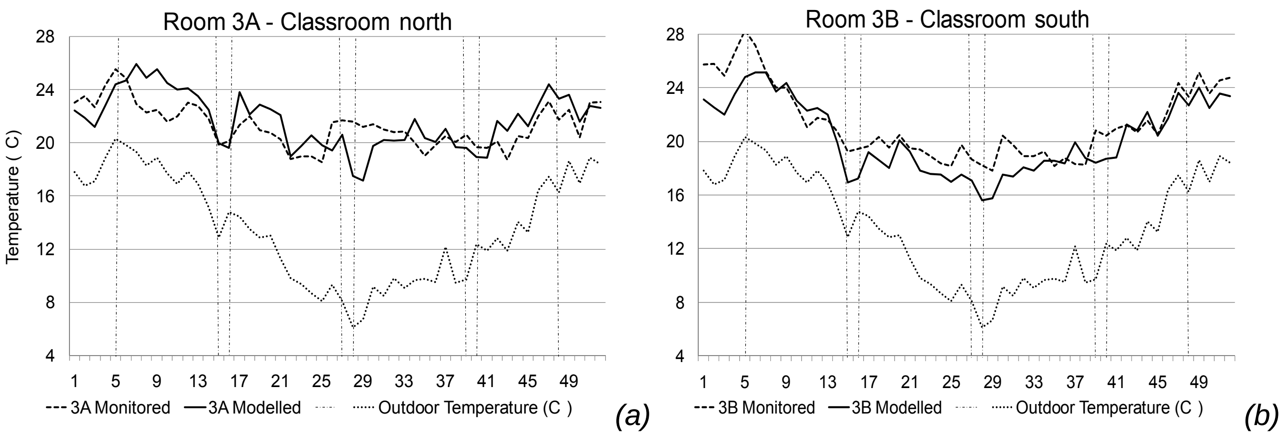


Figure 5-14: Weekly averaged room air temperature in rooms on Level 3 - the general classroom facing north (a) and facing south (b).

In all four graphs in Figure 5-13 and Figure 5-14 the influence of study breaks is apparent in the indoor temperatures of both monitored and modelled data (though less clear in the restaurant) with an anticipated and consistent decrease of air temperature during these breaks in both the monitored and modelled data.

There is evidence of the agreement between monitored and modelled temperatures having a dependence on room orientation. Particularly in Figure 5-14 it can be seen that air temperature variation between summer and winter is higher in rooms facing south compared with rooms facing north. In this same figure, monitored air temperature in room 3B facing south is often higher than the modelled air temperature during the whole year, but in the same figure, in room 2A facing north, monitored air temperature is often higher than modelled air temperature during cold, and lower during warmer periods of the year. In Table 5-14 in rooms facing north, modelled maximum temperature is 1.3°C to 3.3°C higher than monitored maximum temperatures, while in rooms facing south, modelled maximum temperature is about 1.5°C lower than monitored maximum temperatures. In rooms facing north, modelled minimum temperature is about 4°C lower than monitored minimum temperature, while In rooms facing south, modelled minimum temperature is 3°C to 6°C lower than monitored minimum temperatures.

Summarising all of the preceding comments on the data presented in Table 5-14, Figure 5-13 and Figure 5-14: Looking at average weekly values throughout a whole year, although average temperatures are similar in real building and models, air temperature swings are much higher in the models. In rooms facing north, the influence of outdoor air temperature on indoor air temperature is lower than in rooms facing south and, particularly in this orientation, modelled temperatures are considerably lower throughout the whole year than monitored air temperatures. In rooms facing north monitored and modelled air temperatures are of a much greater similarity.

5.6.4.1 Indoor air temperature in Level 2 - detailed temperature analysis

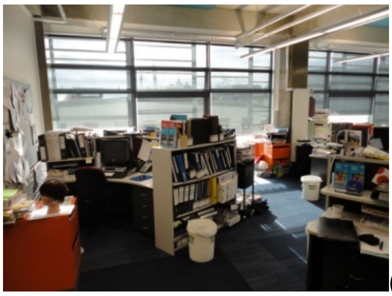
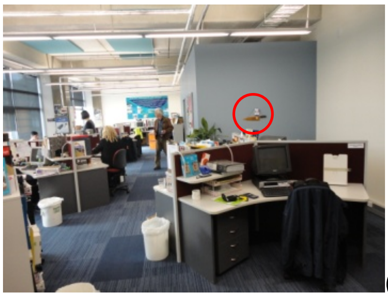
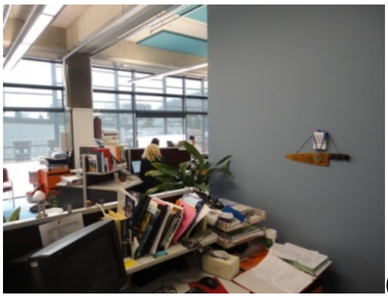

(a)

(b)

(c)

Figure 5-15: Level 2 Staff room – Picture (a) north facing windows, picture (b) total office overview, and picture (c) air temperature sensor location.

In the two rooms with air temperature sensors located in Level 2, the exact location of the sensor has been identified. In Figure 5-15 a sequence of three pictures of the Staff Room (2A) on the north façade of Level 2, can be seen. The size of the room and density of occupancy can be appreciated in a panoramaic view produced by pictures (a) and (b); also in picture (b) the exact location of the air temperature sensor can be appreciated (inside a red circle). A detailed view of the air temperature sensor can be seen in picture (c).

To reduce uncertainty about the accuracy of the method used for comparison between monitored and modelled indoor air temperatures, and to assess if the comparison clearly captures the influence of HVAC systems on indoor air temperature, a comparison has been made between whole year weekly average air temperature of buildings during 24 hours (i.e. both occupied and unoccupied hours), and the building's occupied hours only (8:00am to 6:00pm). This comparison is shown in Figure 5-16. While monitored air temperature remains constant in both graphs, modelled air temperature varies significantly between graphs. Since there is a large variation of temperature between day and night during a 24 hour period, particularly in the modelled air temperature (see analysis of Table 5-14 and Figure 5-13 and Figure 5-14), when reducing the extent of data included in the graphs, from 24 hours to occupied hours only, the significant drop of temperature during night time is not integrated into the average value, which subsequently produces a significantly higher total average value. Average monitored air temperature, over occupied hours only is 0.4°C higher than the same value over a 24 hour period. In the case of average modelled temperature of occupied hours is 2.3°C higher than monitored averaged values over 24 hours.

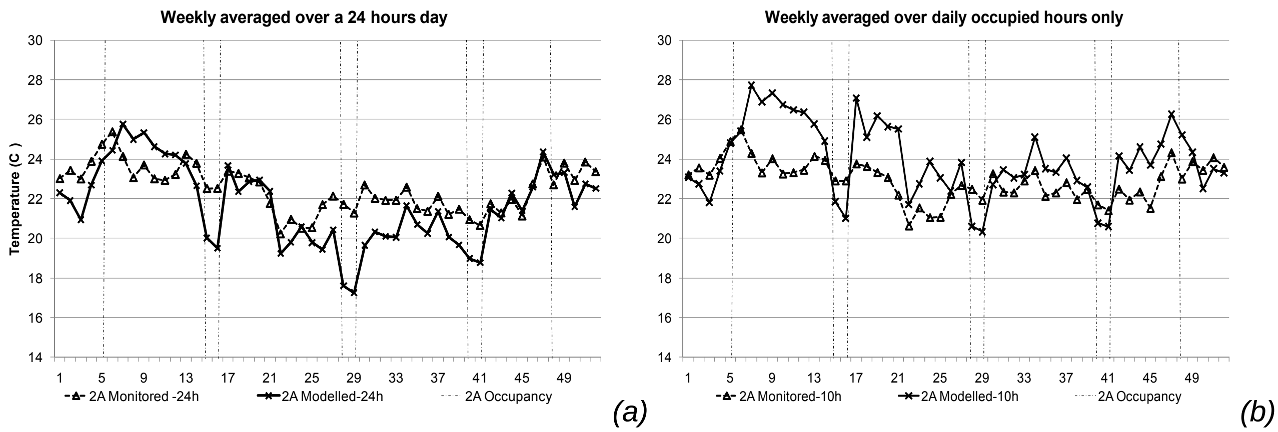


Figure 5-16: Room 2A north - Average weekly air temperature (a), and average weekly air temperature for building's occupied hours only (b).

A comparison between half hour monitored and modelled indoor air temperatures during one week in the study break (5-11 April), and one week in the middle of the second semester (August 30 to September 5) can be seen in Figure 5-17. Graphs in Figure 5-17 are representative of one week without heating and – nominally – no occupation, lighting, and equipment internal gains (a), and one week with heating, occupation, lighting, and equipment internal gains (b). It can be seen in Figure 5-17 that when the building is unconditioned and unoccupied (a), modelled indoor air temperature during the day is close to but consistently below the monitored data. During the night modelled temperatures drop significantly in comparison with monitored temperatures during the same period so that, overall, the model's over-estimation of the diurnal swing is once again apparent. When the building is heated and occupied (Figure 5-17 (b)), indoor air temperature during the day the modelled temperature profile clearly exceeds the monitored temperature profile (with the exception of the last day which is an unoccupied Sunday), and during the night modelled temperatures again drop significantly when compared with monitored data, following the trend that night temperature does in (a).

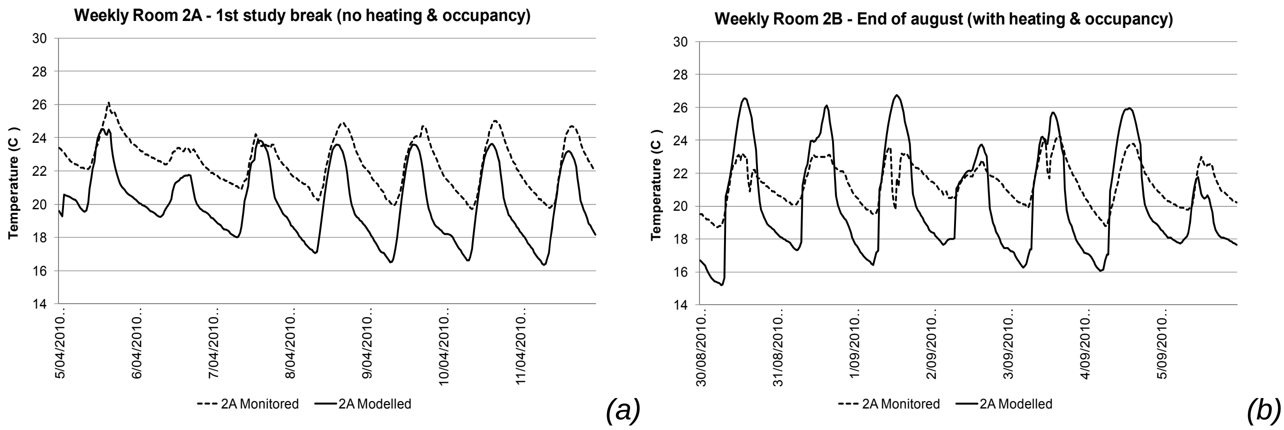


Figure 5-17: For Room 2A (north), half hour temperature graph for one week without heating and general occupancy (a), and one week with heating and general occupancy (b).

Temperatures profiles in modelled conditioned and unconditioned indoor environment are offset profiles to outdoor dry-bulb temperatures. This is not the case when looking at monitored indoor environments where temperatures are more stable during day and night and less influenced by outdoor dry bulb temperature. This can be seen more in detail in Figure 5-18 where there are two graphs with one day of half hour recorded temperature in room 2A during an unheated and unoccupied day (a) compared with the same room during a heated and occupied day (b). Also included in both graphs in Figure 5-18 is the hourly outdoor dry-bulb temperature.

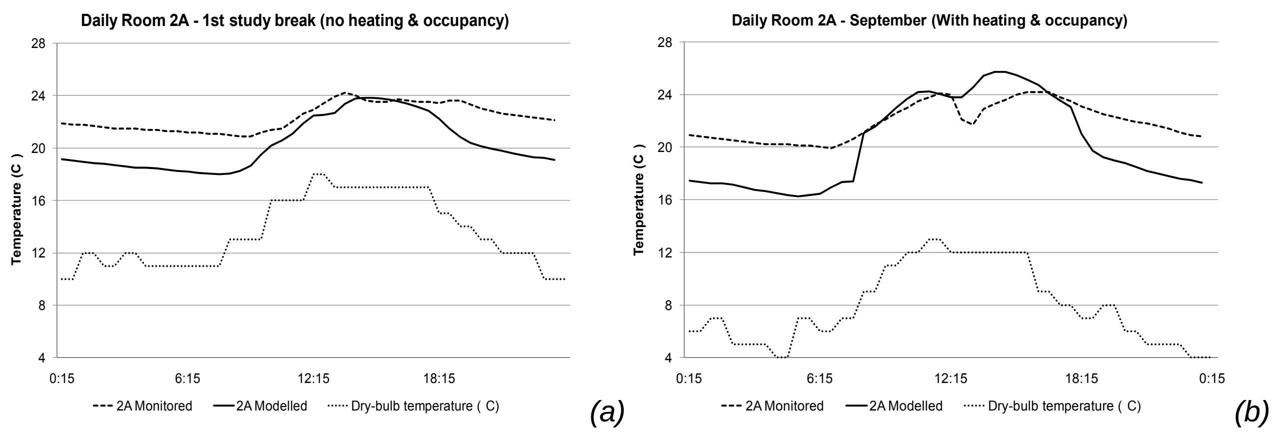


Figure 5-18: For Room 2A (north), half hour temperature graph for one day without heating and general occupancy (a), and one day with heating and general occupancy (b).

Figure 5-18 shows that monitored air temperature is less responsive to outdoor air temperatures and also to conditioning heat than modelled temperature is. Whenever there is a heat input, the modelled temperature responds faster and increases to a higher level than the monitored temperatures. Similarly when there is no heat input and the outdoor temperature drops, the modelled indoor temperature drops more quickly and to a lower level than the monitored data.

This greater responsiveness of indoor temperature to outdoor conditions and to space conditioning in the model could be due to a number of reasons but these have not been tested or analysed in detail from a temperature perspective because they are outside the primary scope of this research. In the Test building analyses in Section 3.11, however, the energy consumption consequences of significant changes in the amount and accessibility of thermal mass was explored. The conclusion that was reached there was that the energy usage was only minimally effected by those changes in that Test building at least. This is somewhat reassuring in the present context because it suggests that over-estimation of diurnal temperature swing – which would normally be associated with a low amount of accessible thermal mass – should not have significant flow-on consequences in modelling the operational energy consumption of the building during occupied hours. Nevertheless, some possible factors contributing to the model's over-estimation of diurnal temperature swing are:

- Since the monitored building is relatively new, it is under-occupied, so day-time internal gains may be less than actually modelled.
- Natural ventilation – which was not able to be measured or monitored – may not occur to the extent that is assumed in the model.

5.6.4.2 Indoor air temperature in Room 2A and 2B in Level 2 - detailed temperature analysis

The indoor air temperature in the staff room (2A) facing north can be seen in Figure 5-19 and for the beauty salon (2B) facing south can be seen in Figure 5-20. Each of the temperature traces in these figures is tracking the weekly variation in the particular temperature, with each data point being the average of the temperature values obtained on an hourly basis during that week (i.e the average of 168 values per week, either monitored or modelled). Included in the analysis capabilities of the VE software is the ability to extract temperature profiles for internal room surfaces of interest. This capability has been utilised to clarify whether or not the surface temperature of the walls where the temperature sensors are located, has an influence on the monitoring of temperature, hence the modelled surface temperature of the wall at each sensor's location has been included in the graphs.

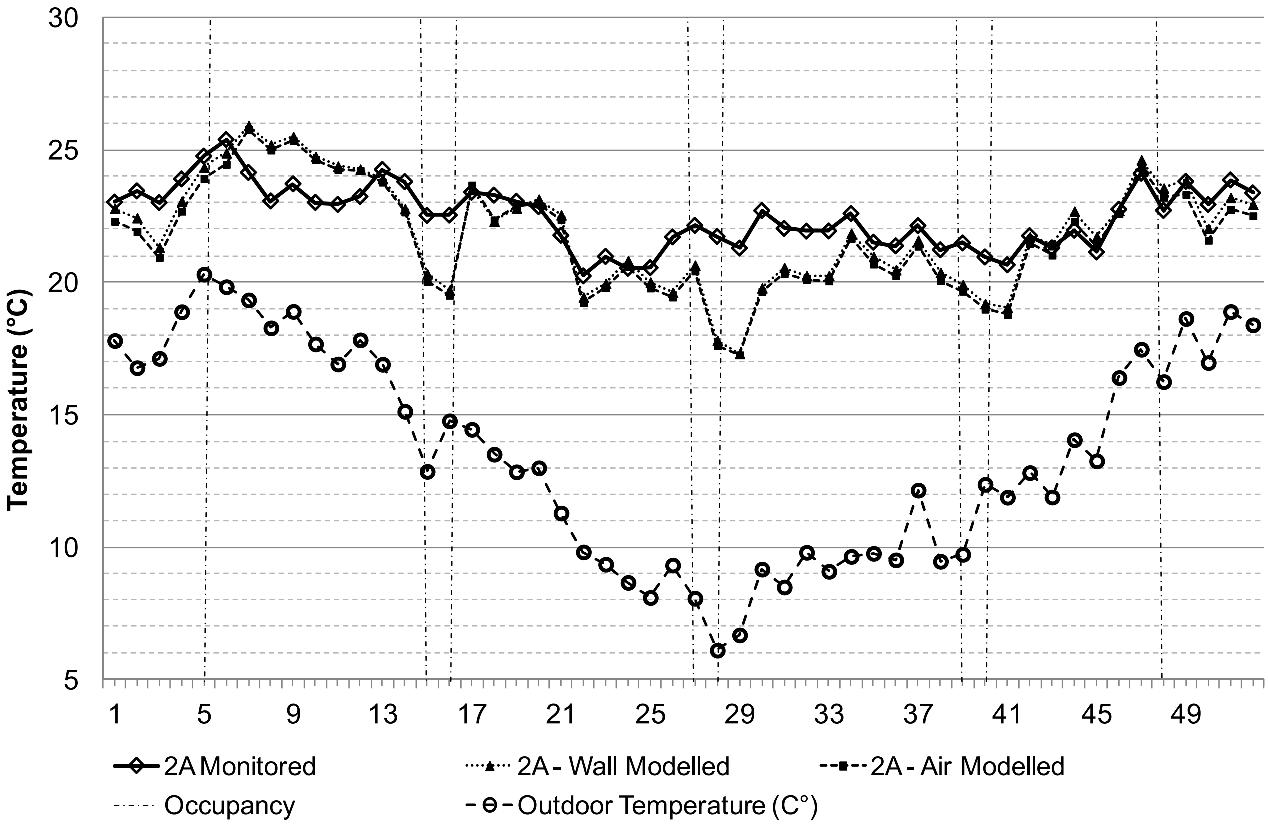


Figure 5-19: Room air temperature – Level 2 Staff Room – North facing.

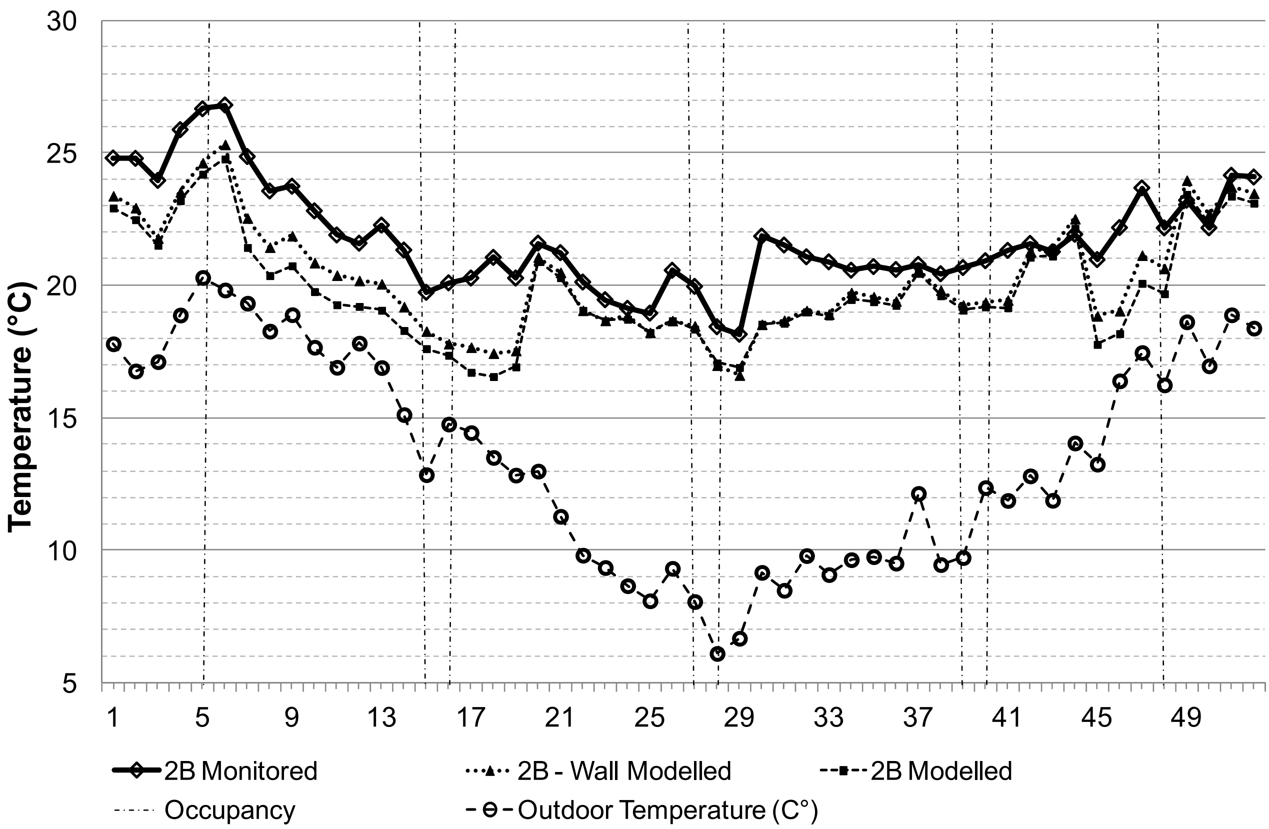


Figure 5-20: Room air temperature – Level 2 Beauty – South facing

Figure 5-19 and Figure 5-20 show that differences between indoor air temperature and wall surfaces temperature are more marked in the room on the south façade than in the room on the north. In both, the south and the north facing rooms, the wall surface temperature is always higher than indoor air temperature.

On the north façade, indoor air temperature and wall surface temperature are very similar with differences that increase during summer months and peaks up to 0.5°C during December and January. On the south façade, indoor air temperature and wall surface temperature have higher difference than those in the north facing room, ranging from 0.1 to 1.1°C difference with peak difference in month of February and March.

Figure 5-13 and Figure 5-14 showed that modelled indoor temperatures are lower than measured indoor temperature in the rooms facing south. In rooms facing north, most of the time modelled indoor temperature is higher than measured indoor temperatures, there being only a few weeks in winter where modelled indoor temperature is lower than measured indoor temperature.

Figure 5-19 and Figure 5-20 show that measured indoor air temperature is normally higher than modelled indoor air temperature in the north and always higher in the south. These figures also show that a wall surface temperature (of the wall where the temperature sensor is located) is higher than indoor air temperature. This suggest that there may be an influence of the surface temperature of the wall where the sensor is located on the measurements this sensor is detecting, increasing the final measurement of indoor air temperature by the sensor. Overall, however, this influence is relatively small and doesn’t account for more than a small fraction of the largest modelled/monitored temperature difference (for the north-facing Staff Room 2A at Week 29, immediately after the mid-year break).

6 Assessment of the accuracy of energy modelling in the Arts building

This chapter describes a simplified calibration process undertaken in the Arts building, to be used as the primary case-study building, later the template for all the alternative case-study building models. A description of a monitoring system designed and installed in that building is given. The chapter includes a comparison of monitored and modelled indoor temperatures. In the case of energy consumption (for which meaningful monitored data was not available), a comparison with other broadly similar educational buildings is described, to give an order of accuracy for the modelling results in the remaining chapters.

6.1 Introduction

An energy and indoor temperature monitoring system was designed for the Arts building. The aim of this monitoring system was two-fold: to calibrate the BEEM modelling undertaken in this research; and to obtain meaningful on-going information for future research in this building (bearing in mind that it is the first multi-storey timber building of this nature built in New Zealand).

The energy and temperature monitoring equipment was installed in the Arts building during late 2010 and beginning of 2011. The commissioning of the building was carried out during January 2011 and occupancy started mid-February 2011. The first metering data for both energy consumption and indoor temperatures was received on February 22.

Due to complications and unreliability in the monitoring of thermal and electrical energy consumption, that data and its subsequent comparison with the BEEM modelling results were not able to be included in this research. Only indoor temperature comparisons are included.

This section describes the design of the monitoring system for thermal and electrical energy consumption in the Arts building, together with a set of room air temperatures in the same building. This section also introduces some of the room air temperature monitoring results and compares them with modelled temperatures.

6.2 Brief description of monitoring system in the Arts building

The Arts building is part of group of three buildings at NMIT, called the Arts and Media complex. Figure 6-1 (a) shows the plan section of the three buildings that form the Arts and Media complex, being the three storey tall Arts building (hatched (a -1)), the single storey workshop building (a - 2) and the ‘Performance’ space (a - 3). Figure 6-1 (b) shows the west elevation of the Arts and Media complex where the buildings height can be appreciated – particularly the three storey tall Arts building (b-1).

Thermal and electric energy are supplied to the Arts and Media complex as a whole. In the case of electricity this is supplied to a central electric board (main) in the Arts building and redistributed to the sub-boards, one in the workshop building and another to the Performance building. There is a similar situation with thermal energy used in LPHW for heating. This is supplied to the Arts building and redistributed to the workshop and the Performance buildings. A problem with this layout of electricity and LPHW distribution is that to extract meaningful data for the Arts building alone, this has to be isolated from main electric energy consumption (total Arts and Media complex) less electric consumption of the workshop and of the Performance space (each having a sub-board). The same approach has to be taken to individualize the thermal energy consumption in the Arts building.

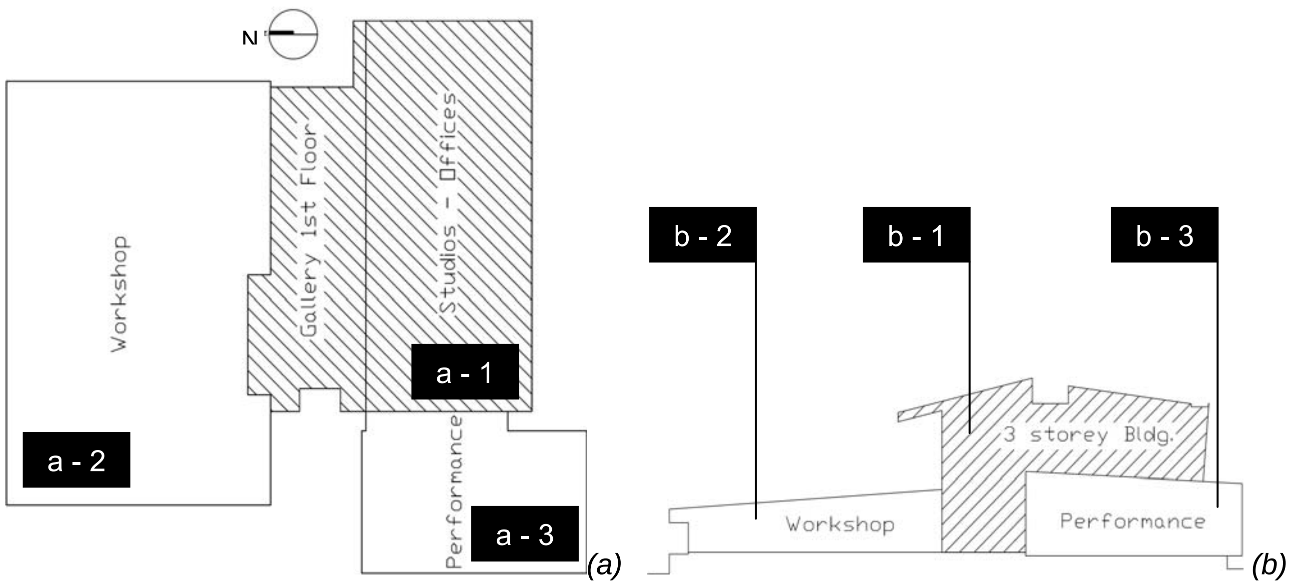


Figure 6-1: Layout of Arts and Media complex – Plan section in (a) and west elevation in (b)

As for the T-Block, temperature monitoring equipment has been installed previously to feed into the BMS for controlling the temperature of air supplied by the air handling unit, and scheduling the opening of windows located in the thermal envelope for natural ventilation. The same company specialising in energy management was in charge of the design and the installation of the system (Schneider Electric, 2011). In Table 6-1 the energy monitoring points for the Arts and Media complex (a) and the temperature monitoring points for the Arts building (b) are summarized.

Table 6-1: List of monitoring equipment for energy in the Arts and Media complex (a) and temperature in the Arts building (b).

Energy

Thermal (3 storey building)	
1	Main Heat Energy
2	Workshop Heat Energy
3	AHU1 Heat Energy
Electric (3 storey building)	
4	Main Board Elec Energy
5	Workshop Elec Energy
6	Performance Elec Energy
Other Electric	
7	AC1 AC2 Cool Energy
8	AHU3 Elec Energy

(a)

Temperature

Room Air Temperature:		
1	Level 1	Multimedia102 Room Temp
2		Gallery103 Room Temp (RM104)
3		Reception Room Temp (RM 109 - RM110)
4		Interview (RM113) & HOS (RM114) Avg Room Temp
5		ProgLeader Kitch Avg Room Temp.
6	Level 2	Studio201 Room Temp
7		Main Gallery Avg Room Temp (Level 2 ?)
8	Level 3	Studio301 Room Temp
9		Workroom302 Room Temp
10		Workroom303 Room Temp
11		Classroom304 Room Temp
Other Temperatures:		
12		OSA Temp (Outside Air Temperature)

(b)

For this research, thermal energy from the campus heating system was the most significant energy being monitored because it represents virtually all of the heating energy input. However, there were problems in the monitoring of the hot water energy and the commissioning of that system is still on-going. Because LPHW flow had to be monitored at three points and LPHW temperature difference had to be monitored in and out of three zones (one for the complex of three buildings and two representing sub-buildings), the inherent potential inaccuracies of obtaining quantities by subtraction between separate measurements was very apparent in the limited data that was able to be obtained. Thus no meaningful data was able to be extracted before this research was drawing to a close. Although electric energy has been monitored, the accuracy of total electricity energy consumption is not the main objective of this research and, because the heat input via hot water was not able to be obtained, the electricity consumption has not been analysed further.

6.3 Benchmark of the modelled heating energy consumption in the Arts building

In the absence of meaningful data from the hot water monitoring system, this section presents the results of the modelled heating energy consumption in the actual Arts building and compares that result with heating energy consumption from a set of three educational buildings in New Zealand. Buildings used in this comparison are the T-Block in NMIT's Nelson campus, and the Erskine and the Rutherford buildings at the University of Canterbury (UoC) main campus in Christchurch, New Zealand. Rather than being a detailed analysis of heating energy consumption in educational buildings in New Zealand, this benchmarking is intended to provide a relative idea of the accuracy of the heating modelling in the Arts building.

Table 6-2: Gross and usable area of building used to benchmark heating energy comparison in the Arts building.

Nelson Marlborough Institute of Technology (NMIT)				University of Canterbury (UoC)			
Arts Bldg.		T-Block		Erskine		Rutherford	
Gross (m^2)	Usable (m^2)	Gross (m^2)	Usable (m^2)	Gross (m^2)	Usable (m^2)	Gross (m^2)	Usable (m^2)
1,981	1,693	2,068	1,991	11,551	5,244	19,368	10,356

Table 6-2 provides the areas of the four buildings compared in this section. The Arts building is the smallest building in this comparison but is close in size to the T-Block (NMIT). Buildings in the University of Canterbury campus on the other hand are much bigger. The comparison of the Arts building with the T-Block is a straightforward comparison between buildings in the same location, with similar usage, thermal envelope and structural thermal mass. The choice of buildings at the University of Canterbury is because these two buildings represent both ends of the spectrum: the much more modern Erskine building has relatively low heating energy consumption whereas the Rutherford building has relatively high heating consumption.

Figure 6-2: Erskine building at the University of Canterbury.

The Rutherford building is an eight-storey reinforced concrete building, built in 1967, and holds the departments of Chemistry and Physics of UoC. The building includes classrooms, lecture theatres and a large area assigned to laboratories. The Erskine building (Figure 6-2) is a complex building with 3 seven-storey office buildings attached to a central atrium that, at the same time, connects the buildings to a library and to computer labs. It is a reinforced concrete building built in 1996 for the Departments of Mathematics and Statistics, and Computer Science. Concepts of

Environmental Sustainable Design (ESD) were included in the design of the Erskine building and the building is regarded as a low-energy building within the UoC campus.

Table 6-3 shows the monthly thermal energy consumption subdivided in gross and usable floor area of the buildings in this comparison. Data in the T-Block and in the Erskine and Rutherford building was monitored during the year 2010 rather than 2011 because 2011 was an abnormal year for UoC campus energy usage due to the disruptions caused by major earthquakes. Data for the Arts building is modelled using a TMY weather file. Energy in both buildings in the UoC campus was provided by the campus Facilities Manager (Sellin, 2011), and the values given include heating and DHW added together (although the latter is expected to be a small portion of the total energy consumption value compared with heating energy consumption.

As it can be seen in this table, when the heating energy consumption is expressed on a per unit gross floor area basis, the modelled heating energy consumption of the Arts building is similar to the metered heating energy consumption in the T-Block and the Erskine building, and much lower than the heating energy consumption in the Rutherford building. When looking at heating energy consumption divided by usable floor area, the modelled heating energy consumption in the Arts building is, again, similar than the metered heating energy consumption of the T-Block, but significantly lower than the energy consumption of each of the two buildings in the UoC campus.

Table 6-3: Thermal energy consumption on heating of the Arts building - Comparison between monitored and modelled

	NMIT - Nelson				UoC - Christchurch			
	Arts Bldg. - Mod.		T-Block - Met.		Erskine - Met.		Rutherford - Met.	
	Gross (kWh/m^2)	Usable (kWh/m^2)	Gross (kWh/m^2)	Usable (kWh/m^2)	Gross (kWh/m^2)	Usable (kWh/m^2)	Gross (kWh/m^2)	Usable (kWh/m^2)
Jan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Feb	0.0	0.0	0.0	0.0	0.1	0.2	0.6	1.2
Mar	0.0	0.0	0.0	0.0	0.6	1.2	3.3	6.2
Apr	0.0	0.0	0.0	0.0	1.5	3.3	5.6	10.4
May	3.5	4.1	2.4	2.5	4.7	10.3	13.6	25.4
Jun	6.1	7.1	6.3	6.3	9.1	20.0	15.6	29.2
Jul	7.8	9.1	7.2	7.5	8.7	19.1	14.9	27.9
Aug	6.5	7.6	5.8	6.0	8.4	18.4	15.5	29.0
Sep	4.1	4.8	4.8	5.0	4.6	10.1	9.3	17.4
Oct	3.0	3.6	2.2	2.3	3.0	6.6	7.2	13.4
Nov	0.0	0.0	0.0	0.0	4.6	10.1	9.3	17.4
Dec	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Σ	**31.1**	**36.4**	**28.4**	**29.5**	**45.1**	**99.3**	**94.9**	**177.5**

Significant differences between heating energy consumption when subdivided into gross and usable area in the Erskine building (UoC) and, to a lesser extent, to the Arts building (NMIT) may be attributed to the influence of the large atrium space within those buildings, which although the whole atrium space is conditioned, this large heating energy is only subdivided by the floor area of the gallery's ground level. The more severe winter climate in Christchurch would also contribute to seemingly superior heating energy performance of the two NMIT buildings.

A final very simple and necessarily very approximate exercise was carried out to estimate the energy necessary to maintain constant indoor temperature, during occupied time only, under constant outdoor temperature in the Arts building. The month chosen for this exercise was August and the temperature was average day-time outdoor temperature taken from real meteorological data. The calculations are included in Appendix K show that about 5.5 kWh/m^2 of gross floor area is the energy necessary to maintain, during August 2011, a constant indoor temperature of 22°C during occupied hours in the Arts building. Again, this value is similar to (about 15% lower) the modelled heating energy consumption (during August in the TMY) divided by gross floor area (6.5 kWh/m^2).

All of the above comparisons, relatively crude though they may be, provide some confidence that the modelled representation of the heating energy requirements of the as-built timber Arts building is reasonable. Clearly it would have been much better if a much more direct comparison was able to be made with data from the installed metering equipment but, as described above, this was not possible.

6.4 Comparison between indoor air temperatures in rooms of the Arts building

In this section the comparison between the monitored and modelled indoor air temperatures is given for a group of rooms in the Arts building that are representative of indoor environmental conditions of spaces facing south and spaces facing north. The specific location of the rooms in the temperature comparison in this section is highlighted in Figure 6-3. The approach taken was to analyse two rooms facing south in each level (in Level 2 there is only one single space facing south) and, for the rooms facing north, temperatures are sensed only in the gallery (one sensor per level) and none in office spaces. There are temperature sensors in all rooms highlighted in Figure 6-3.

The period of time analysed in this section is from Saturday the 22nd of February until the end of August 2011. This period corresponds to the time between the start of the air temperature monitoring process in the Arts building until the end of the analysis of data on this research.

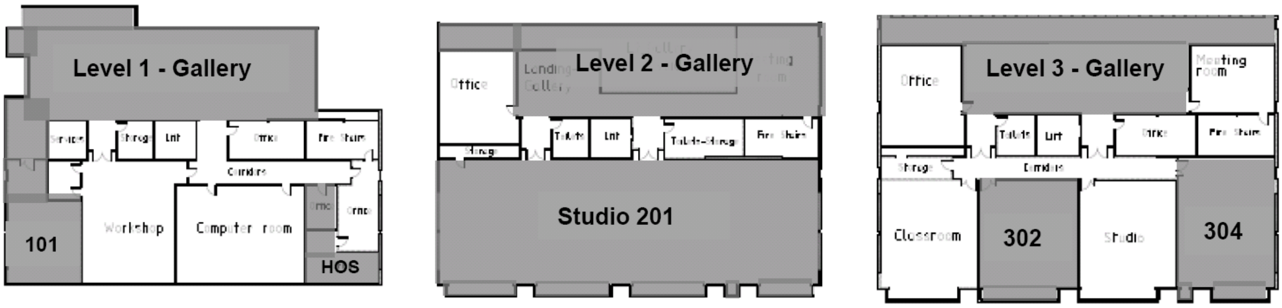


Figure 6-3: Rooms where air temperature has been monitored in the Arts & Media building - From left to right, levels 1, 2 and 3 respectively.

Monitored data is sensed under real climatic conditions and, using the same methodology as was used for the T-Block in Section 5.4, a weather file with real meteorological data was created for a direct comparison between monitored and modelled results. The custom weather file uses real data until August 2011,and for the remaining months of the year, TMY data is used. Added into the temperature analysis graphs that follow, it is the outdoor dry-bulb temperature for the year 2011.

6.4.1 Arts building - rooms facing south on Level 1:

The modelled and metered weekly average indoor air temperatures for two rooms in Level 1 of the Arts building are compared in Figure 6-4 in which (a) is for the Studio room (RM 101) and (b) is for the Interview room/Head of School office (HOS).

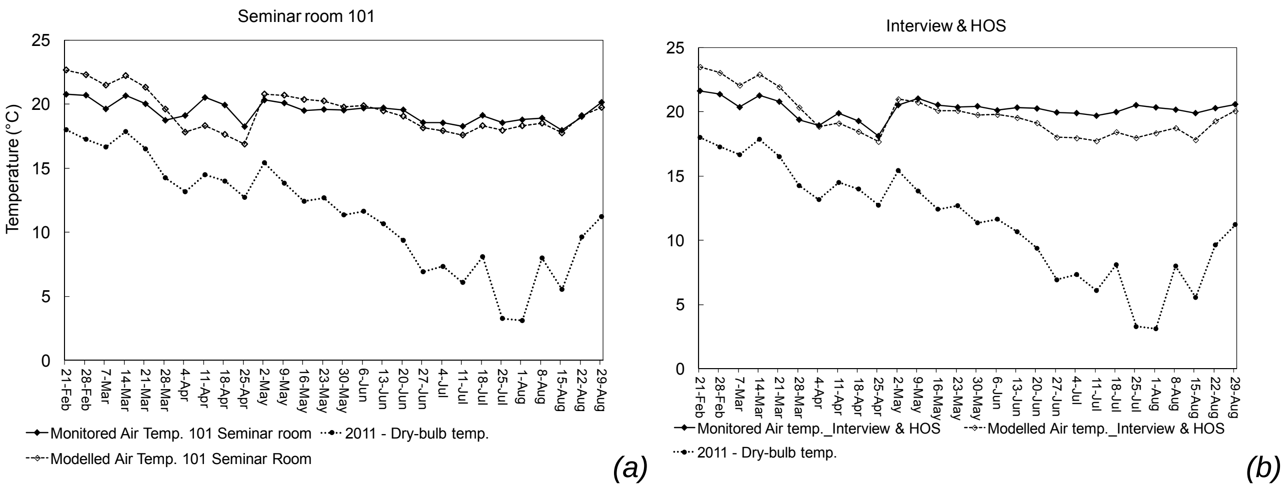


Figure 6-4: On level 1 - Seminar room (a) and Head of School office (b), 24 hours average indoor temperature analysis.

Both the monitored and the modelled indoor temperatures are reasonably similar in the Seminar room (a) during the heating season (from May 2nd), with the monitored average temperature sometimes slightly exceeding the modelled value, and sometimes vice versa. In the temperature comparison on the Interview/HOS room, however, the modelled temperature is consistently lower than monitored temperature during the heated period and, in general, the divergence increases as the weekly average outdoor temperature drops with a peak temperature difference of about 2.5°C in the week commencing July 25. This would translate to the model underestimating the heat losses (and hence the heating energy requirement) of this particular room during the coldest outdoor temperatures. In both rooms in Figure 6-4, before the heating season starts on May 2nd (see Section 4.5.3 for detail in the annual heating schedule) monitored temperature follows the pattern of outdoor temperature, with a constant ΔT of about 5°C between outdoor and indoor temperature, with indoor temperature being higher. The monitored temperature, on the other hand is more constant and, although the pattern is similar to the outdoor temperature, ΔT varies across the unheated period, increasing while outdoor temperature decreases.

Monitored 24-hour average temperature in Room 101 is the same in the monitored and the modelled data (19.4°C). Indoor monitored air temperature's 24hour standard deviation from the mean average temperature is 0.8°C while the corresponding modelled value is 1.6 °C. This is consistent with results available in Section 5.6.3 (Air Temperature comparison in T-Block) where a higher indoor air temperature fluctuation between day and night was observed in the model than in the monitored building. Analysis of Room Interview/HOS indoor temperature shows similar results to those in Room 101. 24-hour averaged monitored temperature in Room Interview/HOS is 20.2°C while the corresponding modelled value is 19.7°C. The comparison of standard deviation between monitored and modelled data is similar in Room 101 and Room Interview/HOS, where the standard deviation in the monitored air temperature is 0.7°C while in the model is 1.7°C. Consistently with results for Room 101, higher temperature fluctuation can be observed in the modelled Room Interview/HOS.

6.4.2 Rooms facing south on Level 2 and Level 3:

The corresponding comparison of indoor temperatures in rooms on Level 2 and 3 is presented in Figure 6-5: (a) shows the temperature analysis of Studio room (201) in Level 2 (single large open space facing south) and (b) is shows the same analysis in Workroom 302 and Classroom 302 in Level 3.

Similar to rooms on Level 1 (101 and Interview/HOS), modelled indoor temperature, before the heating season started follows the pattern of outdoor temperature but with a constant offset of about 5 K. Also during the unheated period prior to May 2nd, monitored indoor temperature in the

Studio room (Level 2), is similar to those in rooms on Level 1, being more constant and with detachment from outdoor temperature. For Rooms 302 and 304, on the other hand, modelled and monitored indoor temperature during the unheated period, are similar with both roughly tracking the pattern of outdoor temperature but displaced higher by about 5 K.

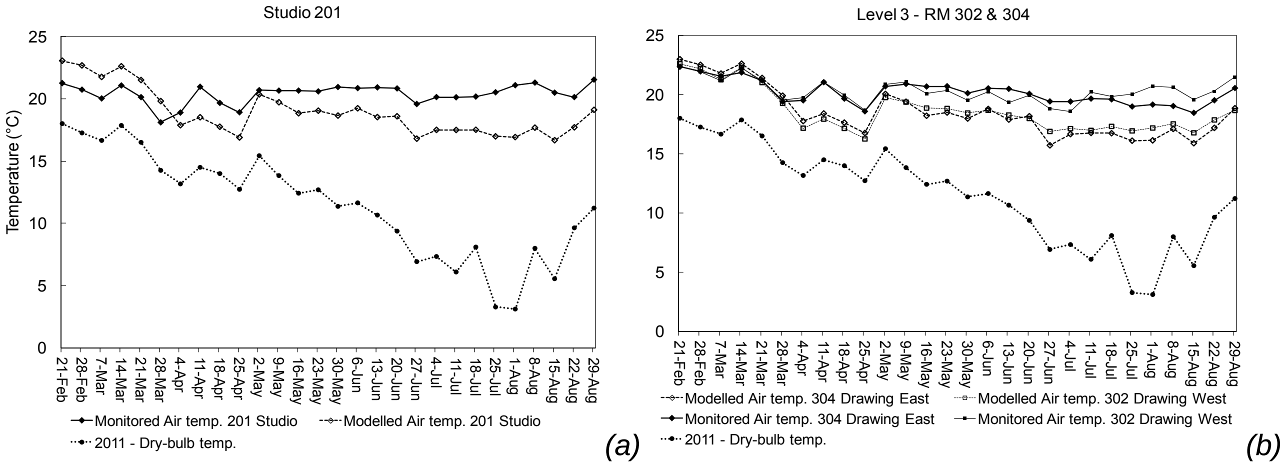


Figure 6-5: Studio room on level 2 (a), and Workroom 302 and Classroom 304 on Level 3 (b), weekly average indoor air temperature analysis.

With heating (from May 2nd), modelled indoor temperature became more constant and, although changes in the outdoor temperature can still be identified in the indoor temperature pattern, ΔT between indoor and outdoor temperature constantly increase across the heated season. In both graphs on Figure 6-5 monitored indoor temperature during heated period is higher than modelled indoor temperature (ΔT of about 2 K). This suggests a possible discrepancy in the set points used for modelling.

6.4.3 Gallery's all levels combined values - air temperature

Both graphs in Figure 6-6 concern the three levels high gallery space facing north. Figure 6-6 (b) is a comparison between the monitored and modelled air temperature in the gallery. A single averaged air temperature for the whole gallery is used as a simplification. This averaged value results from there bring three temperature sensors located in each of the three levels of the gallery, and these monitored values for that space are already averaged into one prior to dispatch to the server, making it impossible to resolve the average monitored value into its constituent components.

To provide a more meaningful comparison, the modelled value is also an integrated value from all three levels of the gallery space. To assess the reliability of using one single averaged air temperature from the air temperature existing at each of the three levels, Figure 6-6 (a) shows a modelled comparison between the three level integrated values and the values for each level individually.

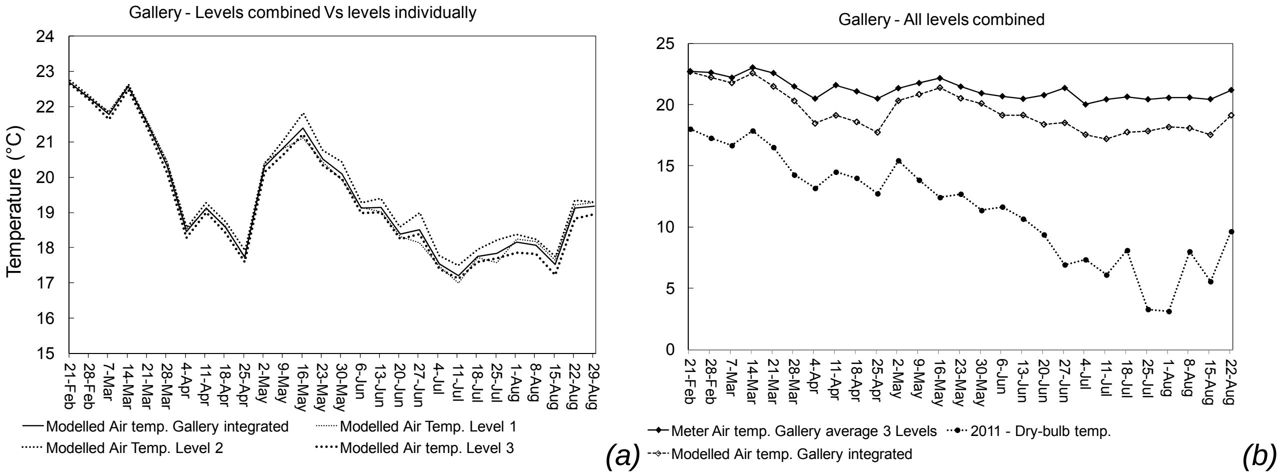


Figure 6-6: Gallery on north façade, 3 levels average air temperature analysis (a) and comparison between the 3 levels averaged temperature and air temperature of each level individually (b).

The integrated gallery air temperature is closely similar to the modelled air temperature at each level. The highest variation of a local level temperature compared to the integrated gallery air temperature correspond to 0.4°C which occurs during the week starting on the 21st of June and is between Level 2 and the gallery integrated air temperature.

In the gallery, modelled air temperature before heating is introduced is, on average, 1.3°C higher than the monitored temperature. The same corresponding difference during the weeks when heating is available is 2.0 °C. Indoor air temperatures during the heated period are more constant during the winter weeks and are less similar to the outdoor temperature patterns than they are during weeks without heating available. Monitored indoor air temperature is higher than modelled indoor air temperature across the entire recorded period regardless of the commencement of heating on May 2nd. Peak temperature difference between modelled and monitored indoor temperature is 3.2°C during the week starting on July 11th (heating season).

6.5 Summary of the accuracy in the modelling of the Arts building

On the one hand, the heating energy consumption subdivided by gross floor area in the Arts building was similar to the corresponding values in the benchmarked buildings. On the other hand when heating energy consumption was divided by usable floor area, the modelled heating energy consumption per square metre of usable area in the Arts building was similar to that in the T-Block building (monitored) in the NMIT in Nelson, but significantly lower than both buildings in the UoC in Christchurch (both monitored). (Clearly influencing any energy comparison between buildings in

Nelson and Christchurch is the fact that the Christchurch winter season is significantly more severe than that in Nelson.) The reasonable correspondence between the modelled energy consumption during the month of August, and an admittedly crude “steady state” representation of the building as a simplified box (Appendix K) provides further evidence that the model is providing a realistic representation of the energy consumption of the Arts building on a macro (monthly) scale, even if it is not possible to draw conclusions about its accuracy on a finer resolution time scale.

The temperature analysis in the Arts building suggests that, during the heating season, the indoor average weekly temperatures in the model generally were lower than the temperatures monitored in the actual building (ΔT of about 2 to 3°C with lower temperatures in the model). There appears to be a broad trend in some – but not all – of the rooms that the model’s under-estimation of the indoor temperature increases as the outdoor temperature drops. Possible explanations of why this might be are:

1. In the model the heat losses from the building through the envelope or via ventilation/infiltration are greater than in the actual building.
2. In the model, internal heat gains from occupancy and or equipment are less than in the actual building (but this possible contributing factor would not necessarily explain why the model’s under-estimation of indoor temperature might have some dependence on the outdoor temperature being particularly low).
3. The model’s representation of the heating system is of inadequate capacity to meet the building’s heating requirements.

Which one of these possibilities (or combination of two or more of them) cannot be determined without monitored data for each of these aspects in the actual building. This shortcoming is a common factor through all of the subsequent modelling variations on the Arts building (concrete- and steel-structured alternatives; improvement from code-compliant to best-practice thermal envelope; and fully air-conditioned commercial operation of the same basic building structure). Hence the consequences of the shortcoming would be broadly similar in all cases so that any conclusions drawn from the comparative study between the buildings (as represented in modelled form) should remain valid.

7 Results of energy modelling analyses

This chapter gives the results of the energy modelling assessment undertaken in all three sets of case-study buildings, with different thermal envelopes. The energy results are presented firstly by the categories in which the buildings were grouped initially and secondly as a combined result for all case-study buildings with an emphasis on space conditioning energy. This describes the BEEM modelling analysis of three possible methods of improving overall indoor comfort conditions and subsequently reducing space conditioning energy consumption in the case study buildings by effectively enhancing thermal mass performance.

7.1 Introductory clarifications to results

This research has used BEEM software to compare the HVAC energy consumption and indoor comfort conditions (using PMV) of nine BEEM models created as variations of three case study buildings, known in this research as the Timber, the Concrete, and the Steel buildings. These three case study buildings are at the same time variations of one actual building, the Arts building, an educational building located in Nelson, New Zealand.

The Timber, Concrete, and Steel buildings were modelled using two different thermal envelopes: The “code-compliant” and the “best-practice” thermal envelope (low energy buildings). Simulations of buildings with the “code-compliant” thermal envelope were undertaken using the Arts building actual HVAC system (educational HVAC system). Buildings with the “best-practice” thermal envelope were modelled not only with the educational HVAC system, but also with an alternative HVAC system called ‘Commercial HVAC system’. The most significant differences of this alternative HVAC system when compared with the ‘educational HVAC system’, are that cooling has been included for the improvement of indoor environmental conditions during summer, and that most of the heating is convective rather than radiant.

Table 7-1: summary of the case study buildings and their respective names in this thesis.

Thermal envelope	HVAC System	
	Educational	Commercial
Code compliant	Timber	
	Concrete	
	Steel	
Best practice	Timber-low	Timber-low-commercial
	Concrete-low	Concrete-low-commercial
	Steel-low	Steel-low-commercial

A comprehensive list of the nine resulting case study buildings, modelled in this research is given in Table 7-1 which is a copy of Table 4-3 first introduced in Section 4.2.

The operational energy assessment in this research includes HVAC energy and also lighting and office equipment energy because the presence of the latter two has a direct influence on the HVAC energy requirements. The energy requirements for domestic hot water services, however, are excluded because they are not influenced by building materials and have a negligible influence on the HVAC requirements. The relative proportions of the energy-end-uses in the modelled Arts building (a), and the modelled Arts building with no DHW (b) can be seen in Figure 7-2. DHW represents 16% of the total energy consumption in the modelled building; by excluding this building independent DHW from comparisons, the relevance of heating energy increases from 55% to a significant 66% of the modelled annual energy budget.

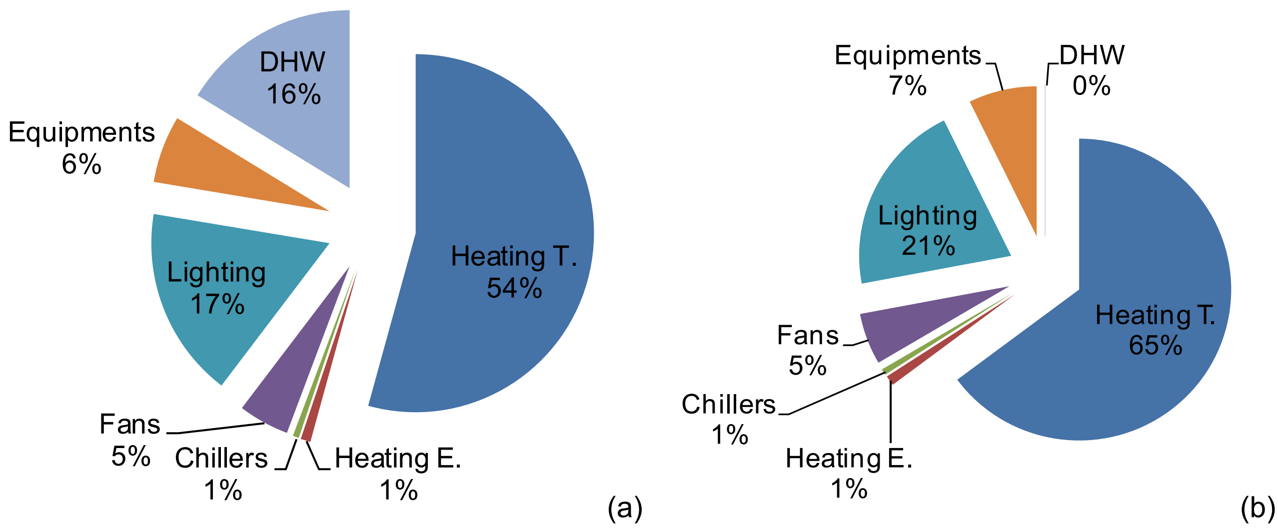


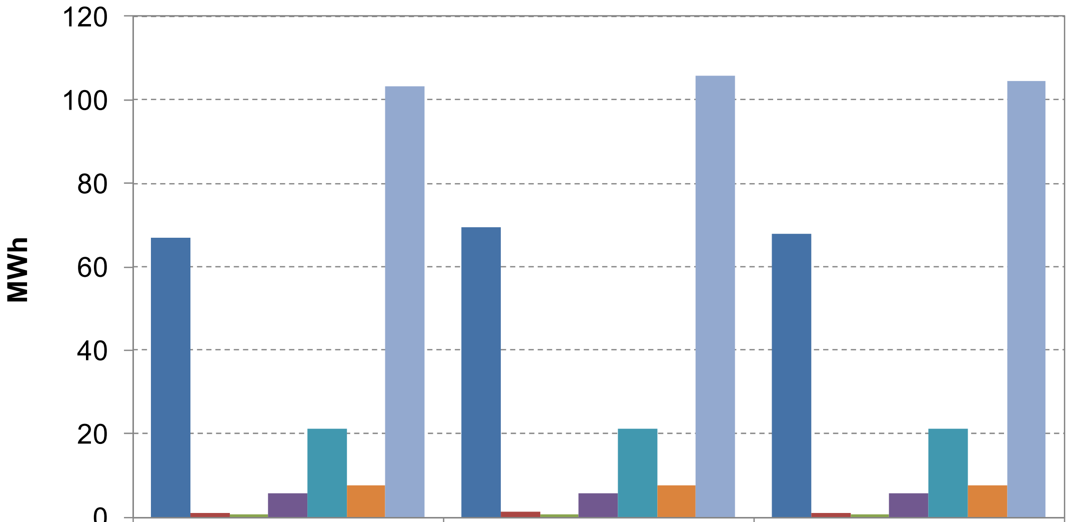
Figure 7-1: Breakdown of annual operational energy end-uses in the modelled Arts building (a) and the modelled Arts building without DHW (b). The circular area is proportional to the value of total annual energy consumption in each case.

As explained in Section 4.3.1 the designers of the alternative Concrete and Steel buildings, chose to use steel purlins (C section steel purlins) in the roof structural design of the Concrete and the Steel buildings. The R value of the roof construction using steel purlins (R 4.0) is lower than the R value of the roof construction in the Timber building (R 5.1) because of the use of LVL purlins instead of steel purlins. With the aim of isolating elements that may temper the differences between the annual operational energy consumption of the Timber, Concrete and steel buildings, a preliminary set of simulations analysing the influences of steel purlins where carried out prior to the final simulation presented in this results chapter. The results of the modelling of the annual operational energy consumption in the Concrete and the Steel buildings using either steel or timber purlins can be seen in Appendix G. The Concrete building with steel purlins uses 2% more thermal energy for heating (about 1.2 MWh/yr) than the same building with timber purlins; in the case of the Steel building the difference is about the same. In the remainder of Section 7, all results presented will have the Concrete and the Steel buildings using timber purlins.

7.2 Assessment of building's operational energy performance

This section presents the results of the annual operational energy analysis of the Timber, Concrete, and Steel buildings with the code-compliant thermal envelope and the same buildings with the best-practice thermal envelope (Timber–low, Concrete–low, and Steel–low). Also in this section, the operational energy analysis of the three building with the best-practice thermal envelope has been modelled with cooling added to the actual HVAC system (Timber-low-commercial, Concrete-low-commercial, and Steel-low-commercial).

7.2.1 Energy consumption in buildings with the code-compliant thermal envelope

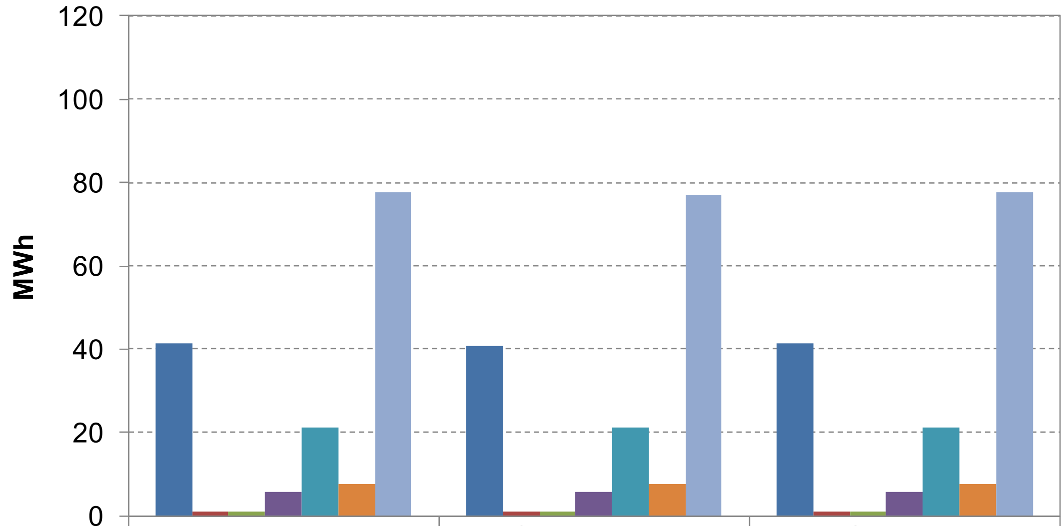


	Timber	Concrete	Steel
Heating (Thermal)	66.9	69.4	68.1
Heating (Electric)	1.1	1.2	1.1
Chillers (Electric)	0.7	0.6	0.7
Fans (Electric)	5.7	5.7	5.7
Lighting (Electric)	21.3	21.3	21.3
Equipment (Electric)	7.5	7.5	7.5
Total (Combined)	103.3	105.8	104.4

Figure 7-2: Total energy consumption (MWh) broken down into end-use energy consumption for the Timber, Concrete, and Steel buildings.

Figure 7-2 shows the annual operational energy consumption, broken down into energy end-uses, of the Timber, Concrete, and Steel buildings (code-compliant thermal envelope). Differences between total energy consumption between Timber, Concrete, and Steel buildings are not significant. The Timber building total energy consumption is 1% lower than the total energy consumption of the Steel building and 2% lower than the Concrete building. Fans, lights, and equipment energy consumption is exactly the same in all three buildings. The small differences are in heating and, less significantly, in chiller energy consumption. HVAC energy (heating, cooling and fan energy) represent about 73% of the total energy consumption; the remaining 27% corresponds to lighting and equipment electricity.

7.2.2 Energy consumption in buildings with the best-practice thermal envelope (No summer operations)

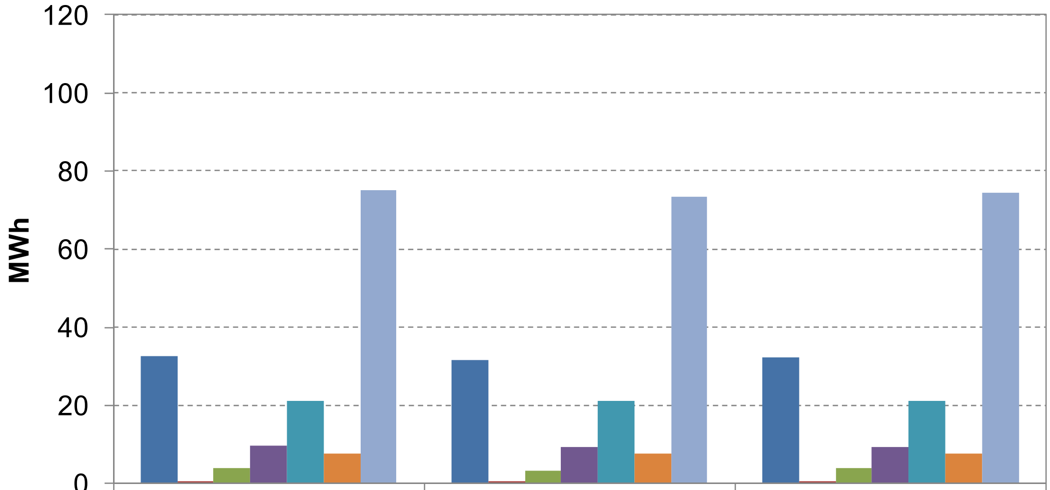


	Timber-low	Concrete-low	Steel-low
Heating (Thermal)	41.3	40.8	41.5
Heating (Electric)	0.9	1.0	0.9
Chillers (Electric)	0.9	0.9	0.9
Fans (Electric)	5.7	5.7	5.7
Lighting (Electric)	21.2	21.2	21.2
Equipment (Electric)	7.5	7.5	7.5
Total (Combined)	77.5	77.1	77.8

Figure 7-3: Total energy consumption broken down into end-use energy consumption for the Timber-low, Concrete-low, and Steel-low.

Although Figure 7-3 illustrates the predictable consequence of an improved level of insulation in any building (i.e. a significant reduction in heating energy requirements), the differences in the energy consumption of the three building types within this “best-practice” category are again insignificant. HVAC energy (heating, cooling and fans energy) has dropped from 73% of the total energy consumption for the buildings with the code-compliant thermal envelope to about 63%.

7.2.3 Energy consumption in buildings with the best-practice thermal envelope and the commercial HVAC system (Year-round operations)



	Timber-low-commercial	Concrete-low-commercial	Steel-low-commercial
Heating (Thermal)	32.6	31.5	32.1
Heating (Electric)	0.5	0.5	0.5
Chillers (Electric)	3.8	3.2	3.8
Fans (Electric)	9.5	9.3	9.3
Lighting (Electric)	21.2	21.2	21.2
Equipment (Electric)	7.5	7.5	7.5
Total (Combined)	75.1	73.3	74.5

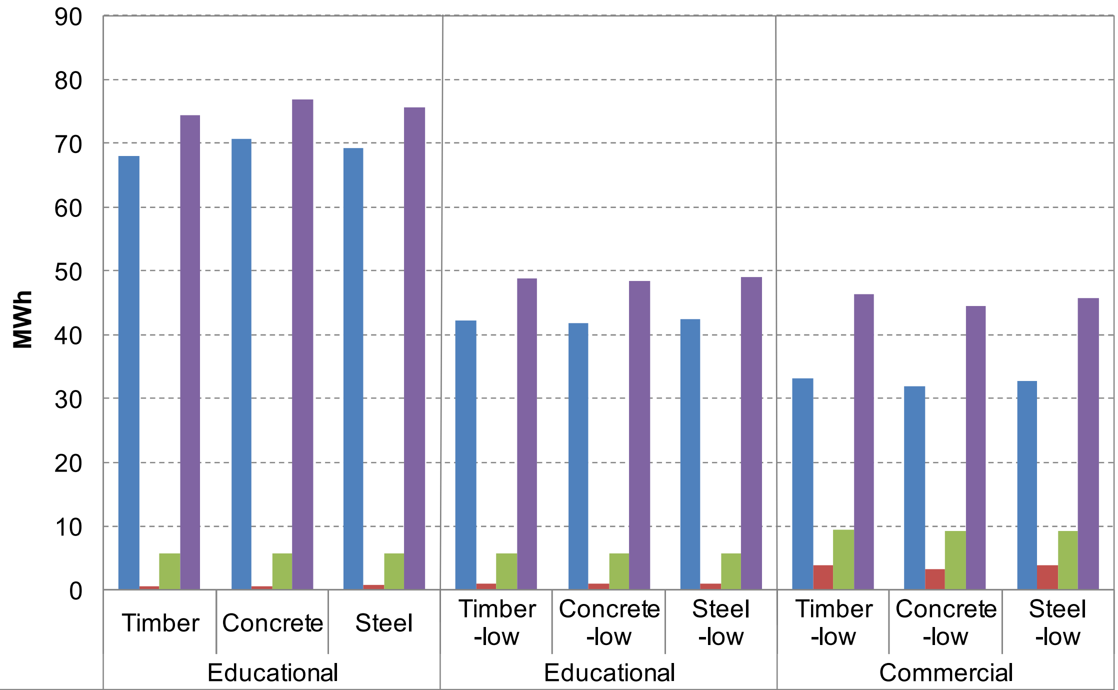
Figure 7-4: Total energy consumption broken down into end-use energy consumption for the Timber-low-commercial, Concrete-low-commercial, and Steel-low-commercial.

Figure 7-4 shows the corresponding data for this third category of buildings (and their operation) that were modelled. Yet again, each component of energy consumption has essentially the same value for all three construction materials.

Particularly in heating energy consumption of the building with best-practice thermal envelope, the buildings with the commercial HVAC system uses less energy than those with the educational HVAC system. The reason for this was initially explained in Section 4.6.3 when the description of the educational and the commercial HVAC systems was given. In broad terms differences arises largely because of changes from radiant (underfloor heated slab and radiators) to more effective convective heating in most of the rooms in the south part of the building.

7.2.4 Assessment of Energy - final discussion

For convenient comparison of all nine case study buildings modelled, Figure 7-5 consolidate the information presented in Figure 7-2 to Figure 7-4. Total averaged energy consumption in the Timber, Concrete, and Steel code-compliant buildings is about 104 MWh, in the best-practice buildings is 78 MWh, and in the best–practice with commercial HVAC system is 74 MWh. Equipment and lighting electricity, which is the same in all case-study buildings (about 29 MWh), has been omitted in this figure so that only HVAC-specific energy uses remain. Averaged total HVAC energy consumption is 76 MWh in the Timber, Concrete, and Steel buildings, 49 MWh in the best-practice buildings, and 46 MWh in the in the best-practice buildings with commercial HVAC system.



	Timber	Concrete	Steel	Timber -low	Concrete -low	Steel -low	Timber -low	Concrete -low	Steel -low
	Educational			Educational			Commercial		
Heating (Comb.)	68.0	70.6	69.2	42.2	41.8	42.4	33.1	32.0	32.7
Chillers (Elec.)	0.7	0.6	0.7	0.9	0.9	0.9	3.8	3.2	3.8
Fans (Elec.)	5.7	5.7	5.7	5.7	5.7	5.7	9.5	9.3	9.3
Total (Comb.)	74.4	76.9	75.6	48.8	48.3	49.1	46.4	44.5	45.8

Figure 7-5: Detailed and Total HVAC-specific energy consumption in all nine cases study buildings in this research.

The relative proportion of each of the HVAC energy components is similar in the code-compliant and in the best-practice buildings, but significantly different in the Low-energy-Commercial buildings. While heating corresponds to 92 and 86% of the total HVAC energy consumption in the code-compliant and in the best-practice building respectively, in the best-practice with commercial HVAC, heating energy corresponds to about 70% of HVAC energy consumption. Chillers correspond to only 1% of the HVAC energy in both the code-compliant and in the best-practice buildings while in the best-practice with commercial HVAC, chillers energy corresponds to 8% of annual HVAC energy. Finally, fans consume 8 and 12% of the total HVAC energy consumption in the code-compliant and in the best-practice buildings respectively, whereas in the best-practice buildings with the commercial HVAC system, fans represent about 20% of the annual HVAC energy consumption. This final increase in the fans' proportion of the HVAC system total energy consumption is consistent with the fact that, in the commercial system, there has been replacement of much of the building's radiative heating (from hot water radiators) with modular fan-driven Parasol units which are able to provide both heating and cooling capacity.

Although there are differences in the relative proportion of the components of HVAC energy between the best-practice buildings and the best-practice buildings with commercial HVAC, these two have a relatively similar total annual HVAC energy consumption even though the latter includes cooling. Average annual heating consumption is about 69 MWh in the code-compliant buildings which is about 65% higher than in the best-practice buildings with an average 42 MWh. Annual heating energy in the best-practice buildings with commercial HVAC, this is on average 33 MWh which is about 27% lower than in the best-practice buildings and about 50% lower than in the code-compliant building.

Chillers annual energy consumption is about 0.7 MWh in the code-compliant buildings, and is about 0.9 MWh (about 30% higher) in the best-practice buildings, because of the obvious influence of increased heat gains in the computer room when the thermal envelope was improved from code-compliant to best-practice standards. In the best-practice buildings with the commercial HVAC, chillers annual energy consumption averages 3.6 MWh which is about five times the chillers energy consumption in the best-practice buildings with the educational HVAC system (cooling in the computer room only). In the code-compliant and the best-practice buildings, fan energy consumption is the same (5.7 MWh), but in the best-practice building with commercial HVAC, this increases to 9.3 MWh (60% higher) mostly because the efficiency of convective heating and cooling is dependent on mechanically supplied air velocity, as noted above. Also the summer night-time mechanical ventilation adds to this difference.

Overall, the best-practice buildings with commercial HVAC, has the lowest total HVAC energy consumption despite having cooling included. The change from radiant heating to convective heating makes the biggest impact on HVAC energy reduction with the increase in chillers energy being less than the reduction in heating energy; this is despite the fact that fans also contributes more to HVAC energy consumption. Part of the following section analyses indoor comfort conditions to see the consequences of changes from radiant to convective heating.

The clear conclusion from these analyses is that differences in the HVAC energy consumption for the Timber, Concrete, and Steel buildings are not significant in any of the three scenarios summarised. The most significant differences are in the best-practice buildings with the commercial HVAC, were the Concrete building has the lowest HVAC energy consumption, being 3 and 4% lower than in the Steel and Timber buildings respectively. Differences in these cases correspond to variations in Chillers and Fans energy consumption more than differences in heating energy consumption.

8 Assessment of indoor environmental conditions

In this chapter, the indoor thermal environmental conditions of the nine case study buildings are examined. The chapter is organised in two main sub-sections: the analysis of indoor comfort conditions using predicted mean vote (PMV); and the assessment of thermal mass surface temperatures and also indoor air temperatures within the buildings.

8.1 Rooms selected for PMV assessment

To have a manageable amount of data from the analysis of indoor environmental conditions in the Arts building it is necessary to choose a reduced number of rooms where the results produced can be extrapolated to the building as a whole. The approach taken for the analysis of the T-Block building's indoor air temperatures in Section 5.6.3 can be taken as a guideline for the analysis in the Arts building. Based on that, one room facing south and one room or zone facing north, preferably on Level 2, provides enough meaningful data for an understanding of indoor environmental conditions in the building as a whole.

(a) (b) (c)

Figure 8-1: Gallery (under construction) – Picture (a) Gallery's Level 1, picture (b) Gallery's Level 2, and picture (c) Gallery's Level 3.

The actual Arts building is a three storey building with an internal layout similar through all three storeys. The north wall of the building is mostly glazed (Level 2 and Level 3), and draws natural light into the main building through a full height gallery (three storeys tall). The gallery combines small enclosed rooms (on Levels 2 and 3) but it is mostly an open circulation space exposed to the north. This can be seen in Figure 8-1 which is a set of three pictures taken in each of the three levels of the gallery space. Picture (a) shows the large portion of the first floor which is occupied by the base of the atrium space. Pictures (b) and (c) show the gallery's Levels 2 and 3 respectively: in

(b) the magnitude of the void on Levels 2 and 3 can be appreciated, and in (c) the circulation area on Level 3 can be seen.

The gallery is flanked by a narrow structural core containing relatively small rooms aligned continuously from the east to the west façade of the building. Exposed to the south, there is a series of relatively large enclosed rooms normally occupied as studio or teaching areas and some offices, particularly in Level 1. Particularly on Level 2 there is only one large studio room (Studio 201) occupying the whole space between the structural core and the external south wall; this space is continuous from the external east to the external west wall. In Figure 5-15 the internal partition between the structural core area and the Studio 201 on Level 2 can be seen (picture (a)), while (b) shows the external south wall of the same studio. The depth of the Studio 201 from the structural core internal wall to the external south wall is apparent in (c).


(a)

(b)

(c)

Figure 8-2: Level 2 Studio room 201(under construction) – Picture (a) internal partition at the north side of the room, picture (b) external wall facing south, and picture (c) room's total transverse span.

The spaces chosen to carry out the assessment of the indoor environmental conditions in this section are the north facing gallery space, with emphasis on the Level 2 of the gallery, and the Level 2 south facing studio 201.

8.1.1 Gallery

The assessment of PMV was restricted to individual zones, averaged values for more than one zone combined being avoided in this part of the analysis because of the possibility of losing relevant detail in the averaging process. In the gallery space a number of thermal zones are interconnected when looking at the VE model. Particularly, Level 2 of the gallery is a composite space interconnecting three zones: the stairs landing space, corridor-balcony between the landing space and the meeting room on the north west corner of the building (Staff room), and the meeting room in the north east corner of the building (Level 2 meeting room).

The assessment of PMV was carried out in two rooms on Level 2 of the gallery space (Figure 8-3), being the Landing-Gallery room (number 1) combining the stairs landing space, corridor-balcony, and the Level 2 meeting room, and the Staff room (number 2). This way the comfort conditions will be assessed in an open space exposed to the gallery and into an enclosed space exposed to the north through the gallery.

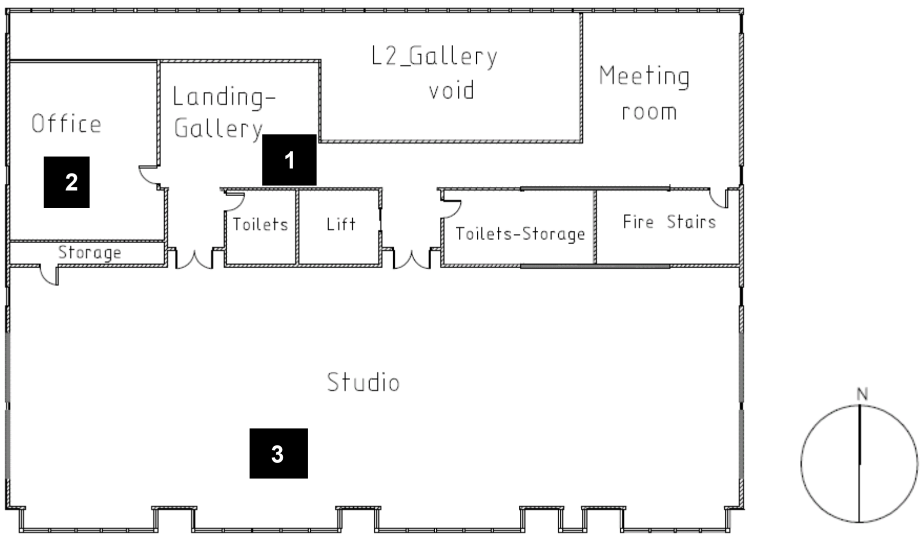


Figure 8-3: Plan section Level 2 of the Arts building with the specified rooms were PMV has been assessed in this research.

The detailed indoor temperature analysis of the nine case study buildings in this research was undertaken in the gallery space as a representative north-facing space, and in the Studio 201 room as a south-facing representative space. The temperatures analysis in the gallery accounts for both, the three storeys high space as an entity and each of the three gallery levels individually. Analysis of the gallery's individual levels was carried out to see the effect of direct radiation into air and surface temperature on Level 2 and Level 3 individually. There is no analysis of an enclosed room facing north because in the Staff Room on Level 2, nor in any of the enclosed spaces on Level 2 or Level 3 was a temperature sensors installed (see Section 6.4 for temperature sensors' locations). Monitored data from temperature sensors was used initially in Chapter 6 to assess the accuracy of the indoor environmental modelling using the BEEM software of choice in this research.

8.1.2 Studio 201

Both PMV assessment, and surface and indoor air temperature analysis of a room located in the south façade of the building was undertaken in Studio 201, in Figure 8-3 (Tag # 3). Choosing Studio 201 as the room representative of spaces facing south is consistent with the approach taken for the detailed temperature analysis in the T-Block building (See Section 5.6.3 for details). Basically since Level 2 is a space supported within suspended floors, and has a reduced exposure to the thermal envelope compared with Level 3, and does not have the influence of the massive concrete slab on ground existing on Level 1, both of these other situations potentially temper the results that this research is looking for. Since a primary emphasis of this research is on the influence of thermal mass into space conditioning energy consumption, the influence of the particular structural fabric of the actual Arts building (Timber building) and its variations in concrete and steel should be most evident from this analysis of air temperatures in Level 2 spaces.

8.2 PMV Analysis

Methodology for the assessment of indoor comfort conditions used in this research is the predicted mean vote (PMV). The definition of PMV from ASHRAE Standard 55-2004 is: *"An index that predicts the mean value of the votes of a large group of persons on a seven-point thermal sensation scale, being: cold, cool, slightly cool, neutral, slightly warm, warm, and hot"* (ASHRAE, 2004).

Table 8-1: Comfort parameters for PMV calculations – Default values available in VE for a "one fits all" sets of parameters for an easy-to-implement assessment.

Comfort parameters			
Clothing levels:	0.7	clo	Default values from VE
Activity Levels	90	W/m^2	Default values from VE

Table 8-1 shows the comfort parameters used in the PMV assessment on Sections 8.2.1, 8.2.2, and 8.2.3. The parameters that normally define of the acceptable comfort zone in the PMV assessment are mainly indoor air and mean radiant temperatures, indoor air relative humidity, activity levels, clothing levels, and air velocity (ASHRAE, 2004). The PMV assessment carried out by the BEEM software of choice in this research (VE), assesses the comfort conditions in the room as whole rather than in specific locations within the space. In that scenario although the software is able to model the flow of air produce by the mechanical and natural ventilation, air speed is not taken into account in the assessment of PMV, which in this case, is mostly determined by indoor air and mean radiant temperature under specifics activity and clothing levels (IES Ltd, 2010b).

Values in Table 8-1 are suggested by VE to produce default results when doing PMV analysis. In Appendix H there is a PMV assessment on the same rooms 1, 2, and 3 on Figure 8-3 but in which the comfort parameters where tailored by varying the clothing levels during winter and summer while keeping the activity levels constant. In Section 8.4 the results in Appendix H will be brought into the discussion.

The comfort parameters in Table 8-1 are clothing levels and activity levels. In the clothing levels the unit used is clo, which is a unit used to express the thermal insulation provided by clothing ensembles (1 clo = 0.155m^2 °C/W) which is equivalent to a light weight suit. The clo value in the default comfort parameters is 0.69 which compares with data from Chapter 8 of the 2009 ASHRAE Handbook – Fundamentals is a value between wearing trousers and a long-sleeve shirt (clo 0.61); such a clothing ensemble increases to clo 0.96 if adding a suit jacket (ASHRAE, 2009). It would not be unreasonable to suggest that for the New Zealand temperate climate, in an indoor conditioned environment wearing a thick fabric long-sleeve shirt and trousers should be reasonably comfortable through all year, although this maybe slightly cool in winter and slightly warm in summer. The term "activity levels" describes the energy generated inside the body due to metabolic activity, defined as 58.2 W/m^2, which is equal to the energy produced per unit surface area of an average person, seated at rest[8]. Activity levels in the default comfort parameters is 90 W/m^2 which is between the office activity of filing standing (80 W/m^2) and walking about (100 W/m^2) (ASHRAE, 2004).

Table 8-2: Comfort scale for PMV calculations.

Thermal sensation scale						
hot	Warm	Slightly warm	Neutral	Slightly cool	cool	cold
+ 3	+ 2	+ 1	0	- 1	- 2	- 3

The ASHRAE thermal sensation scale, which was developed for use in quantifying people's thermal sensation, is defined in Table 8-2 (ASHRAE, 2004). The PMV model uses heat balance principles to relate metabolic rate, clothing insulation, indoor air and mean radiant temperatures, and relative humidity, to the average response of people on the scale in Table 8-2. The ASHRAE Standard 55-2004 suggest a acceptable thermal environment for general comfort in the range of PMV from -0.5 PMV to +0.5 PMV (ASHRAE, 2004).

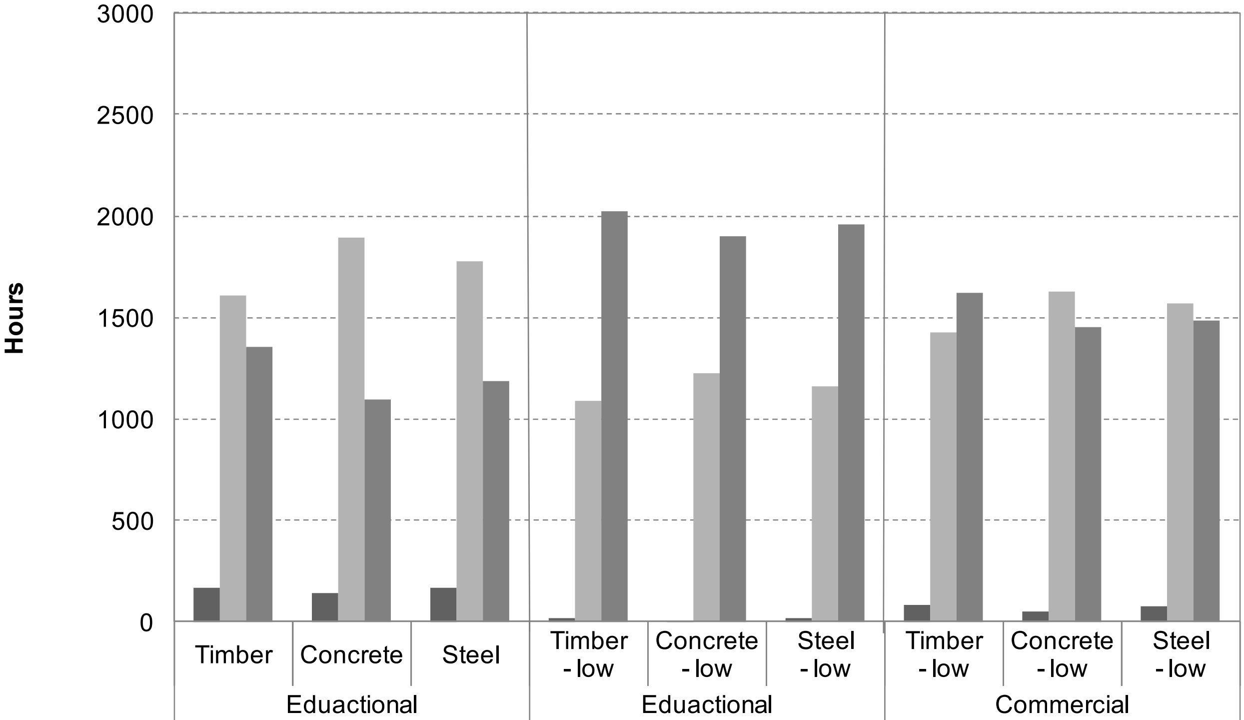
The PMV assessment in this section is restricted to building's occupied hours only, which based on the schedules of occupancy presented on Section 4.5, are Monday to Saturday, from 8:00 AM to 6:00 PM continuously from January to December.

8.2.1 PMV in the Landing-Gallery space in Level 2 – North façade

Figure 8-4 shows the results from the PMV modelling of the Landing-Gallery space (Room 1) in the Timber, Concrete, and Steel, buildings, with code-compliant and the best-practice thermal

[8] The surface area of an average person is 1.8 m^2.

envelope. For the best-practice buildings the results of the PMV when convective cooling and heating operates in the building (commercial HVAC system) has been also included in Figure 8-4.



	Timber	Concrete	Steel	Timber - low	Concrete - low	Steel - low	Timber - low	Concrete - low	Steel - low
	Eduactional			Eduactional			Commercial		
< -0.50	169	140	170	21	6	18	83	54	74
-0.50 to 0.50	1609	1895	1776	1086	1222	1157	1427	1625	1571
> 0.50	1353	1096	1185	2024	1902	1955	1620	1452	1486

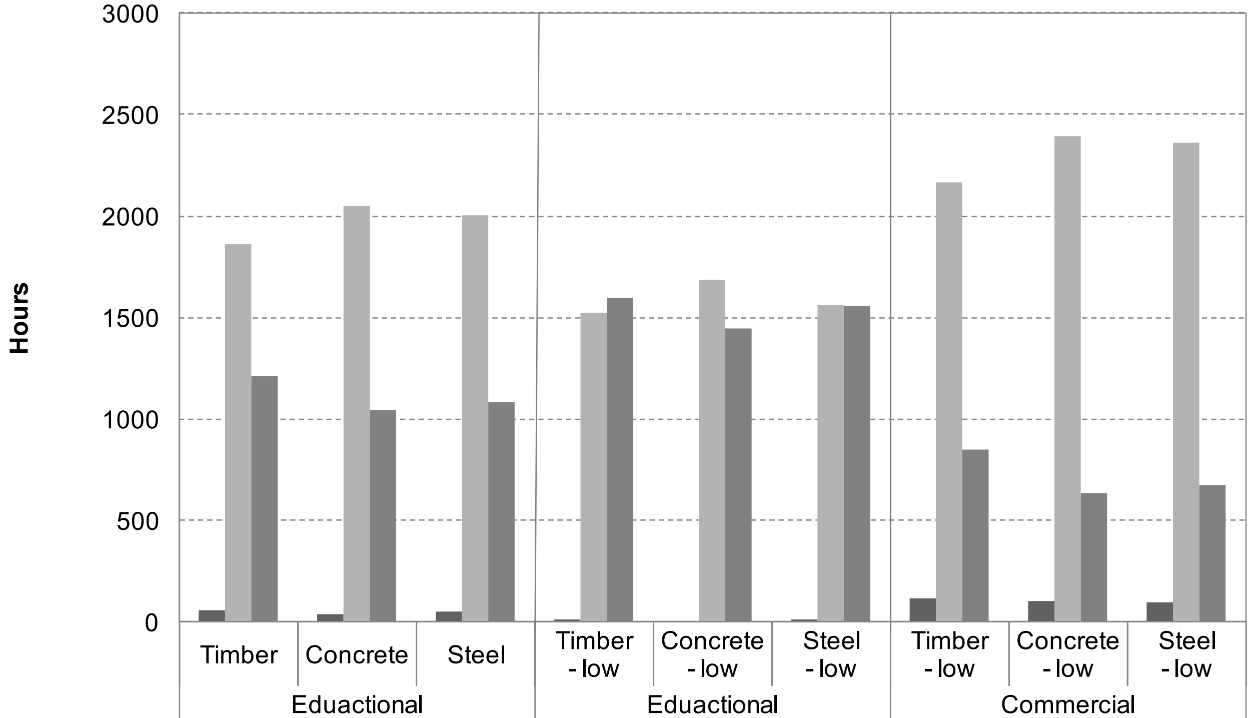
Figure 8-4: PMV of Landing-Gallery room in level 2, north facing.

It can be seen in Figure 8-4 that the number of hours within comfortable environmental conditions is not particularly high in any of the three buildings under any of the three scenarios studied (in comparison with PMV assessment of the Staff room and Studio 201). The highest number of hours within comfortable environmental conditions is in the code-compliant buildings (averaged 56% of the occupied time), followed by the best-practice buildings with the commercial HVAC system (averaged 50% of the occupied time). Particularly in the best-practice buildings with the educational HVAC system, the number of hours within comfortable environmental conditions is very low (average 37% of the occupied time). Almost all of the time in which the buildings are not within comfortable environmental conditions, occurs when indoor environmental conditions are slightly warmer to hot (> 0.50 in the scale given in Table 8-2). In the code-compliant buildings, this environmental condition represents 40% of the time; in the best-practice buildings is 63% and in the best-practice building with the commercial HVAC system is about 50%.

Figure 8-4 also shows that in all of the three scenarios studied in this research, the Concrete building has the longest period of time within comfortable environmental conditions, followed by the Steel building and with the Timber building being the least comfortable. In the code-compliant buildings, the Concrete building has 6% (119 hours) more hours in a comfortable range than the Steel building and 15% (286 hours) more than in the Timber building. In the best-practice buildings, the Concrete building has 5% (65 hours) more hours in a comfortable range than the Steel building and 11% (137 hours) more than in the Timber building. Finally in the best-practice building with the commercial HVAC system, the Concrete building has 3% (54 hours) more hours in a comfortable range than the Steel building and 12% (198 hours) than in the Timber building.

8.2.2 PMV in Staff room in Level 2 – North façade

The Staff room is the only room in the north side of the building in which there is direct supply of air from the AHU, and there is cooling in the case of the best practice building with the commercial HVAC system. Figure 8-5 shows the results from the PMV modelling of this room in the Timber, Concrete, and Steel, buildings, under the three scenarios studied in this research: code-compliant buildings, best-practice buildings, and best-practice buildings with the commercial HVAC system.



	Timber	Concrete	Steel	Timber - low	Concrete - low	Steel - low	Timber - low	Concrete - low	Steel - low
	Eduactional			Eduactional			Commercial		
< -0.50	58	39	48	11	0	9	116	101	99
-0.50 to 0.50	1862	2047	2002	1525	1687	1563	2163	2394	2358
> 0.50	1210	1044	1080	1594	1444	1559	851	636	674

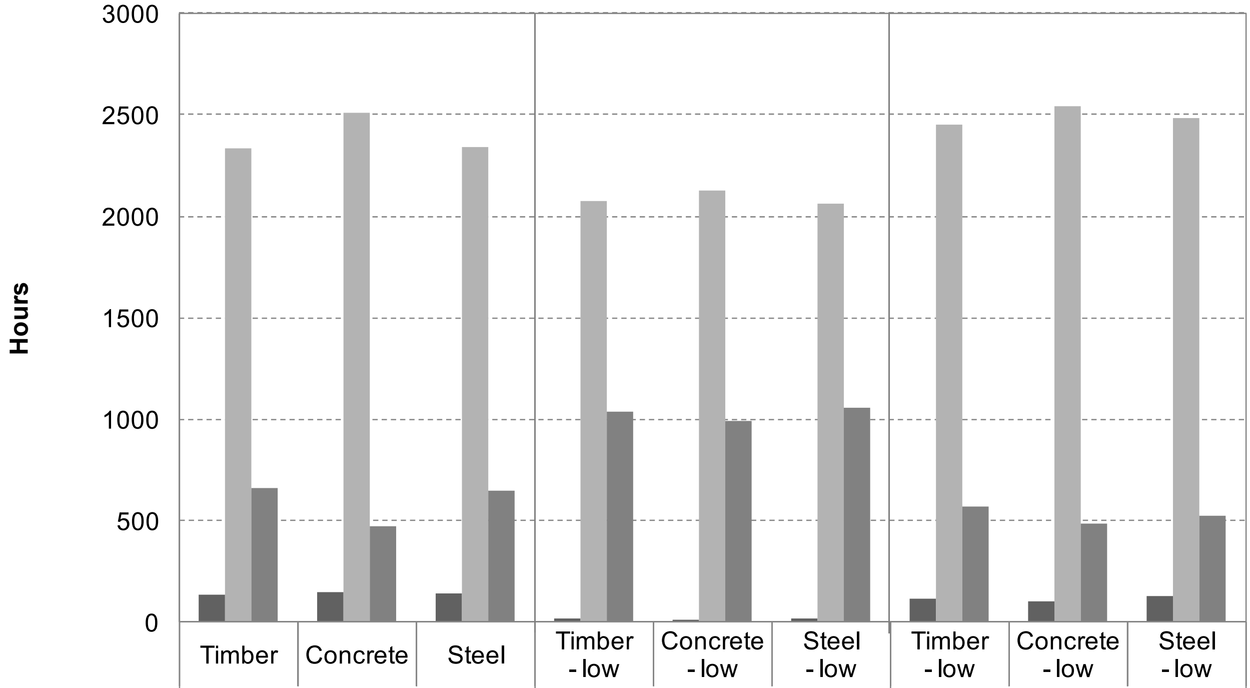
Figure 8-5: PMV of Staff room on level 2, north facing.

It can be seen in Figure 8-5 that the amount of hours within comfortable environmental conditions vary significantly in each of the three different scenarios with the highest amount of hours within comfortable environmental conditions in the best-practice buildings with the commercial HVAC system (averaged 56% of the occupied time), followed by the code-compliant buildings (averaged 63% of the occupied time). Consistent with Landing-Gallery space, the best-practice building with the educational HVAC system have the lowest amount of hours within comfortable environmental conditions, and in this case, average about 50% of the occupied time. Also similar to the Landing-Gallery space, most of the time in which the buildings are not within comfortable environmental conditions, is because indoor environmental conditions are slightly warmer to hot (> 0.50 in the scale given in Table 8-2) but the proportion of time during which these conditions prevail is significantly reduced compared with the Landing-Gallery space.

Again Figure 8-5 also shows that for this space, in all three scenarios the Concrete building has the longest period of time within comfortable environmental conditions, followed closely by the Steel building and with the Timber building being the least comfortable. Generally, the differences between the hours of slightly warmer to hot conditions in each of the three structural types is not as great for this space as it was for the landing-gallery.

8.2.3 PMV in Studio room in Level 2 – South façade

For the Studio 201 (Room 3) the corresponding PMV analyses in the Timber, Concrete, and Steel, buildings, under the three scenarios studied in this research are presented in Figure 8-6.



	Eduactional			Educational			Commercial		
	Timber	Concrete	Steel	Timber - low	Concrete - low	Steel - low	Timber - low	Concrete - low	Steel - low
< -0.50	135	147	143	20	14	18	114	105	126
-0.50 to 0.50	2335	2508	2339	2073	2125	2059	2450	2541	2481
> 0.50	661	475	649	1038	991	1054	567	485	524

Figure 8-6: PMV of Studio 201 on level 2, south facing.

Of the three spaces selected for the PMV analysis, this room (see Figure 8-6) displays the most acceptable comfort conditions in each of the nine case study buildings (three structural types in each of the three groups). Although the hours of out-of-comfort conditions are significantly lower - especially in comparison with the Landing-Gallery – they are still dominantly slight over-heating rather than under-heating. As in all cases considered here, most of these “over heated” hours are accumulated during the summer period and therefore would be described better as being conditions of "under-cooling".

One difference to be noted of Figure 8-6 is that the ranking order in Studio 201 is slightly different than the ranking order in both of the rooms on the north side of the building. Although in Studio 201 the Concrete building also has the longest period of time within comfortable environmental conditions in all three scenarios, this is followed more closely by the Steel and the Timber buildings with the Timber building sometimes more comfortable than the Steel building. In the code-compliant buildings, the Concrete building has 7% more hours in a comfortable range than the Steel and the Timber buildings, both having about the same amount of hours in a comfortable range. In the best-practice buildings, the Concrete building has only 2% more hours in a comfortable range than the Timber building this time, and 3% than in the Steel building. Finally in the best-practice buildings with the commercial HVAC system, the Concrete building has 2% more hours in a comfortable range than the Steel building and 4% than in the Timber building.

8.2.4 Assessment of the Influence of default comfort parameters

In Appendix H an alternative PMV assessment was carried out for the same three rooms in this section. The conditions for this alternative PMV assessment were basically a reduction of the clothing levels for the summer months to 0.2 clo (corresponding to sportswear), and an increment of the same values during winter months to 1 clo (equivalent to wearing trousers, a long-sleeve shirt, plus a long-sleeve sweater). Activity levels were kept constant to about 70 W/m^2 equivalents to a sedentary work – standing. The results of the variable PMV assessment in Appendix H shows not a significant variation in the amount of hours within a comfortable environment but significant reduction of hours in which indoor environmental conditions are slightly warmer to hot, and even a greater increment of the hours in which the indoor environmental conditions are slightly cool to cold. In broad terms, in the variable PMV analysis, the average total amount of hours within a comfortable environment is 13% lower compared with the default PMV analysis. Hours of slightly cool-to-cold indoor environment are 38% higher in the variable PMV than in the default PMV analysis. Although the clothing levels were increased during winter conditions in the variable PMV assessment, the reduction of activity levels (from 90 W/m^2 in the default PMV assessment to 70 W/m^2 in the variable PMV assessment) have a more significant influence in the outcome of this assessment with a consequent increase in the amount of hours where environments are slightly cool-to-cold. Finally, the hours of slightly warm to hot indoor environments are 24% lower in the variable PMV than in the default PMV analysis. Results in Appendix H are significant because they suggest that default values are an acceptable generalization to assess comfort conditions, and that if variations in clothing or in activity levels occur these will have a higher influence in the amount of hours out of comfortable environmental conditions more than changes into the hours within comfortable environmental conditions.

8.3 Indoor air and surfaces temperature comparison between the Timber, Concrete and Steel buildings:

The aims of this section are:

- To study the influence of building's fabric on indoor environmental conditions;
- To identify how building fabric influences the PMV assessment;
- To find correlations between building's fabric and energy assessment.

To achieve these objectives, not only the indoor air temperature but also the surface temperatures of the buildings constructive elements that have the most significant amount of thermal mass have been analysed in the Timber, Concrete, and Steel Code-compliant buildings and, in some cases, in the Low-energy buildings.

The central part of the analysis is to identify a correlation between surface temperatures of massive structural elements exposed to indoor environments and the resultant air temperature of the rooms where these massive elements are placed. The focus is on recognizing differences between the influences on room air temperature of massive structural elements when these are built using timber (in the Timber building) or concrete (in the Timber, Concrete, and Steel buildings).

The Structural elements with high quantities of thermal mass were initially identified in Section 4.4; structural suspended floors, structural shear walls, and stand-alone walls (representation of the structural columns, beams, and rafters into the BEEM models) were recognized as having the higher capacitance (C value) of all other construction in the Timber, Concrete, or Steel buildings.

As explained in the introduction to this section (Section 8.1), the detailed indoor temperature analysis of the Arts building was undertaken in the gallery space as being representative of north-facing spaces, and in the Studio 201 room as a south-facing representative space. The temperature analysis in the gallery accounts for both the three storey high space as an entity and each of the three gallery levels individually.

8.3.1 Whole year, weekly averaged temperature:

A preliminary comparison using weekly average temperatures over a complete year between indoor air temperatures in the Timber, Concrete and Steel code-compliant buildings with the educational HVAC system, can be seen for the Gallery space (integrated 3 levels air temperature) in Figure 8-7 and for the Studio 201 room in Figure 8-8.

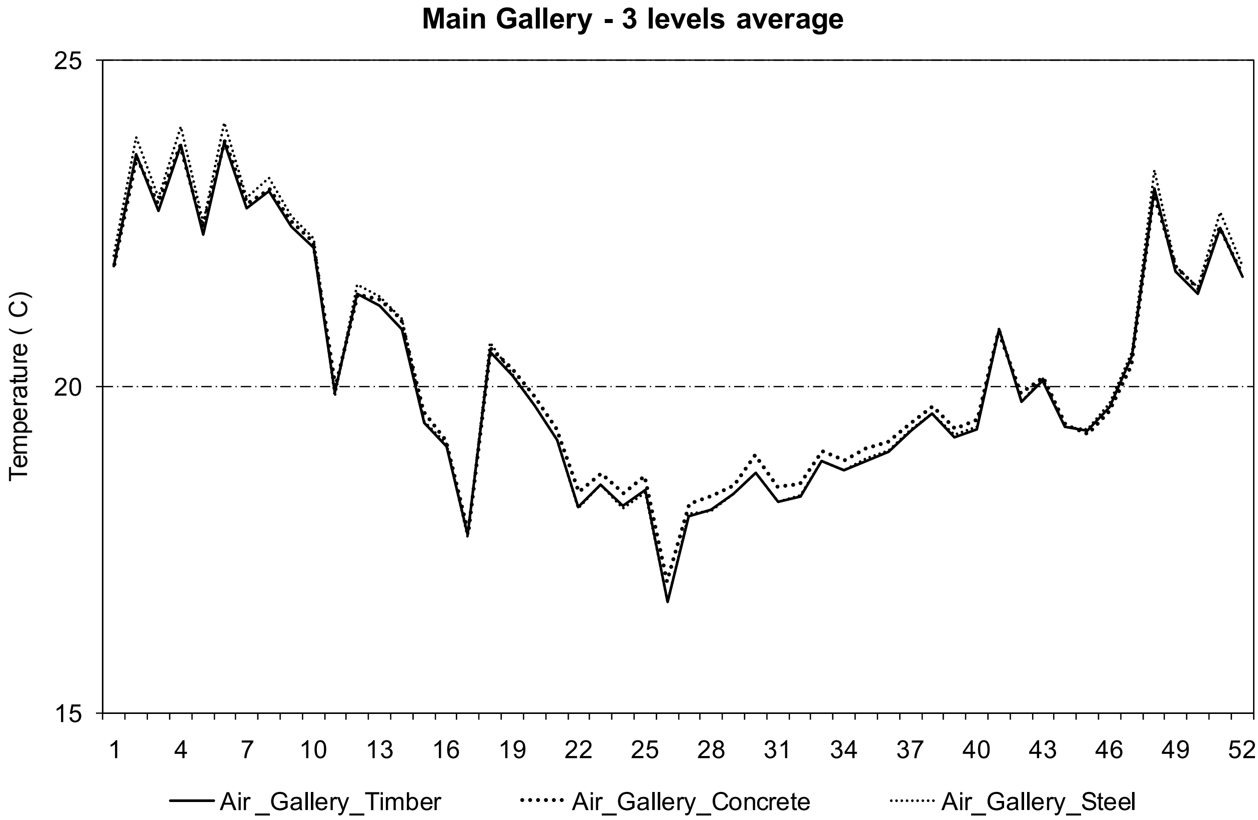


Figure 8-7: Main gallery's three levels weekly averaged temperature across a complete year.

Differences between indoor air temperatures in any of the three different buildings are not significant when looking at weekly averaged values in any of the two spaces chosen for temperature differences analysis. In the north facing gallery (Figure 8-7) the highest temperature difference registered is only 0.4°C between the Steel and the Concrete buildings during the last week of November (Week 48 in graph); average difference in all cases is also negligible.

A slightly higher peak temperature difference can be seen in the Studio 201 (Figure 8-8) where a difference of 0.8°C between the Steel and the Concrete building also during the last week of November (Week 48 in graph) can be seen. Average temperature difference is only 0.3°C between the Steel and the Concrete building.

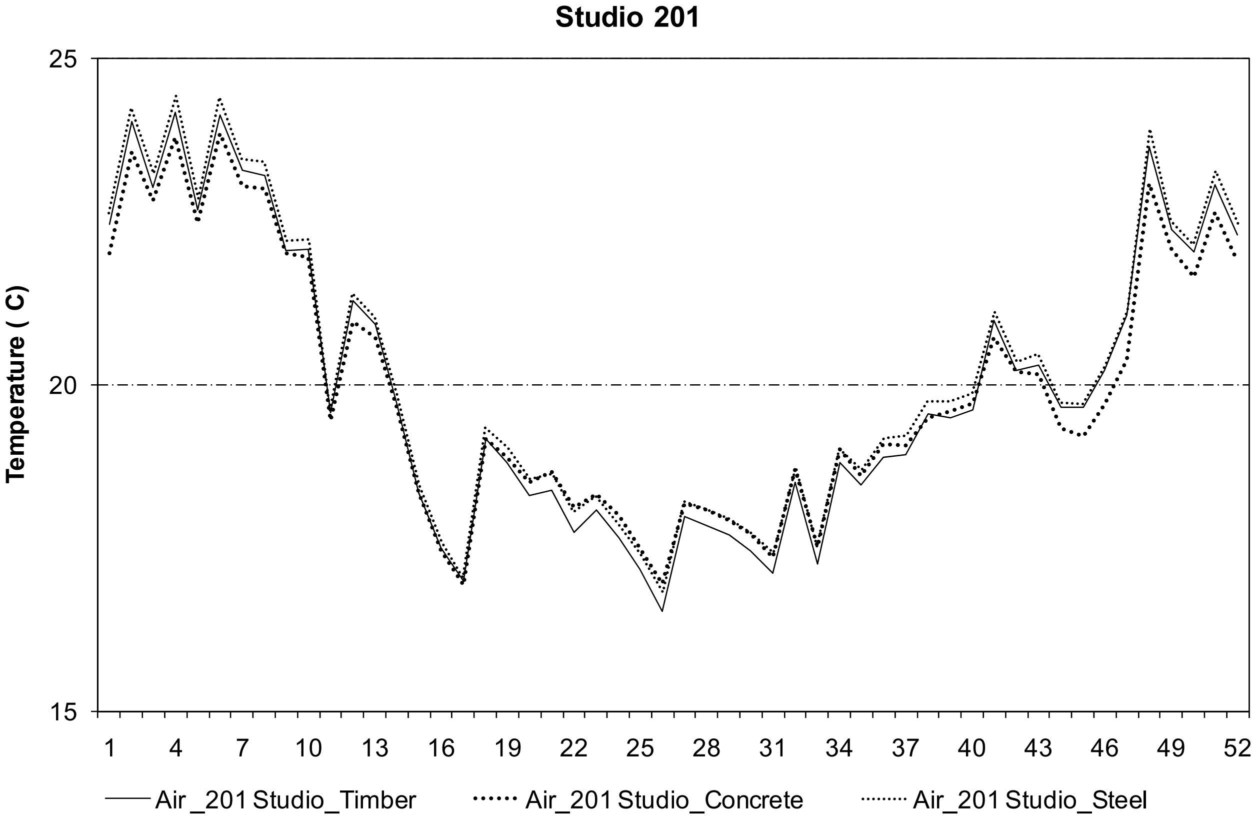


Figure 8-8: Studio room on Level 2 (south facing) weekly averaged indoor air temperature across a complete year.

To obtain a more meaningful comparison between both air temperatures and surface temperatures of massive structural elements, a much more detailed look into temperature fluctuation needs to be carried out. Since the comparison between the Timber, Concrete, and Steel buildings in this research is produced using BEEM software, daily and hourly temperature fluctuations can be easily obtained.

8.3.2 Hourly temperature comparison – The choice of a winter and a summer representative week

This section shows the detailed indoor air and surfaces temperature analysis in the Timber, Concrete, and Steel code-compliant and in the best-practice buildings with the educational HVAC system. The time step for graphical result presentation is hourly and the period of time that will be analysed will be one week. In such a period of time the detailed dynamics of temperature fluctuation can be observed in detail. Two separate weeks were chosen for the indoor temperature analysis in this section: one representative of summer conditions and one of winter conditions. In Figure 8-9 a graph containing outdoor dry-bulb temperature, direct normal radiation and diffuse horizontal radiation during the summer representative week (from Monday February 1st until

Sunday February the 7th) is shown. In Figure 8-10 the same parameters for the winter representative week (From Monday June 28th until Sunday 4th of July) are given. Climate data in Figure 8-9 and Figure 8-10 are taken from the TMY weather file of Nelson. As explained earlier in Section 4.5.2 climate data in TMY files are typical meteorological values generated from a data bank much longer than a year in duration, specifically, the climate data in the summer representative week is from the year 2000, and in the winter representative week is a mixture of climate data from the years 1997 (June - first three days) and 2006 (July - last four days); see Table 5-10 for details in TMY climate data sourced.

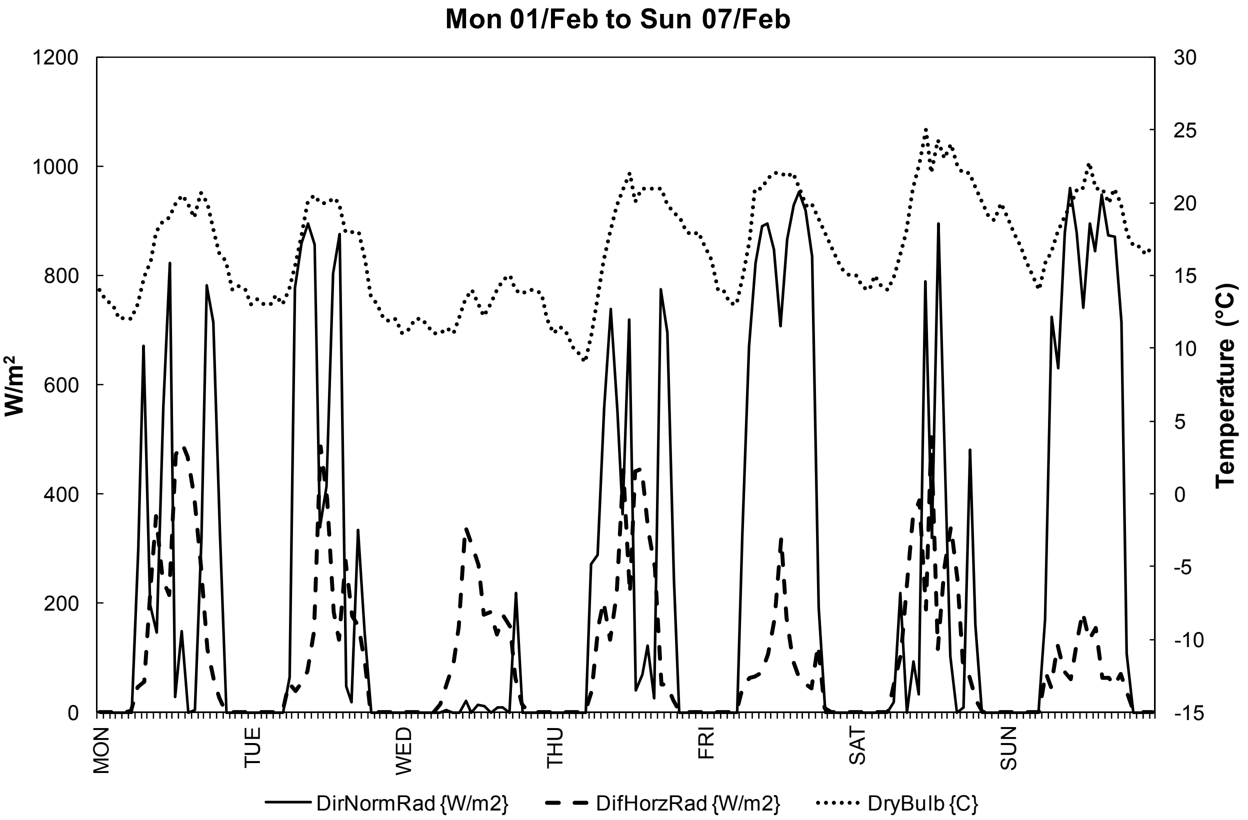


Figure 8-9: For a week representative of summer conditions, dry-bulb temperature, direct radiation and diffuse horizontal radiation are given.

There are no data for total sky cover or opaque sky cover in the TMY file for Nelson. The two climate characteristics that most significantly influence indoor environmental conditions in buildings that are available in the TMY weather file are dry-bulb temperature and direct solar radiation (Duffie & Beckman, 2006). The chosen summer representative week combines days with very low direct radiation immediately followed by days with very high direct radiation; this is to assess the response of air and surfaces temperature to clear changes in outdoor environmental conditions. Particularly on Wednesday February 3rd, peak direct radiation is as low as 219 W/m^2 at 7:30 pm but the previous day (Tuesday February 2nd) records shows a peak direct radiation of 896 W/m^2 at

10:30 am and on the following day (Thursday February 4th), direct radiation peak to 774 W/m^2 at 6:30 pm. Although peak direct solar radiation in the TMY file is recorded on December 26th with 1063 W/m^2 at 1:30 pm, peak radiation during the representative summer week is on Sunday February 7th with 947 W/m^2 at 11:00 am, corresponding to a 116 W/m^2 (about 10%) lower direct radiation (intensity) than in the whole year peak.

The most important factor in choosing this particular summer representative week was that, during this week, changes in direct radiation had a noticeable influence on dry-bulb temperature. It is not always the case that dry-bulb temperature is responsive to changes in direct or diffuse radiation but, in the chosen week although daily maximum dry-bulb temperature is mostly constant during the week, it drops significantly during Wednesday February 3rd with a maximum temperature during that day of 15°C at 7:00 pm, compared with a peak of 21°C the day before and 22°C the day after. That drop of temperature during Wednesday February 3rd corresponds to the significant drop of direct solar radiation. Although peak dry-bulb temperature in the TMY is 27°C on Friday January 15th at 4:00 pm, peak dry-bulb temperature during the summer representative week is 25°C on Saturday February 6th at 1:00 pm.

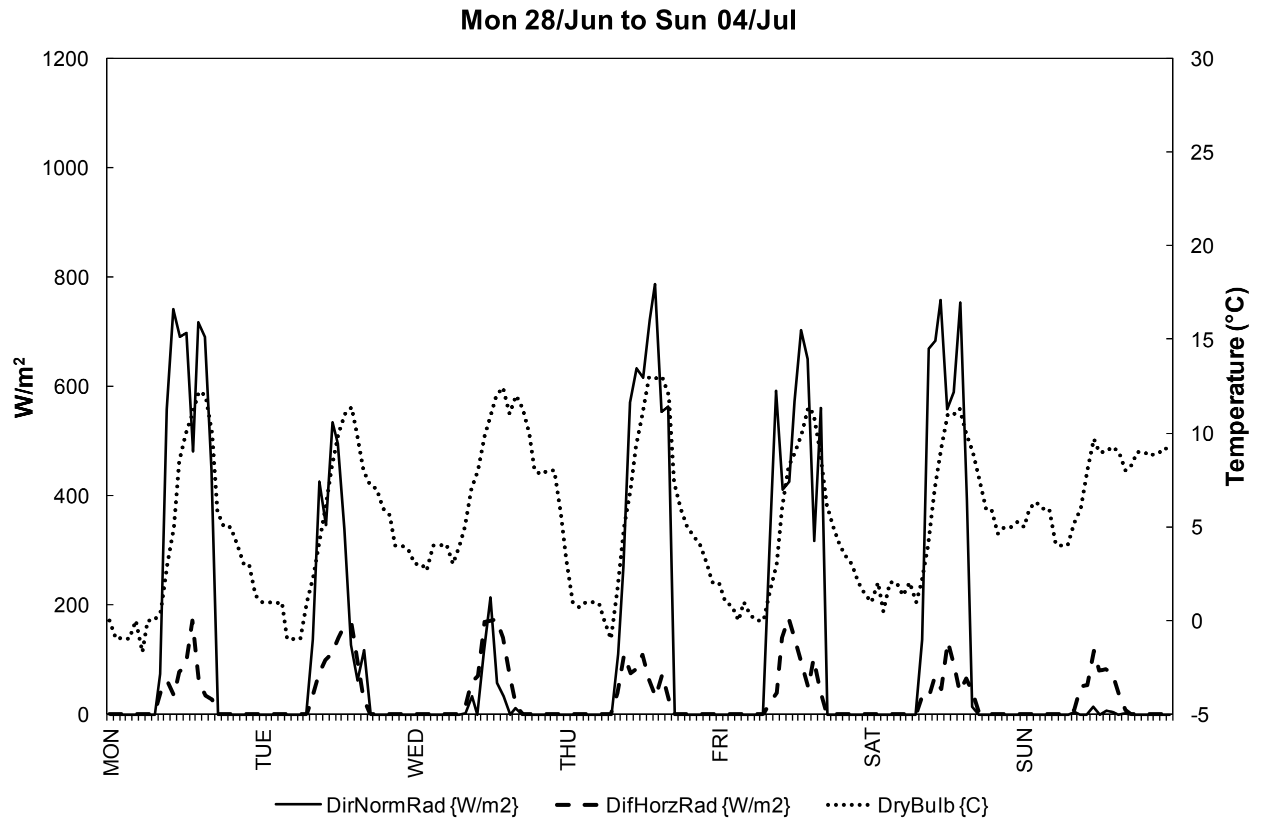


Figure 8-10: For a week representative of winter conditions, Dry-bulb temperature, direct radiation and diffuse radiation are given.

The choice of the winter representative week (from Monday June 28th until Sunday July 4th) follows roughly the same methodology as that used for the summer representative week, but added to that is the fact that, included in this week, is the day with the peak annual heating energy consumption (Monday June 28th) with a peak load of about 167 kW at 8:00 am. Similar to the summer representative week, Wednesday of this week (June 30th) has a very low direct radiation (peak of 213 W/m^2) compared with peak 535 W/m^2 the previous day and 787 W/m^2 the following day. This 787 W/m^2 peak value is about 25% lower than the whole year peak value for direct radiation intensity.

Unlike the summer representative week, weekly variations on direct radiation have little influence on dry-bulb temperature during the winter representative week. Daily maximum dry-bulb temperature remains relatively constant with an average of 11.6°C with a range from maximum 12.4°C on Wednesday June 30th (day with lowest direct radiation) to maximum 9.7°C on Sunday the July 4th.

8.3.3 Surfaces to be assessed

In the following section, the building's structural elements chosen for surface temperature analysis are: structural suspended floors, structural shear walls, and stand-alone walls. As it was initially explained in Section 4.4, for the purpose of this research the LVL and the concrete structural shear walls and stand-alone walls are considered to have high thermal mass. Particularly in the case of the Steel building, no shear walls or stand-alone walls were included in the energy and indoor space environmental modelling, because these are light-weight elements structured in steel which is considered to have negligible thermal mass. Only in the suspended floor system of the Steel building (Comflor ® system), was thermal mass accounted for. As a matter of fact, the Comflor ® system has a relatively high volume of concrete (0.13 m^3/m^2), which is greater than the floor system in the Timber building (Potius ® system 0.08 m^3/m^2 of concrete) or in the Concrete building (Interspan ® system with 0.10 m^3/m^2 of concrete).

Because stand-alone walls are an abstraction of real structural elements such as columns and beams, they are considered mostly in the way they affect indoor air temperatures. However, assessing their surface temperature is considered less reliable than the assessment of the surface temperature of a real building element such as a shear wall or a floor surface. In the Studio 201 room (south-facing), surface temperature is assessed from shear walls and floors, while in the gallery space (north-facing) surface temperature is assessed in stand-alone walls. This is because the floor surface is relatively low in that area (mostly void space) and there are no shear walls available. All graphs include the air temperature of the room/zone in which the particular surface of interest is located to allow the possible influence of thermal mass on indoor air temperature to be identified.

8.3.4 Gallery temperature analysis – North facing

The north-facing gallery space is particularly interesting, not only because of its exposure to direct normal radiation (only in Level 2), but also because mechanically supplied air is less influential on indoor air temperature than in rooms placed in the south side of the building. As it was explained in Section 4.6.2, the AHU first supplies air to rooms in the south part of the building, and the air subsequently migrate to rooms in the north part of the building. Because of this, internal gains produced in rooms on the south increases the temperature of the air before it arrives in rooms in the north, in particular to the gallery space. Because of this, a smaller temperature difference exists between the mechanically supplied air and indoor air temperature in north facing spaces.

8.3.4.1 Level 2 Gallery – Detailed temperature analysis

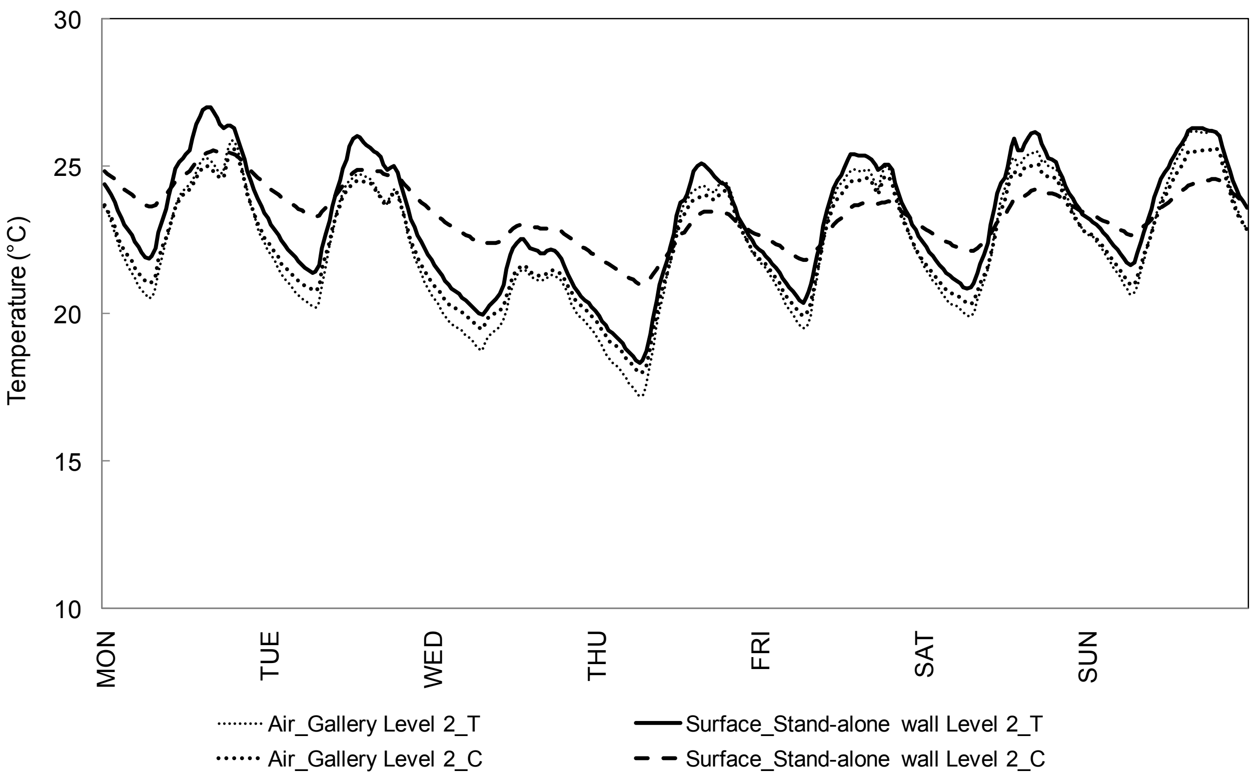


Figure 8-11: Summer representative week: Level 2 Gallery, stand-alone walls surface temperatures in the code-compliant Timber (_T) and Concrete (_C) buildings.

Stand-alone wall surface temperatures, together with room air temperature in Level 2 of the Gallery space of the Timber and Concrete code-compliant buildings during the summer representative week can be seen in Figure 8-11; and Figure 8-12 is the equivalent for the winter representative week. Level 2 is the only level in the gallery that does receive direct solar radiation, particularly in winter. As can be seen in the Arts building cross-sections on Figure 4-2, Section 4.1.2 on the north side of Level 3 the influence of a relatively large roof overhang blocks the direct sunlight on Level 3 during the whole year and on Level 2 during summer.

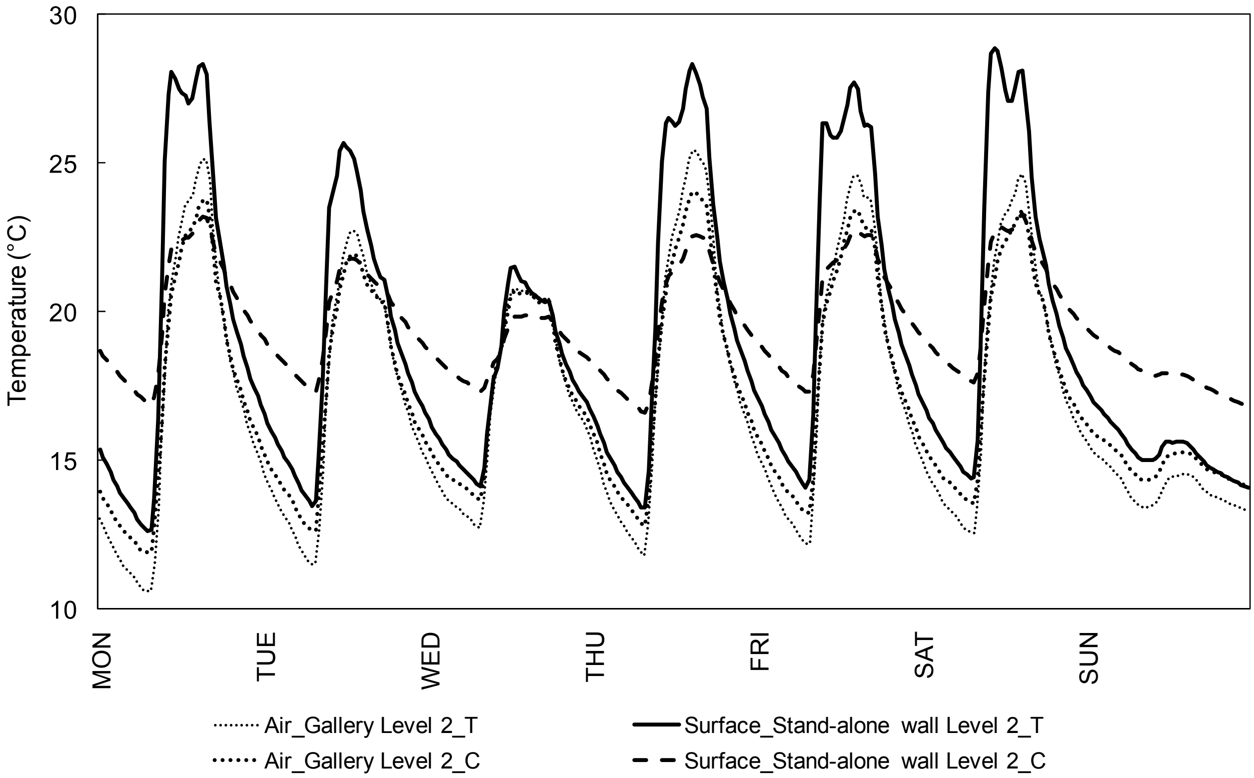


Figure 8-12: Winter representative week: Level 2 Gallery, stand-alone walls surface temperatures in the code-compliant Timber (_T) and Concrete (_C) buildings.

Relevant observations relating to Figure 8-11 and Figure 8-12 are:

- In the summer representative week, the timber stand-alone surface temperature has a daily fluctuation similar to that of the air temperature and essentially in phase. Generally the timber surface temperature is offset above the air temperature by about one degree.
- The concrete surface temperature displays a much smaller amplitude, demonstrating the energy-buffering characteristics due to the higher thermal capacity of this material.
- There is no strong evidence of significant phase difference – either leading or lagging – between the concrete surface temperature and the corresponding air temperature. During the summer, however, there is very limited solar gain directly to the concrete surface so the surface energy balance is dominated by convective heat exchange.
- Although the effect of direct normal radiation on the surface of the timber and concrete stand alone wall shows a radical increment of surface temperatures in both the timber and the concrete surface, the surface's temperature of the timber stand-alone wall increases to a much higher temperature than in the concrete surface.

- Peak surface temperatures for the concrete wall remain cooler than air temperature but, in the Timber building, the surface temperature of the timber wall is much higher than the air temperature in that building.
- There is a variation of about 1°C higher during daily peak air temperature in the Timber building compared with the Concrete building and during the night temperature in the Timber building drops also about 1°C below the Concrete building air temperature.

In the timber stand-alone wall: Without direct normal radiation, the timber surface temperature has a daily fluctuation similar to that of the air temperature, normally being higher by less than 1°C. With exposure to direct normal radiation, however, the timber surface's temperature increases to a much higher temperature than the air temperature.

In the concrete stand-alone wall: Without direct normal radiation, the concrete surface responds more slowly than air temperature, and does not normally increases above air temperature. With direct radiation exposure, surface temperature variation during day and night is higher but still lower than air temperature. Peak surface temperature is also lower than air temperature.

These observations are consistent with the characteristics of these wall materials: Compared with the concrete stand-alone wall, the timber stand-alone wall has relatively little capacity to buffer some of the heat/energy when direct radiation is available, but seems to be a relatively good heat buffer when the incident radiation intensity is much lower.

8.3.4.2 Level 1 and Level 3 Gallery – Air and surfaces temperatures

Stand-alone wall surface temperatures, together with room air temperature in Level 1and on Level 3 of the Gallery space for Timber and Concrete code-compliant and best-practice buildings, can be seen during the summer representative week in Figure 8-13, and during the winter representative week in Figure 8-14.

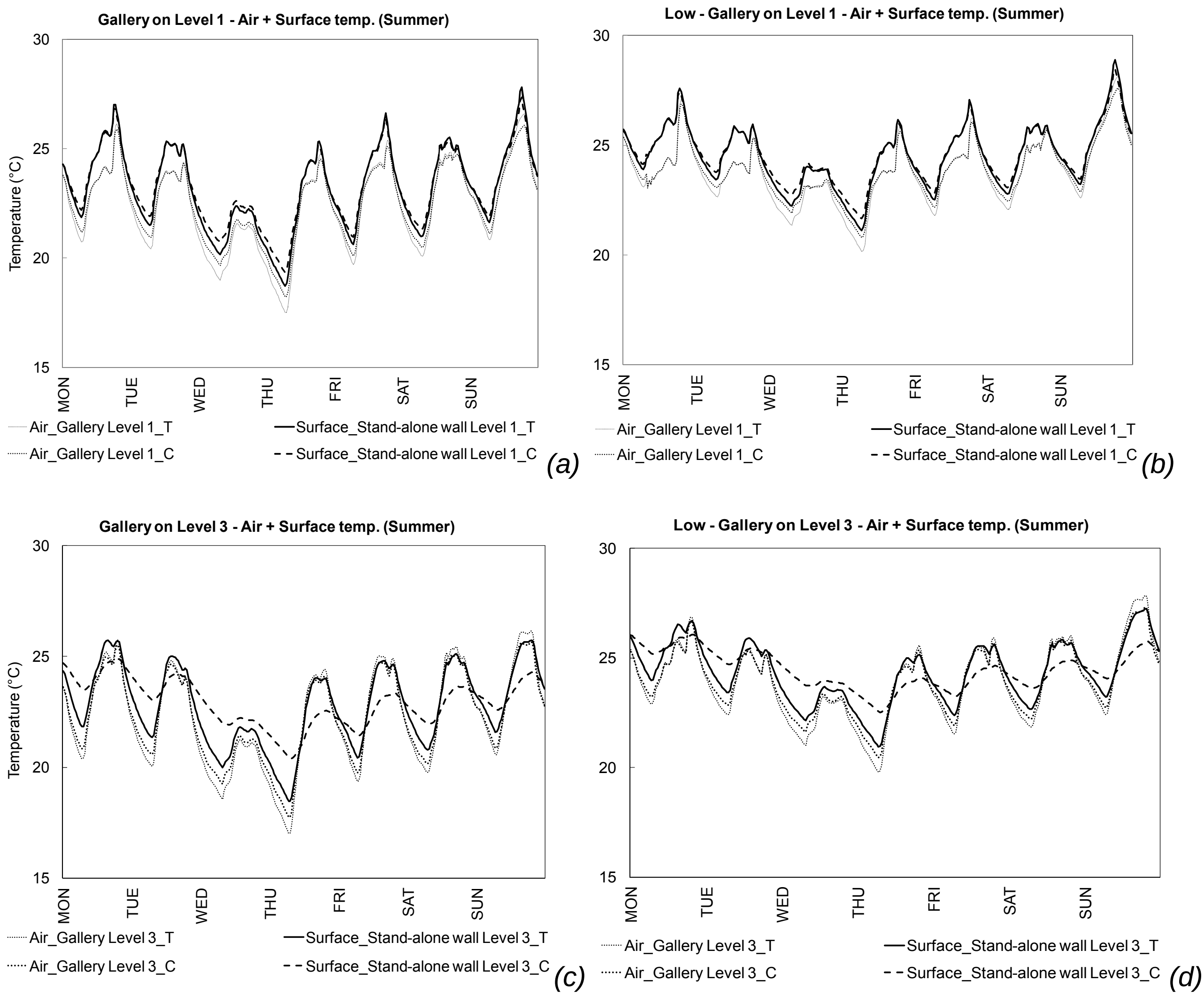


Figure 8-13: Stand-alone wall surface temperatures and indoor air temperatures during the summer representative week – On Level 1 of the code-compliant (graph (a)) and best-practice (graph (b)) Timber and Concrete buildings, and on Level 3 of the code-compliant (graph (c)) and best-practice (graph (d)) Timber and Concrete buildings.

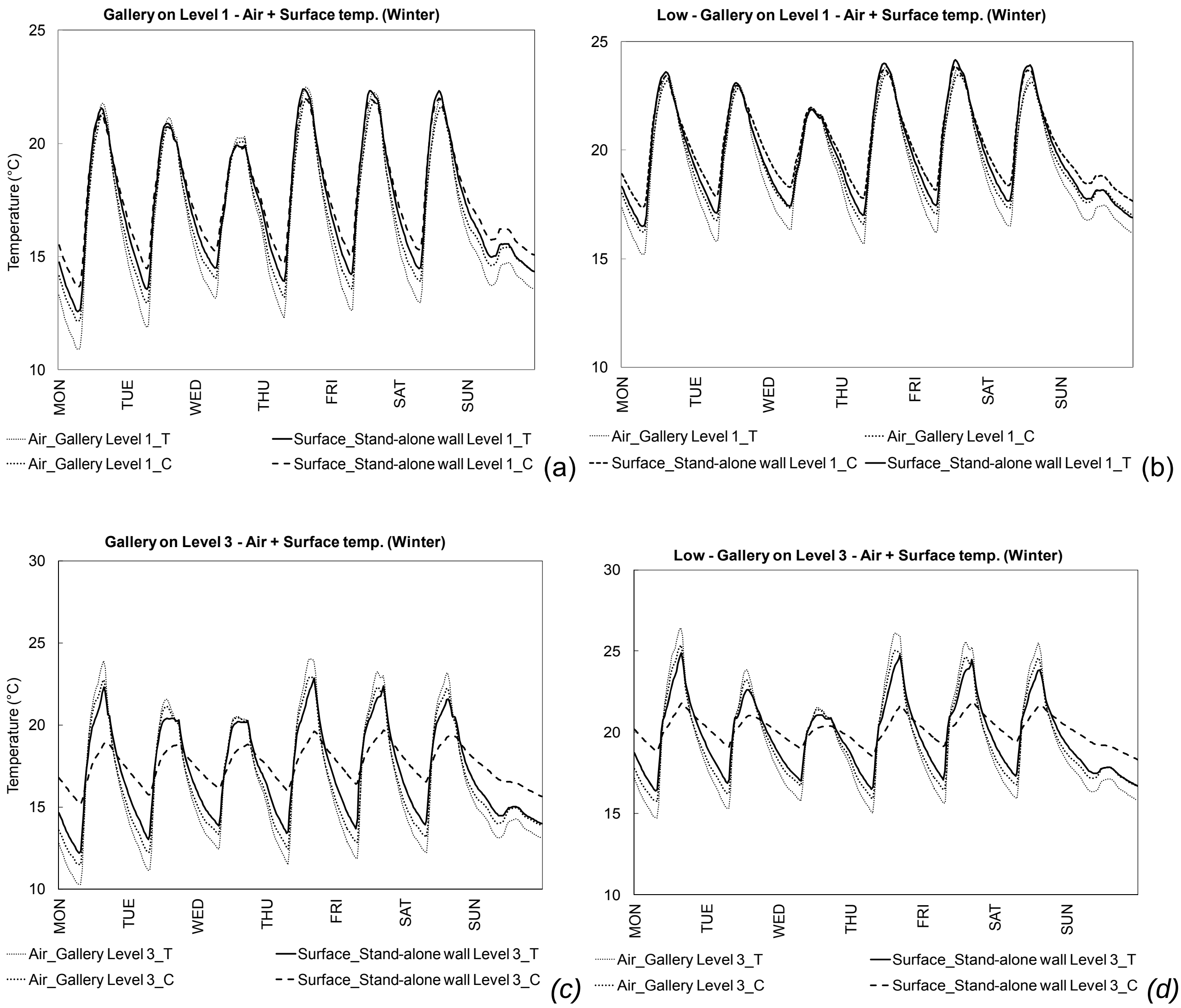


Figure 8-14: Stand-alone wall surface temperatures and indoor air temperatures during the winter representative week – On Level 1 of the code-compliant (graph (a)) and best-practice (graph (b)) Timber and Concrete buildings, and on Level 3 of the code-compliant (graph (c)) and best-practice (graph (d)) Timber and Concrete buildings.

Relevant observations relating to Figure 8-13 and Figure 8-14 are:

- On Level 1, the surface temperatures of the timber and concrete stand-alone wall are similar, and these are higher than their respective indoor air temperatures.
- On Level 3 the surface temperature of the concrete stand-alone wall does not swing significantly between day and night. In contrast, the surface temperature on the timber stand-alone wall vary significantly between day and night and is similar (slightly higher) than the indoor air temperature.
- Gallery's Level 1 air temperature is very similar in the Timber and Concrete buildings during the day and is slightly lower in the Timber building during the night (about 1°C lower).

- In both Figure 8-13 and Figure 8-14 the daily air and surface temperature peaks in the code-compliant buildings are slightly lower than in the best-practice buildings. During the night, both air and surface temperatures drop significantly lower in the code-compliant building compared with the best-practice building. In the best-practice case, air and surface temperatures in the Timber building are lower than in the Concrete building. This is consistent in the Studio 201 and in all three levels of the Gallery. The effect of increasing insulation values in the thermal envelope is an increment of both lowest and highest indoor air temperature during summer and only lowest indoor temperatures during winter.

8.3.5 Studio 201 surface and air temperature analysis – South facing

8.3.5.1 Studio 210 - Shear walls

Shear wall surface temperatures, together with room air temperature in the Studio 201 for the Timber and Concrete code-compliant buildings, can be seen during the summer representative week in Figure 8-15 and during the winter representative week in Figure 8-16. Because Studio 201 is facing south, there is no direct normal radiation influencing indoor environmental conditions, resulting in outdoor dry-bulb temperature being a stronger influence than in the north façade.

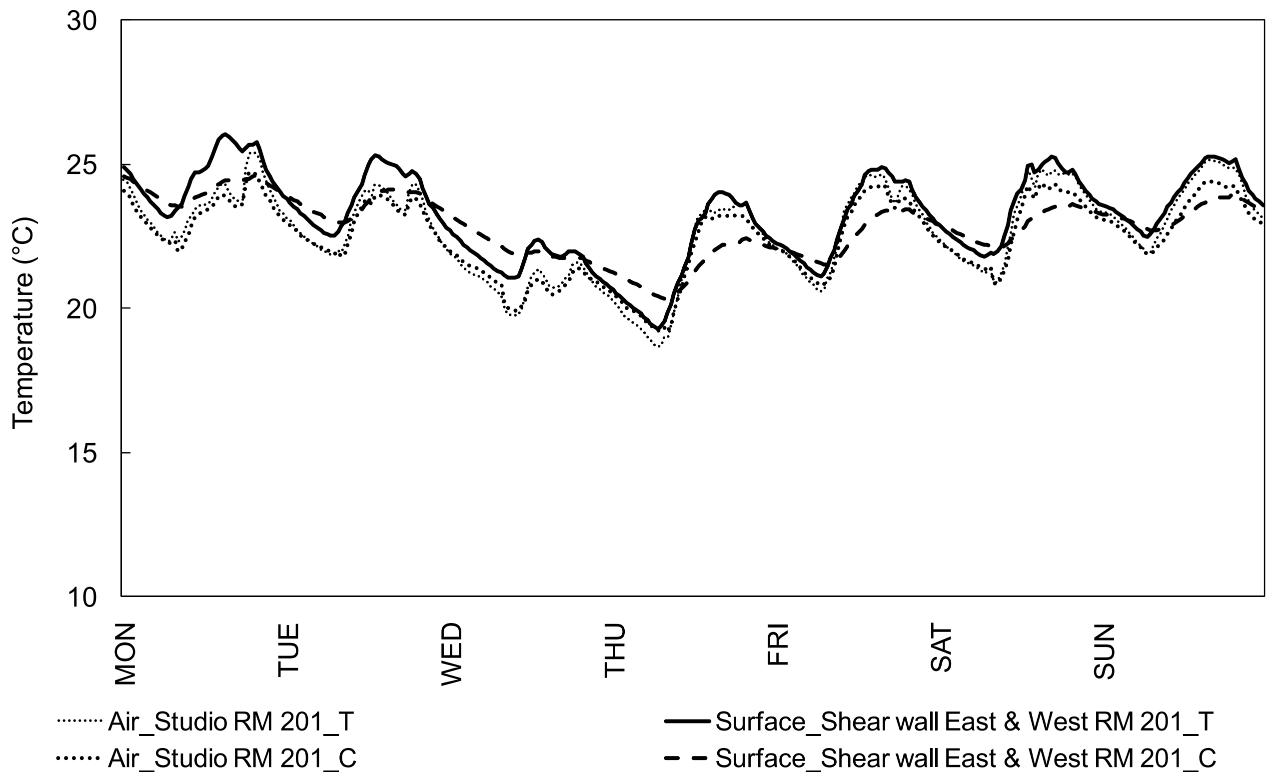


Figure 8-15:– Shear wall surface temperature in the code-compliant Timber and Concrete buildings during the summer representative week.

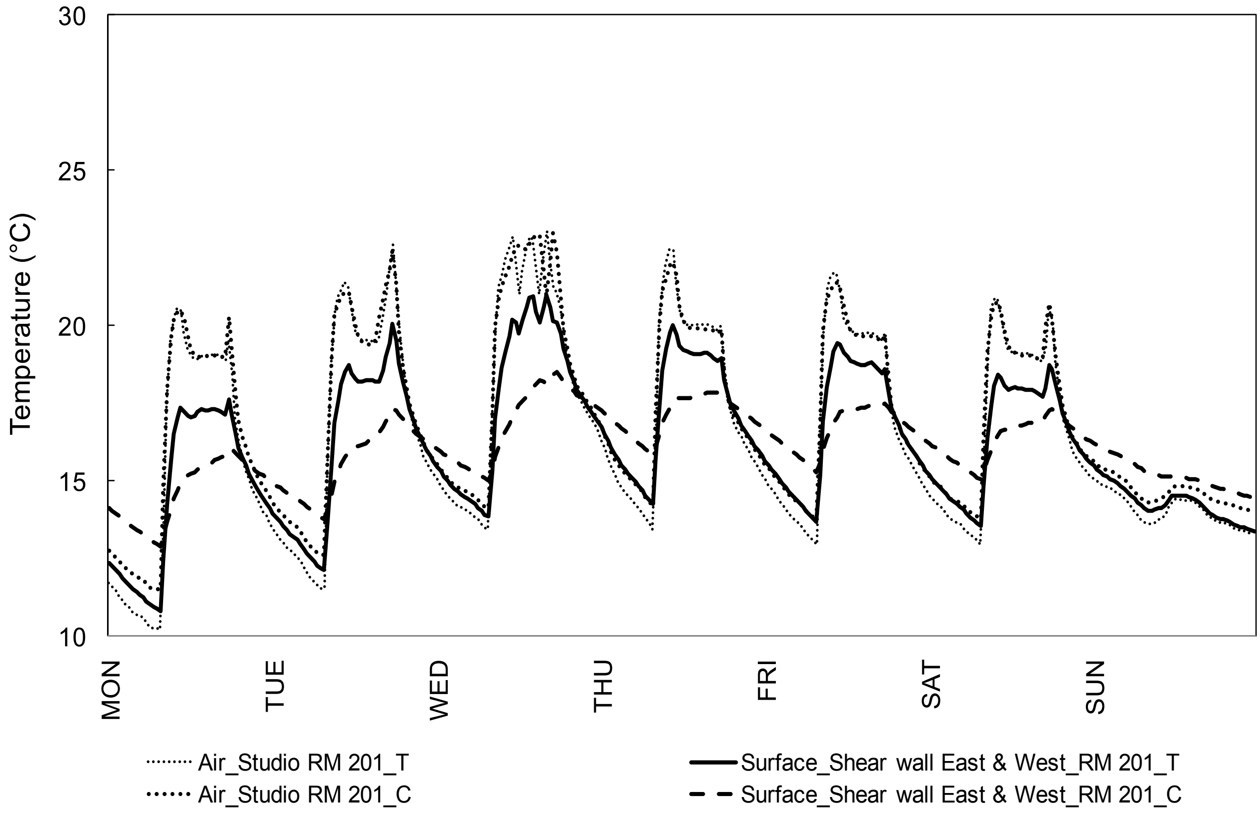


Figure 8-16: Shear wall surface temperatures in the code-compliant Timber and Concrete buildings during the winter representative week.

From Figure 8-15 and Figure 8-16, relevant observations are:

- Indoor air temperature is very similar in the Timber and Concrete buildings; especially during the summer representative week. During winter, indoor air temperature in the Timber building drops during the night significantly more than in the Concrete building.
- During the summer representative week, surface temperatures in shear walls are higher than indoor air temperature, but this is reversed during the winter representative week.
- Surface temperature in the timber shear wall is higher and much closer to indoor air temperature (higher in winter, lower in summer) than surface temperature in the concrete shear wall. In the concrete shear wall, surface temperature is higher than indoor air temperature during unoccupied hours and lower than indoor air temperature during occupied hours.

Due to a higher capacitance in the concrete shear wall, changes in surface temperature occur more slowly than in the timber shear wall. Furthermore, the surface temperature does not peak in the concrete shear wall as high as it does in the timber shear wall. Summer, surface temperature in shear walls is higher than indoor air temperature, but in winter, surface temperature is lower than indoor air temperature. Although there is forced convection due to higher air velocity, the heat transfer between air and materials is not particularly high, or at least not high enough to significantly influence indoor air temperature. Higher heat transfer can be seen more clearly in rooms facing north where direct radiation is incident on wall surfaces.

Incidentally, there is evidence in Figure 8-16 that the as-modelled heating system did indeed have sufficient heating capacity to achieve the set-point temperature of 22°C (remembering that this set-point had an associated dead band of 2 K). Referring back to the earlier discussion (Section 6.5) on the apparent shortfall (compared with monitored values), this means that the third explanation offered there is not valid. Hence it must be some combination of the other possible explanation which contributes to the lower weekly average temperatures, but there is insufficient evidence to identify which one or ones it might be.

8.3.5.2 Studio 201 – Floor surface temperature

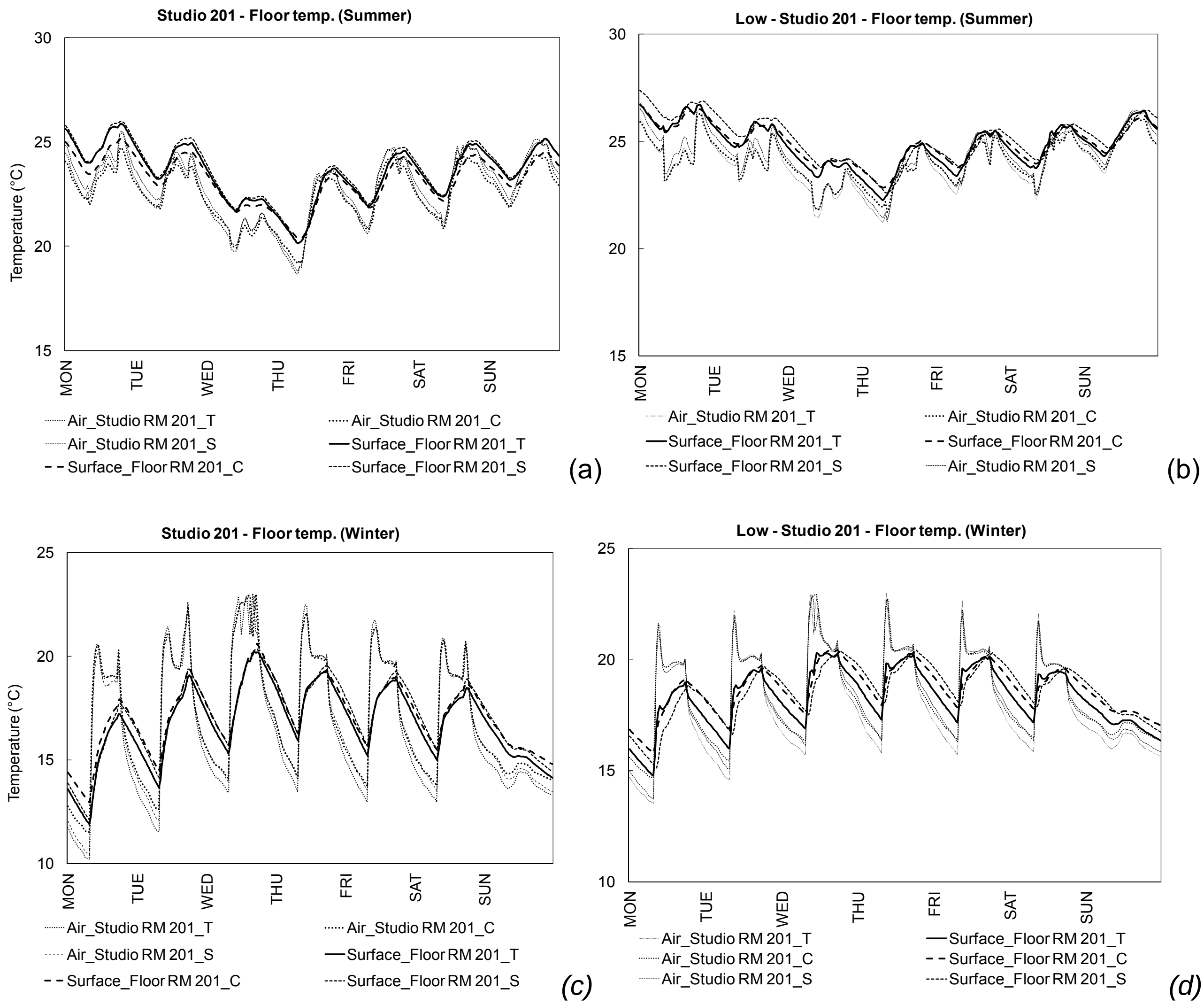


Figure 8-17: On Studio 201, floor surface's and indoor air temperature - During the summer representative week in the code-compliant (a) and best-practice (b) buildings, and during the winter representative week in the code-compliant (c) and best-practice (d) buildings.

In Figure 8-17 the floor surface temperatures and room air temperature can be seen during the same summer and winter representative weeks in the Studio 201 for the Timber, Concrete, and Steel code-compliant and best-practice buildings[9].

Specific comments related to plots on Figure 8-17 are:

- The most significant differences of indoor air and surfaces temperature in the code-compliant and the best-practice buildings are; a milder temperature swing during day and night with an average increase of temperatures particularly during summer. During winter, minimum temperatures are higher in the best-practice building but peak temperatures during the day are similar.
- Compared with shear walls surface temperatures, floor surface temperatures are very similar in the all three buildings in both thermal envelope scenarios. All three floor systems are composite floors: concrete-timber (Timber and Concrete building) and concrete-steel (Steel building), having a concrete surface exposed to the interior space having a thickness ranging from 75 mm in the Concrete and Timber building, to about 150mm in the Steel building. This common factor of the surface material being concrete has resulted in similarities in surface temperature.
- The indoor air temperature in the Steel building is very similar to that in the Timber and Concrete building during summer. Differences are more evident during the winter representative week where night time indoor air temperature of the Timber building drops further compared with temperatures in the Concrete and in the Steel buildings.

[9] In the graphs in Figure 8-17, temperature range in the left side vertical axis, during summer representative week (15°C to 30°C) is different than the temperature range during winter representative week (10°C to 25°C), this is to keep in the graph a 15°C temperature scale suitable for the analysis of relatively small temperature differences in such a small graphs.

8.4 Discussion of indoor environmental conditions

8.4.1 PMV assessment - final discussion

Looking at the results using a default PMV assessment, in all three rooms analysed in this section most of the time in which the buildings are not within comfortable environmental conditions, is because indoor environmental conditions are slightly warmer to hot (> 0.50). There is, however, a small amount of hours in all three rooms, but mostly in the code-compliant buildings and in the best-practice buildings with the commercial HVAC system, where the indoor environmental conditions are slightly cool to cold (<-0.5 in the scale given in Table 8-2). The amount of hours in this category is quite similar in the Landing-Gallery and in the Studio 201 and slightly lower in the Staff room. There are essentially no slightly cool-to-cold hours in the best-practice buildings.

In the Landing-Gallery the time within comfortable environmental conditions is the lowest of any of the rooms in which PMV assessment was carried out. In all three scenarios, it is in the code-compliant buildings where the highest amount of time with comfortable environmental conditions exist; this is followed by the best-practice building with the commercial HVAC system, where the hours within comfortable environmental conditions is almost equivalent to the hours with slightly warm-to-hot environmental conditions. The best-practice buildings exhibit the undesirable characteristic that the hours with slightly warm-to-hot environmental conditions are considerably higher than the hours within comfortable indoor environment. Although differences are not significant, the Concrete building is always the most comfortable, and Timber the least. In fact it is only in the code-compliant scenario, that the landing-gallery in the Timber building has more hours with a comfortable environment than hours in a slightly warm to hot indoor environment.

In the Staff room, from all three scenarios, it is the best-practice buildings with the commercial HVAC system which exhibit the highest amount of hours with comfortable environmental conditions followed by the code-compliant buildings. In the best-practice buildings, the hours within comfortable environmental conditions are almost equivalent to the hours with slightly warm to hot environmental conditions. More specifically, time with slightly warm to hot environmental conditions is higher in the Timber building, equivalent in the Steel building, and lower in the Concrete building than the time within comfortable indoor environment. Although differences between indoor environmental conditions between the Timber, Concrete, and Steel buildings are more marked than in the Landing-Gallery space, these are still not significant. In this room, the Concrete building is always the most comfortable followed closely by the Steel building and with the Timber more clearly in a lower position.

For the Studio 201; the third and final space subjected to PMV analysis, the hours within comfortable environmental conditions is the highest of the three rooms. Although it is the best-practice buildings with the commercial HVAC system where the amount of time with comfortable environmental conditions is the highest, this is very similar to the code-compliant buildings. The main difference is that in the best-practice buildings with the commercial HVAC system the Timber, Concrete, and Steel buildings have very similar hours with comfortable environmental conditions while in the code-compliant buildings these hours are higher in the Concrete building followed by the Steel and the Timber with almost the same outcome. The best-practice buildings have the least time with comfortable environmental conditions but the number of these hours is still very high compared with hours with slightly warm to hot environmental conditions. Although differences are not significant, the Concrete building is always the most comfortable, followed by the Steel and the Timber with very similar outcomes.

It is worth noting again that the modelling of the indoor temperatures in T-block appeared to over-estimate the diurnal swing but that this seemed to have had a minimal impact on the broad agreement between the modelled and monitored values for the operational energy usage for this building. In making that observation (in Section 5.6.3) it was remarked that an overestimate of diurnal swing would not necessarily result in the model predicting fewer hours of desirable thermal comfort conditions either, because the model's low estimate of the daily temperature minima would occur outside the occupied hours during which thermal comfort was of importance.

This reasoning is mentioned here because if, for the Arts building (the primary focus of this research), the diurnal swing is also being overestimated in the modelling of some of the spaces, the PMV analysis – which was totally based on modelled temperatures – would conclude that for some hours the perceived thermal comfort was outside the accepted comfort range whereas, in reality, those same hours might lie within the comfort range. If this argument is accepted, the consequences would be that for all of the building case studies in this research, it is probable that the number of hours in which thermal comfort has been determined (from PMV analysis) as being over-cool or over-hot are higher than they would be in the actual building. In other words, the assessments of likely perceived thermal comfort within any of the buildings that were modelled is likely to be a little pessimistic.

8.4.2 Surface and air temperatures - Discussion

Surfaces and air temperatures were analysed in two rooms: on the Landing-Gallery, facing north and therefore frequently exposed to direct solar radiation, and on the Studio 201, facing south. As a consequence, in rooms facing north the mechanisms of heat transfer between the surrounding environment and the materials includes both radiation and convection. In rooms facing south the mechanism of heat transfer between the surrounding environment and the materials is dominated by convection.

When radiation is the dominant heat transfer mechanism, higher heat transfer can be seen more clearly. Because the timber wall has much lower capacity to buffer heat than a concrete wall, the surface temperature in timber increases to a much higher temperature than for concrete surfaces. Peak surface temperature in the timber wall is much higher than indoor air temperature. On a concrete wall, the maximum surface temperature increases to a lower temperature than air temperature. The concrete wall surface temperature responds more slowly than both the timber wall surface temperature and the air temperature.

When convection is the dominant heat transfer mechanism, a lower heat transfer can be seen, and the capacity to buffer heat is similar in the timber and concrete walls. Still, the surface temperature of the timber walls is higher than in the concrete wall and has a daily fluctuation similar to the air temperature (normally higher temperature but by less than a degree across the day). Surface temperature on the concrete walls responds to daily temperature fluctuation more slowly than air temperature, and is lower than indoor air temperature during occupied hours (conditioned) and higher during unoccupied hours (unconditioned).

As a result of space pre-conditioned mechanically supplied air, indoor air temperature during summer in the Concrete building is very similar to that in the Timber and Steel buildings (Compared with the Concrete building, the Timber building indoor air temperature is about 1°C higher during the day and 1°C lower during the night). During winter conditions on the other hand, night time indoor air temperature of the Timber building drops significantly lower than in the Concrete and in the Steel buildings. The forced convection that should occur because of the high indoor air velocity in rooms with mechanical ventilation appears not to increase significantly the heat transfer between air and materials which appears to be insufficient to significantly influence indoor air temperature.

Lower heat loss through the thermal envelope reduces diurnal temperature swing with an average increase of indoor temperatures, particularly during summer. It also increases the maximum air and surface temperatures during the day, and during the night higher lower temperatures occur. The effect of increasing insulation values in the thermal envelope produces an increase of both minimum and maximum indoor air temperature during summer, but only minimum indoor temperatures during winter. During winter, minimum temperatures are higher in the best-practice building but peak temperatures during the day are similar to those in the code-compliant buildings.

9 Improvement of energy performance and comfort conditions

This chapter describes possible improvement of the energy performance and comfort conditions of the Arts Timber building by using three possible methods of improving overall indoor comfort conditions and subsequently reducing space conditioning energy consumption. These three methods are night-time ventilation, exterior louvres, and the use of Phase-Change-Materials (PCM).

9.1 Night-time ventilation and solar shading system replacement

This chapter analyses alternatives scenarios to achieve a reduction of space conditioning energy consumption, while at the same time improving indoor environmental conditions of the best-practice buildings with a commercial HVAC system. This building group represents the buildings in which the thermal envelope has been upgraded to a New Zealand best-practice standard, and at the same time these buildings are modelled using HVAC systems that include cooling and in which heating and cooling systems in place have a high performance for a relatively low energy consumption. As it was established initially in Section 4.6.2, to assess the effect that night-time ventilation has on the influence of thermal mass on cooling energy consumption and indoor comfort conditions, this section compares energy and PMV results of the best-practice buildings with commercial HVAC system, with and without night-time ventilation. The schedule and conditions of operation can be seen in Section 4.6.2; in the commercial HVAC system without night-time ventilation, the AHU operates during week days (including Saturday) from 8:00 am until 6:00 pm (see Section 4.5.3 for more details).

9.1.1 Louvres

In Section 4.1.2 where a cross-section of the actual Arts building was shown, a relatively large overhang can be seen as an extension of the roof on the north side of Level 3. The overhang is designed such that on Level 3, no direct solar radiation can reach the interior space year round, and on Level 2 direct solar radiation is available in interior spaces during winter only from March until September, but more significantly during May -July, when the solar altitude angle is below 45°. No windows facing north are available in Level 1, but the gallery in that level gets diffuse natural light from Level 2 and 3. This is because in the actual Arts building there is an unmodelled construction attached the north side of Level 1.

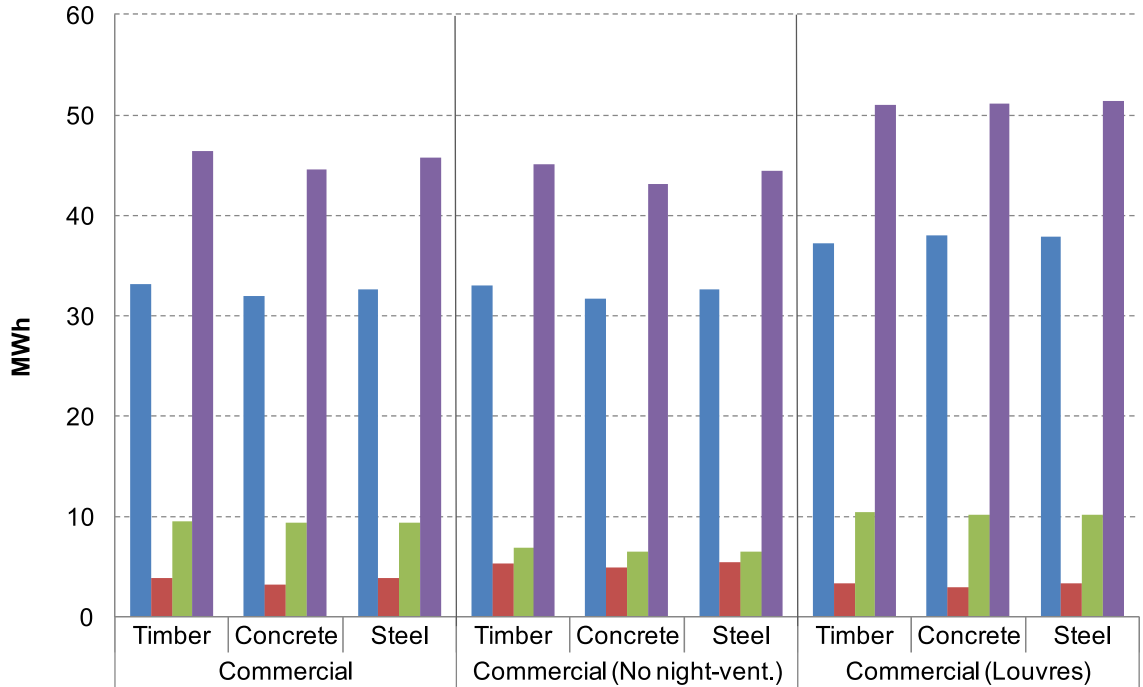
A better control of the transmission of direct solar radiation into indoor environments can improve indoor environmental conditions and, possibly, reduce conditioning energy in the Arts building

(Timber) and in its alternatives in Concrete and Steel. External louvres are an appropriate alternative to achieve this and can be easily modelled using the BEEM software of choice in this research (VE). The overhang was replaced by louvres placed over the glazed area on the north side of Level 2 and 3. The approach taken for the modelling of louvres in VE was by making them control the transmission of solar radiation, homogeneously across the glazed area. Table 9-1 shows the factors for controlling transmission of solar radiation by the louvres modelled in VE. It can be seen that just above a solar angle of 60° the louvres start reducing the solar radiation transmission by 50% and over an angle of 75° transmission is reduced to 0%. Louvres were modelled in the best-practice buildings using the commercial HVAC system, basically to see the impact of them on not only heating energy but also on cooling energy.

Table 9-1: Solar radiation transmission factor for louvres.

Transmission factor at 15° increment (values in range 0.0 - 1.0)						
0°	15°	30°	45°	60°	75°	90°
0.00	0.00	0.00	0.00	0.50	1.00	1.00

9.2 Results on energy consumption



	Commercial			Commercial (No night-vent.)			Commercial (Louvres)		
	Timber	Concrete	Steel	Timber	Concrete	Steel	Timber	Concrete	Steel
Heating (Comb.)	33.1	32.0	32.7	33.0	31.7	32.5	37.3	38.0	37.9
Chillers (Elec.)	3.8	3.2	3.8	5.2	4.9	5.4	3.3	2.9	3.3
Fans (Elec.)	9.5	9.3	9.3	6.9	6.5	6.5	10.4	10.2	10.2
Total (Comb.)	46.4	44.5	45.8	45.1	43.2	44.4	50.9	51.1	51.4

Figure 9-1: Energy consumption in all cases compared in this section.

In Figure 9-1, the space conditioning energy consumption information of the best-practice buildings with the commercial HVAC system (commercial), is compared against the same set of case study buildings and HVAC system but without night-time ventilation (“No night- vent.”), and the same set of case study buildings and HVAC system (with night-time ventilation) but with louvres instead of the actual overhang.

Total conditioned energy consumption is very similar in the commercial buildings (average of 45.6 MWh/yr) and in the buildings with no night-time ventilation (average of 44 MWh/yr), but higher in the buildings with louvres (average 51 MWh/yr). The increment of total conditioning energy consumption in the buildings with louvres when compared to the commercial buildings is mostly in heating energy (about 15% higher) and, less significantly, in fan energy consumption (average is 9% higher). Chiller energy is actually lower (about 12%) in the buildings with louvres than in the commercial buildings. Slightly lower total space conditioning energy in the buildings with no night-time ventilation compared with the commercial buildings is, for obvious reasons, in fans energy (about 30% lower); chiller energy on the other hand is larger in the buildings without night-time ventilation.

Differences in total space conditioning energy consumption between building construction types (Timber, Concrete, and Steel) are insignificant in buildings with louvres (1% difference between the highest (Concrete) and the lowest (Timber) space conditioning energy consumer). The proportional difference of the space conditioning energy consumption between each building construction type is the same in the commercial buildings and in buildings with no night-time ventilation (a 4% difference between the highest (Timber) and the lowest (Concrete) space conditioning energy consumption).

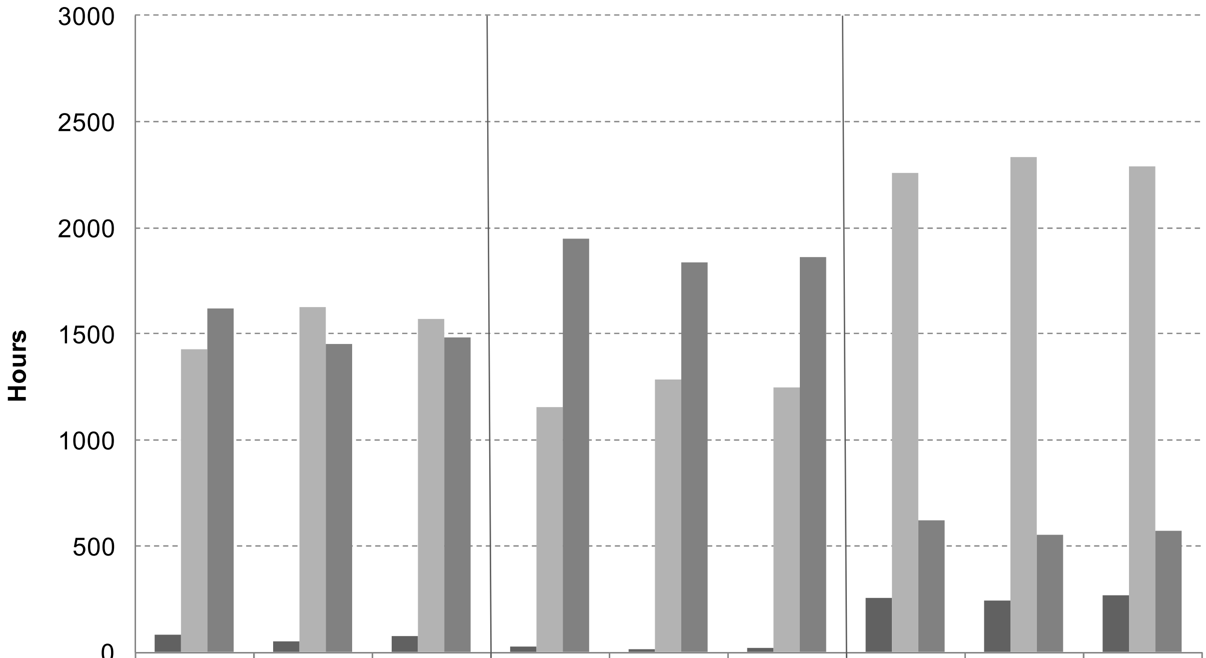
There is a reduction of heating energy consumption together with an increment of chiller energy consumption in the building with no night-time ventilation compared with commercial buildings. In those cases, although differences are not significant (+- 1MWh/year), with the timber building having lower heating demand and higher cooling demand than the concrete building.

9.3 Results of PMV assessment

9.3.1 PMV of the Landing-Gallery space – North façade

Figure 9-2 shows the results from the PMV assessment of the Landing-Gallery space in the best-practice buildings with the commercial HVAC system (commercial), is compared against the same set of case study buildings and HVAC system but without night-time ventilation (“No night-vent.), and the same set of case study buildings and HVAC system (with night-time ventilation) but with louvres instead of the actual overhang (”Louvres”).

The amount of hours within a comfortable indoor environment in the buildings with louvres (73% of the time) is significantly higher than in the commercial buildings (about 50% of the time), and in the buildings with no night-time ventilation (40% of the time). This is mainly because of the reduction of hours in warm-to-hot environments which represent a 20 % in the buildings with louvers, a 50% in the commercial buildings and a 60 % in the buildings with no night-time ventilation. Time within cool-to-cold environments is low across all cases, ranging from 8% in the buildings with louvres to 1% in the buildings with no night-time ventilation (2% in commercial buildings).



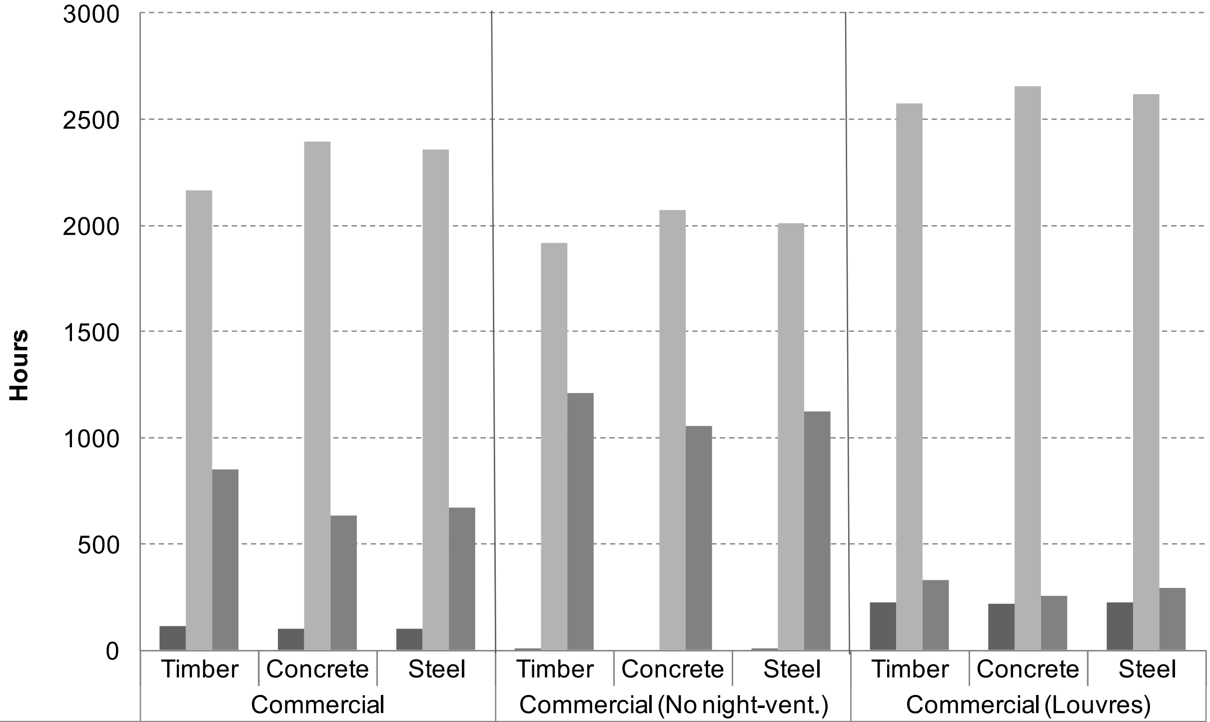
	Timber	Concrete	Steel	Timber	Concrete	Steel	Timber	Concrete	Steel
	Commercial			Commercial (No night-vent.)			Commercial (Louvres)		
< -0.50	83	54	74	29	11	22	256	242	268
-0.50 to 0.50	1427	1625	1571	1156	1283	1246	2256	2336	2288
> 0.50	1620	1452	1486	1946	1837	1863	619	553	574

Figure 9-2: Landing gallery on level 2 north orientation – PMV comparison of the commercial building with two variations.

9.3.2 PMV in Staff room Level 2 – North façade

The Staff room is the only room in the north side of the building in which there is direct supply of air from the AHU, and there is cooling in the case of the best-practice building with the commercial HVAC system. Figure 9-3 shows the results from the PMV assessment of the Staff Room in the commercial buildings, compared against the buildings with no night-time ventilation, and the buildings with louvres.

The overall results of the PMV assessment in the Staff Room in all three building groups follow the same pattern as in the Landing-Gallery space, but with an increment of hours within comfortable conditions across all building groups. Again, the amount of hours within a comfortable environment is the highest in the building with louvres (84%) followed by the commercial building (74%) and the buildings without night-time ventilation (64%). Hours of warm-to-hot environmental conditions are very low in the buildings with louvres (9%) and relatively high in buildings with no night-time ventilation (36%) with the commercial buildings in between (23%). Again, the amount of hours within cool-to-cold environments is very low – negligible.



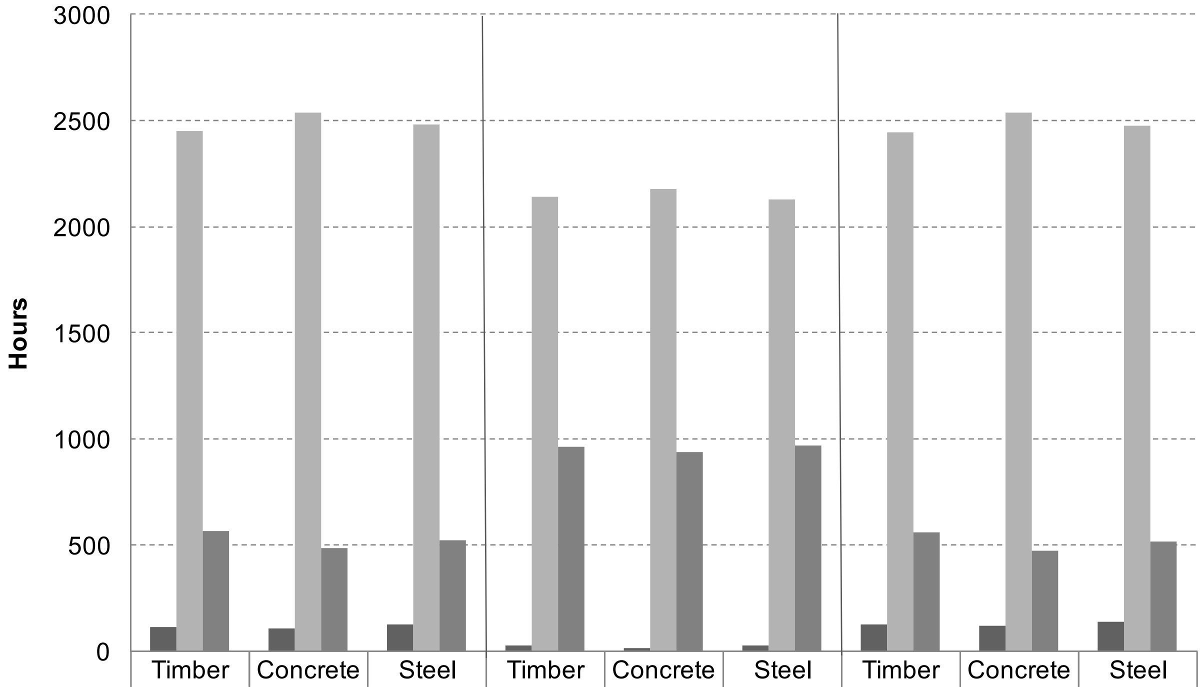
	Commercial			Commercial (No night-vent.)			Commercial (Louvres)		
	Timber	Concrete	Steel	Timber	Concrete	Steel	Timber	Concrete	Steel
< -0.50	116	101	99	5	0	1	226	219	223
-0.50 to 0.50	2163	2394	2358	1916	2073	2009	2577	2656	2616
> 0.50	851	636	674	1209	1058	1121	328	256	292

Figure 9-3: Staff room on level 2 north orientation – PMV comparison of the commercial building with two variations.

Differences in the PMV assessment between building construction types (Timber, Concrete, and Steel) of spaces on the north façade of the arts building are not significant. It can be said that the amount of hours within comfortable environmental conditions is always (but not significantly) higher in the Concrete building, and lower in the Timber building (average difference of 5% of the occupied time across all scenarios).

9.3.3 PMV in Studio room in Level 2 – South façade

Figure 9-4 shows the results from the PMV assessment of the Studio 201 (South façade) in the commercial buildings, the buildings with no night-time ventilation, and in the buildings with louvres. The pattern presented in the results of the PMV assessment of the Studio 201 (south façade) is different from the pattern of results in the Landing-Gallery space and in the Staff room, which are both on the north façade. Both the commercial building and the buildings with louvres have practically the same PMV results, with relatively high amount of hours within comfortable conditions (about 80%), with only 17% of the occupied hours within warm-to-hot environment, and a low 4% of occupied hours within cool-to-cold hours. In the buildings with no night-time ventilation, the amount of occupied hours within warm-to-hot environment increases significantly to 36% reducing the amount of hours within comfortable conditions to 70%. Hours of cold-to-cold environment in that building are practically nonexistent.



	Commercial			Commercial (No night-vent.)			Commercial (Louvres)		
	Timber	Concrete	Steel	Timber	Concrete	Steel	Timber	Concrete	Steel
< -0.50	114	105	126	26	12	29	124	120	138
-0.50 to 0.50	2450	2541	2481	2140	2178	2131	2445	2536	2478
> 0.50	567	485	524	965	941	970	561	475	515

Figure 9-4: Studio room 201 on level 2 south orientation – PMV comparison of the commercial building with two variations.

Differences between building constructions types (Timber, Concrete, or Steel) are even lower than in rooms on the north façade of the building. Again the Concrete buildings spend some more hours within a comfortable environment by reducing the hours of warm-to-hot environment.

9.3.4 Discussion on improvement of energy performance and comfort conditions

The replacement of the overhang by louvres has a large impact into improving comfort conditions in rooms facing north, increasing the amount of hours within comfortable conditions by about 30%. Improvement to comfort conditions comes with an energy penalty, however, with a 12% increment of annual space conditioning energy consumption (Although cooling energy is reduced by 12%, heating energy consumption is 16% higher with proportionally a much larger energy consumption than cooling).

Overheating is the main reason for discomfort in the commercial buildings. By reducing the transmission of high solar radiation into the building (for a sun angle above 60° the louvres start to reduce direct radiation transmission) overheating is reduced but an increment on heating energy is required. The presence of louvres also tempers the difference in comfort conditions between buildings constructions types. On the other hand, the increment of the transmission of direct solar radiation makes differences more significant. These analyses, and the conclusions drawn from them, are for the situation of the louvres being installed with a fixed angle. Louvres having a variable tilt angle (either motorised, or seasonally adjustable) are a means of reducing unwanted solar gains at times of the year or times of day when overheating would occur, but admitting solar gains when it would be energy-beneficial to do so.

When there is no night-time ventilation the amount of hours of warm-to-hot environments increases but proportional differences between buildings construction types remain very similar. This reduction in hours within comfortable environmental conditions in buildings with no night-time ventilation implies less space conditioning energy consumption in those buildings, mostly because of the reduction in fan energy consumption, although there is an increment on chiller energy consumption.

Although not significantly, in all three scenarios the Concrete building has the higher amount of hours within comfortable environment and the lower space conditioning energy, followed by the Steel and the Timber buildings. These differences are negligible when louvres are used instead of the overhang.

9.4 Improvement of the energy performance and comfort conditions of the Timber building – use of PCM

9.4.1 PCM materials - Introduction

An alternative to improve the thermal capacity of light-weight buildings is the use of phase change materials (PCM). PCM materials not only absorb sensible heat as the indoor temperature increases but also absorb latent heat when melting, and release the stored heat when freezing, both at an almost constant temperature. PCM can be used in buildings to significantly improve the thermal mass as they have a much greater ability to store heat than conventional building materials such as concrete. Concrete has a sensible heat storage capacity of 1.0 kJ/kgK, whereas an inorganic phase change material such as calcium chloride hexahydrate can store up to 193 kJ/kg during phase transition (Ip, Dyball, & Miller, 2008).

A significant development in phase change technology is the ability to microencapsulate PCMs. Microencapsulation is the packaging of micron-sized PCM materials (both liquids and solids) in the form of capsules, ranging from less than 1μm to more than 300μm. Microencapsulated PCMs can be used to introduce high thermal storage capacity into conventional building materials such as gypsum plaster, concrete, and plasterboard (Ip, et al., 2008).

In this section, a modelling exercise to illustrate the effect of PCM into indoor environmental conditions of the actual Arts building (Timber buildings) was carried out. The PCM material of choice for this exercise was microencapsulated PCM embedded in plasterboard. Micronal ® are microencapsulated, formaldehyde-free latent heat stores made from highly pure waxes, and can be manufactured with three different melting points being 21°C, 23°C, and 26°C. Micronal ® is used embedded in plasterboards available in the market with the brand name of PCM Smart–Board ® (BASF, 2011).

The BEEM software used in this research (VE) is not designed to model PCM materials. There is a modelling approximation that can be done using the Apache HVAC tool, by creating a thermal zone (representative of the PCM material) which can handle the phase change aspects by injecting heat and cooling into the room to which the PCM material is exposed (IES Ltd, 2010a). This is a time consuming trial and error method and this author has strong reservations about the validity of the underlying methodology, especially with the nature of the equations which the VE Users' Manual suggests for the calculation of rate of heat flow into the material, and the dynamic nature of the latent heat capacity of the PCM material.

An alternative approach to illustrate the effect of PCM materials is the use of a different BEEM software called PCM-Express which was developed in co-operation with the Fraunhofer Institute for Solar Energy Systems (ISE), and the Valentin energy-software company (Valentin Energiesoftware, 2011). PCM-Express is a room/zone-oriented calculation core, where a database of material (with emphasis on PCM materials) and constructions is available. Alternatively, specific materials or constructions can be created. In PCM-Express, generic HVAC systems can be used and set up by using predefined systems such as vapour-compression cooling, and radiator heaters.

The main limitation of PCM-Express is its weather files database which is Europe-specific and does not allow the use of alternative weather file extensions such as the one used in VE software (.fwt) or in the Energy-Plus software (.epw). Alternatively the Meteorom software can be used to download New Zealand specific weather data that can be used by the PCM-Express software, but Meteorom has to be purchased and the licence is expensive (Meteotest, 2011). The approach taken here for what was only intended to be an illustrative exercise was to search for a location in Europe (available in the PCM-Express data base) with climate conditions similar to Nelson, New Zealand. In this exercise the European city chosen to represent Nelson climatic conditions is Milan, Italy.

Table 9-2: Climate data comparison between Nelson, New Zealand and Milan, Italy.

	Spring			Summer			Autumn			Winter			
Nelson	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Year
Average high °C	14.9	16.8	18.7	20.5	22.4	22.4	20.8	18.1	15.2	12.9	12.4	13.1	17.4
Average low °C	5.4	7.9	9.8	11.8	13.0	12.9	11.4	8.2	4.9	2.4	1.6	3.1	7.8
Daily mean °C	10.2	12.4	14.3	16.2	17.7	17.7	16.1	13.2	10.1	7.7	7.0	8.1	12.6
Milan	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Year
Average high °C	13.2	17.5	21.9	26.1	28.9	27.7	24.3	18.8	10.2	5.4	4.6	8.2	17.2
Average low °C	3.3	7.0	11.2	15.0	17.3	16.7	13.5	8.4	3.6	-0.9	-1.9	0.1	7.8
Daily mean °C	8.3	12.3	16.6	20.6	23.1	22.2	18.9	13.6	6.9	2.3	1.4	4.2	12.5

Table 9-2 shows the comparison of temperature data between Nelson and Milan. Although average high and low temperature do not seem to match, particularly during summer and winter conditions, the daily mean temperature between the two locations is relatively similar. Yearly average high and low temperatures are a perfect match between the two locations.

9.4.1.1 Setup of models in PCM-Express

The PCM-Express software produces results as comparison of two rooms (exactly the same geometry) but one with PCM material and the other without. The rooms are set up simultaneously and there is a constant dialog menu asking for the construction, HVAC systems and schedules of operation for both rooms at the same time.

The room chosen for the modelling with PCM-Express is Level 2 of the gallery space, because this is the space in the Arts building that spends the most time exposed to direct solar radiation. A detail of the geometry can be seen in 'project report' in Appendix J. The buildings were modelled using a similar HVAC system as the commercial HVAC system used in the best-practice buildings, being a centralized mechanical ventilation system with convective cooling and radiant heating (HVAC in Level 2 gallery).

The PCM material used was PCM Smart–Board ® with embedded Micronal ® with a melting point at 23°C. The set point for heating was set to maintain temperature at 20°C, and the set point for cooling was set to maintain temperature at 24°C. Through using a PCM material with a melting point of 23°C the hours that the space remains at this temperature with no space conditioning should be greater in the room with PCM material than for the corresponding room without PCM material due to the buffering action of PCM. In the room with PCM materials, this was applied to the interior surfaces of the walls (internal and externals), but not to the mostly-glazed “north” wall (actually “south” in the model because Milan, is located in the northern hemisphere). No PCM material was applied to ceilings because in the Arts building the suspended floors are made of timber (with concrete topping), which was deliberately left exposed.

9.4.2 Results of PCM materials analysis:

The results for PCM-Express are presented in a “project report” available in Appendix J. Figure 9-5 and Figure 9-6 shows the most significant graphs extracted from this appendix, representing the hourly indoor operative temperature during the day of the year on which PCM effect was the highest (Figure 9-5), and the distribution of operative organized in temperature bins at 1°C increments, covering a range from 14°C to 30°C (Figure 9-6).

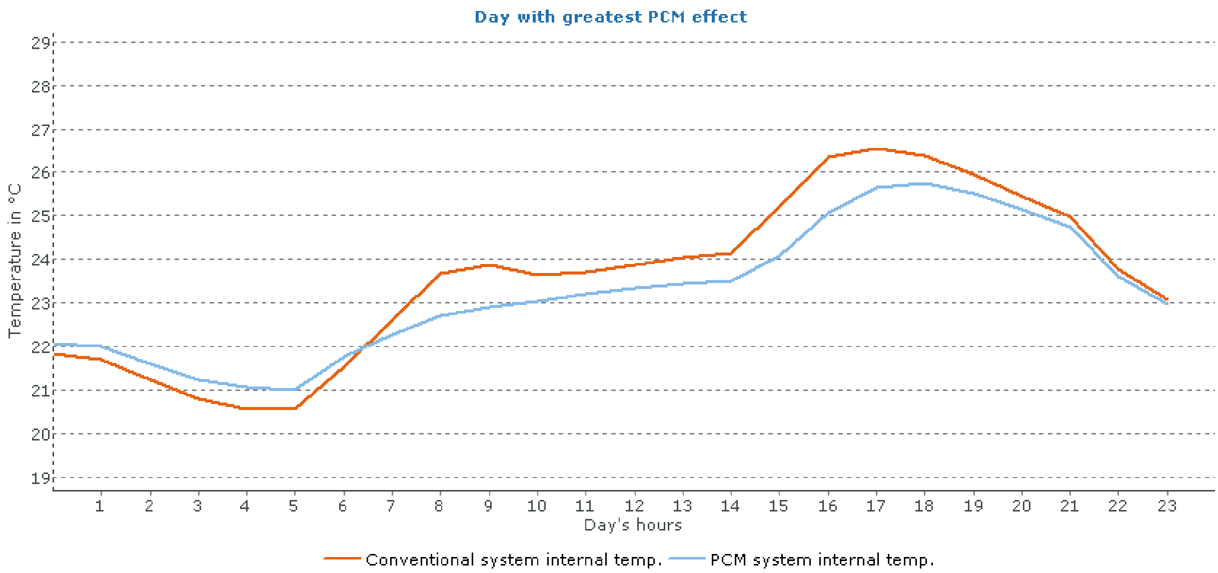


Figure 9-5: Day with greatest PCM effect (12 of April – mid-spring in the northern hemisphere).

Despite the relatively large portion of the available indoor surface area which was covered with PCM materials, the maximum effectiveness of the PCM in these circumstances is not particularly high, with a peak highest temperature difference of about 1°C during that day.

In Figure 9-6 it can be seen that the percentage of time in which rooms remains within a comfortable range of indoor operative temperature (21–26°C) for the room without PCM material is maintained within that range for 63% of the occupied time, while the room with PCM material the corresponding value is 64%. This small increment of 1% of the time within comfortable temperatures in the room with PCM materials is very low for the amount of surface available in the studied space which was covered with PCM materials (60% of the internal walls surfaces).

The effect of the PCM material is most evident in the range of temperature that goes from 16°C to 23°C. Above 24°C the influence of the cooling system means that both rooms, having reached 24°C, spend about the same time within the range of temperature from 24°C to 30°C.

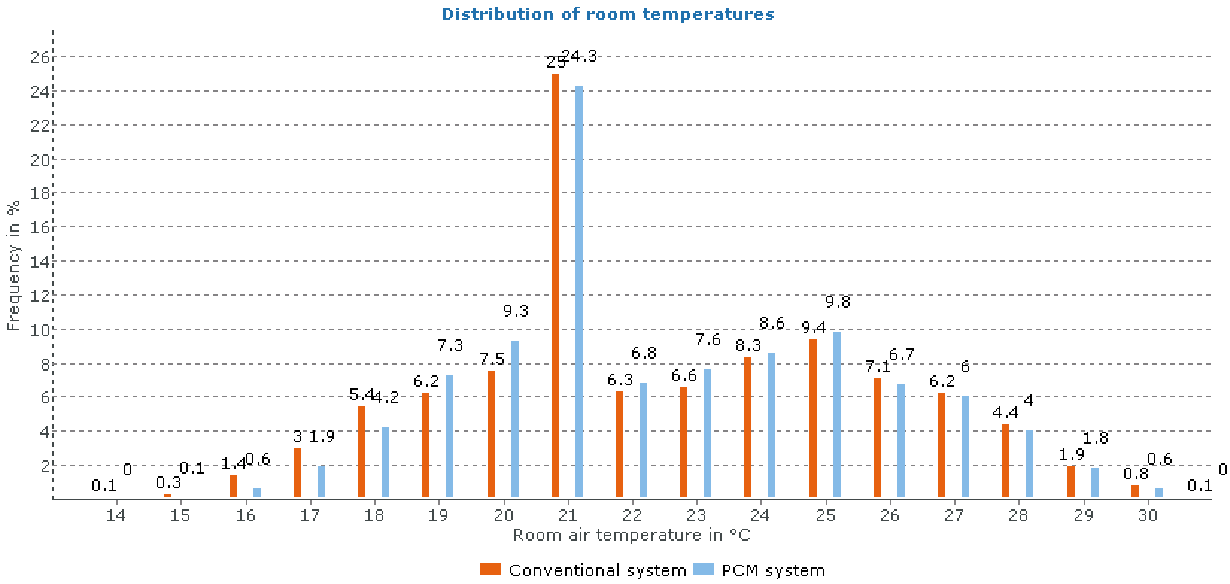


Figure 9-6: Distribution of room temperature in a room equivalent to landing gallery on level 2 – comparison of the space as built and with PCM materials in the south, east, and west walls.

For the particular space (Level 2 Gallery) that was analysed in this exercise to illustrate the possible benefits of using PCM materials in a light weight building such as the actual Arts building (Timber) in a location with a climate similar to Nelson, New Zealand, the results produced show very little benefit from using PCM materials to improve indoor environmental conditions. Because the explanation for this is that the amount of indoor wall surfaces is not particularly high in the gallery space (due to a lack of internal partitions) and also because no ceilings were lined in PCM materials. It is potentially a good material to use in buildings with more internal partitions where most of the constructions are lined in wallboards. It can be also suggested that for a climate with high daily temperature fluctuations with higher maximum and lower minimum temperatures the effectiveness of PCM materials would be enhanced.

It is unfortunate that the constraints of the VE software used in all of the other modelling analyses meant that it was unsuited to the task of truly quantifying the effectiveness of PCM materials as a potential means of increasing the effective thermal mass of the Arts building in a way that would have negligible structural implications.

10 Research conclusions:

This chapter summarizes the conclusions and recommendations for further research.

This research has studied the influence of the thermal mass of structural and finishing construction materials on the space conditioning energy consumption and indoor comfort conditions of medium sized multi-storey buildings.

A modelling comparison has been undertaken between three very similar medium sized educational buildings, each designed using structural systems made primarily of timber, concrete or steel. The concrete and steel buildings have been designed (but not built) to replicate an actual three-storey 1980 m^2 gross floor area educational building, with a timber structure and timber concrete composite floors. Three additional buildings called the Timber-Low, Concrete-Low and Steel-Low buildings were designed – also hypothetical - where insulation values of external walls and roof as well as the glazing and window framing, were significantly increased to a level of best practice, to reduce the impact of heat losses on the comparison. Each building was modelled with two different thermal envelopes (code compliant and New Zealand best practice), and different heating regimes for educational and commercial use, using HVAC system with heating only (educational scheme) and HVAC system with heating and cooling (commercial scheme).

The analysis of each of these case study buildings includes the modelling of operational energy use with an emphasis on HVAC energy consumption, and the assessment of indoor comfort conditions using Predicted Mean Vote (PMV).

In addition to these specific case study buildings, a related but somewhat simpler Test building model was developed. This was used as a vehicle for investigating the sensitivity of the building's thermal behaviour (again assessed by operational energy use and PMV) to changes in the type of proprietary concrete flooring system used. One outcome of this particular modelling was that it confirmed that is possible to include an excessive amount of accessible thermal mass, making the building "sluggish" to changing conditions and even increasing the operational energy requirement during the occupied hours for which thermal comfort is required.

10.1 Conclusions

In Section 1.3 of the introductory chapter, the original objectives of this research were presented as a series of eight questions that were to be answered. These same eight questions are repeated below (*Italics*), each followed by the corresponding conclusion which has been drawn from the findings of this work.

1. *Does a concrete, steel, or timber multi-storey building, as currently built in New Zealand, contain enough thermal mass to have an effect on the space conditioning energy consumption?*

Regardless of whether the buildings are constructed mainly with concrete, steel or timber as the principal structural and non-structural materials, thermal mass has a relatively low impact on operational energy consumption for the particular operating regime of the Arts building of this study – at least in the temperate climate for which the modelling comparison was carried out.

Because, as shown in several previous studies, the operational energy is by far the largest component of life-cycle energy use, this first conclusion suggests that the life-cycle energy usage of a building to be used for educational purposes in a temperate climate is relatively insensitive to the choice of primary structural material.

2. *For a concrete, steel, or timber multi-storey building, as currently built in New Zealand, does the thermal mass influence the indoor environmental conditions?*

While the variations in operational energy usage between buildings having different primary structural materials (timber, concrete and steel) may have been shown to be small, consideration of environmental comfort – as evidenced by PMV considerations – has shown that the concrete-based constructions consistently give the smallest number of hours outside the accepted comfort range.

Nevertheless, the variation in the total hours of out-of-comfort-range conditions is comparatively small for the three building types within a given level of envelope insulative performance.

Discomfort in buildings in this research most often resulted from overheating of the indoor environments rather than because environments were cool or cold. It was found that the time in which the buildings would produce cold/cool environments was similar in the Timber, Concrete, and Steel buildings. However, when indoor temperature increases, the influence that different thermal mass materials have in moderating indoor temperatures became more evident in the amount of hours of warm-to-hot environments.

3. *Are there optimal locations for thermal mass materials, and are those locations dependent on what those materials are?*

The influence of thermal mass on comfort conditions varies significantly depending on building orientation and exposure to solar radiation. While comfort conditions of spaces exposed to the north were better in the Concrete building than in the Timber building, for example, comfort conditions in both buildings were very similar in spaces exposed to the south.

When incident solar radiation is the dominant heat exchange mechanism between thermal mass and the surrounding environment, concrete thermal mass shows a slow response to temperature change (slower than air temperature), while timber thermal mass has a very dynamic response to solar radiation as its surface temperature can increase significantly above air temperature, leading to the occupants' perception of more rapidly changing indoor environmental conditions because mean radiant temperature is a component of perceived thermal comfort.

As a consequence, more comfortable conditions will be achieved in timber buildings if the incidence of direct solar radiation on to timber surfaces is avoided. In other words, potential overheating in timber buildings can be controlled by limiting direct solar radiation on internal timber surfaces.

For a building constructed of mixed (concrete and timber) materials, better indoor environmental conditions will occur if direct solar radiation impinges on internal concrete surfaces rather than on internal wood surfaces.

These constraints do not preclude the use of timber as an interior finishing material; for example, there will be minimal detrimental consequences (and some positive thermal mass benefits) if exposed timber is used on ceilings generally, and on all interior surfaces in spaces on the south side of buildings.

These conclusions, which have been deduced from the extensive quantitative modelling undertaken in this research, are consistent with the common understanding that the most effective interior locations for surfaces having high thermal mass potential (such as concrete) is where they will be exposed directly to solar radiation (so-called primary thermal mass).

4. *In which way does the improvement of the thermal envelope from code-compliant to best-practice influence indoor environmental conditions and space energy consumption of buildings?*

Without intervention by the controls of an HVAC system, a consequence of lowering the heat losses through the thermal envelope by adding insulation is that diurnal temperature swing is reduced and average indoor temperatures are increased, particularly during summer. The maximum air and surface temperatures increase during the day, and the minimum temperature increases during the night.

The immediate consequence of an improved level of insulation from code-compliant to best-practice is a 10% reduction in heating energy requirements. Although increasing insulation values in the thermal envelope gives lower heating energy consumption - which is to be expected - this also leads to a danger of overheating in summer conditions if insufficient thermal mass is accessible, and/or inadequate ventilation is provided. In that case mechanical cooling is required which further increases the energy demand on the building.

5. *Are HVAC systems (which are almost always controlled by sensing dry-bulb indoor temperature), sensitive in any way to the thermal mass available in the three building structural types?*

Despite the presence of thermal mass, indoor environmental conditions are dominantly driven by HVAC systems, if installed, and thermal mass has a relatively low influence in these conditions. Forced convection produced by mechanical ventilation tempers the effectiveness of different thermal mass materials and this is most evident in spaces where convection is the main mechanism for heat transfer between the air and the thermal mass.

6. *Does night-time ventilation improve indoor environmental conditions and subsequently the response of HVAC systems to the availability of thermal mass in the three building structural types?*

Night-time ventilation is another way of improving the effectiveness of thermal mass as a means of acting as an energy store and hence buffering heat, and does so in a similar way for all materials.

7. *Will good management of direct solar radiation have an impact on the building's indoor conditions when concrete or timber are used as thermal mass materials?*

External fixed louvres have been shown to increase comfort conditions significantly by reducing the number of hours in a warm-to-hot environment. By reducing direct solar radiation, convection became a more relevant heat exchange mechanism. This shift made different thermal mass materials perform in a similar way.

Paradoxically louvres will produce an increase HVAC energy consumption, particularly in heating energy, because of the reduction in direct solar gains into the building. In other words, external louvres can be an effective means of managing direct solar radiation but excessive use of them will require additional heating energy in winter. (An often-used approach which maintains the shading benefits of louvres during summer months when the potential for overheating is greatest, but allows the admission of solar radiation, if desired, during the heating season, is to use louvres fitted with either manual or BMS-controlled motorized tilting capability. This approach was not modelled in this research.)

8. Will phase change material increase the effective thermal mass in a timber-framed building?

Phase change materials (PCM) applied to the timber building as a way of increasing effective thermal mass in a zone exposed to solar radiation, show little benefits to overall indoor comfort conditions. Since the space where PCM was modelled was the gallery space, which is an open space without many internal partitions, not enough surfaces were available to install PCM materials. PCM would work better in buildings with large areas of available surfaces (walls, partitions and ceilings) which could be lined with wallboards with embedded PCM.

10.2 Future research

In Section 5.1 one of the reasons for the lack of meaningful results for heating energy consumption in the Arts building was because there was uncertainty in the operation of the flow meter (and/or temperature sensors) for the monitoring of heating energy consumption. A calibration of the flow meters needs to be undertaken; the best way to do this would be to compare flows actually recorded against a flow alternatively captured with an ultrasonic flow meter. Based on the outcomes from the calibration of the flow meters, their level of accuracy could be obtained and, from that, a decision reached on the reliability of the data that has been recorded. In any case, at least one year's data has to be analysed to produce any meaningful outcome from monitoring. This data could then be used for a more reliable calibration of the actual VE model used in this research and, based on that, new modelling exercises could be performed. Also a real time comparison of the heating energy consumption between the metered data of the T-Block and the Arts building could be obtained. That comparison would also act as a benchmark between a concrete and a timber building. Indoor temperature analysis could also be included in that comparison.

Possible reasons why the models of the Arts building achieve weekly average temperatures which were about 2°C higher than the monitored temperature during the heating season should be investigated. Possibly related to this apparent deficiency in the modelling is the fact that for T-block at least, the diurnal temperature swings predicted by the model were consistently smaller than the equivalent monitored temperature swings; this too should be investigated.

The versatility and capabilities of building modelling software packages are constantly progressing. Software that may have become available very recently should be assessed with a view to possible changing from the one used in this research (which included very extensive HVAC modelling capability that was particularly useful for some aspects of the current research), to a modelling software which is able to represent the detail of the building materials, their location and their behaviour more conveniently.

Modelling of the buildings was carried out with the finishes and surface materials as installed in the actual Arts building (e.g. vinyl and carpet). It would be informative to explore the consequences of changing some or all of these finishing materials (e.g. no floor finishes). In this way it may be possible to identify more clearly the differences in the energy performance and indoor environmental conditions of the buildings.

While the simplified, concrete-structured Test building was a useful tool for exploring and quantifying the energy usage and thermal comfort consequences of adding significantly more thermal mass to a suspended flooring system, and artificially enhancing the thermal accessibility of that floor to the air space below, there is other floor-related research that would be worthwhile. This suggestion is made because the timber buildings modelled in this study had timber-concrete composite floors, with concrete topping on a timber lower surface. However, more recent multi-storey timber buildings in New Zealand and overseas have a number of different floor systems. Some buildings have all-wood floors such as cross-laminated timber flat panels or timber Tee-beams or timber box beams, with no concrete available as thermal mass at the floor level. Some of these floors have a suspended ceiling, and others expose the wood to view. Another very different system (used in the Massey University building in Wellington) has a precast timber-concrete composite floor system where the 100mm thick concrete slab is visible (and available as thermal mass) on both the top and bottom surfaces, supported on composite timber floor joists, and timber beams and columns. The thermal performance of all of these alternative floor systems needs to be investigated.

Because of its north-facing, three-level gallery space, and the relatively high proportion of glazing on its south façade, the Arts building, which was the focus of this case study, can be regarded as being atypical in comparison with the majority of commercial buildings. It would therefore be informative to conduct a similar modelling comparison on a building which is more representative of a typical commercial building. It would be desirable to model a more generic building where simple architectural changes can be made with comparative ease. This would allow, for example, a sensitivity analysis of the influence of window size on indoor environmental conditions to be performed.

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Appendices:

A. Modelling of the test building and its comparison with the Arts building:

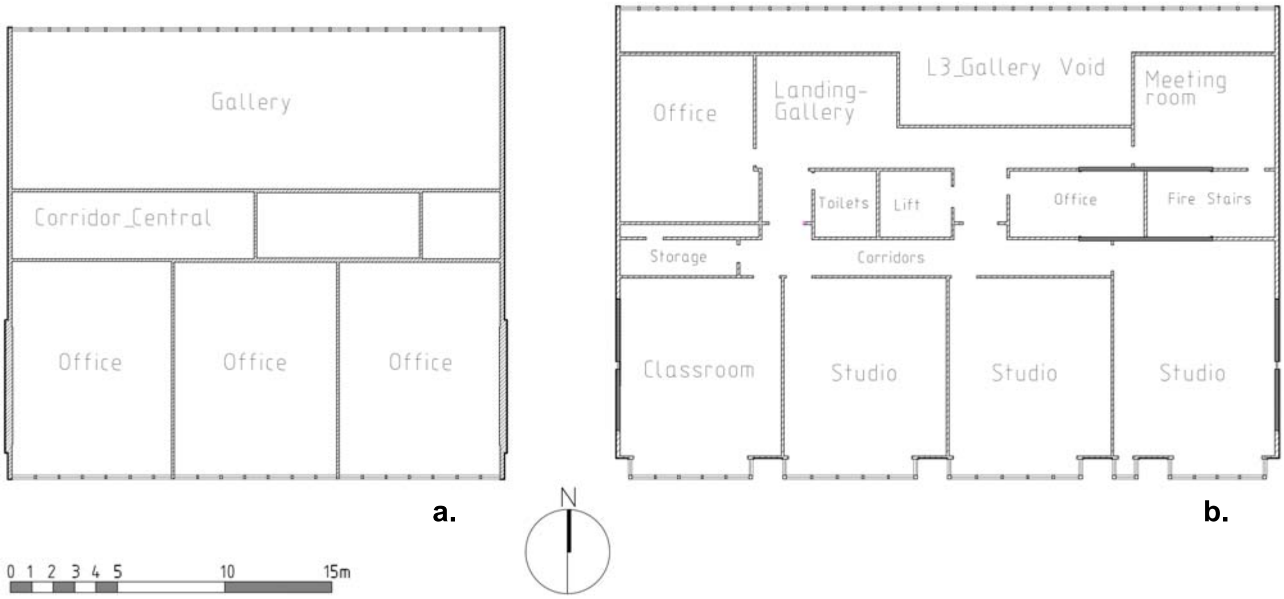


Figure A-1: Comparison of the plan section on Level 1 of the test building (a) and the Arts building (b).

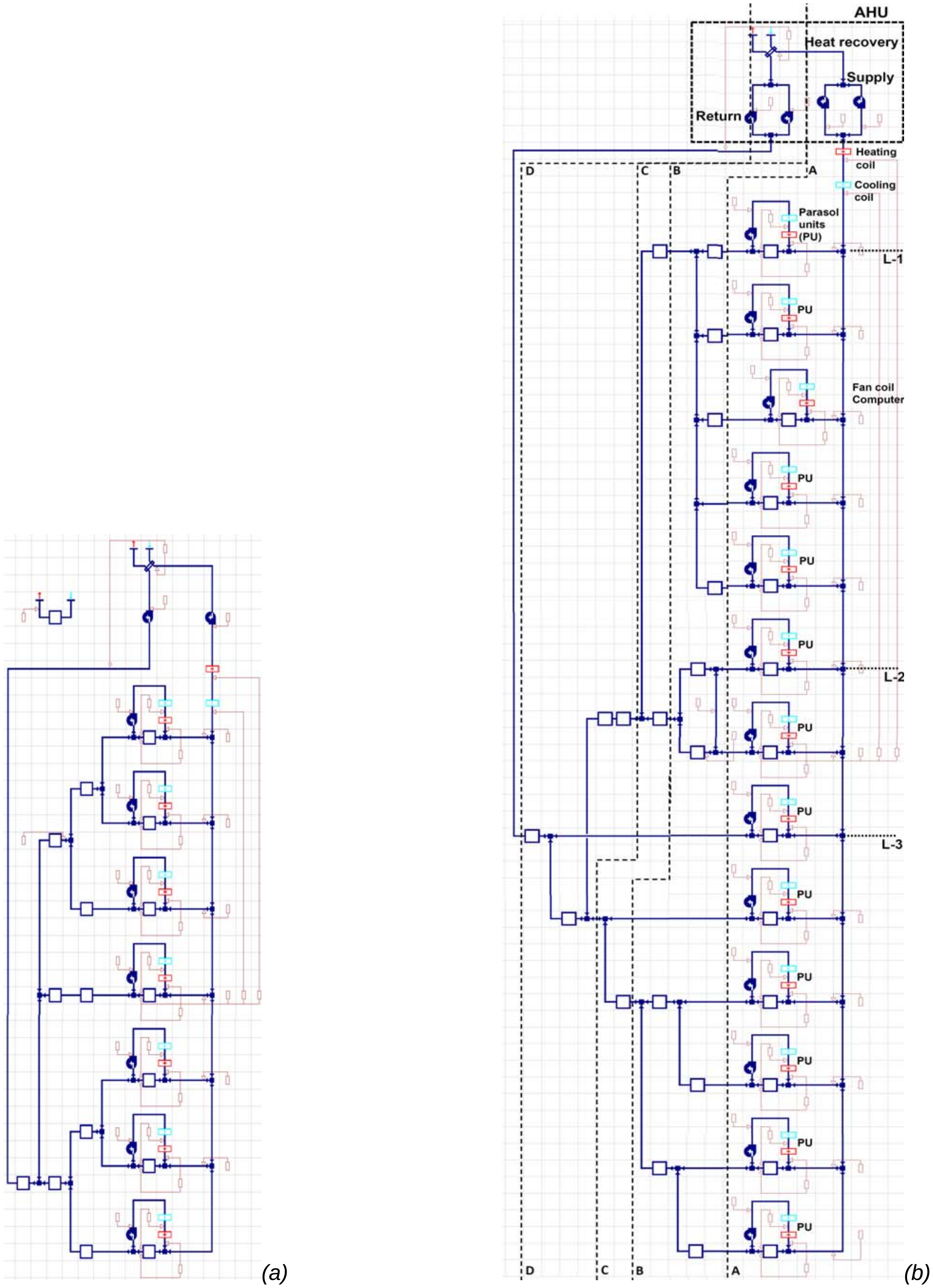


Figure A-2: Schematic network of the HVAC system - educational (a) and commercial (c) - in Virtual Environment's Apache HVAC tool, and schematic of an induced air (Parasol ®) unit in (b).

B. Representation of Solar Insolation in VE Apache

As was mentioned in Section 3.9.1, within VE Apache the required solar tracking algorithms are contained within the SunCast module. Normally the inner workings of these calculations are invisible to the user, but it is possible to access generated tables which illustrate how the insolation incident upon a surface of interest (either external or internal) is resolved and quantified as an input to the thermal modelling of that surface. This may be helpful in interpreting in particular the consequences of solar insolation which is incident upon the surface of a thermal mass element.

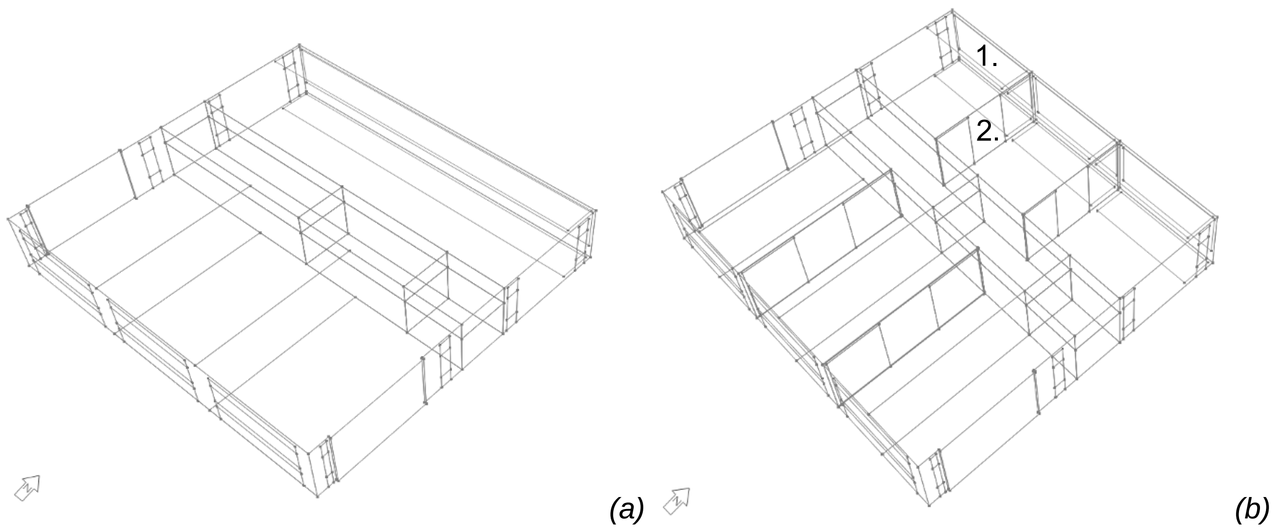


Figure B-1: an interior view of Level 2 of the simplified model, without internal stand-alone walls (a), and with internal stand-alone walls (b). (1) Identifies an external wall, and (2) identifies one of the internal stand-alone-walls.

Figure B-1 shows the location of two representative walls in the Test building model for which measurements of area of insolation as a percentage of the surface area of walls (external and internal) are further represented in a flexigrid format in Table B-1, Table B--2, and Table B-3. These tables illustrate the way in which SunCast tracks solar intensity values across external and internal walls as if they are experiencing each hour the average solar intensity value uniformly over the entire component.

Table B-1: Exterior wall (1), external insolation type.

Month	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00
Jan						0	0	0	100	100	100	100	100	100	100	100	0	0	0					
Feb						0	0	100	100	100	100	100	100	100	100	100	100	0	0					
Mar							100	100	100	100	100	100	100	100	100	100	100	100						
Apr								100	100	100	100	100	100	100	100	100	100							
May								100	100	100	100	100	100	100	100	100	100							
Jun								100	100	100	100	100	100	100	100	100								
Jul								100	100	100	100	100	100	100	100	100	100							
Aug								100	100	100	100	100	100	100	100	100	100							
Sep							100	100	100	100	100	100	100	100	100	100	100	100						
Oct						0	100	100	100	100	100	100	100	100	100	100	100	0						
Nov						0	0	100	100	100	100	100	100	100	100	100	0	0	0					
Dec					0	0	0	0	100	100	100	100	100	100	100	100	0	0	0					

Table B-1 shows the calculation of the shading results for the design day (15th of each month) during every month, displayed in flexigrid format and showing the area of insolation as a percentage of the surface area. In the case of external walls, both external and internal insolation data can be extracted, as can be seen in Table B–2 and Table B-3 respectively.

Table B--2: Exterior wall (1), internal insolation type.

Month	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00
Jan						0	0	0	0	0	0	0	0	0	0	0	0	35	23.2					
Feb						0	0	0	0	0	0	0	0	0	0	0	0	0	36.6					
Mar							0	0	0	0	0	0	0	0	0	0	0	0						
Apr								0	0	0	0	0	0	0	0	0	0							
May								0	0	0	0	0	0	0	0	0	0							
Jun								0	0	0	0	0	0	0	0	0								
Jul								0	0	0	0	0	0	0	0	0	0							
Aug								0	0	0	0	0	0	0	0	0	0							
Sep							0	0	0	0	0	0	0	0	0	0	0	0						
Oct						0	0	0	0	0	0	0	0	0	0	0	0	17.9						
Nov						0	0	0	0	0	0	0	0	0	0	0	0	33.3	19					
Dec					0	0	0	0	0	0	0	0	0	0	0	0	16.5	27.9	19.3					

Table B-3: Internal wall (2), internal insolation type

Month	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00
Jan						0	0	0	3.4	1.9	0	0	0	0	0	0	0	0	0					
Feb						0	2	3.7	2.6	3	6.1	8.5	0	0	0	0	0	0	0					
Mar							6.3	18.4	28.6	36.9	37.5	34.8	0	0	0	0	0	0						
Apr								51.1	50.8	48.6	47.5	38.9	0	0	0	0	0							
May								58.3	65.2	59.7	57	41.8	0	0	0	0	0							
Jun								51.6	70	64.6	61.4	51.8	0	0	0	0								
Jul								53.1	69.3	63.2	59.9	53.3	0	0	0	0	0							
Aug								59	59.4	54.5	51.9	44.7	0	0	0	0	0							
Sep							24.6	38.8	38.9	43.1	42.7	28.3	0	0	0	0	0	0						
Oct						17.9	1.9	3	7.3	13.5	17.1	0	0	0	0	0	0	0						
Nov						0	0	3	2.6	0.6	0.1	0	0	0	0	0	0	0	0					
Dec					0	0	0	0	3.3	1.8	0	0	0	0	0	0	0	0	0					

Table B-3 similarly shows the calculation of the shading results for the design day during every month, for the case of an internal wall for which only internal insolation data is available.

C. Constructions

Table C-1: Timber, concrete and steel buildings; R – C values of materials

	TIMBER ∑R	TIMBER ∑C		CONCRETE ∑R	CONCRETE ∑C		STEEL ∑R	STEEL ∑C
Windows								
External glazing	0.25	15.0	External glazing	0.25	15.0	External glazing	0.25	15.0
Internal glazing	0.32	11.3	Internal glazing	0.32	11.3	Internal glazing	0.32	11.3
External wall								
External light wall	2.81	20.7	External light wall	2.81	20.7	External light wall	2.81	20.7
External shear wall LVL	2.74	172.3	External shear wall Concrete	1.41	463.2			
Internal wall								
Internal partitions light	2.70	26.0	Internal partitions light	2.70	26.0	Internal partitions light	2.70	26.0
Internal shear wall LVL	1.45	169.4	Internal shear wall Concrete	0.13	460.0			
Suspended ceilings								
Gib board	2.70	30.7	Gib board	2.70	30.7	Gib board	2.70	30.7
Acoustic tile	0.31	19.6	Acoustic tile	0.31	19.6	Acoustic tile	0.31	19.6
Structural suspended floor								
Potius carpet	1.12	248.3	Interspan carpet	0.73	245.4	Comflor carpet	0.42	284.4
Potius vinyl	0.78	249.0	Interspa vinyl	0.40	246.1	Comflor vinyl	0.08	285.1
Concrete suspended floor								
Suspended concrete floor	0.13	428.4	Suspended concrete floor	0.13	428.4	Suspended concrete floor	0.13	428.4

Table C--2: Continuation of Table A-1 – 'Timber, concrete and steel buildings; R – C values of materials'.

	TIMBER ∑R	TIMBER ∑C		CONCRETE ∑R	CONCRETE ∑C		STEEL ∑R	STEEL ∑C
External overhang floor								
Floor cantilever ligt	5.07	196.7	Floor cantilever ligt	5.07	196.7	Floor cantilever ligt	5.07	196.7
Floor cantilever heavy	5.15	461.2	Floor cantilever heavy	5.15	461.2	Floor cantilever heavy	5.15	461.2
Roof								
Roof timber	5.12	55.9	Roof timber	5.12	55.9	Roof timber	5.12	55.9
			Roof steel	4.01	28.5	Roof steel	4.01	28.5
Heated slab								
Heated slab-vinyl	0.09	106.5	Heated slab-vinyl	0.09	106.5	Heated slab-vinyl	0.09	106.5
Heated slab-clear	0.09	105.6	Heated slab-clear	0.09	105.6	Heated slab-clear	0.09	105.6
Slab on gound								
Slab on ground	3.44	1545.9	Slab on ground	3.44	1545.9	Slab on ground	3.44	1545.9
Slab on ground-heated	3.41	1440.1	Slab on ground-heated	3.41	1440.1	Slab on ground-heated	3.41	1440.1

The constructions highlighted in grey are those that are unique for that particular building, whereas non-highlighted constructions are common to the four buildings. For instance, in 'Windows' constructions the same external glazing is used in the Timber, Concrete, and Steel buildings but an external glazing with a higher R-value is used in the Timber-Low building.

Table C-3: Timber-low, concrete-low, steel-low buildings; R – C values of materials

	TIMBER-LOW ∑R	∑C		CONCRETE-LOW ∑R	∑C		STEEL_LOW ∑R	∑C
Windows								
PVC frame; Argon filled	0.50	15.0	External glazing	0.50	15.0	External glazing	0.50	15.0
Internal glazing	0.32	11.3	Internal glazing	0.32	11.3	Internal glazing	0.32	11.3
External wall								
External light wall -low	4.55	21.2	External light wall -low	4.55	21.2	External light wall -low	4.55	21.2
External shear wall LVL- low	4.20	173.2	External shear wall concrete	2.87	464.2			
Internal wall								
Internal partitions light	2.70	26.0	Internal partitions light	2.70	26.0	Internal partitions light	2.70	26.0
Internal shear wall LVL	1.45	169.4	Internal shear wall concrete	0.13	460.0			
Suspended ceilings								
Gib board	2.70	30.7	Gib board	2.70	30.7	Gib board	2.70	30.7
Acoustic tile	0.31	19.6	Acoustic tile	0.31	19.6	Acoustic tile	0.31	19.6
Structural suspended floor								
Potius carpet	1.12	248.3	Interspan carpet	0.73	245.4	Comflor carpet	0.42	284.4
Potius vinyl	0.78	249.0	Interspa vinyl	0.40	246.1	Comflor vinyl	0.08	285.1
Concrete suspended floor								
Suspended concrete floor	0.13	428.4	Suspended concrete floor	0.13	428.4	Suspended concrete floor	0.13	428.4

Table C-4: Continuation of Table A-3 – 'Timber-low, concrete-low, steel-low buildings; R – C values of materials'.

	TIMBER-LOW			CONCRETE-LOW			STEEL_LOW	
	∑R	∑C		∑R	∑C		∑R	∑C
External overhang floor								
Floor cantilever ligt	5.07	196.7	Floor cantilever ligt	5.07	196.7	Floor cantilever ligt	5.07	196.7
Floor cantilever heavy	5.15	461.2	Floor cantilever heavy	5.15	461.2	Floor cantilever heavy	5.15	461.2
Roof								
Roof timber -low	9.41	48.0	Roof timber	9.41	48.0	Roof timber	9.41	48.0
Heated slab								
Heated slab-	0.09	106.5	Heated slab	0.09	106.5	Heated slab	0.09	106.5
Heated	0.09	105.6	Heated	0.09	105.6	Heated	0.09	105.6
Slab on gound								
Slab on ground	3.44	1,546	Slab on ground	3.44	1,546	Slab on ground	3.44	1,546
Slab on ground heated	3.41	1,440	Slab on ground heated	3.44	1,546	Slab on ground heated	3.44	1,546

D. Thermal templates

Table D-1: Level 2 thermal zones area and volume.

Level 1 - Conditioned thermal zones	Area (m^2)	Volume (m^3)
Computer room		
Computer	84.4	314.9
Office_Core		
Interview	8.9	33.3
DB-Comms	9.1	23.4
Reception-Mail	19.3	51.7
Office_Perimeter		
Staff-Program leader	22.6	84.5
Head of Sch-Program leader	19.7	73.4
Classroom_Perimeter		
Textile	79.7	326.9
Seminar	61.0	203.5
Gallery		
Gallery 1st Floor	211.4	862.9
∑	516	1,975

Level 1 - Unconditioned thermal zones	Area (m^2)	Volume (m^3)
Storage & circulation_Core		
Storage Seminar	8.7	22.5
Link Corridors	34.2	88.3
Link Seminar-Gallery	10.3	26.6
Storage & circulation_Perimeter		
Fire Stair	18.3	76.3
Unoccupied & Voids & Mass		
Ceiling_Link Corridor	10.3	14.8
Ceiling Concrete_Computer	27.7	9.6
Ceiling_Computer	56.9	23.7
Services	9.8	40.7
Lift	10.5	43.8
Ceiling_DB-Comms	9.1	13.3
Ceiling_Link	7.3	10.8
Ceiling_Link Corridors	34.2	50.2
Ceiling_Reception-Mail	19.3	28.3
Ceiling Concrete_Textile	0.9	1.0
Ceiling Concrete_RM 114-116	15.7	5.4
Ceiling_RM 113-114-115-118	37.0	15.4
Ceiling-Seminar	45.3	18.9
Ceiling Concrete_Seminar	15.8	5.5
∑	371	495

Table D-2: Level 2 thermal zones area and volume.

Level 2 - Conditioned thermal zones	Area (m^2)	Volume (m^3)
Gallery		
Gallery Void	3.1	326.2
Landing-Gallery	104.4	401.9
Office_Perimeter		
Staff	46.8	180.3
Classroom_Perimeter		
Studio	328.3	1,264.2
Toilets		
DB-Toilet	9.1	23.5
Toilets-Storage	19.4	50.1
∑	511	2,246

Level 2 - Unconditioned thermal zones	Area (m^2)	Volume (m^3)
Storage & circulation_Core		
Link	5.9	15.3
Link	5.7	14.7
Storage & circulation_Perimeter		
Storage-Duct	6.0	23.2
Fire Stairs	18.4	70.9
Unoccupied & Voids & Mass		
Lift	10.6	40.7
Ceiling_Link	7.7	8.8
Ceiling_Link	7.4	8.5
Ceiling_Toilet	9.1	10.5
Ceiling_Toilets-Storage	19.4	22.3
Ceiling Concrete_Studio	9.6	5.2
∑	100	220

Table D-3: Level 3 thermal zones area and volume.

Level 3 - Conditioned thermal zones	Area (m^2)	Volume (m^3)
Office_Perimeter		
Staff meet	34.7	100.1
Staff	49.3	142.1
Classroom_Perimeter		
Drawing Central	82.5	316.2
Drawings West	82.5	316.2
Studio seminar	81.7	313.6
Drawings East	82.0	348.2
Gallery		
Ceiling-Roof_Staff	34.0	57.3
Ceiling-Roof_Gallery	95.7	222.9
Gallery	67.4	190.5
L3_Void	4.4	281.2
Toilets		
DB-Toilets	9.1	23.5
Toilet-Storage	19.4	50.1
∑	643	2,362

Level 3 - Unconditioned thermal zones	Area (m^2)	Volume (m^3)
Storage & circulation_Core		
Fire Stairs	18.4	67.5
Storage staff	3.9	14.4
Store	9.0	23.3
Storage & circulation_Perimeter		
Corridor Studios	32.0	82.6
Unoccupied & Voids & Mass		
Lift	10.6	38.8
Ceiling-roof_DB-Toilet	9.1	8.8
Ceiling-roof_Toilet-Storage	19.4	18.8
Ceiling-roof_Link	7.4	7.1
Ceiling-roof_Link	7.7	7.4
Ceiling-roof_Staff-Corridor	15.7	10.4
∑	133	279

E. Mechanical Ventilation and heating data

Table E-1: Educational HVAC system's mechanical ventilation and radiant heating data.

Thermal template & Room name	Mechanical Ventilation			Heating			
	Supply (L/s)		Return (L/s)	Radiators			Underfloor heating (kW)
	Direct	Indirect		R - 1 (4.6 kW)	R - 2 (3.8 kW)	R - 3 (2.7 kW)	
Level 1							
Computer room							
Computer	250						
Office_Core							
Interview	30						0.6
Reception-Mail	30						2.2
Office_Perimeter							
Staff-Program leader							1.3
Head of Sch-Prg led.							1.2
Classroom_Perimeter							
Textile	125						5.0
Seminar	125						3.4
Gallery							
Gallery 1st Floor		560	560				12.3
Σ	560	560	560	0.0	0.0	0.0	26.0
Level 2							
Gallery							
Gallery Void			750				
Landing-Gallery		750		4.6	3.8		
Office_Perimeter							
Staff	125			4.6			
Classroom_Perimeter							
Studio	625				23.0	8.1	
Σ	750	750	750	9.2	26.9	8.1	0.0
Level 3							
Office_Perimeter							
Staff meet	125				3.8		
Staff	125			4.6			
Classroom_Perimeter							
Drawing Central	125				3.8	2.7	
Drawings West	125				3.8	2.7	
Studio seminar	125			4.6	3.8		
Drawings East	125			4.6	3.8		
Gallery							
Gallery		750		4.6			
Ceiling-Roof_Staff							
Ceiling-Roof_Gallery			2060				
L3_Void							
Σ	750	750	2060	18.4	19.2	5.4	0.0

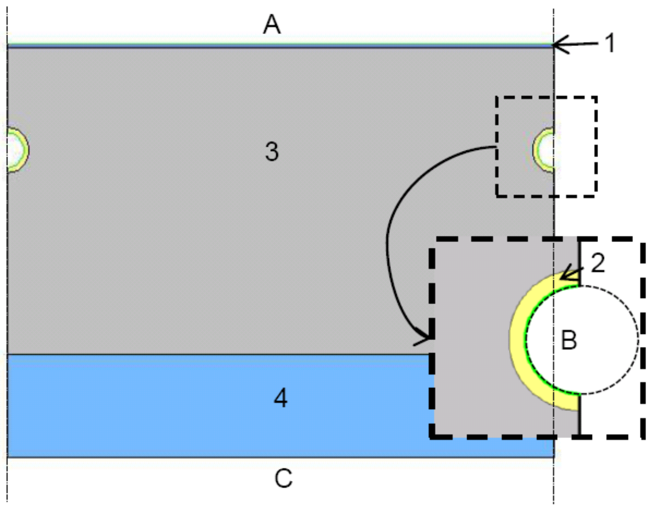
Table E-2: Commercial HVAC system's mechanical ventilation and radiant heating data.

Thermal template & Room name	Mechanical Ventilation: Supply (L/s) Direct	Mechanical Ventilation: Supply (L/s) Indirect	Mechanical Ventilation: Return (L/s)	Heating + Cooling: Parasol Units Heating (kW)	Heating + Cooling: Parasol Units Cooling (kW)	Heating + Cooling: Radiators R - 1 (4.6 kW)	Heating + Cooling: Radiators R - 2 (3.84 kW)	Heating + Cooling: Underfloor heating (kW)
Level 1								
Computer room								
Computer	250							
Office_Core								
Interview	30			2.7	2.1			
Reception-Mail	30			2.7	2.1			
Office_Perimeter								
Staff-Program leader				5.1	6.3			
Head of Sch-Prg led.				5.1	6.3			
Classroom_Perimeter								
Textile	125			2.7	2.1			
Seminar	125			2.7	2.1			
Gallery								
Gallery 1st Floor		560	560					12.3
Σ	560	560	560	21.1	20.8	0.0	0.0	12.3
Level 2								
Gallery								
Gallery Void			750					
Landing-Gallery		750				4.6	3.8	
Office_Perimeter								
Staff	125			2.7	2.1			
Classroom_Perimeter								
Studio	6265			13.5	10.3			
Σ	6390	750	750	16.2	12.3	4.6	3.8	0.0
Level 3								
Office_Perimeter								
Staff meet	125			2.7	2.1			
Staff	125			2.7	2.1			
Classroom_Perimeter								
Drawing Central	125			2.7	2.1			
Drawings West	125			2.7	2.1			
Studio seminar	125			2.7	2.1			
Drawings East	125			2.7	2.1			
Gallery								
Gallery		750	2060			4.6		
Ceiling-Roof_Staff								
Ceiling-Roof_Gallery								
L3_Void								
Σ	750	750	2060	16.2	12.3	4.6	0.0	0.0

Table E-1 and Table E-2 show the specific flow of mechanically supplied air into each conditioned space in the actual Arts building; data is organized by levels. Air flow is primarily subdivided in 'Supply' and 'Return', subsequently only 'Supply' is subdivided into 'Direct supply' and 'Indirect Supply'. The rationale behind the sub-classification of 'Supply' is based in Figure 4-9 Section 4.6.1 of the thesis main document, where the mechanical air distribution network by levels is subdivided in four segments being: A, B, C, and D.

F. THERM analysis of under-floor heated slab conductivity

To simulate an embedded pipe, a section, of the heated slab in between pipes was cut. The boundary condition of the water: T=40°C and λ=5000 W/m^{2}K, maintaining all the layers of the floor, as represented in Figure F-.



	Material	Conductivity (W/(m*K))	Emissivity
1	Vinyl	0.79	0.9
2	PEX (Tubing)	0.38	0.9
3	Cast Concrete	1.6	0.55
4	EPS	0.025	0.9

	Boundary Conditions	Temperature (°C)	Film Coeffcient
A	Inside	20	7.7
B	PEX (Inside tubing)	40	5000
C	Adiabatic	0	0

Figure F-1: A cross-section of the concrete slab with embedded hydronic tubing is described in THERM as a repeatable segment bounded by the heated surface (top), centre of the tubing (sides), and midpoint between tubes (either side). Boundaries other than the tube interiors and heated surface are adiabatic.

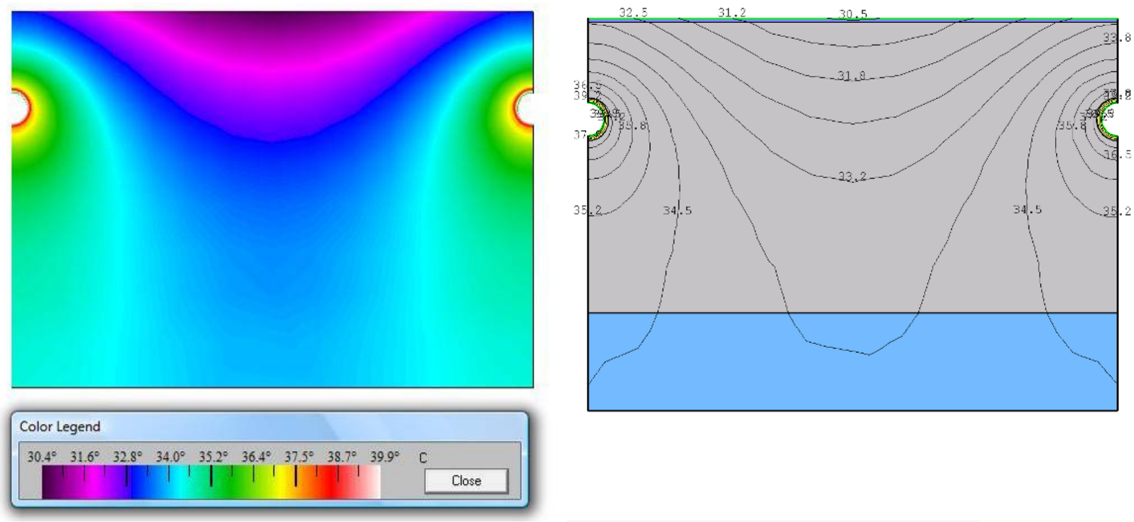
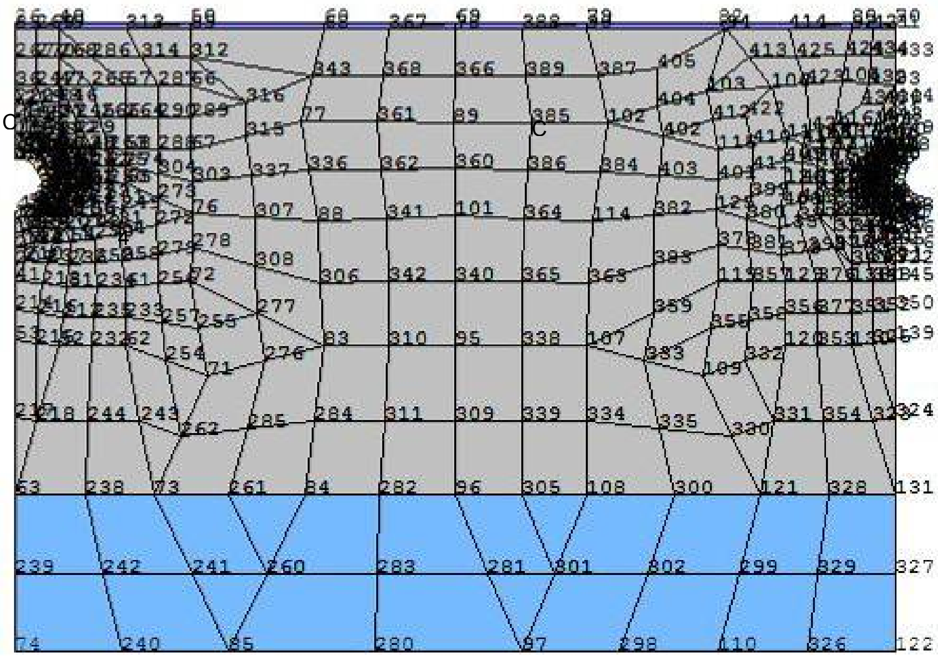


Figure F-2: Colorized/shaded and isothermal contours indicate the distribution of temperatures resulting from the finite-element model of two-dimensional heat transfer between boundary conditions.

Vertical lines trough the pipes became lines of symmetry that represent adiabatic boundaries on the THERM model which is a correct representation of a recurring pattern of hydronic pipes. The resistance at the top surface value of 0.12 m^2K/W and, with a modelled average surface temperature of 31.8°, the heat flow into the air above (22 °C) was determined to be 90 W/m^2.

For steady state, the same upward rate of heat flow must be taking place through the concrete below the pipes, so for a truly 1-D floor model with a uniform layer of 40° C water at a depth of 50mm below the top surface, an effective thermal conductivity of 0.548 W/mK for the cast concrete was determined.



Node	Temperature [°C]
26	32.9
40	32.8
50	31.6
60	30.7
69	30.4
79	30.7
82	31.6
80	32.8
70	32.9
Average	31.8

Figure F-3: Finite-element mesh at section through bisected hydronic tubing – table indicating nodes number and temperature at node.

Figure F-33 presents a simple way of checking the consistency of the initial TERM model which was undertaken. A new THERM model was set up consisting of a uniform slab of concrete, 50mm thick and having the deduced thermal conductivity value (0.55 W/mK). A bottom boundary condition of water at 40° C with the same extremely high effective conductivity from water to concrete as the existing model has between water and PEX was imposed. The upper boundary condition should be exactly the same as in the existing model, i.e. convection to air at 22°C. The simple slab model results in a uniform upper surface temperature of 31.8° C.

G. Influence of steel purlins on space conditioning energy

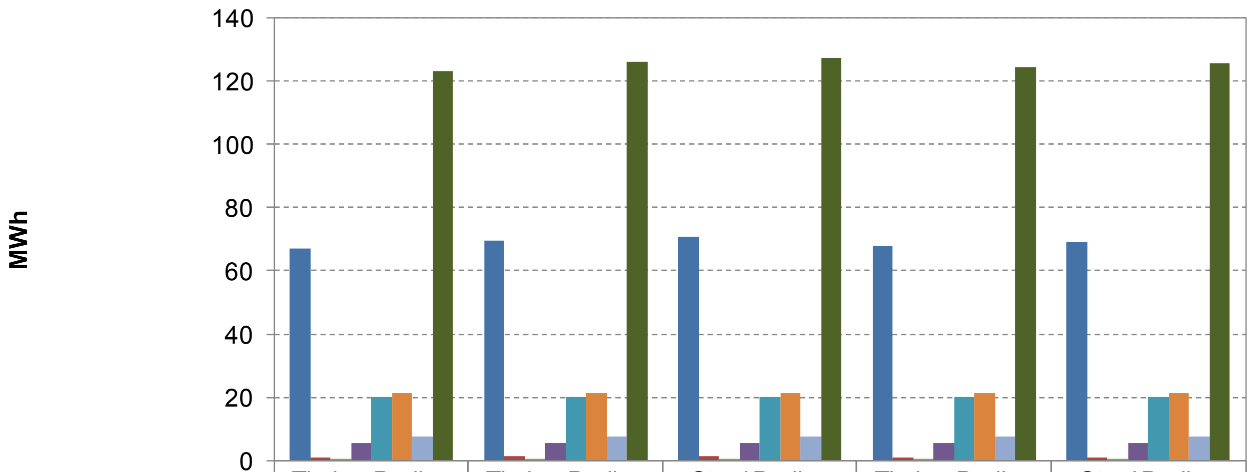
Table G-1: Total and end-use energy consumption for the Timber building, the Concrete building (with steel purlins in the roof), and the Steel building (with steel purlins in the roof).

	R	C	R	C	R	C	R	C	R	C	R	C	R	C	∑R	∑C
Roof Timber Purlins	0.04	0.0	0.00	2.2	0.14	24.8	4.56	1.2	0.20	17.6	0.07	10.1	0.10	0.0	5.12	55.9
	Outside surface		Profiled Steel		Plywood		Bridged Insulation		Timber		Gib Board		Inside surface			
Roof Steel Purlins	0.04	0.0	0.00	2.2	0.14	16.1	3.81	1.4	0.06	8.7	0.10	0.0			4.01	28.5
	Outside surface		Profiled Steel		Plywood		Bridged Insulation		Gib Board		Inside surface					

R: m^2K/W C: KJ/m^2K

Table G-2: Total and end-use energy consumption for the Timber building, the Concrete building (with steel purlins in the roof), and the Steel building (with steel purlins in the roof).

	Timber		Concrete Builiding				Steel Building			
			Timber Purlins		Steel Purlins		Timber Purlins		Steel Purlins	
	Thermal	Electric	Thermal	Electric	Thermal	Electric	Thermal	Electric	Thermal	Electric
Heating	66.9	1.1	69.4	1.2	70.6	1.2	68.1	1.1	69.3	1.1
Chillers	0.0	0.7	0.0	0.6	0.0	0.6	0.0	0.7	0.0	0.7
Fans	0.0	5.7	0.0	5.7	0.0	5.7	0.0	5.7	0.0	5.7
DHW	0.0	20.1	0.0	20.1	0.0	20.1	0.0	20.1	0.0	20.1
Lighting	0.0	21.3	0.0	21.3	0.0	21.3	0.0	21.3	0.0	21.3
Equipments	0.0	7.5	0.0	7.5	0.0	7.5	0.0	7.5	0.0	7.5
∑	66.9	56.4	69.4	56.4	70.6	56.4	68.1	56.4	69.3	56.4
Total (MWh)	**123.3**		**125.8**		**127.1**		**124.5**		**125.7**	



	Timber	Concrete Builiding		Steel Building	
	Timber Purlins	Timber Purlins	Steel Purlins	Timber Purlins	Steel Purlins
Heating (Thermal)	66.9	69.4	70.6	68.1	69.3
Heating (Electric)	1.1	1.2	1.2	1.1	1.1
Chillers (Electric)	0.7	0.6	0.6	0.7	0.7
Fans (Electric)	5.7	5.7	5.7	5.7	5.7
DHW (Electric)	20.1	20.1	20.1	20.1	20.1
Lighting (Electric)	21.3	21.3	21.3	21.3	21.3
Equipments (Electric)	7.5	7.5	7.5	7.5	7.5
Total (Combined)	123.3	125.8	127.1	124.5	125.7

Figure G-3: Total and end-use energy consumption for the Timber building, the Concrete building (with steel purlins in the roof), and the Steel building (with steel purlins in the roof).

H. Variable PMV assessment

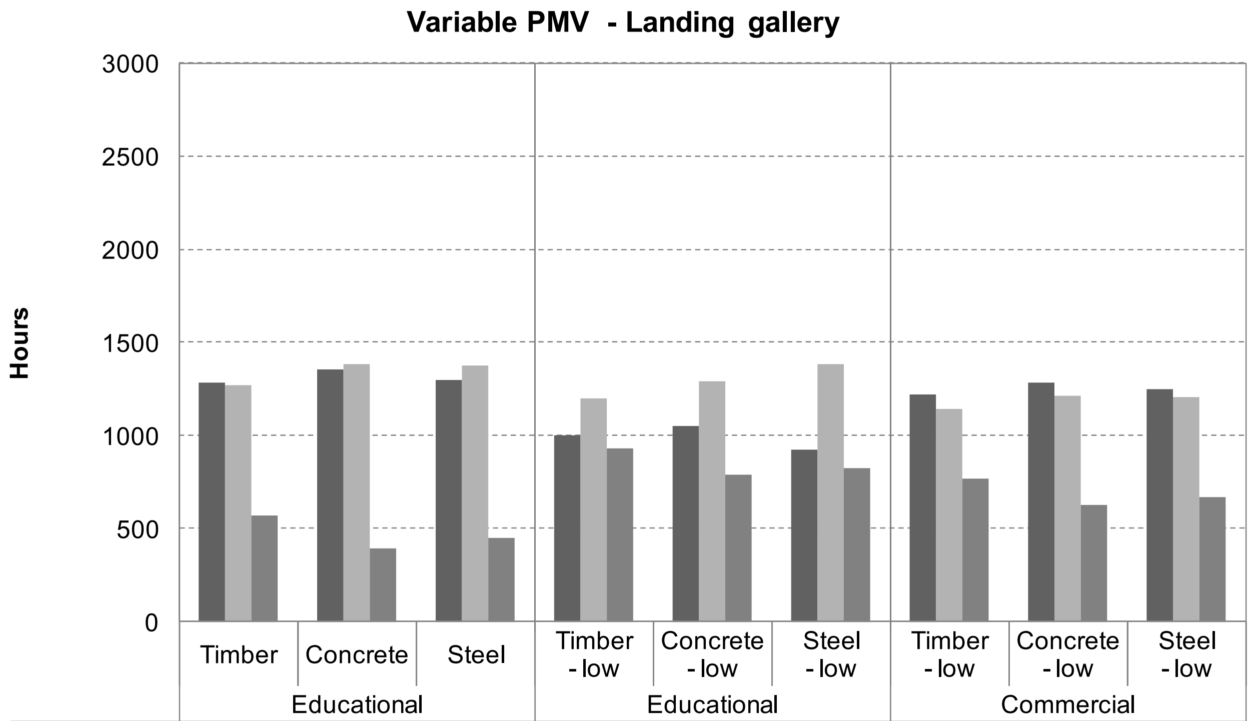
Table H-1: Comfort parameters for PMV calculations – Alternative to default values.

Comfort parameters in winter conditions

Clothing levels:	1	clo	Male / Office / Medium	From 1/JAN to 14/MAR
Activity Levels	69.8	W/m^2	Sedentary work, standing	From 15/OCT to 31/DEC

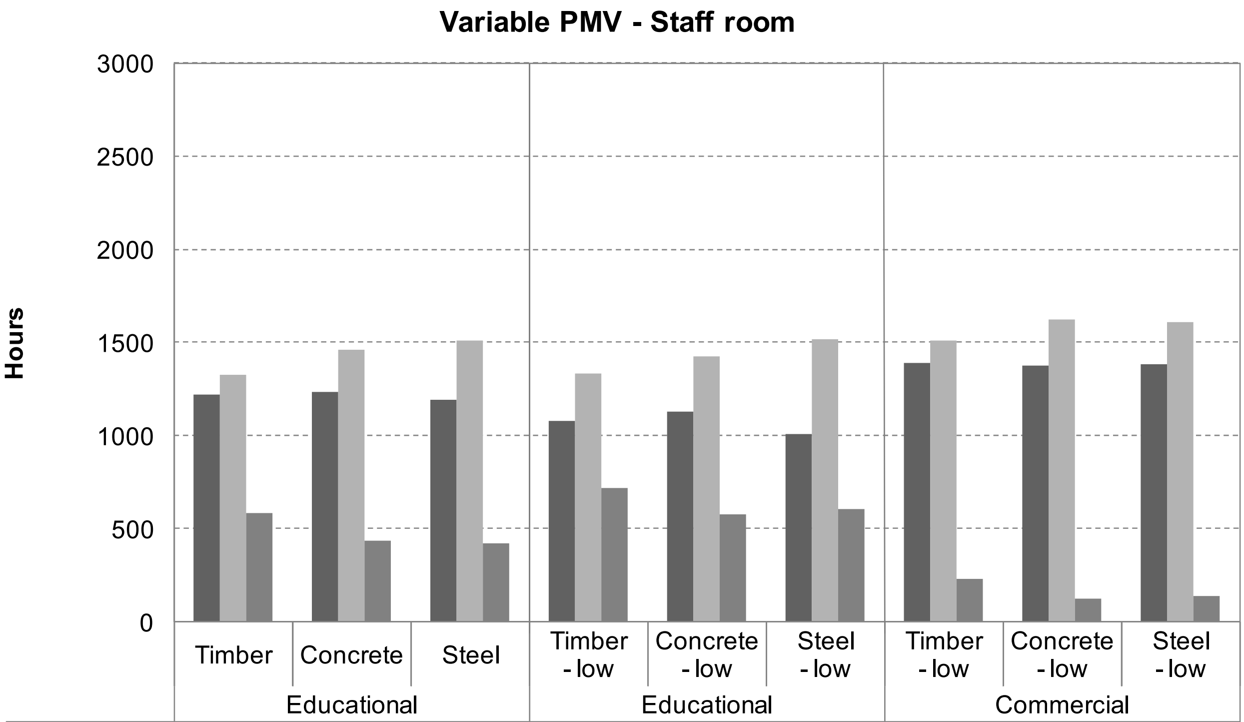
Comfort parameters in summer conditions

Clothing levels:	0.2	clo	Sportwear	From 15/MAR to 14/OCT
Activity Levels	69.8	W/m^2	Sedentary work, standing	



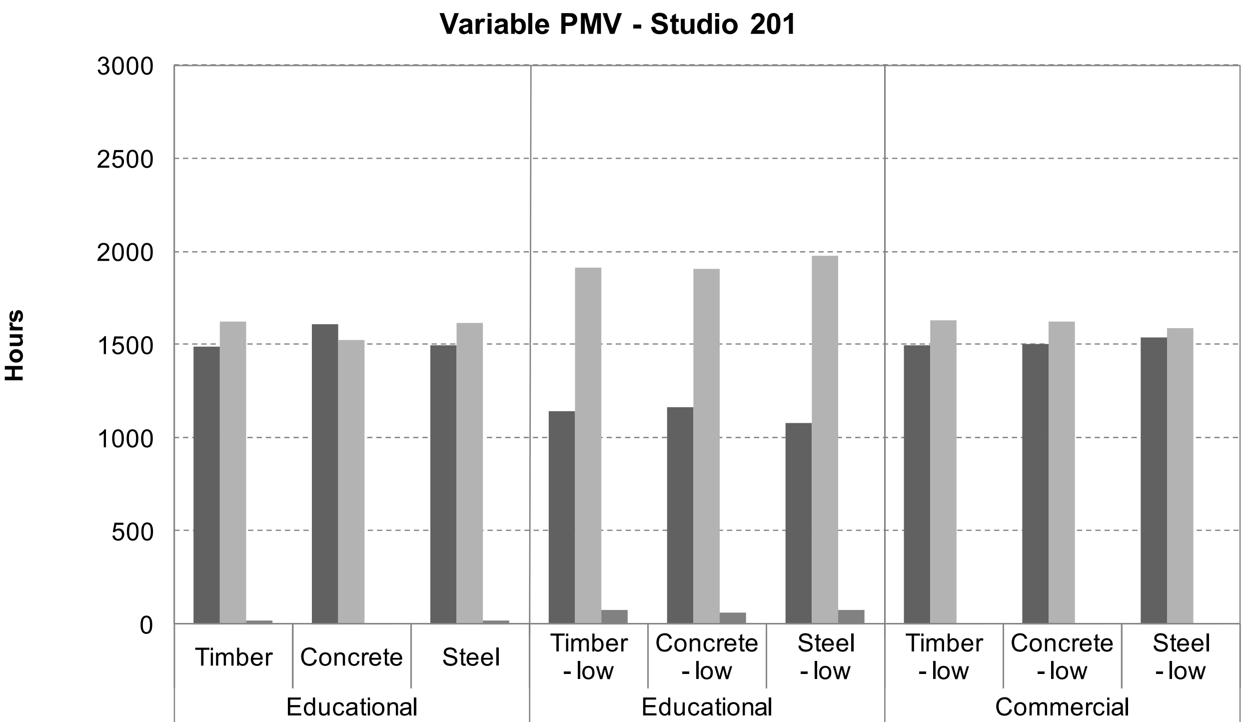
	Educational			Educational			Commercial		
	Timber	Concrete	Steel	Timber - low	Concrete - low	Steel - low	Timber - low	Concrete - low	Steel - low
< -0.50	1287	1358	1302	1000	1049	921	1221	1285	1251
-0.50 to 0.50	1273	1380	1378	1201	1292	1381	1144	1216	1207
> 0.50	571	392	451	929	790	828	766	630	673

Figure H-1: Variable PMV analysis of Landing-Gallery space on level 2, north facing.



	Timber (Educational)	Concrete (Educational)	Steel (Educational)	Timber - low (Educational)	Concrete - low (Educational)	Steel - low (Educational)	Timber - low (Commercial)	Concrete - low (Commercial)	Steel - low (Commercial)
< -0.50	1218	1235	1195	1076	1128	1011	1388	1379	1383
-0.50 to 0.50	1327	1458	1510	1337	1428	1516	1508	1624	1608
> 0.50	586	438	425	718	575	603	234	128	139

Figure H-2: PMV of Staff room on level 2, north facing.



	Timber (Educational)	Concrete (Educational)	Steel (Educational)	Timber - low (Educational)	Concrete - low (Educational)	Steel - low (Educational)	Timber - low (Commercial)	Concrete - low (Commercial)	Steel - low (Commercial)
< -0.50	1489	1607	1497	1146	1161	1078	1494	1506	1540
-0.50 to 0.50	1621	1522	1615	1912	1910	1977	1632	1622	1585
> 0.50	21	2	19	73	60	76	5	3	5

Figure H-3: PMV of Studio 201 on level 2, south facing.

I. PCM analysis

Table I-1: Materials used in the analysis done in PCM-Express software.

	Thickness (m)	Conductivity (W/(m*K))	Density Kg/m^3	Specific Heat Capacity KJ/(kg*K)
1 Suspended floor construccion				
1.1 Arts_Suspended floor slab (Potius)				
Cork linoleoum (THAM)	0.003	0.08	700	1.6
DIN EN 12524 Reinforced concr.	0.075	2.50	2400	1.0
DIN EN 12524 Timber materials Plywoo	0.095	0.10	500	1.5
2 Roof construccions				
2.1 Roof sloping roof (SmartBoard 23)				
Micronal PCM SmartBoard 23	0.015	0.20	770.0	Depending on temp.
Glass Wool (THAM)	0.190	0.04	30.0	1.0
DIN EN 12524 Timber materials Plywoo	0.012	0.10	500	1.5
Air Layer (THAM)	0.055	0.05	1.0	1.0
Roof tile (THAM)	0.010	0.75	1500.0	0.9
2.2 Roof sloping roof (GIB)				
DIN EN 12524 Plasterboard panels 900	0.015	0.25	900.0	1.0
Glass Wool (THAM)	0.190	0.04	30.0	1.0
DIN EN 12524 Timber materials Plywoo	0.012	0.10	500	1.5
Air Layer (THAM*)	0.055	0.05	1.0	1.0
Roof tile (THAM*)	0.010	0.75	1500.0	0.9
3 Internal partitions				
3.1 Internal wall (GIB)				
DIN EN 12524 Plasterboard panels 900	0.015	0.25	900.0	1.0
Glass Wool (THAM*)	0.100	0.04	30.0	1.0
DIN EN 12524 Plasterboard panels 900	0.015	0.25	900.0	1.0
3.2 Internal wall (SmartBoard 23)				
Micronal PCM SmartBoard 23	0.015	0.20	770.0	Depending on temp.
Glass Wool (THAM*)	0.100	0.04	30.0	1.0
Micronal PCM SmartBoard 23	0.015	0.20	770.0	Depending on temp.

Table I-2: Materials used in the analysis done in PCM-Express software.

	Thickness (m)	Conductivity (W/(m*K))	Density Kg/m^3	Specific Heat Capacity KJ/(kg*K)
3 External walls				
3.1 External wall (GIB)				
DIN EN 12524 Plasterboard panels 900	0.015	0.25	900.0	1.0
Glass Wool (THAM*)	0.170	0.04	30.0	1.0
OSB (THAM*)	0.015	0.13	630.0	1.5
Mineral rendering (THAM*)	0.020	0.80	1900.0	0.9
3.2 External wall (SmartBoard 23)				
Micronal PCM SmartBoard 23	0.015	0.20	770.0	Depending on temp.
Glass Wool (THAM*)	0.170	0.04	30.0	1.0
OSB (THAM*)	0.015	0.13	630.0	1.5
Mineral rendering (THAM*)	0.020	0.80	1900.0	0.9

*THAM: Transient heat and moisture value

J. Report from PCM-Express

Project data

Object location: Milano, Italy
Climate data (basis of simulation): Milano
The results are based on a comparison between a PCM system and a conventional system (without PCM).

Building services

	PCM system	Conventional system
Ventilation		
Natural ventilation with windows:	existent	existent
Mechanical ventilation:	existent	existent
Summer night ventilation:	existent	existent
Heat recovery:	nonexistent	nonexistent
Earth heat transferrer:	nonexistent	nonexistent
Heating Technology		
Night reduction:	existent	existent
Desired Temperature:	20 °C	20 °C
Heating period:	1.9 - 31.5	1.9 - 31.5
Radiator output:	54 W/m²	54 W/m²
Panel heating:	nonexistent	nonexistent
Ventilation system heating register:	nonexistent	nonexistent

Building services

	PCM system	Conventional system
Refrigeration Technology		
Refrigeration Technology:	existent	existent
Desired Temperature:	24 °C	24 °C
Info on target temperature:	absolute	absolute
Cold source:	Compression cold	Compression cold
Maximum cooling output:	13 kW	13 kW
Panel cooling:	nonexistent	nonexistent
Ventilation system cooling register:	existent	existent

Room parameters

Room composite 1	
Frequency of composite:	1
Room 1	
Length:	30 m
Width:	7.6 m
Height:	4 m
Alignment wall 1:	South
Furniture:	nonexistent
Profile - inner loads:	Office, IL, day 100% night 7.6%, weekend 7.6%
Inner loads:	11 W/m²
Profile - mech. ventilation:	HVAC office
Mechanical ventilation:	0.8 1/h
Floor	
Construction:	Arts_Suspended floor slab (Potius)
Installation situation:	to room of same temp.
Wall 1	
Construction:	Arts_External wall lightweight (Giboard)
Installation situation:	to outside air
Window:	existent
Window area:	90 %
Shading factor:	0
Window type:	NZ PVC/Wooden Frame IGU - R0.5
Wall 2	
Construction of conventional system:	Arts_External wall lightweight (Giboard)
Construction of PCM system:	Arts_External wall lightweight (Smart Board 23)
Installation situation:	to outside air
Window:	existent
Window area:	15 %
Shading factor:	0
Window type:	NZ PVC/Wooden Frame IGU - R0.5
Wall 3	
Construction of conventional system:	Arts_Internal wall, dry lining (Giboard)
Construction of PCM system:	Arts_Internal wall, dry lining (SmartBoard 23)
Installation situation:	to room of same temp.

Room parameters

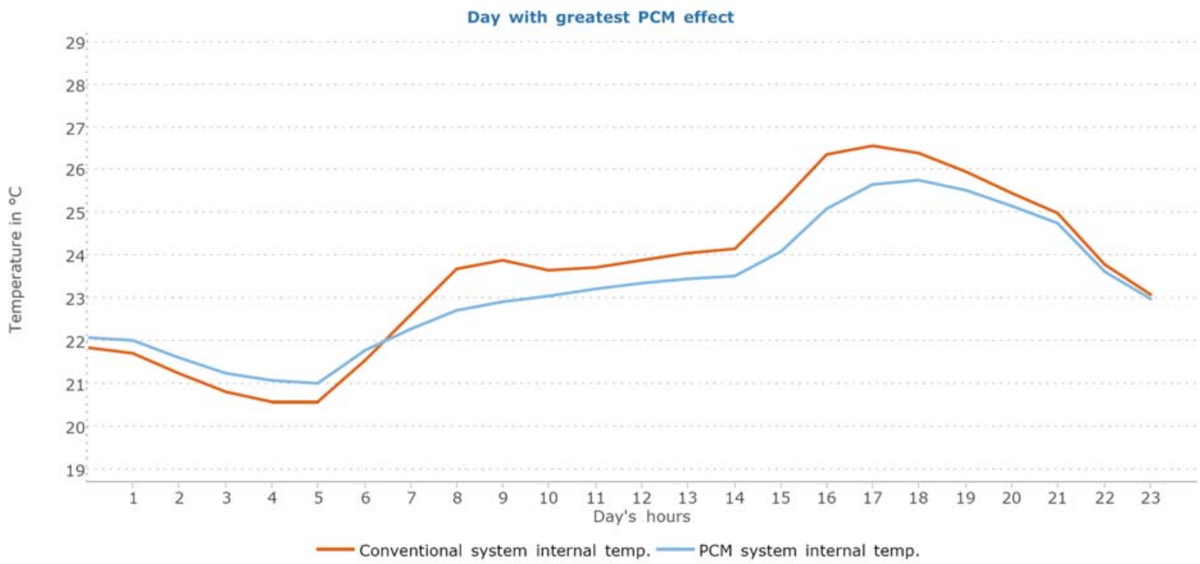
Wall 4

Construction of conventional system:	Arts_External wall lightweight (Giboard)
Construction of PCM system:	Arts_External wall lightweight (Smart Board 23)
Installation situation:	to outside air
Window:	existent
Window area:	15 %
Shading factor:	0
Window type:	NZ PVC/Wooden Frame IGU - R0.5

Ceiling

Construction:	Arts_Suspended floor slab (Potius)
Installation situation:	to room of same temp.

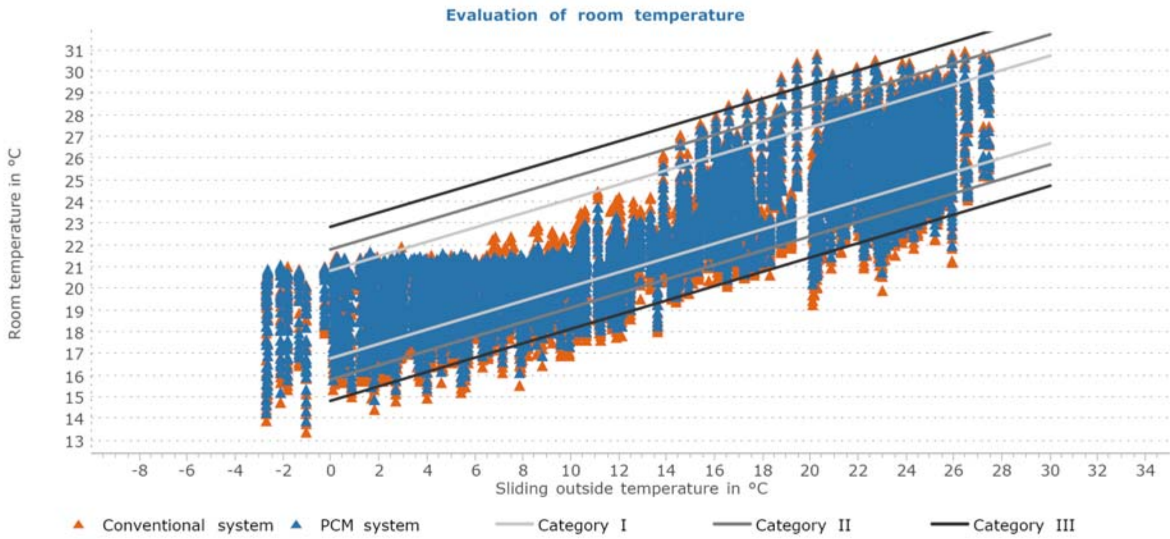
Simulation results

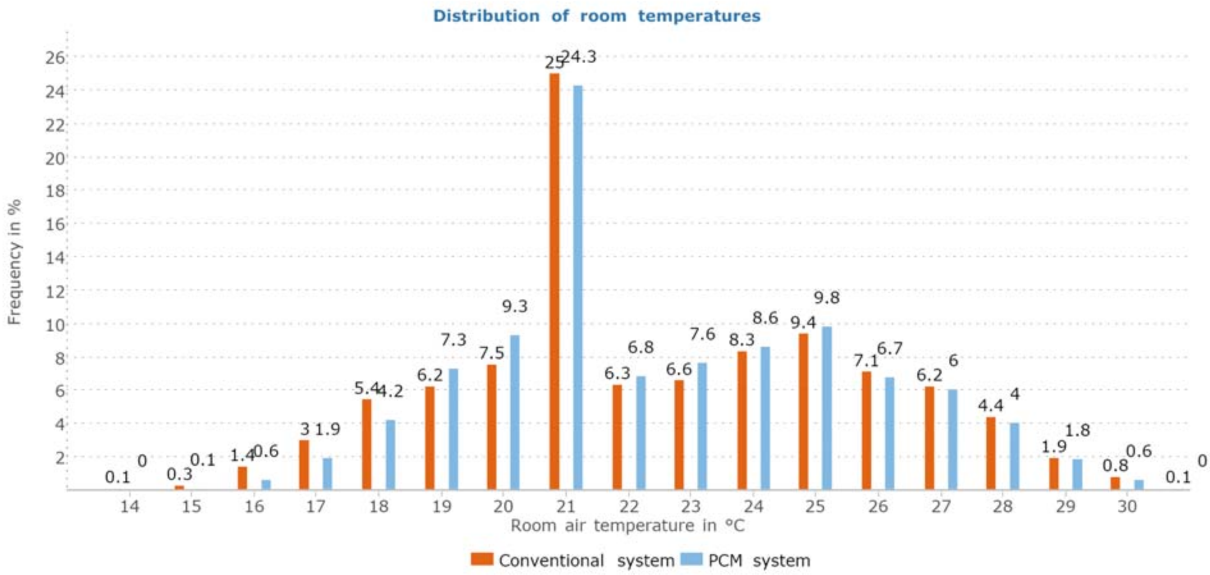


The results were determined by a mathematical model calculation. The actual yields for the room simulation may differ, because of fluctuations in the weather, thermal exchanges in the room and other factors. The results are no substitute for specialist planning.

Simulation results

Room composite 1 - Room 1





K. Simplistic model of heating required for Arts building during August 2011

Envelope component	Gross area	Glazing	Unglazed	R-value	A/R	
N. wall	391	192	199	2.8	71.1	
E. wall	272	54	218	2.8	77.9	
S. wall	475	323	152	2.8	54.3	
W. wall	381	74	307	2.8	109.6	
N. glazing		192		0.3	640.0	
E. glazing		54		0.3	180.0	
S. glazing		323		0.3	1076.7	
W. glazing		74		0.3	246.7	
Roof	629			5.1	123.3	
Floor (gound floor)	676			3.4	198.8	
				Total	**2778**	W/K

T_indoor	22	°C			
T_outdoor	12	°C	Delta_T	**10**	K
			=> Avg envelope losses	**27.8**	kW
			Seconds in month	1116000	s
			Energy req'd	**31006**	MJ/month
			Per day	1000	MJ/day

Ventilation:

Flow rate	2.0	cu.m/s			
Density	1.24	kg/cu.m			
Mass flow	2.48	kg/s			
Cp	1.0	kJ/kg-K	Power	**24.8**	kW
Hours per day	10				
			Occupied seconds in month	936000	s
			Energy recovery efficiency	65	%
			Energy req'd	**8124**	MJ/month

Air leakage	0.25	AC/h			
Volume	4836	cu.m			
Flow rate	0.34	cu.m/s			
Mass flow	0.42	kg/s	Power	**4.16**	kW
			Unoccupied seconds in month	180000	s
			Energy req'd	**750**	MJ/month
			Total energy required	**39880**	MJ/month
			Per day	1286	MJ/day
Total Groos floor area:	2028			5.5	kWh/m²/month