THE INFLUENCE OF THERMAL MASS ON THE SPACE CONDITIONING ENERGY AND INDOOR COMFORT CONDITIONS OF BUILDINGS

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ABSTRACT

This paper describes a modelling comparison between three very similar medium sized educational buildings located in the temperate climate of Nelson, New Zealand, each designed using structural systems made primarily of timber (actually built), concrete or steel (both hypothetical).

The buildings were analysed using two different insulation values in the thermal envelope, one sufficient to comply with the New Zealand Building Code and another with "best practice" insulation levels. The thermal mass in the structural material was added to each room in the model as a stand-alone internal wall.

The HVAC system in the buildings includes hydronic heating, mechanical ventilation with heat recovery, and cooling in a computer room only. HVAC energy consumption, and indoor comfort conditions using Predicted Mean Vote (PMV) are assessed.

INTRODUCTION

Several researchers have found that the energy used to operate buildings is by far the largest component of life-cycle energy use - much bigger than the embodied energy (Cole and Kernan 1996; Voss, et al. 2007; Loehnert, et al. 2008; Perez 2008; Perez, et al. 2008).

Earlier research in New Zealand (John, et al. 2008; Perez, et al. 2008) studied the life-cycle energy consumption and CO_2 emissions of three similar six-storey commercial buildings with the structure primarily of concrete, steel or wood, each designed, for low operational energy consumption of about 84 to 88 kWh/m^2/yr. The results showed that timber buildings had lower initial and maintenance embodied energy, but had larger operational energy consumption than the concrete and steel buildings. Subsequently, timber buildings have a larger life-cycle-energy consumption than concrete buildings.

In (Perez, et al. 2008) it was suggested that differences between annual operational energy consumption of the concrete and timber buildings were consistent with differences in quantities of thermal mass exposed to indoor spaces in each building type, and the structural components acting as thermal bridges in the envelope walls.

This paper presents new research on the influence that thermal mass has on indoor environmental conditions and subsequently on HVAC performance when different structural systems with different quantities of thermal mass are used in buildings.

Most buildings have their major sources of thermal mass in primary structural elements. Most of these primary structural elements are hidden or embedded in floors, walls or ceilings. If exposed to indoor spaces, primary structural elements such as columns or beams are not an optimized source of thermal mass. Thermal mass does make a difference, in terms of influencing the indoor thermal conditions, when its surface is exposed to habitable spaces, most effectively as ceilings but normally as floors (Braham et al. 2001).

In buildings which are designed to allow the thermal mass to influence the indoor thermal conditions, thermal mass is normally added in the form of oversized concrete structural elements (Paevere et al. 2008). There are large environmental benefits in keeping structural systems light-weight, mostly in terms of embodied energy but, in common design practice, buildings which introduce thermal mass into their HVAC design strategy almost always add large volumes of concrete. When deciding how much concrete to include in a "Low Energy" building, a life-cycle perspective needs to be taken.

This research modelled the performance of three similar medium sized educational buildings, located in the temperate climate of New Zealand, each designed using primarily concrete, steel or wood. By including in the modelling the thermal mass in the structural material and finishing, this research aims to identify how thermal mass influences the performance of HVAC systems and to see the real impact of thermal mass on operational energy use.

SCOPE AND METHODOLOGY

The research is based in a modelling comparison of operational energy use with an emphasis on HVAC energy consumption, and the assessment of indoor comfort conditions using Predicted Mean Vote (PMV) of three medium size educational building, each designed using structural systems made of timber, concrete and steel (the buildings being designated as Timber, Steel and Concrete for labelling purposes). The Concrete and Steel buildings have been designed (but not built) to replicate the Timber building which is an actual three-storey educational building (1980 m^2 gross floor area) with a timber structure and timber-concrete composite floors.

The operational energy use and the indoor comfort conditions were modelled using Virtual Environment (Integrated Environmental Solutions (IES) Ltd 2010). The HVAC system in the actual building includes radiant heating systems, mechanical supply and extraction of air, and a heat recovery unit in the mechanical ventilation system. Only one computer room has mechanical cooling. All three buildings were modelled using the same HVAC system, operating only between 8am and 6pm six days per week (the buildings are unoccupied on Sundays). Two groups of simulations were produced to assess the influence of thermal mass. The first was a base scenario where the insulation level of the envelope, roof, and windows, was sufficient to comply with the New Zealand Building Code. In the second scenario, insulation values were significantly increased to a level of "best practice", to reduce the impact of heat losses on the comparison. (This second set of modelled buildings are labelled as TimberLow, SteelLow and ConcreteLow.)

In this exercise, the operational energy assessment 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 material in all the structural components exposed to indoor spaces was quantified for each space in each of the three case study buildings. The thermal mass in the structural material was then added to each room in the model, as a stand-alone internal wall, in order to include the effect of this thermal mass in the modelling. The additional materials in the structural components were shown to significantly increase the amount of thermal mass available in the Concrete building and in the Timber building, but made very little difference to the Steel building.

CASE STUDY DESCRIPTION

The Concrete and Steel buildings are hypothetical designs of alternatives to an actual three storey Timber building. The actual Timber building was built 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.

Actual Timber building construction

The Timber building has been built using a state-of-the-art timber structural system made primarily of Laminated Veneer Lumber (LVL). Primary structural columns and beams are connected using fixed screwed connections, with post-tensioned LVL shear walls used for wind and earthquake resistance. The floor system includes a 75mm concrete topping over an LVL board horizontally placed as permanent formwork and supported on LVL joists. The envelope is mostly light-weight insulated walls although the thick structural shear walls made of LVL are embedded in portions of the East and West facades. There is a glass curtain wall on most of the North façade, and a large window area on the South façade. All external windows are double glazed in aluminium frames without thermal breaks.

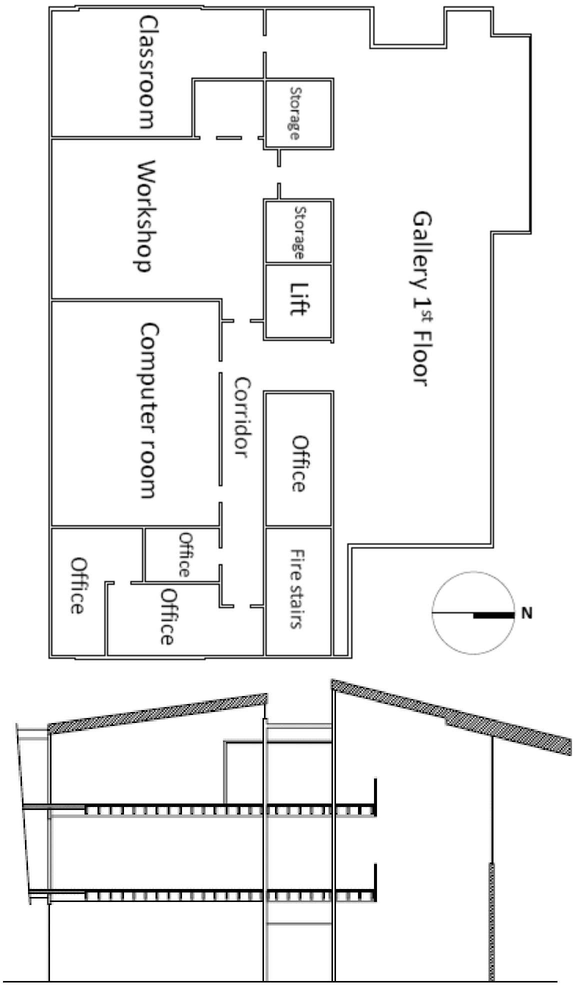


Figure 1: Plan of level 1 and cross section of the Arts and Media building

Figure 1 shows the first floor plan of the Timber building. This floor plan is the same for all three buildings. 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 building through a full height gallery. The gallery is three storeys tall and combines a series of enclosed rooms and open circulation spaces orientated and exposed to the gallery void. The gallery is flanked by a narrow structural core containing narrow service space and linkages between the gallery and flexible multi-use seminar and studio spaces exposed to the South wall.

The height for each floor is 4.35 m, 4.0 m, and average 4.7 m in Level 1, Level 2, and Level 3 respectively. The percentage of the external wall which is glazed by façade is 50% in the North facade, 65% in the South facade, and approximately 20% in the East and West façades. Total percentage of areas of glass in the envelope wall is 42%.

Construction of the Timber, Concrete, and Steel buildings

The architectural design of Timber building was by Nelson based Architectural consultant (Irving, Smith Jack Architects Ltd), and the structural design was by the local branch office of a global engineering consultant (Aurecon). For the design of the alternative Concrete and Steel buildings the same architects and structural engineers were engaged to develop the architectural and structural designs.

Most of the changes in Concrete and Steel buildings compared to the actual Timber building were in the replacement of the structural system. No changes were made to most of the external and internal walls, the windows, suspended ceilings, heated slab, and slab-on-ground.

The main source of thermal mass is located in the structure with each structural system having three major components providing thermal mass to the whole building, namely: shear walls; suspended floor; and; to a lesser degree, columns and beams.

Each of these three structural elements is characterized thermally by its resistance R and capacitance C. For materials with thermal conductivity of k, specific heat c_p, density ρ, and thickness L, these were calculated according to the formulae:

$R = L/k$ [unit = m^2K/W]

$C = \rho c_p L$ [unit = $KJ/m^2.K$]

External and internal shear walls

Shear walls are part of the seismic design of the timber structural system of the Timber building and they were re-designed in concrete and steel for the structural design of the Concrete and the Steel buildings respectively.

The shear walls are embedded in the external East and West walls, and in internal walls (the shaft enclosing the fire stair). For the purpose of this research, the LVL and the concrete 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. The volume of LVL in the timber shear wall is 0.19 m^3/m^2 and the volume of concrete in the concrete shear wall is 0.2 m^3/m^2, meaning that they are both nominally 200 mm thick.

Structural suspended floors

The Timber building has a prefabricated stressed skin "Potius" composite floor system made of long span vertically oriented LVL joists supporting an horizontally oriented LVL board that acts as a permanent formwork and a structural top flange working in composite action with a cast in-situ mesh-reinforced concrete topping. In this Potius floor system, the volume of concrete is 0.08 m^3/m^2 and the volume of LVL is 0.10 m^3/m^2 (joists included).

In the Concrete building the floor system used is a proprietary Interspan® flooring system consisting of 200 mm 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. In the Interspan floor 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 is a proprietary 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 than both the Potius and the Interspan systems; the volume of steel is only 0.001 m^3/m^2.

Columns, beams and rafters – Stand-alone walls

There was an intentional architectural design decision in the actual Timber building of leaving structural elements exposed to the habitable spaces. When re-designing the Concrete and the Steel buildings, the same architectural design concept was applied.

For each habitable and conditioned space in the timber and concrete buildings, the volume of exposed LVL and concrete respectively from structural columns, beams, and rafters was calculated. In the same way as for structural shear walls, only the LVL and concrete used in structural columns, beams, and rafters were considered to have significant thermal mass.

It can be seen in Table 1 that although the thicknesses of the LVL shear wall (189 mm) and the concrete shear wall (200 mm) are similar, due to higher density and specific heat capacity of concrete, the concrete shear wall has a significantly higher C value. Suspended structural floor systems have a large C value mostly because of the concrete in the systems. The Steel building has the biggest C value in the suspended floors systems followed by the timber and the concrete building respectively. "Stand-alone walls" refers to specifically created walls that were inserted in the model to represent the volume of materials in columns and beams exposed to habitable spaces. In Table 1 a range of R and C values given for the thinnest and the thickest stand-alone LVL and concrete walls is presented.

Table 1: Timber and concrete buildings, structural material's R – C values

	Shear Walls				Suspended Floor		Stand-alone walls	
	External		Internal					
	∑R	∑C	∑R	∑C	∑R	∑C	∑R	∑C
Timber	2.7	172	1.5	169	0.8	249	0.5 - 6.2	54 - 717
Concrete	1.4	463	0.1	460	0.4	246	0.1 - 0.8	184 - 2760

Thermal envelope

Two different thermal envelopes were applied to each of the three buildings in this research; the first was a base scenario where the insulation level of the envelope, roof, and windows was sufficient to comply with the New Zealand Building Code. In the second scenario, insulation values were significantly increased to a level of "best practice", to reduce the impact of heat losses when looking at the influence of thermal mass provided by the structural systems.

Compared with the basic Timber, Concrete, and Steel buildings, the corresponding Low buildings (with the "best practice" thermal envelope) have no structural or major architectural modifications but the increment of insulation batts in the existing external walls and roof cavity, and the changing of all external windows from standard double gazing on aluminium frame to double glazing windows with Argon gas between glass panels, and thermally broken PVC frames.

Table 2: Thermal envelope variation between the code-compliant buildings type to the best practice buildings type

	External glazing		External Walls						Roof	
			External light Wall		Shear wall Concrete		Shear wall LVL			
	∑R	∑C	∑R	∑C	∑R	∑C	∑R	∑C	∑R	∑C
Code Compliant	0.3	15	2.8	21	1.4	463	2.7	173	5.1	56
Low Energy	0.5	15	4.6	21	2.9	463	4.2	173	9.4	56

Table 2 shows the variation of R and C values in external glazing, external walls, and roof of the code-compliant and low energy buildings in this research. There are no variations of thermal envelope between the Timber, Concrete, and Steel buildings. It can be seen that the increment of insulation only influences R values but adds no capacitance to the thermal envelope.

SIMULATION

Buildings thermal and energy simulations in this research were performed using Virtual Environment (VE), an interconnected set of building performance-modelling tools from Integrated Environmental Solutions (IES).

The actual Timber building is located in Nelson, in New Zealand's northern South Island. All comparisons were carried out using the Typical Meteorological Year weather file of Nelson. The Nelson-Marlborough region is the sunniest part of New Zealand, with warm, dry and settled weather predominant during summer, and usually mild overall winter days. 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 (NIWA National Institute of Water & Atmospheric Research 2011).

All six buildings were simulated as typical educational buildings using schedules for simulations based on NZS 4243 for general occupancy, plug loads, and HVAC operation (Standards New Zealand 2007). Educational buildings in New Zealand are not expected to operate during most of the summer period, so cooling is normally not required for most of the teaching facilities and offices. Cooling is only made available in computer laboratories because of large internal gains. Heating only operates 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.

HVAC system

A great level of detail was used to carefully model the HVAC system of the actual Arts and Media building using the Apache HVAC tool from VE, to examine in detail the expected performance of the HVAC system when this was coupled together with a building model created using the VE building modeller ModelIT. In this research, one single Apache HVAC file is coupled to six different models created in ModelIT. Models in ModelIT are the Timber, Concrete, and Steel buildings with a code-compliant, and a low energy ("best practice") thermal envelope each.

The HVAC system in the actual Timber building includes mechanical ventilation provided by a centralized Air Handling Unit (AHU) combining supply (2000 lt/sec) and return of air (2000 lt/sec). 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 works in winter conditions recovering heat from warm return air to preheat incoming fresh air.

Heating in Level 1 is provided mostly by a hydronic heated slab (total capacity is 26 kW). Heating in Levels 2 and 3 is provided by hot water radiators (total heating capacity in Level 2 is 44 kW and in Level 3 43 kW). There is a fan coil 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. A computer room of 85 m^2 located in Level 1 is the only room with cooling.

Hot water is sourced from a Diesel boiler with a capacity to deliver up to 200 kW at 80% efficiency; no water distribution losses in the system were allowed for. Electric water pumps were included to distribute hot water from the main boiler to the heated slab in Level 1 and radiators in Levels 2 and 3. Cooling is sourced from an electric air-cooled chiller with a cooling capacity of 12 kW and a motor power of 5 kW, no distribution losses were accounted for in the system.

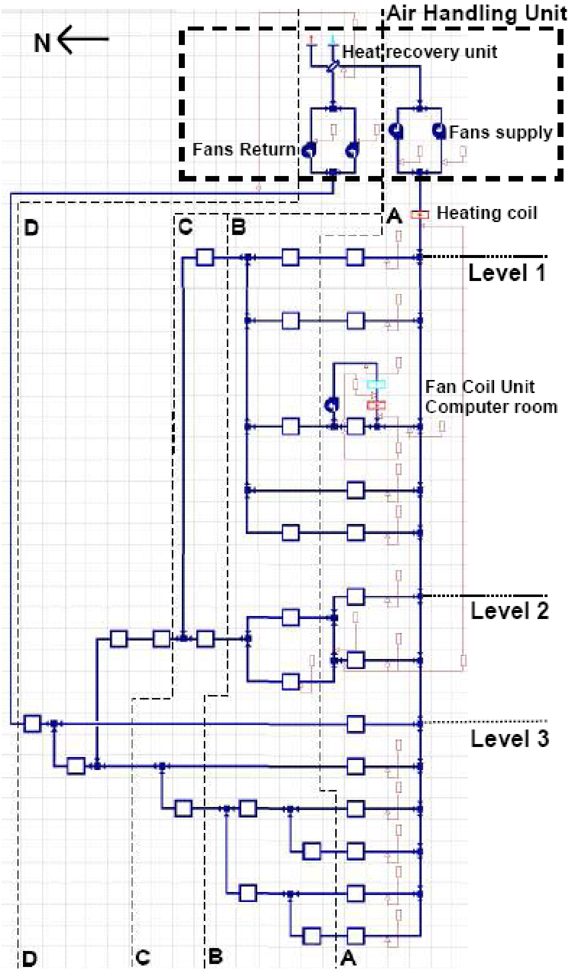


Figure 2: Schematic of the Mechanical ventilation system with heat recovery unit and underfloor heating network in Virtual Environment's Apache HVAC tool.

Figure 2 shows the schematic of the HVAC system in the actual Arts and Media building, created in the VE Apache HVAC tool. It can be seen that the AHU supplies air through a network integrated mainly by rooms and air connectors. Supply fans directly supply air to rooms in the south façade of Level 1, Level 2, and Level 3 respectively. Each individual level is subdivided into segments representing the flow of air through each floor from air supply via 'Segment A' through 'Segments B', and 'Segment C', to final air return via 'Segment D'.

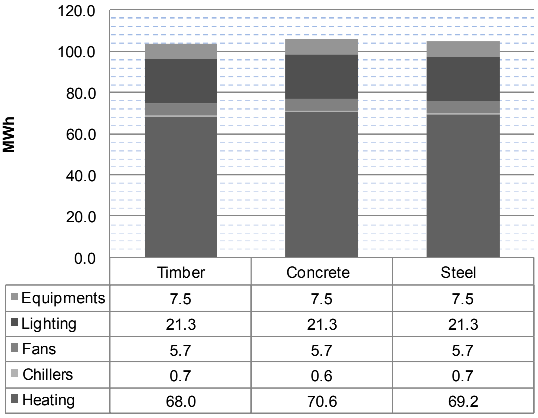
Internal gains and infiltration

Internal gains associated with equipment were included in the computer room and in all office spaces. Total occupancy is approximately 170 people. Occupant internal gains are either latent or sensible: sensible gains are assumed to be 56 % and latent gains 46 % of the occupant space gain component. A specific illuminance value (lux) per square meter of floor area was assigned to each room; illuminace values were set in accordance with NZS 4243: Part 2: Lighting (Standards New Zealand 2007). The installed power density is 3.8 W/m2/ (100 lux) and this is used to calculate the total sensible gains.

Infiltration is set to be 0.25 air changes per hour (ac/hr) in all rooms located adjacent to the building thermal envelope, and is 0 ac/hr in fully internal rooms (Standards New Zealand 2006).

DISCUSSION OF RESULTS:

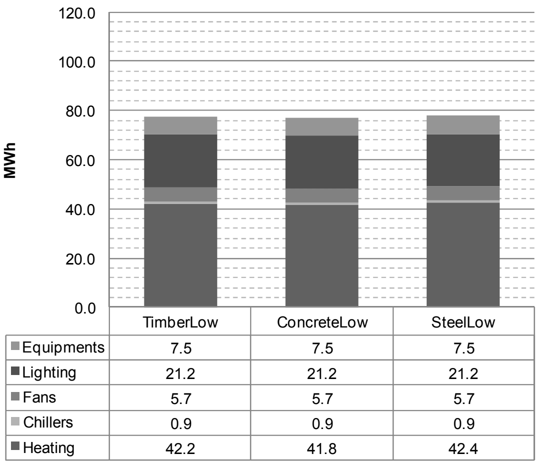
Results assessment of building's operational energy performance



	Timber	Concrete	Steel
■ Equipments	7.5	7.5	7.5
■ Lighting	21.3	21.3	21.3
■ Fans	5.7	5.7	5.7
■ Chillers	0.7	0.6	0.7
■ Heating	68.0	70.6	69.2

Figure 3: Total energy consumption (MWh) broken down into end-use energy consumption for the Timber, Concrete, and Steel buildings.

Figure 3 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.



	TimberLow	ConcreteLow	SteelLow
■ Equipments	7.5	7.5	7.5
■ Lighting	21.2	21.2	21.2
■ Fans	5.7	5.7	5.7
■ Chillers	0.9	0.9	0.9
■ Heating	42.2	41.8	42.4

Figure 4: Total energy consumption broken down into end-use energy consumption for the TimberLow, ConcreteLow, and SteelLow buildings.

Figure 4 shows the annual operational energy consumption, broken down into energy end-uses, of the timberLow, concreteLow, and steelLow buildings ("best practice" thermal envelope). Differences between total energy consumption between the TimberLow, ConcreteLow, and SteelLow builldings are not significant. The ConcreteLow building total energy consumption is 1% lower than the total energy consumption of the TimberLow and the SteelLow building. Again, fans, lights, and equipment energy consumption is exactly the same in all three buildings. Chiller energy is also the same between the three buildings but there is a small difference in heating energy consumption. HVAC energy (heating, cooling and fan energy) represent about 63% of the total energy consumption; the remaining 37% corresponds to lighting and equipment electricity.

Assessment of building's thermal comfort conditions

ANSI/ASHRAE Standard 55-2004 defines Predicted Mean Vote (PMV) as: "An index that predicts the mean value of the votes of a large group of persons on the seven-point thermal sensation scale, being: cold, cool, slightly cool, neutral, slightly warm, warm, and hot" (American Society of Heating Refrigerating and Air-Conditioning Engineers Inc 2004).

Table 3 shows the comfort parameters for clothing levels, activity levels, and air speed. These parameters were taken by default from VE software.

Table 3: Comfort parameters used in the PMV calculations –Default values

Comfort parameters

Clothing levels:	0.61	clo	Trousers, long-sleeve shirt
Activity levels:	80	W/m^2	Office activity: Filing, Standing
Air speed:	0.1	m/s	

Assessment of PMV was carried out in only two rooms in the Arts and Media building (Figure 5). The two rooms are located in Level 2 of the building. Room 1 is an office room and is representative of a room exposed to the North. Room 2 is a large studio space and is representative of a room exposed to the South.

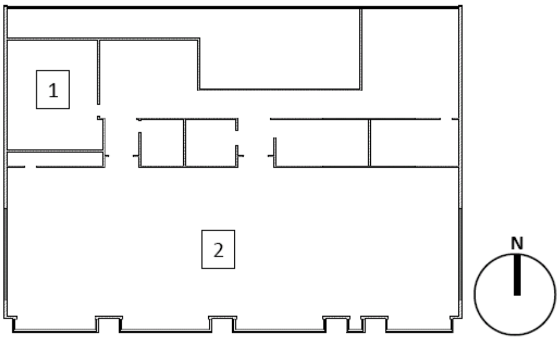
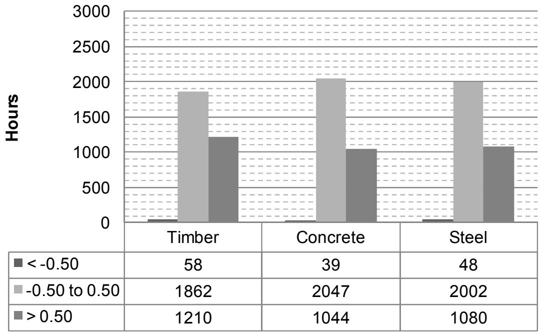


Figure 5: Plan section Level 2 of the Arts and Media building with the specified rooms were PMV has been assessed in this research.

The ANSI/ASHRAE Standard 55-2004 suggests an acceptable thermal environment for general comfort in the range of PMV from -0.5 PMV to +0.5 PMV (American Society of Heating Refrigerating and Air-Conditioning Engineers Inc 2004).

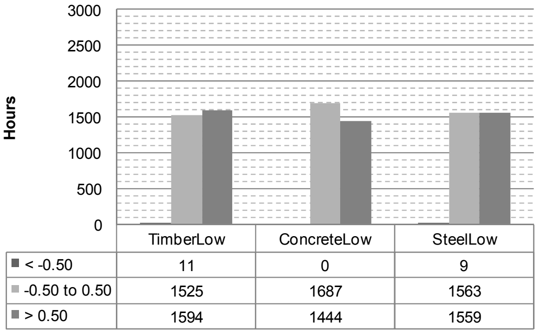
Results PMV



	Timber	Concrete	Steel
■ < -0.50	58	39	48
■ -0.50 to 0.50	1862	2047	2002
■ > 0.50	1210	1044	1080

Figure 6: PMV of office room in Level 2, North façade in the Timber, Concrete, and Steel buildings.

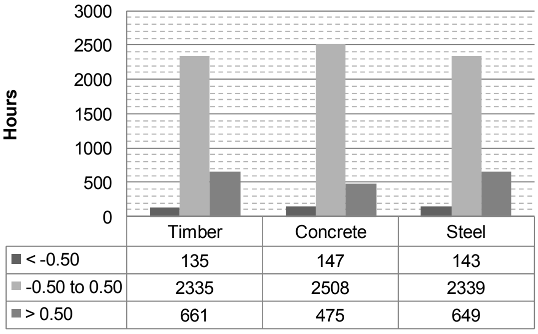
Figure 6 shows the results from the PMV modelling of the office room (Room 1) in the Timber, Concrete, and Steel, buildings. In Figure 6 the Concrete building has the longest period of time within comfortable environmental conditions, followed closely by the Steel building with an 2% fewer hours in the range of comfortable environmental conditions when compared with the Concrete building. The Timber is least comfortable with an equivalent 9% fewer hours in the range of comfortable environmental conditions than the Concrete building maintains.



	TimberLow	ConcreteLow	SteelLow
■ < -0.50	11	0	9
■ -0.50 to 0.50	1525	1687	1563
■ > 0.50	1594	1444	1559

Figure 7: PMV of office room in Level 2, North façade in the TimberLow, ConcreteLow, and SteelLow buildings.

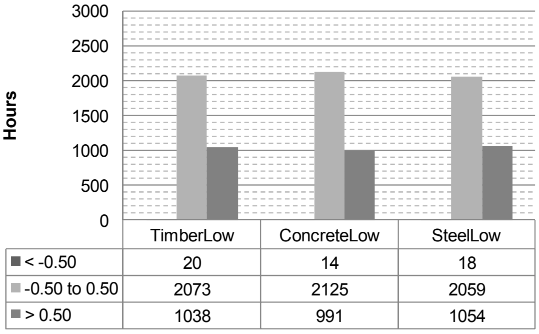
The equivalent PMV analyses for the same room in the “Low” versions of the three buildings is summarised in in Figure 7. Again it the concrete-based construction which has the longest period of time within comfortable environmental conditions, followed by the SteelLow building (7% fewer hours) and TimberLow (10% fewer hours).



	Timber	Concrete	Steel
■ < -0.50	135	147	143
■ -0.50 to 0.50	2335	2508	2339
■ > 0.50	661	475	649

Figure 8: PMV of Studio room in Level 2, South façade in the Timber, Concrete, and Steel buildings.

For the studio room (Room 2) the corresponding anaylses are presented in Figure 8 (for the basic versions of the three building structure types) and Figure 9 (for the “Low” versions of these same buildings). In Figure 8 it is yet again the Concrete building which exhibits the longest period of time within comfortable environmental conditions, with the Steel and the Timber buildings both achieving those same comfort conditions for 7% fewer hours.



	TimberLow	ConcreteLow	SteelLow
■ < -0.50	20	14	18
■ -0.50 to 0.50	2073	2125	2059
■ > 0.50	1038	991	1054

Figure 9: PMV of Studio room in Level 2, South façade in the TimberLow, ConcreteLow, and SteelLow buildings.

Finally, in Figure 9 the same ranking order (i.e. ConcreteLow has the longest period of time within comfortable environmental conditions, with the SteelLow and the TimberLow buildings both achieving about 3% fewer hours of equivalently comfortable conditions .

CONCLUSIONS

This paper describes a modelling comparison analysing HVAC energy consumption, and indoor comfort conditions in three very similar medium sized buildings, each designed using structural systems made primarily of timber, concrete or steel. The main conclusions are:

1. Regardless of whether the buildings are constructed mainly with concrete, steel or timber as the principal structural and non-structural materials, the influence of thermal mass has a relatively low impact on operational energy consumption for the weekly operating regime of the educational institution building of this study – at least in the temperate climate for which the modelling comparison was carried out.
2. Because, as shown in several previous studies, the operational energy is by far the largest component of 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.
3. 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.
4. 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.
5. There is, however, a significant increase in the number of hours of out-of-comfort-range conditions (e.g. from 1210+58 =1268 hours for Timber to 1594+11=1605 hours for TimberLow) if superior envelope insulation is adopted without any compensating increase in thermal mass to absorb temperature spikes during periods of relatively high solar gain.

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