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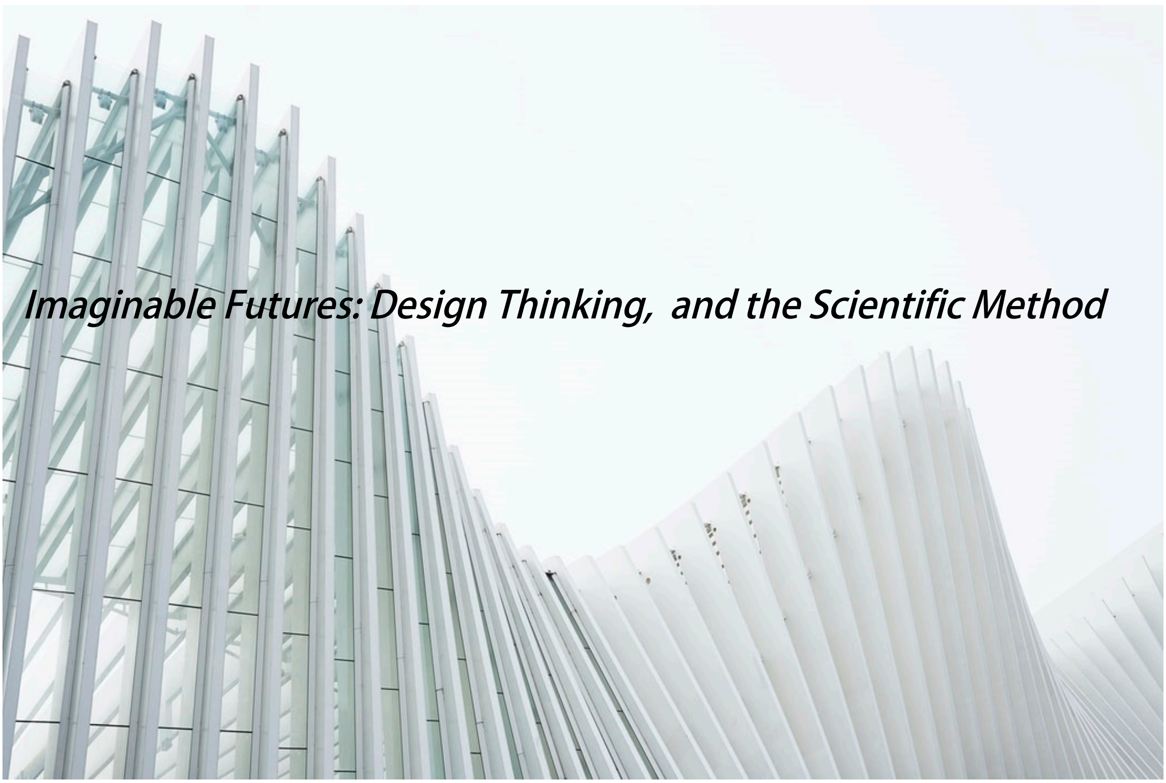

# *Imaginable Futures: Design Thinking, and the Scientific Method*


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# Thermal Performance of School Building not only Impact Indoor Thermal Comfort

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**Abstract:** Auckland has a temperate climate with comfortable warm, dry summers and mild, wet winters. Auckland school building thermal design not only focuses on winter indoor thermal comfort but also indoor health condition related to high relative humidity. A conventional Auckland school has a number of low-rise, isolated buildings with light weight envelopes. In over 90% of Auckland schools, each isolated building only has one to four classrooms. For these types of school buildings with a big ratio of building surface to volume, the thermal performance of building envelope becomes the most important design factor for indoor thermal and health conditions. Field study data of winter indoor microclimate of three classrooms with different insulation and thermal mass in their building envelopes are used for this study. The study not only compares and evaluates winter indoor thermal condition but also indoor health conditions of classrooms with different *R-value* and thermal mass in their envelopes. Increasing *R-value* without thermal mass in building envelope can increase winter indoor thermal conditions but cannot reduce fluctuations of indoor air temperature and relative humidity. Adding thermal mass in building envelope with similar *R-value* not only can improve indoor thermal condition but also improve indoor health conditions.

**Keywords:** Building thermal performance; indoor health condition; indoor thermal comfort; school building envelope.

## 1. Introduction

The World Health Organisation recommends a minimum indoor temperature of 18 °C; and 20–21 °C for more vulnerable occupants, such as older people and young children (WHO, 1987; WHO, 2009a;). Previous studies show that the minimum threshold of indoor temperature required for limiting respiratory infections is 16 °C: there is increased risk of respiratory infections when indoor temperatures are below 16 °C (Collins, 1986; Braubach, Jacobs, & Ormandy 2011). Indoor temperatures below 12 °C can cause short-term increases in blood pressure and blood viscosity, which may increase winter morbidity and mortality due to heart attacks and strokes. When elderly people are exposed to indoor temperatures of 9 °C or below for two or more hours, their deep body temperature can start decreasing (Lloyd, 1990; Hunt, 1997; Goodwin, 2000). Extreme low indoor temperature not only negatively impacts occupants' thermal comfort but also occupants' health conditions.

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Most of the factors that adversely affect health, such as bacteria, viruses, fungi, mites, etc., have increases associated with high indoor relative humidity. Maintaining indoor relative humidity between 40% and 60% can minimise the indirect health effects (Arundel, Sterling, Biggin, & Sterling, 1986). Maintaining indoor relative humidity below 50% can reduce indoor dust mites and their allergens, mite populations are almost eliminated in winter when indoor relative humidity is maintained within 40 to 50% (Arlian, Bernstein, & Gallagher, 1982; Korsgaard, 1982; Murray & Zuk, 1979). A range of 60–80% relative humidity provides ideal conditions for the reproduction of mites. Mites are hardy, surviving and multiplying best when relative humidity is 75-80% (Arundel, Sterling, Biggin, & Sterling, 1986). The indoor relative humidity required by dust mites to thrive is 75–80% or higher (Arlian Bernstein, & Gallagher, 1982; Arlian, Rapp, & Ahmed, 1990; Arlian, Neal, & Vyszenski-Moher, 1999; Arlian, Yella, & Morgan, 2010; Hart, 1998). According to international and national standards, indoor relative humidity should be lower than 60% for optimum indoor air quality (ASHRAE, 1993a; SNZ, 1990; DBH, 2001). The threshold of indoor relative humidity for mould survival and growth conditions is 60%. Mould growth is likely on almost any building material if equilibrium relative humidity of the material exceeds 75–80% (Coppock, 1951; Block, 1993; Pasanen et al., 1992). Mould germination requires not only high relative humidity (80%) but also time (30 days) (Hens, 2000). One option to prevent mould growth on indoor surfaces is to control the indoor relative humidity to a level below the threshold (80%) of mould germination (Su, 2006; ASHRAE, 1993b). New Zealand has some of the highest levels of indoor dust mite allergens in the world (Siebers, Wickens, and Crane 2006). Visible mould growth on indoor surfaces is a common problem in over 30% of New Zealand houses (Howden-Chapman *et al.* 2005). Previous study shows that indoor mean relative humidity adjacent to the floor must be maintained below 70% and indoor relative humidity adjacent to the floor must be maintained below 75% for 20 hours a day during winter and below 80% all the time in winter to control indoor dust-mite allergens at an acceptable level. If durst-mite allergen in the carpet can be maintained at an acceptable level, relative humidity adjacent to the floor can be controlled below the threshold for dust mites to thrive (75%) for 20 hours a day during the winter, the house is unlikely to have a mould problem in the local climate with mild and wet winters (Su and Wu, 2019).

According to the New Zealand Ministry of Education, in New Zealand there are 14637 school buildings built from pre-1940s to 1990s (see Figure 1). There could be a significant number of New Zealand school classrooms without sufficient insulation in their envelopes and with single glazing windows. Auckland has a temperate climate, with comfortable warm, dry summers and mild, wet winters. High relative humidity during the Auckland winter is a major issue for building indoor health conditions. An Auckland school building normally does not need air condition for cooling during the summer (window ventilation and ceiling fan) only need space heating during the winter. School building thermal design should more focus on winter thermal performance and indoor health conditions. There are about 425 schools built in Auckland before 2010. An Auckland school commonly includes a number of low-rise isolated buildings with a timber structure and lightweight envelopes spread over a large site. Most Auckland schools have a number of low-rise isolated buildings with one to four classrooms in rows. Most classrooms have a big external surface area which includes two sides or three sides of external walls and roof surface areas. For this type of school buildings, the building envelope becomes the most important building element for building thermal performance.

From 2010 to 2014, the redevelopment of Avondale College represents one of the biggest school rebuilding programs in New Zealand's history. The project includes 92 new and refurbished teaching and resource spaces. It is the first time for the insulated precast panels to be used as the main structure and building envelope of a number of new buildings in a secondary school in New Zealand. Three classrooms with different insulation levels and thermal mass in their building envelopes in the Avondale College are selected for this study. Table 1 shows the construction elements of the three classrooms. The classroom 1 is in a new building with precast insulated concrete panel wall and concrete structure, the classroom 2 is in a retrofitted building without thermal mass in its envelopes, and the classroom 3 is an old prefabricated classroom without thermal mass in its envelopes. The three classrooms used space heating during the school hours (from 8:30am to 3:30pm). Based on the field study data of indoor microclimate of the three classrooms, the study not only compares and evaluates indoor thermal conditions but also indoor health conditions of three classrooms with different insulation levels and with or without thermal mass in their envelopes during the Auckland winter.

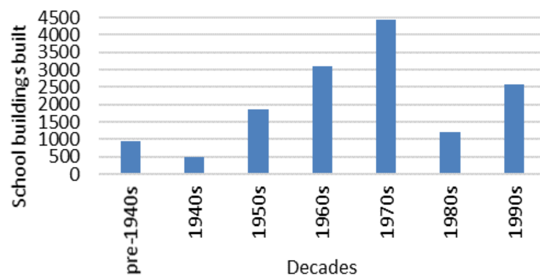


Figure 1. Number of school buildings built from pre-1940s to 1990s in New Zealand

Table 1 Construction elements of the 3 classrooms

| Building elements | Classroom 1 | Classroom 2 | Classroom 3 |
|---|---|---|---|
| Structure | Precast concrete | Timber | Timber |
| Roof | Steel, R3.2 polyester insulation, 200mm air gap and suspended ceiling tile system | Steel roof, R2.9 polyester insulation, 13mm Plaster board ceiling | Iron roofing, R1.9 old fiber insulation |
| Wall | N, E, W walls: Precast insulated concrete panels (70mm external concrete, 40mm XPS rigid insulation, Internal 150mm concrete); S wall: Fundamax laminate panels | Fundamax high pressure laminate cladding, 90mm framing with R2.2 polyester insulation | Timber/Plasterboard, R1.5 old fiber insulation |
| Floor | Concrete floor with 40mm XPS rigid insulation under slab | Hardwood floorboards, Floor 150mm joists with R2.4 (150mm polyester) | Old carpet, wood floorboards, R0.9 polyester insulation |
| Glazing | Double glazing | Double glazing | Single glazing |

## 2. Research method

Indoor air temperatures and relative humidity near ceiling and floor of the three classrooms and outdoor air temperature and relative humidity under the eaves of the roof were continuously measured at 15-minute intervals 24 hours a day by Lascar EL-USB-2 USB Humidity Data Logger during the winter months. Both very low and high relative humidity can not only cause some physical discomfort but also negatively affect indoor health conditions. All field study data of air temperatures and relative humidity of indoor and outdoor have been converted into percentages of winter time related to different ranges of indoor air temperature and relative humidity. The study used percentages of winter time when indoor air temperatures are greater than or equal to 16°C, 18°C, 20°C and 22°C to mainly compare indoor thermal conditions and use percentages of winter time when indoor air temperatures are lower than 16°C, 12°C, 10°C and 9°C to compare indoor health conditions. The study used indoor mean relative humidity and percentages of winter time when indoor relative humidity is greater than or equal to 40%, 50%, 60%, 70%, 75%, 80%, 90% and in the range of 40% to 60% for the purposes of comparing indoor healthy conditions of the three classrooms with different insulation and thermal mass in their building envelopes. The study investigates the 24-hour mean variations of winter indoor air temperatures of the three classrooms, and identifies the difference in indoor thermal and health conditions of the three classrooms, especially during a winter evening, night and early morning without space heating. All field study data of air temperatures have been converted into hourly mean air temperature during the winter.

# 3. Data analysis

## 3.1. Indoor air temperature and indoor thermal and health conditions

During the winter time (see Table 2) indoor mean air temperature of the classroom (19.0°C) with sufficient insulation and thermal mass in the building envelope is 1.7°C higher than the retrofitted classroom (17.3°C) with sufficient insulation and without thermal mass in the building envelope and 4.1°C higher than the prefab classroom (14.9°C) without sufficient insulation. Percentage of winter time in the classroom with thermal mass in the building envelope (74%) is 34% higher than the retrofitted classroom (21%) and 59% higher than the prefab classroom when indoor air temperatures are greater than or equal to 18°C. During the winter night time (7pm to 7am) without space heating (see Table 3) indoor mean air temperature of the classroom (19.0°C) with thermal mass is 2.8°C higher than the retrofitted classroom (15.8°C) and 4.5°C higher than the prefab classroom (14.1°C). Percentage of winter time in the classroom (70%) with thermal mass is 54% higher than the retrofitted classroom (16%) and 65% higher than the prefab classroom (5%) when indoor air temperatures are greater than or equal to 18°C. During the school hours (8:30am to 3:30pm) with space heating (see Table 4) indoor mean air temperature of the classroom (19.6°C) with thermal mass is 0.2°C higher than the retrofitted classroom (19.4°C) and 3.8°C higher than the prefab classroom (15.8°C). Percentage of winter time in the classroom (80%) with thermal mass is 10% higher than the retrofitted classroom (70%) and 53% higher than the prefab classroom (27%) when indoor air temperatures are greater than or equal to 18°C. Increasing insulations and adding thermal mass in the school building envelope not only can improve indoor mean air temperature but also significantly increase the percentage of winter time when indoor mean air temperatures meet the minimum requirement for indoor thermal comfort and healthy conditions.

Table 2 Winter indoor temperature and pecentage of winter time related to different teperature ranges

| Classrooms | | Prefab | | | Retrofit | | | Thermal mass | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Indoor spaces | Floor | Ceiling | Mean | Floor | Ceiling | Mean | Floor | Ceiling | Mean | Outdoor |
| Average (°C) | 14.6 | 15.2 | 14.9 | 17.0 | 17.5 | 17.3 | 18.9 | 19.2 | 19.0 | 12.2 |
| Max (°C) | 20.8 | 24.2 | 22.0 | 29.1 | 28.2 | 27.4 | 24.0 | 25.5 | 24.2 | 20.6 |
| Min (°C) | 6.7 | 5.4 | 6.0 | 8.7 | 8.3 | 8.5 | 14.5 | 14.2 | 14.3 | 1.9 |
| Fluctuation | 14.1 | 18.9 | 15.9 | 20.5 | 20.0 | 18.9 | 9.5 | 11.3 | 9.8 | 18.7 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time T≥16°C | 31% | 42% | 37% | 61% | 65% | 63% | 94% | 93% | 94% | 11% |
| Time T≥18°C | 9% | 22% | 15% | 36% | 42% | 40% | 73% | 75% | 74% | 2% |
| Time T≥20°C | 0% | 8% | 3% | 16% | 25% | 21% | 26% | 32% | 30% | 0% |
| Time T≥22°C | 0% | 2% | 0% | 5% | 11% | 7% | 1% | 6% | 3% | 0% |
| Time T≥24°C | 0% | 0% | 0% | 1% | 3% | 1% | 0% | 0% | 0% | 0% |
| Time T≥26°C | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

Table 3 Winter night indoor temperature and pecentage of winter night time related to different teperature ranges

| Classrooms | Prefab | | | Retrofit | | | Thermal mass | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Indoor spaces | Floor | Ceiling | Mean | Floor | Ceiling | Mean | Floor | Ceiling | Mean | Outdoor |
| Average (°C) | 14.2 | 14.0 | 14.1 | 15.8 | 15.8 | 15.8 | 18.6 | 18.6 | 18.6 | 10.7 |
| Max (°C) | 18.9 | 20.1 | 19.5 | 22.3 | 23.9 | 23.1 | 21.5 | 22.0 | 21.7 | 17.7 |
| Min (°C) | 7.3 | 6.0 | 6.7 | 9.1 | 8.8 | 9.0 | 14.7 | 14.4 | 14.6 | 2.0 |
| Fluctuation | 11.6 | 14.1 | 12.8 | 13.2 | 15.1 | 14.2 | 6.7 | 7.6 | 7.2 | 15.7 |
| Time T≥16°C | 21% | 24% | 23% | 47% | 46% | 46% | 93% | 92% | 93% | 1% |
| Time T≥18°C | 4% | 6% | 5% | 16% | 16% | 16% | 70% | 70% | 70% | 0% |
| Time T≥20°C | 0% | 0% | 0% | 2% | 4% | 3% | 16% | 18% | 17% | 0% |
| Time T≥22°C | 0% | 0% | 0% | 0% | 1% | 0% | 0% | 0% | 0% | 0% |
| Time T≥24°C | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Time T≥26°C | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

Table 4 Winter school hours' indoor temperature and pecentage of winter school hours related to different teperature ranges

| Classrooms | Prefab | | | Retrofit | | | Thermal mass | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Indoor spaces | Floor | Ceiling | Mean | Floor | Ceiling | Mean | Floor | Ceiling | Mean | Outdoor |
| Average (°C) | 14.9 | 16.6 | 15.8 | 18.6 | 20.1 | 19.4 | 19.4 | 19.9 | 19.6 | 14.3 |
| Max (°C) | 20.8 | 24.2 | 22.0 | 29.1 | 28.2 | 27.4 | 24.0 | 25.5 | 24.2 | 20.6 |
| Min (°C) | 6.7 | 5.4 | 6.0 | 8.7 | 8.3 | 8.5 | 14.6 | 14.4 | 14.5 | 2.6 |
| Fluctuation | 14.1 | 18.9 | 15.9 | 20.4 | 19.9 | 18.9 | 9.4 | 11.1 | 9.6 | 17.9 |
| Time T≥16°C | 38% | 60% | 51% | 79% | 87% | 85% | 95% | 95% | 95% | 27% |
| Time T≥18°C | 13% | 41% | 27% | 61% | 77% | 70% | 78% | 83% | 80% | 7% |
| Time T≥20°C | 0% | 18% | 7% | 35% | 59% | 48% | 38% | 51% | 46% | 0% |
| Time T≥22°C | 0% | 4% | 0% | 13% | 31% | 20% | 4% | 16% | 9% | 0% |
| Time T≥24°C | 0% | 0% | 0% | 3% | 8% | 4% | 0% | 1% | 0% | 0% |
| Time T≥26°C | 0% | 0% | 0% | 0% | 1% | 1% | 0% | 0% | 0% | 0% |

Indoor air temperatures of the classroom with thermal mass in their building envelopes are more stable than the prefab classroom and the retrofitted classroom during the winter time (24 hours) with space heating during the school hours (see Figure 2) and the winter night time (7:00pm to 7:00am) without space heating (see Figure 3). Indoor air temperature fluctuations of the prefab classroom and the retrofitted classroom without thermal mass in their building envelopes are significantly larger than the classroom with thermal mass as the lightweight structure and building envelope heat up quickly and also cool down quickly. Large fluctuation can cause very low indoor air temperatures during the winter evening, night and early morning before the school hours (see Figure 4). Minimum hourly mean air temperature of the prefab classroom (12.6°C) and the retrofitted classroom (14.1°C) are significantly lower than the classroom with thermal mass (17.8°C) during the winter evening, night and early morning before the school hours (see Figure 4). Increasing indoor hourly mean air temperatures of the retrofitted classroom from 14.1°C (at 6:30am) to 18°C (at 10:00 am) takes over 3 hours, which not only negatively impact indoor thermal comfort but also cost more space heating energy to heat up the space. Increasing insulation in the building envelope without thermal mass can increase indoor mean air temperature but cannot reduce the fluctuation of indoor air temperature during the winter. Adding thermal mass in the building envelope not only can increase indoor mean air temperature but also reduce fluctuation of indoor air temperature.

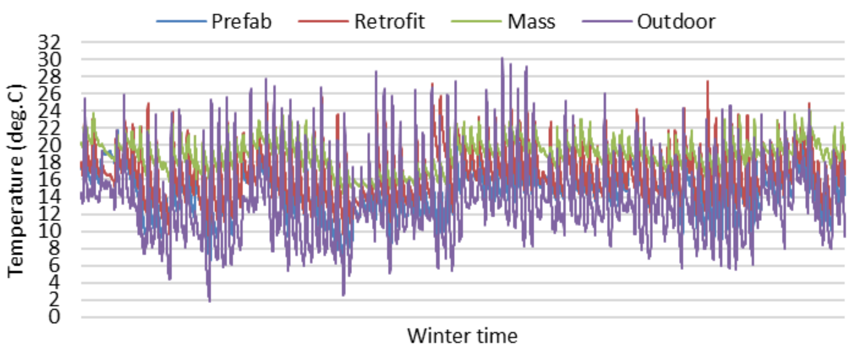


Figure 2 Fluctuation of indoor temperature of the three classroom during the winter time (24 hours)

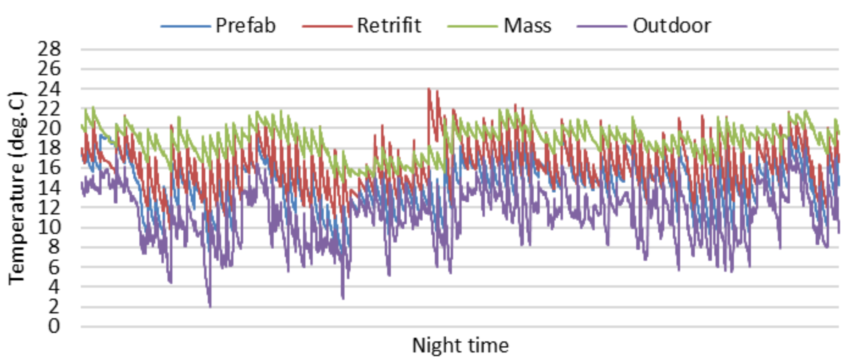


Figure 3 Fluctuation of indoor temperature of the three classroom during the night time (7pm to 7am)

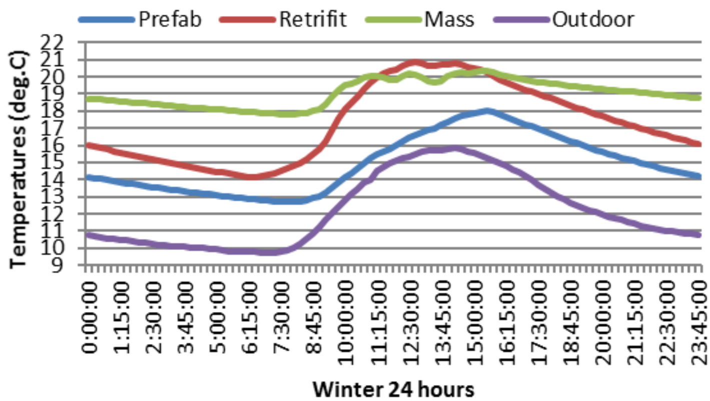


Figure 4 Winter indoor and outdoor hourly mean air temperatures of the three classrooms

Indoor hourly mean air temperatures of the classroom with thermal mass are higher or close to 18°C during a winter evening, night and early morning (see Figure 3). There are at least 7 hours of space heating during the school hours from 8:30am to 3:30pm. When heat is lost from indoor to outdoor through the building envelope of the classroom with thermal mass, some heat will be stored in the thermal mass in the building envelope and released to the indoor space late after the heater is turned off, which can continuously maintain the indoor air temperature at a high level during the evening, night and early morning. For the prefab classroom and the retrofitted classroom without thermal mass in their envelopes, when the heat is lost from indoor to outdoor through the building envelopes, not much heat is stored in their building envelopes, and the indoor temperature will sharply decrease without space heating, which causes very low indoor air temperatures during the evening, night and early morning. Very low indoor temperature not only can impact thermal comfort but also can negatively impact occupants' health. During the winter time (see Table 5), percentage of winter time of the prefab classroom without sufficient insulation and the retrofitted classroom with sufficient insulation and without thermal mass, when indoor air temperatures are lower than 16°C, 14°C, 12°C, 10°C, and 9°C, are significantly higher or clearly higher than the classroom with sufficient insulation and thermal mass in the building envelope. Adding thermal mass in the building envelope not only can improve indoor thermal comfort and energy efficiency for space heating but also can raise the baseline of winter indoor air temperature and improve indoor healthy thermal conditions for occupants.

Table 5 Pecentage of winter time related to low indoor air temperature ranges

| Classrooms | | Prefab | | | Retrofit | | | Thermal mass | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Indoor spaces | Floor | Ceiling | Mean | Floor | Ceiling | Mean | Floor | Ceiling | Mean | Outdoor |
| Average T (°C) | 14.6 | 15.2 | 14.9 | 17.0 | 17.5 | 17.3 | 18.9 | 19.2 | 19.0 | 12.2 |
| Max T (°C) | 20.8 | 24.2 | 22.0 | 29.1 | 28.2 | 27.4 | 24.0 | 25.5 | 24.2 | 20.6 |
| Min T (°C) | 6.7 | 5.4 | 6.0 | 8.7 | 8.3 | 8.5 | 14.5 | 14.2 | 14.3 | 1.9 |
| Fluctuation | 14.1 | 18.9 | 15.9 | 20.5 | 20.0 | 18.9 | 9.5 | 11.3 | 9.8 | 18.7 |
| Time T<9°C | 2% | 3% | 2% | 0% | 0% | 0% | 0% | 0% | 0% | 18% |
| Time T<10°C | 4% | 7% | 6% | 0% | 0% | 0% | 0% | 0% | 0% | 25% |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Time T<12°C | 16% | 17% | 17% | 3% | 3% | 3% | 0% | 0% | 0% | 46% |
| Time T<14°C | 38% | 35% | 36% | 16% | 15% | 15% | 0% | 0% | 0% | 70% |
| Time T<16°C | 69% | 58% | 63% | 39% | 35% | 37% | 6% | 7% | 6% | 89% |

## 3.2. Indoor relative humidity and indoor health conditions

As indoor relative humidity increases or decreases are associated with a decrease or increase of indoor air temperature, very low indoor air temperature can cause very high relative humidity. During the winter time (see Table 6), the indoor mean relative humidity of prefab classroom (70%) without sufficient insulation and thermal mass is about 10% higher the retrofitted classroom (60%) with sufficient insulation and without thermal mass in the building envelope and the classroom with sufficient insulation and thermal mass in the building envelope (58%). Maintaining the indoor relative humidity between 40% and 60% can minimize the indirect health effects such as bacteria, viruses, fungi, mites, etc. Percentage of winter time of the classroom (67.4%) with sufficient insulation and thermal mass in the building envelope, when indoor relative humidity is in the range of 40% to 60%, is 21.4% higher than retrofitted classroom (46.0%) with sufficient insulation and without thermal mass in the building envelope and 64.7% higher than prefab classroom (2.7%) without sufficient insulation and thermal mass in the building envelope. Indoor mean relative humidity of the prefab classroom is higher than the range of 40% to 60%. Indoor mean relative humidity of the retrofitted classroom and the classroom with thermal mass are in the range of 40% to 60% during the winter time. Sufficient insulation in the school building envelope can increase winter indoor mean air temperature and decrease winter indoor mean relative humidity. Adding thermal mass in the building envelope not only decrease winter indoor mean relative humidity but also increase winter time when indoor relative humidity is in the range of 40% to 60%, which can improve indoor health conditions.

Table 6 Winter indoor temperature and pecentage of winter time related to different relative humidity ranges

| Classrooms | | Prefab | | | Retrofit | | | Thermal mass | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Indoor spaces | Floor | Ceiling | Mean | Floor | Ceiling | Mean | Floor | Ceiling | Mean | Outdoor |
| Average RH (%) | 70 | 70 | 70 | 61 | 59 | 60 | 58 | 57 | 58 | 80 |
| Max RH (%) | 84 | 85 | 84 | 84 | 83 | 84 | 77 | 76 | 76 | 99 |
| Min RH (%) | 51 | 52 | 53 | 28 | 32 | 30 | 37 | 33 | 35 | 35 |
| Time RH≥40% | 100% | 100% | 100% | 99% | 98% | 99% | 100% | 100% | 100% | 100% |
| Time RH≥50% | 100% | 100% | 100% | 91% | 84% | 88% | 90% | 89% | 90% | 98% |
| Time RH≥60% | 97% | 96% | 97% | 57% | 49% | 53% | 33% | 31% | 32% | 93% |
| Time RH≥70% | 53% | 53% | 53% | 11% | 8% | 9% | 4% | 3% | 3% | 78% |
| Time RH≥75% | 16% | 15% | 14% | 2% | 2% | 2% | 1% | 0% | 0% | 69% |
| Time RH≥80% | 1% | 2% | 1% | 1% | 1% | 1% | 0% | 0% | 0% | 58% |
| Time RH≥85% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 44% |
| Time RH≥90% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 26% |
| Time RH≥100% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Time 40%≤RH≤60% | 3.2% | 3.8% | 2.7% | 41.9% | 49.1% | 46.0% | 66.5% | 68.6% | 67.4% | 7.5% |

## 4. Couclusions

In New Zealand, there are a significant number of schools buildings built before 2000 without sufficient insulation and single glazing window. Those old school buildings have poor thermal performance, very low indoor temperature and high relative humidity during the winter time, which can negatively impact indoor thermal and health conditions for occupants. In the current situation, retrofitting old school building mainly focus on increase *R-value* (sufficient insulation and double glazing window) in the building envelope (without considering thermal mass effect), which can maintain winter indoor mean air temperature at acceptable level durng the school hours with space heating, but cannot reduce the large fluctuation of winter indoor air temperatures and prevent very low indoor air temperatures during the winter evening, night and early morning.

Increasing insulation and adding thermal mass in a school building envelope not only can increase winter indoor mean air temperature but also reduce fluctuation of winter indoor air temperature. Adding thermal mass in a school building envelope with sufficient insulation and double glazing window not only can increase indoor mean air temperature but also significantly increase the percentage of winter time when indoor mean air temperatures meet the minimum requirement (18°C) for indoor thermal comfort and healthy conditions. Adding thermal mass in a school building envelope with sufficient insulation and double glazing window not only can raise the baseline of winter indoor air temperature, which can improve indoor thermal comfort and energy efficiency for space heating, but also significantly reduce percentages of winter time when indoor air temperatures are lower than 16°C, 12°C, 10°C and 9°C, which can prevent very low winter indoor air temperature and maintain indoor healthy thermal conditions.

Adding thermal mass in a school building envelope with sufficient insulation and double glazing window not only can increase the percentage of winter time, when indoor mean air temperatures meet thermal comfort and healthy thermal conditions, but also significantly increase the percentage of winter time, when indoor relative humidity is maintained between 40% and 60%, which can minimize the indoor indirect health effects such as bacteria, viruses, fungi, mites, etc. The classroom with sufficient insulation and thermal mass in the building envelope has a lower percentage of winter time than the classroom with sufficient insulation and without thermal mass when indoor relative humidity is greater than or equal to 60%, 70%, 75% and 80%. For the future school development, adding thermal mass in the school building envelope with sufficient insulation and double glazing window is very important for winter indoor thermal comfort conditions, indoor healthy conditions and energy efficiency of space heating under a temperate climate with a mild and wet winter.

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