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Mixed Mode is Better than Air Conditioned Offices for Resilient Comfort: Adaptive Behaviour and Visual Thermal Landscaping

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Abstract: This work investigated future building resilience, regarding thermal comfort, energy, health, and accommodating user behaviours and individual requirements by comparing mixed mode (MM) and fully air conditioned (HVAC) offices. Recently, offices are designed, as a fully HVAC sealed-box, while no particular guidelines or standards cover MM buildings. Although providing adaptive opportunities was demanded by occupants and predicted as an important asset for future offices; recently, centrally-operated systems are replacing them. In this work, MM and HVAC offices were compared using field studies of thermal comfort on 13 office buildings with overall 4,776 datasets in three countries: Japan, Sweden and Norway. Statistical analysis was applied on the Japanese datasets, while visual thermal landscaping (VTL) on the Swedish and Norwegian offices. The MM building had 16% higher overall comfort, 32% satisfaction and health conditions, as compared to the HVAC building. However, extra care is needed in designing MM buildings and user-friendly thermal controls, as they have the potential to be energy efficient by using natural ventilation and a variety of adaptive opportunities to achieve comfort. Overall, MM buildings were found more resilient regarding thermal comfort, energy, health, coping with future pandemics (e.g. COVID), and accommodating individual needs, as compared to HVAC buildings.

Keywords: Resilient comfort, MM buildings, HVAC offices, Adaptive behaviour, Visual thermal landscaping

Introduction

Today's world is facing an energy crisis and space heating and cooling are responsible for 40% of the energy use in the EU (European Community, 2018). Also, the COVID-19 global pandemic calls for careful considerations for future design of resilient buildings. Fully HVAC offices with fixed windows are becoming increasingly common. Although providing adaptive opportunities was predicted as an important asset for future offices (Leaman and Bordass, 2005); recently, centrally operated systems are replacing adaptive opportunities in office buildings removing any occupant control (Bordass et al., 1993, Roaf et al., 2004). However, there is a high demand from end users for the availability of adaptive opportunities (e.g. openable windows) in the workplace (Van der Voordt, 2004) and it was reported to improve user satisfaction by 30% and thermal comfort by 20% (Shahzad, 2014).

Mixed Mode and Air Conditioned Buildings

A fully HVAC building is centrally operated with no thermal control opportunities for occupants; windows are fixed and they cannot be opened. It operates on either cooling or heating mode according to season with no other options. Regarding the MM approach, there is no particular design (Brager et al., 2000) or standards (Kim et al., 2019). Thermal comfort standards and models are not suited for MM buildings (Borgeson and Brager, 2011) and no consideration has been included either, as they are provided for either fully naturally ventilated or HVAC buildings (Deuble and de Dear, 2012). According to Brager et al. (2000) an MM or a hybrid building is essentially 'a hybrid approach to space conditioning that combines natural ventilation with mechanical ventilation and cooling'. However, it should not be mistaken with a HVAC building equipped with openable windows, as an MM building is more sophisticated and its performance is complex (Brager, 2006). Usually it involves an intelligent control strategy and the design of the building envelope, which accommodates natural ventilation. There are different classifications for MM buildings, such as contingency, zoned and complementary (CBE, 2013). The latter is divided into three subcategories, including alternate, changeover and concurrent (CIBSE, 2000). In order to change between different modes of the building, particularly in the changeover strategy, the use of technology is quite common, such as external temperature sensors, internal window opening sensors and automated louvers. In the concurrent strategy, air conditioning and openable windows operate simultaneously, according to occupant needs. However, when the system detects that the windows have been opened, the air conditioning will be reduced automatically (CIBSE, 2000, Brager et al., 2000) to preserve energy. Ackerly et al. (2011) explains that designers need to better understand the end user and on the other hand the awareness of the end user regarding the operation of the control systems is important, particularly in MM buildings.

Thermal Comfort and Satisfaction

High occupant satisfaction levels are reported in MM buildings (Bordass et al., 2001, Brager and Baker, 2008, Rijal et al., 2017). HVAC buildings aim for a narrow band of indoor temperatures, while it does not guarantee occupant comfort (Arens et al., 2010). Kim et al. (2019) found that occupants considered a wide range of the indoor thermal environment comfortable, which is in contrast to the application of a narrow band of indoor temperatures, which are currently practiced in offices. Some HVAC buildings are reported to have lower indoor temperatures in summer, as compared to the ASHRAE Standard 55 (Mendell and Mirer, 2008). Takasu et al. (2017) found the comfort temperature in MM Japanese offices between 23.5°C and 26.6°C. Rijal et al. (2017) found different comfort temperatures, when different systems were in operation in Japanese offices: 25.4°C for cooling; 24.3° for heating; and 25°C for natural ventilation mode.

Thermal Comfort

For occupants, to feel in control is important (Rollins and Swift, 1997) and lack of control can increase building related symptoms (Rayner, 1997). The availability of adaptive opportunities, particularly thermostat and accessible openable windows, highly increase occupant satisfaction (Brager et al., 2000). Visibility (Lomas et al., 2008), simplicity, user friendliness, responsiveness, and accessibility of the thermal control systems are very important to ensure occupants' satisfaction (Leaman, 1993, Leaman, 1996). In MM buildings, well designed automated or manual control systems are required to bring together air conditioning and natural ventilation; otherwise, the building may not perform well or consume too much energy (Brager et al., 2000). Users tend to make good use of the control systems provided in MM buildings, such as windows, fans, heating and cooling systems (Rijal et al., 2009). Occupant control over the windows in MM buildings increases user's thermal comfort and satisfaction over the fixed windows in HVAC buildings (Raja et al., 2001, Heiselberg et al., 2002, Bluyssen, 2009, Brager and Baker, 2009). In MM buildings, clothing and window opening adjustments were reported during different seasons (Rijal et al., 2017 & 2019). Kim et al. (2019) found adaptive behaviour of occupants during the free running mode, as compared to the AC mode.

Energy

Balancing energy and thermal comfort is important (Shahzad et al., 2015 & 2017). One of the key aims of an MM building is to save on the cooling energy demand of the building (Brager and Borgeson, 2007). By using openable windows and reducing the HVAC system, up to 15 to 80% (Brager et al., 2000, Kim et al., 2019) energy can be saved (Emmerich, 2006). Through simulation, Hoyt et al. (2015) found that by widening the indoor temperature range, significant energy can be saved. 3°C increase in the setpoint of temperature in summer, results in 29% energy saving; and 1°C decrease in winter results in 34% energy saving. MM buildings are reported to use less energy, as compared to HVAC buildings (Kim et al., 2019).

Health

There is a debate in the field, as to whether or not air conditioning is responsible for building related symptoms, particularly that the recognition of this health issue was acknowledged shortly after the introduction of HVAC systems (Shahzad, 2013). HVAC buildings are reported to have a high level of building related symptoms (Finnegan et al., 1984, Jaakkola et al., 1991, Rollins and Swift, 1997, Brasche et al., 2001). High risk of ocular, nasal, pharyngeal symptoms and lethargy is reported in mechanically ventilated buildings (Jaakkola and Miettinen, 1995). Difficulties with skin, mucous membranes and nervous system are reported in HVAC buildings (Brasche et al., 2001). Lower symptoms are reported in naturally ventilated buildings (Jaakkola and Miettinen, 1995). Seppanen and Fisk (2001) reported higher building related symptoms (30 to 200%) in HVAC buildings, as compared to naturally ventilated buildings. However, the design of the building and its ventilation system are the key factors in increasing occupant health, as a poorly designed natural ventilation had higher levels of building related syndromes, as compared to HVAC buildings (Shahzad, 2013). According to the World Health Organisation, natural ventilation can reduce the infection rate (Atkinson et al., 2009), particularly the COVID-19 (WHO, 2020). Openable windows are mainly suggested to reduce the risks of the COVID-19 disease. In HVAC buildings, increasing the air filtration, air flow rate and a higher proportion of outdoor air in the air circulation are recommended (WHO, 2020).

Objectives

This work investigated the differences between MM (MM) and fully HVAC office buildings regarding thermal comfort, building performance, energy, health, adaptive behaviour, and accommodating individual needs. The aim of this work was to provide guidelines for resilient buildings for the future. Field test studies of thermal comfort were applied on 4,776 datasets in 13 MM and HVAC offices in Japan, Sweden and Norway.

Research Methods

Field studies of thermal comfort were applied in MM and fully HVAC office buildings in three countries: Japan, Norway and Sweden. The case study buildings were located in Tokyo, Yokohama, Oslo, and Stockholm, respectively. The Japanese data was collected between August 2014 and October 2015, which included over a year of monthly surveys. The Swedish and Norwegian data were collected in summer 2012 and each respondent was surveyed three times a day. The key thermal comfort questions are presented in Table 20.1 and the main environmental data included dry bulb temperature, relative humidity and mean radiant temperature. Outdoor temperature and relative humidity were recorded from the nearest meteorological station in the Japanese case studies and directly from the site in the Norwegian and Swedish buildings.

Table 20.1 Main thermal comfort questions.

Scale	1	2	3	4	5	6	7
TSV	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
	Very cold	Cold	Slightly cold	Neutral (Neither hot, nor cold)	Slightly hot	Hot	Very hot
TP	Much warmer	Warmer	Slightly warmer	No change	Slightly cooler	Cooler	Much cooler
	Much warmer	A bit warmer	No change	A bit cooler	Much cooler		
OC	Very uncomfortable	Uncomfortable	Slightly uncomfortable	Neutral	Slightly comfortable	Comfortable	Very comfortable
	Very uncomfortable	Uncomfortable	Slightly uncomfortable	Slightly comfortable	Comfortable	Very comfortable	

TSV: Thermal Sensation Vote, TP: Thermal Preference, OC: Overall comfort.

Note: Upper line is ASHRAE scale used in Norway and Sweden, and lower line is used in Japan.

Overall thirteen buildings, including seven MM and six fully HVAC buildings, and 4,776 datasets were included, as demonstrated in Table 20.2. All MM buildings had openable windows for natural ventilation purposes. All HVAC buildings had fixed windows and they were running as fully HVAC sealed-boxes. All HVAC buildings provided a uniform thermal environment both throughout the office building and throughout the study period. There were hardly any temperature differences throughout the day and less than 2°C temperature fluctuations throughout the year were recorded.

Table 20.1 Main thermal comfort questions.

Scale	1	2	3	4	5	6	7
TSV	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
	Very cold	Cold	Slightly cold	Neutral (Neither hot, nor cold)	Slightly hot	Hot	Very hot
TP	Much warmer	Warmer	Slightly warmer	No change	Slightly cooler	Cooler	Much cooler
	Much warmer	A bit warmer	No change	A bit cooler	Much cooler		
OC	Very uncomfortable	Uncomfortable	Slightly uncomfortable	Neutral	Slightly comfortable	Comfortable	Very comfortable
	Very uncomfortable	Uncomfortable	Slightly uncomfortable	Slightly comfortable	Comfortable	Very comfortable	

TSV: Thermal Sensation Vote, TP: Thermal Preference, OC: Overall comfort.

Note: Upper line is ASHRAE scale used in Norway and Sweden, and lower line is used in Japan.

Analysis and Results

Statistical analysis is the most common method in assessing thermal comfort (Shahzad, 2014). However, it excludes spatial context analysis and individual differences (Shahzad, 2019). Thus, this research applies a double analysis methods system using both traditional statistical analysis and the VTL model (Shahzad, 2019). The VTL model provides a platform for a qualitative and intuitive interpretation of data based on the meaning, individual information (e.g. comfort survey), connections between individuals, their environment and other individuals within the context. In this work, the larger Japanese dataset was analysed using SPSS statistical analysis,. While VTL model was used to analyse the Swedish and Norwegian datasets.

Statistical Analysis

This section compares the MM and HVAC buildings in the Japanese dataset. Figure 20.1 demonstrates indoor and outdoor temperatures in the two building types. Figure 20.1A shows that the indoor temperature of the MM buildings had a wider range of 12.5°C, meaning 17.8°C to 30.3°C. The HVAC buildings had a much narrower range of indoor temperatures (6°C), between 22°C and 28°C. Figure 20.1B shows the yearly indoor temperature in each building. Although each building had a slightly different set point of temperature, there is hardly any seasonal temperature changes in the HVAC buildings, while the MM buildings had wider seasonal temperature differences (up to 2°C).

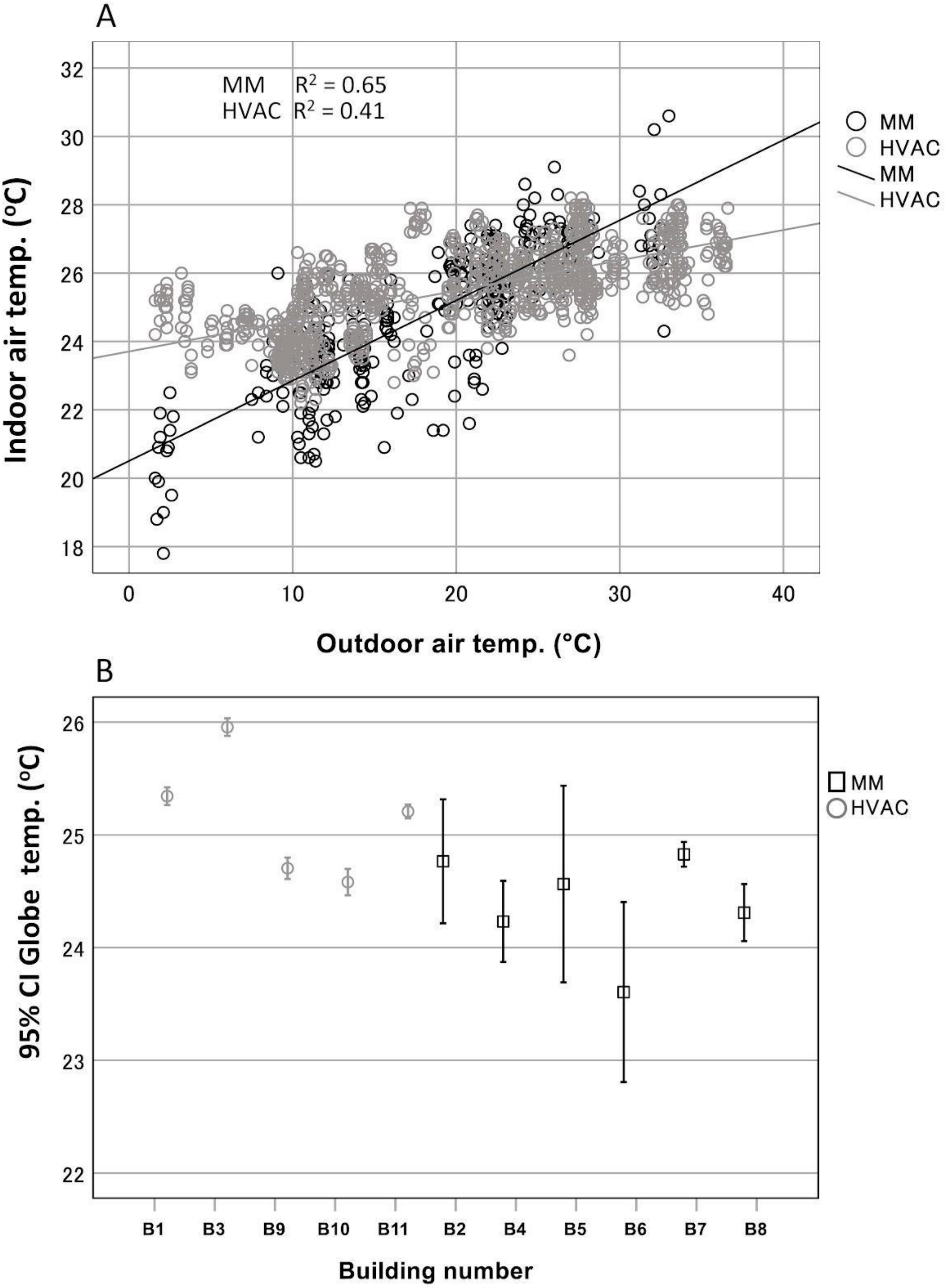


Figure 20.1 Temperature analysis. A: Indoor and outdoor temperatures; B: Indoor globe temperatures by building.

Figure 20.2 demonstrates monthly performance differences and users' views. Monthly indoor temperature ranges in the HVAC buildings were much more limited than the MM buildings. The temperature ranges in MM buildings were higher during the summer (27°C) and lower in the winter (22°C). No significant differences were found between thermal sensation, thermal preference and overall comfort of the two building types, except that the MM building had a slightly higher monthly range.

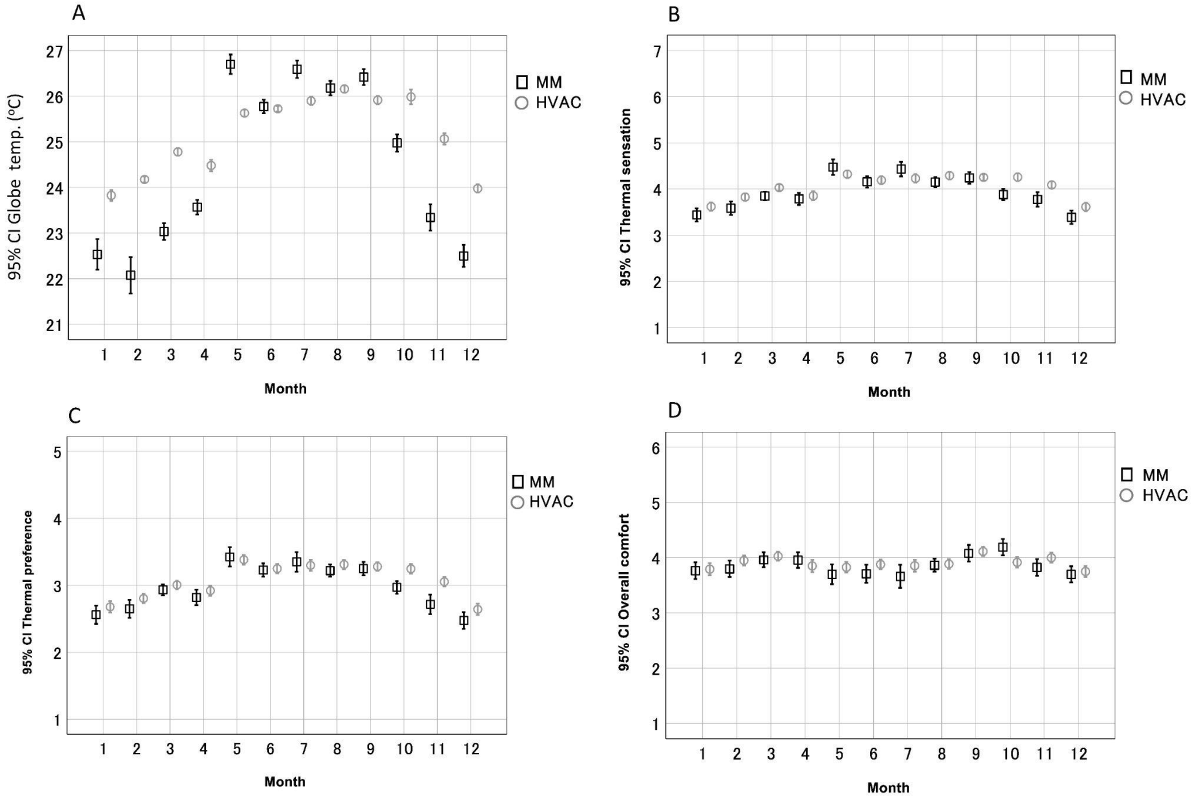


Figure 20.2 Monthly differences. A: Globe temperature; B: Thermal sensation; C: Thermal preference; D: Overall comfort.

Figure 20.3 demonstrates user behaviour according to the survey and observation. Participants responded to behaviour questions regarding the changes they made in the past fifteen minutes, when feeling hot (Figure 20.3A) and cold (Figure 20.3B). As some control systems (windows or fans) were in use all day; the researchers also recorded their observations (Figure 20.3C). Figure 20.3A shows that some passive behaviours, when feeling hot (eating/drinking something cold; rolling up sleeves and taking off shoes), were used more in the HVAC buildings than the MM buildings. Figure 20.3B shows that, when occupants felt cold in both building types, they adopted passive behaviours mainly, including eating or drinking something warm, using a blanket and putting on layers. These options were more used in the MM buildings, particularly the warm meal or drink and the blanket use. The rest of the options were not much used in either of the buildings. The observed behaviours however, tells a different story. In the MM buildings, the adaptive opportunities which were mainly used included windows (15%) fans (20%) and local heaters (11%). However, none of them were provided in the HVAC buildings. No significant difference was found between the use of clothing, heating and desk fan. Clothing and heating were highly used in both building types.

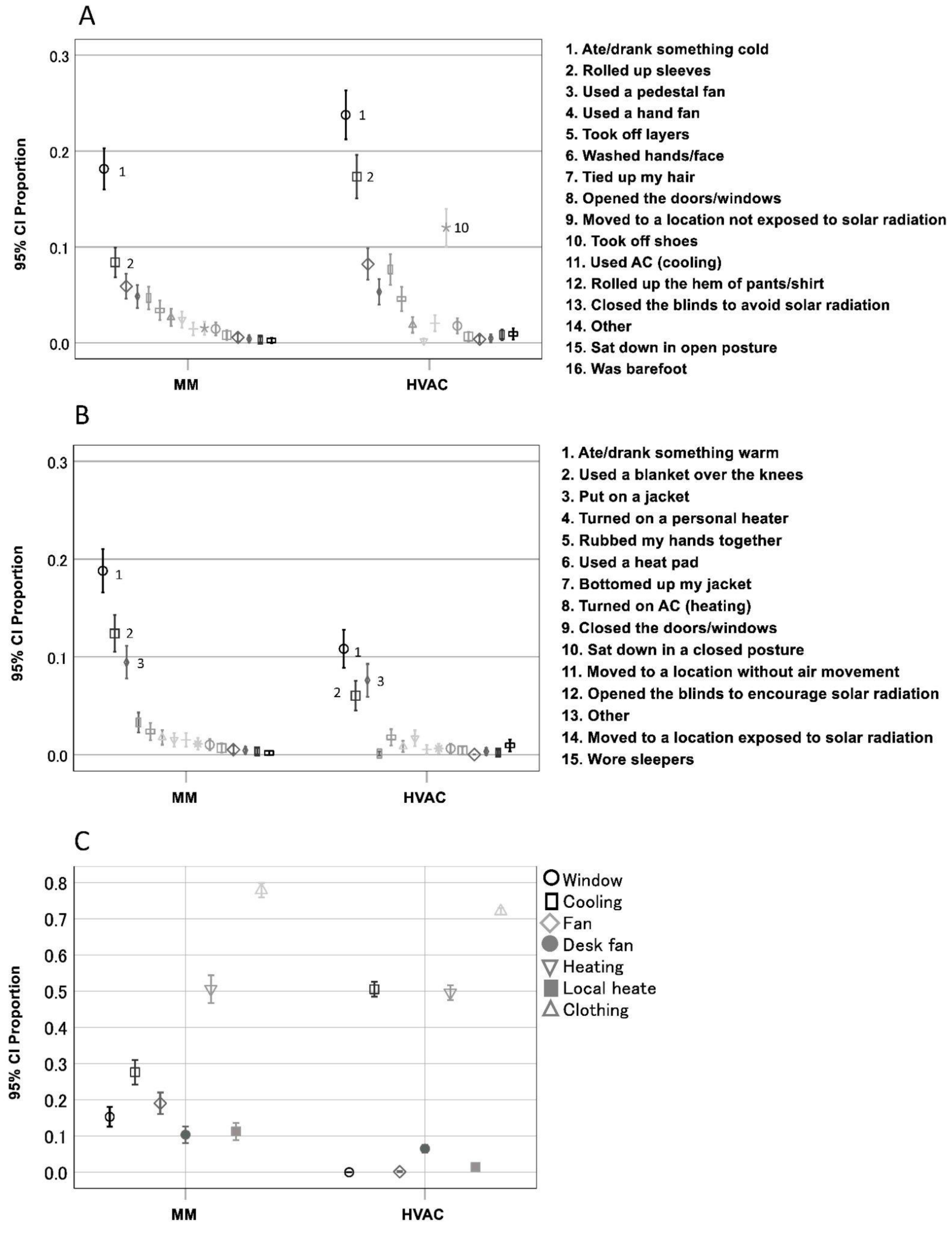


Figure 20.3 Cool, warm and observed behaviours. A: Cool behaviours, when feeling warm; B: Warm behaviours, when feeling cool; C: Observed behaviours.

Further investigation into seasonal indoor conditions and thermal control use were applied, as presented in Figures 20.4 and 20.5. As observed in Figure 20.4A, the HVAC buildings provided a very consistent and uniform thermal environment during each season with hardly any indoor temperature changes. Some seasonal temperature differences (up to 2°C) were observed in each building. On the contrary, the indoor temperature of the MM buildings was much more varied (up to 4°C), particularly in spring and autumn, when mainly windows were used. During summer and winter, the indoor temperature was much more consistent and uniform, although still slightly higher variations were observed, as compared to the HVAC buildings. Windows were mostly closed in winter in MM buildings, as presented in Figure 20.4B.

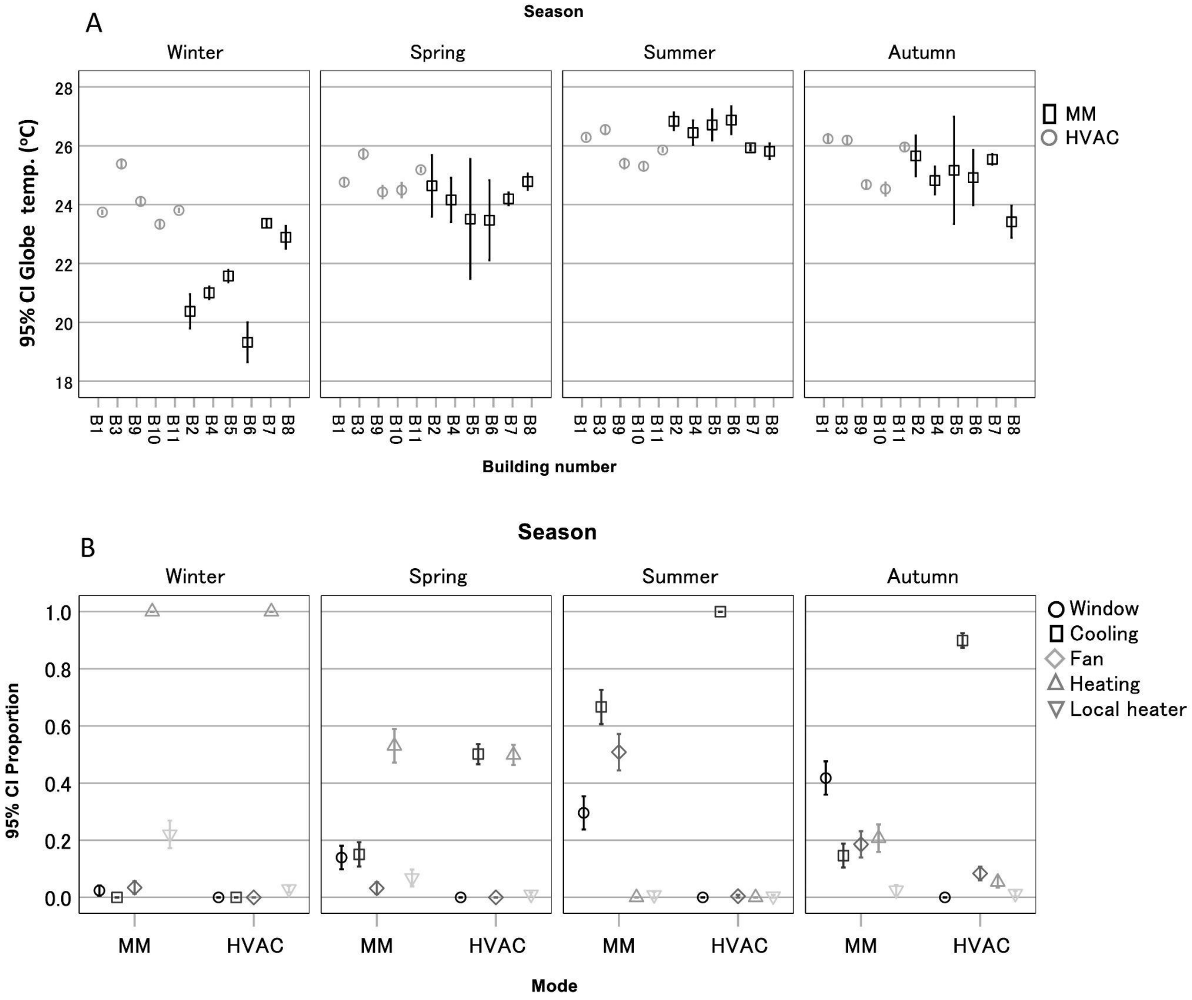


Figure 20.4 Seasonal indoor temperature and observed behaviours. A: Globe temperature; B: Observed behaviours.

Figure 20.5 demonstrates cool and warm behaviour differences between the MM and HVAC buildings in different seasons. Figure 20.5A demonstrates occupant behaviour, when feeling warm. The behaviours were quite similar in both MM and HVAC buildings in every season. The main difference in spring and summer was that rolling up the hem of the trousers or skirts were more used in the HVAC than the MM buildings. In autumn, the occupants of the HVAC buildings used more rolling up the sleeves, rolling up the hem of trousers or skirts, and removing clothing layers. In winter not much cool behaviours were reported, when feeling warm, except having a cold drink or meal in the HVAC buildings. Figure 20.5B demonstrates occupant behaviour, when feeling cold. The pattern of behaviours were again quite similar between the two building types, particularly in spring, summer and autumn. The key difference in winter was higher degree of adaptive behaviours in the MM buildings. For example, having a warm drink or meal (20% higher), the use of blanket (20% higher) and the use of thicker layers (10% higher) were much more used in the MM buildings, as compared to the HVAC buildings.

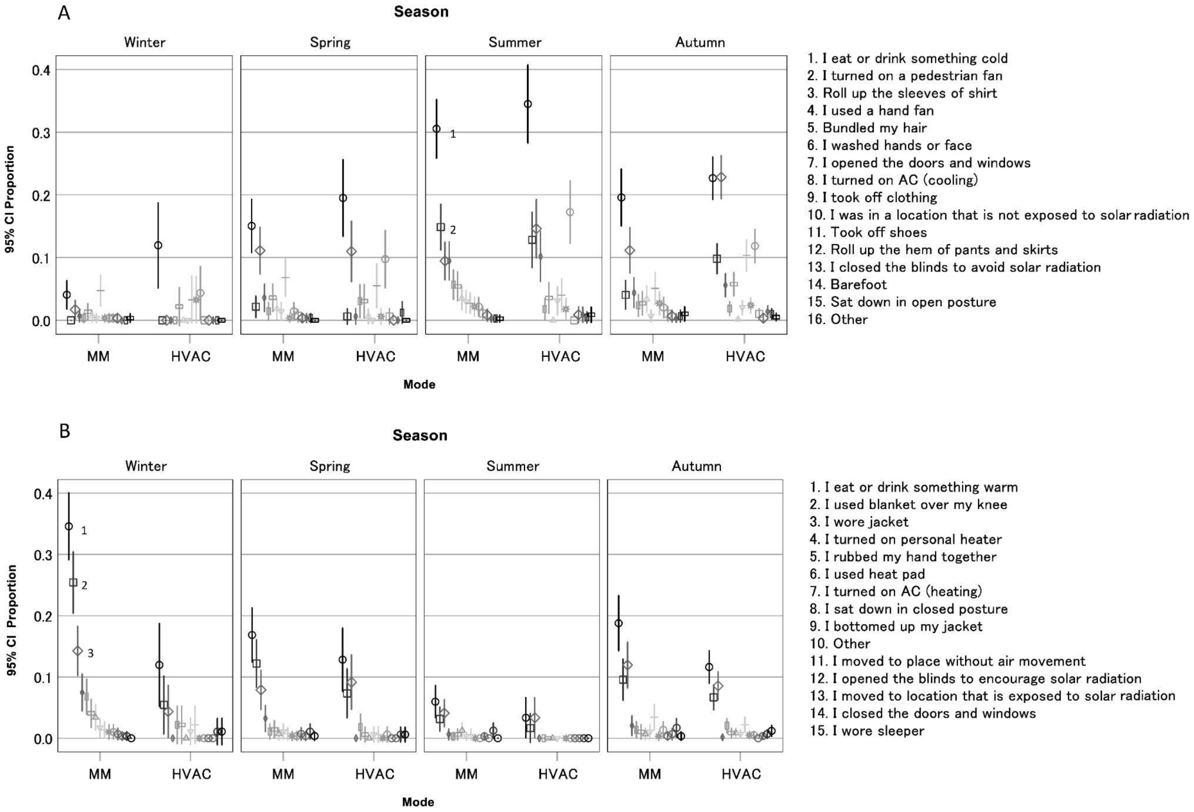
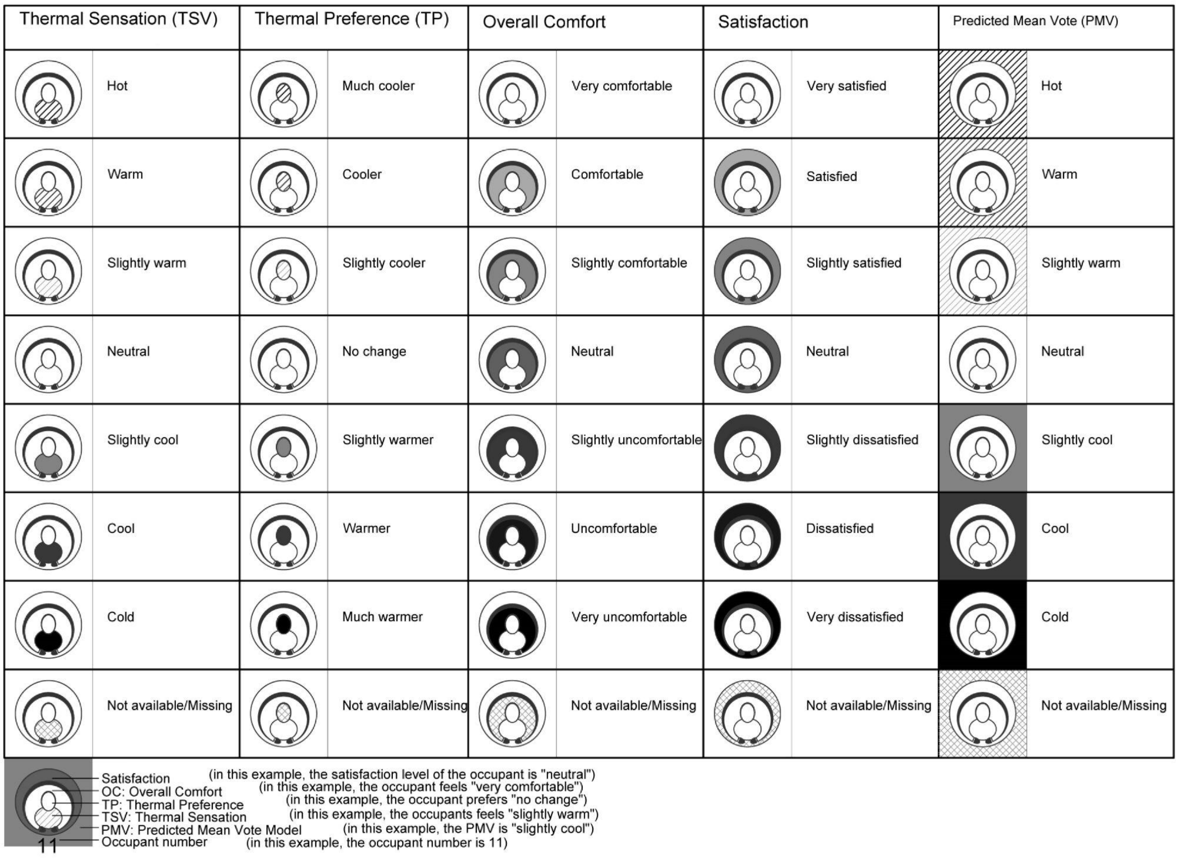


Figure 20.5 Seasonal cool and warm behaviours. A: Seasonal cool behaviours, when feeling warm; B: Seasonal warm behaviours, when feeling cool.

Visual Thermal Landscaping (VTL)

The VTL model was developed through architectural knowledge and expertise. All information, regarding surveyed and observed data, were mapped on the plan of the building using a colour coding system (Shahzad et al., 2019). Personal information, location, close proximity to the windows, control systems, neighbouring colleagues, architectural, spatial, and contextual information were demonstrated and analysed through this method. The VTL method was adapted to a grey scale format for this work. Figure 20.6 shows how to read the information on the pictograms. The white colour represents a satisfactory or comfortable condition (neutral TSV, no change TP, very satisfied). The darker the colour, the more uncomfortable the condition (e.g. hot or cold TSV, much cooler or much warmer TP, very uncomfortable). One end of the overall comfort and satisfaction scales is positive, which is represented with white (very comfortable and very satisfied); while the other end is negative, which is represented with black (very uncomfortable and very dissatisfied). The most comfortable option on the TSV, TP and PMV scales are in the middle (neutral and no change), while the two ends are the same degree change (hot and cold). Thus, the same colour has been used for both ends of the scale, while one end has turned into a dashed format (e.g. hot TSV).



Thermal Sensation (TSV)	Thermal Preference (TP)	Overall Comfort	Satisfaction	Predicted Mean Vote (PMV)
Hot	Much cooler	Very comfortable	Very satisfied	Hot
Warm	Cooler	Comfortable	Satisfied	Warm
Slightly warm	Slightly cooler	Slightly comfortable	Slightly satisfied	Slightly warm
Neutral	No change	Neutral	Neutral	Neutral
Slightly cool	Slightly warmer	Slightly uncomfortable	Slightly dissatisfied	Slightly cool
Cool	Warmer	Uncomfortable	Dissatisfied	Cool
Cold	Much warmer	Very uncomfortable	Very dissatisfied	Cold
Not available/Missing	Not available/Missing	Not available/Missing	Not available/Missing	Not available/Missing

Satisfaction (in this example, the satisfaction level of the occupant is "neutral")
OC: Overall Comfort (in this example, the occupant feels "very comfortable")
TP: Thermal Preference (in this example, the occupant prefers "no change")
TSV: Thermal Sensation (in this example, the occupants feels "slightly warm")
PMV: Predicted Mean Vote Model (in this example, the PMV is "slightly cool")
Occupant number (in this example, the occupant number is 11)

Figure 20.6 The legend to read the pictograms for the VTL model.

Figure 20.7 demonstrates the VTL analysis of the Norwegian MM building and the Swedish HVAC building. In the HVAC building, the facilities (printer room, meeting rooms etc.) were located in the middle of the open plan office and occupants sat next to the window or a seat away from the window. All windows were fixed, while internal blinds were the only available adaptive opportunity. The MM building was designed, as individual offices with a variety of thermal control systems, including an openable window, a thermostat, internal and external blinds. Thus, personalised thermal control was possible resulting in different indoor conditions, including neutral and slightly cool PMV conditions. On the contrary, the HVAC building provided a uniform thermal environment with a slightly cool PMV. In the HVAC building, individual differences were observed in both perception and preference of the thermal environment. This was quite visible in occupants, who sat closely together. For example, S07 and S08 shared an immediate environment. S07 considered the thermal environment as slightly warm and preferred slightly cooler temperatures, while S08 considered the thermal environment as cold and preferred a much warmer temperature. They both reported feeling quite uncomfortable and dissatisfied; although, the degree of the negative feelings were much stronger in the S08 case. Another example is S09, S10 and S11, as S09 felt slightly cool and preferred slightly warmer, S11 felt slightly warm and preferred slightly cooler, while S10 felt neutral and preferred no change.

Some occupants shared similar TSV, but their TP was quite different. For example, S12 and S13 both felt slightly cool, while S13 preferred slightly warmer and S12 preferred no change in the temperature. This was reflected in the differences between their comfort and satisfaction levels, as S12 was very satisfied and very comfortable; while S13 was slightly satisfied and neutral comfort level. Another observation is regarding occupants, who shared similar type perceptions, but different intensities; which was reflected in different intensities in their preferences. For example, S01 and S02 both felt towards the cool side; however, S02 felt slightly cool, while S01 felt cold. Although both preferred warmer temperatures, their preferences were different in terms of intensity, as S02 (with TSV=cold) preferred warmer, while S01 (with TSV=slightly cool) preferred much warmer.

No particular pattern was found between occupants' responses with close proximity to the windows or the orientation of the building. Despite the uniformity and consistency of the thermal environment throughout the day, only 40% of the respondents were consistent in their perception and preference of the thermal environment throughout the day (three times a day survey). 60% of the participants had different perceptions and preferences throughout the day.

In the Swedish HVAC building, occupants only wore trousers, while no skirts or dresses were observed. The follow up interviews confirmed that several ladies considered the office uncomfortably cool and not suitable for exposed legs. Two female occupants mentioned the need for extra clothing layers upon entering the building in summer, due to uncomfortably cool indoor conditions. This suggests that energy was used to cool the building in summer, while this was uncomfortably cool for some occupants. Thus, energy can be saved by increasing the set point of temperature during summer, while enhancing thermal comfort.

In the MM building, the occupants set the indoor environment. 16 workstations (62%) had a neutral PMV and the remaining 10 workstations (38%) had a slightly cool PMV. As a result, the overall comfort of the MM building was 16% higher than the HVAC building and the satisfaction level of the MM occupants was 28% higher than the HVAC occupants. Also, further analysis revealed that the PMV was not consistent throughout the day in 17 out of 26 cases (65%). In 18 cases (69%), the indoor conditions were not in line with the orientation of the windows and solar gain. 24 participants (92%) were not consistent regarding their perception and preference of the thermal environment throughout the day. In the MM building, 48% of the cases, the respondents preferred no change in the thermal environment. In the HVAC building 60% of the occupants preferred a change in the thermal environment, with a majority preferring slightly warmer to much warmer temperatures.

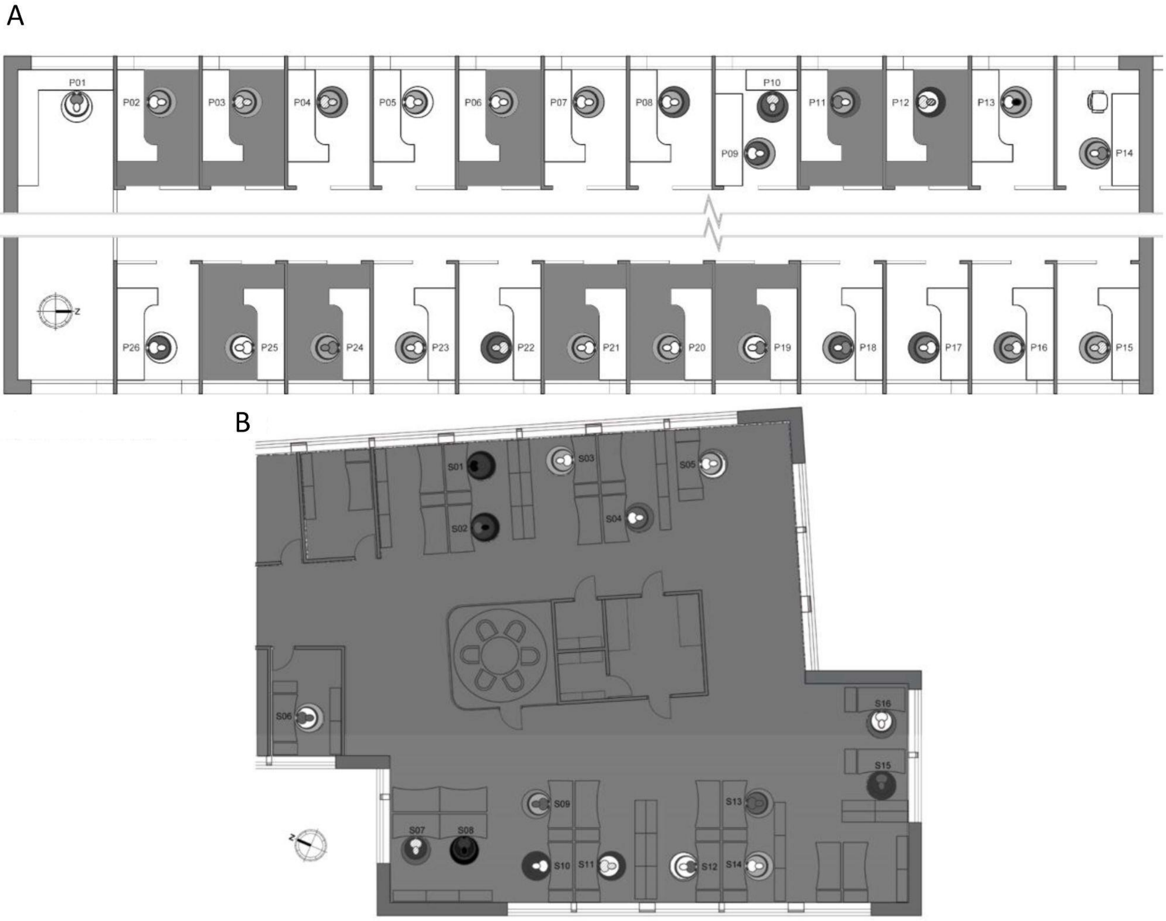


Figure 20.7 VTL analysis. A: MM building in Norway; B: HVAC building in Sweden.

In the MM building, in 75% of the cases (58 out of 77 responses), the participants reported a comfortable or very comfortable status. This number dropped down to 59% (22 out of 37 responses) in the HVAC building, suggesting that the overall comfort level of the MM building was 16% higher than the HVAC building. In the MM building, 60% of the cases reported feeling satisfied or very satisfied with the thermal environment. This number dropped down to 32% in the HVAC building, suggesting that the satisfaction level in the MM building was 28% higher, as compared to the HVAC building.

Energy and Health

The energy consumption of the Norwegian MM building was 552.8 KWh/m^2 per year, while it was 98.6 KWh/m^2 per year in the Swedish HVAC building. The energy consumption of the MM building was over five times higher than that of the HVAC building. Observations revealed that the windows were constantly left open in the MM building, while cooling was in operation. The follow up interviews revealed that windows were left open during winter, when the heating was on. Japanese MM buildings were changeover, and thus, windows were firmly shut during the winter. Also, during the summer, careful consideration was given to opening the windows to ensure that the AC is off.

Building related symptoms were investigated in the Norwegian and Swedish buildings. These symptoms included dry or watery eyes; blocked or runny nose; dry or irritated throat; chest tightness; headaches; and tiredness. Overall, the occupants of the Swedish HVAC building suffered up to 23.3% more from building related symptoms, as compared to the respondents of the Norwegian MM building (Table 20.3). However, tiredness in the MM building was 13.8% higher than the HVAC building.

Table 20.3 Percentage of the occupants “never suffered” from the symptoms.

Symptoms	MM (%)	HVAC (%)	Difference (%)
Dry or watery eyes	65.4	58.8	6.6
Blocked or runny nose	76.0	70.6	5.4
Dry or irritated throat	84.6	76.5	8.1
Chest tightness	96.2	94.1	2.1
Headaches	64.0	47.1	16.9
Tiredness	33.3	47.1	-13.8

Discussion

Thermal Comfort

The results indicated that the HVAC offices provided a uniform thermal environment with limited seasonal temperature differences throughout the year. However, MM offices provided a more dynamic thermal environment, which was more connected to the outdoor thermal conditions. This worked better with occupants’ seasonal clothing expectations. The yearly temperature fluctuations in the HVAC buildings in Japan were negligible, while a wider yearly temperature range was observed in the MM buildings (up to 4°C). Higher summer temperatures (27°C) and lower winter temperatures (22°C) were observed in MM buildings suggesting adaptation to outdoor temperatures. On the other hand, in HVAC buildings, the temperatures were respectively 26°C and 24°C in an attempt to provide consistent indoor temperatures regardless of the season or outdoor temperatures.

In the Swedish HVAC office, despite the consistency and uniformity of the indoor temperature throughout the day, only 40% of the occupants were consistent in their perception and preference of the thermal environment throughout the day. 65% temperature fluctuations were observed throughout the day in the Norwegian MM office and in several cases this was not consistent with the outdoor temperature or the building orientation, suggesting individual differences in temperatre settings. 92% of the occupants were not consistent regarding their thermal perceptions and preferences, suggesting the dynamic aspect of thermal comfort, as discussed by Shahzad et al. (2018). In 48% of the cases, occupants preferred no change in the temperature, regardless of their thermal sensation.

Adaptive Opportunity

By providing a uniform thermal environment and lack of adaptive opportunities (only blinds), the Swedish HVAC building did not respond to individual differences in perception or preference of the thermal environment. The individuals seated close together had very diverse and in cases quite contrasting thermal perceptions and preferences. On the contrary, the Norwegian MM building provided a variety of adaptive opportunities for individuals to regulate the thermal environment to find their own comfort, which responded well to individual differences. As a result, the respondents of the Norwegian MM building had higher overall comfort (16%) and satisfaction (28%) levels, as compared to the participants of the Swedish HVAC building.

Similar trends in the availability of adaptive opportunities were observed in the Japanese HVAC and MM buildings. In the Japanese MM buildings, opening the windows was highly used, particularly in spring and autumn, suggesting that the building was free running as much as possible. Openable windows, pedestal fans and local heaters were highly used in the MM buildings, while the HVAC buildings did not provide such opportunities. Cooling was much less used in the MM buildings, as compared to the HVAC buildings. Passive behaviours were highly adopted in both building types. The occupants of the HVAC buildings reported using cool behaviours, when feeling warm during autumn and winter, which was not the case in the MM buildings. This suggests that some occupants felt uncomfortably warm during the heating season. In winter, much more use of adaptative behaviours were observed in the MM buildings, as compared to the HVAC buildings.

Health

Generally, HVAC buildings are associated with higher risks of building related symptoms (Finnegan et al., 1984, Jaakkola et al., 1991, Rollins and Swift, 1997, Brasche et al., 2001), while natural ventilation is associated with better health conditions (Jaakkola and Miettinen, 1995). Natural ventilation can reduce the infection rate (Atkinson et al., 2009). Shahzad (2013) argues that the design of the building and ventilation system is important in maintaining occupant health. She recommends against prejudgments, as a poorly designed natural ventilation can put occupant health at risk. To reduce the spread of the COVID-19 disease, WHO (2020) recommended the use of natural ventilation. In case air conditioning is in use, WHO suggested a higher rate of indoor air exchange and to reduce mixing the old and fresh air. An MM building designed for smaller office spaces and equipped with openable windows may be a better option to make the building more resilient for future pandemics, as compared to large open plan offices relying only on air conditioning. During the COVID-19 situation, large gatherings were not recommended and only small gatherings were allowed in order to slow down the spread of the virus. Also, natural ventilation and providing barriers between desks were recommended (UK Government, 2021). In this work, occupants of the Swedish HVAC building suffered up to 23.3% more from building related symptoms, as compared to the respondents of the Norwegian MM office.

Energy and Occupant Behaviour

Energy was needed to maintain the constant temperature all year round in the HVAC buildings, as they were constantly either cooled down or warmed up. The MM buildings had the advantage of relying on natural ventilation almost half of the year, which according to Brager et al. (2000) suggests less cooling demand and thus energy saving. However, the Norwegian MM building used over five times more energy than the Swedish HVAC building. The simultaneous opening of the windows, while heating and particularly cooling was in operation was suggested to be the main cause of this energy use in the MM building. This suggests that careful consideration is required in designing an MM building, as a good design of the system can save energy, while a poorly designed system can significantly add to the energy use of the building. For example, in the concurrent strategy, air conditioning and openable windows operate simultaneously, according to occupant needs. When the system detects the windows have been opened, the air conditioning can be reduced automatically (CIBSE, 2000, Brager et al., 2000). This was not applied in the Norwegian MM building. Also, although a thermal control unit was available, visible and accessible at the entrance of every office space, this digital unit was observed, as quite complicated in use, which was confirmed by the follow up interviews. This confirms the findings of Leaman (1993, 1996) regarding the importance of the simplicity of the thermal control systems. Although the energy use of the Swedish HVAC building was quite low, many occupants felt uncomfortably cool in the summer, suggesting unnecessarily cooling the building. Thus, additional energy was being used to cool the building, while 61% of the occupants were not comfortable. So, energy can be saved by increasing the temperature setting (Rijal et al. 2021).

In the Japanese MM buildings, windows were firmly shut during the winter. Also, during the summer, careful consideration was given to opening the windows to ensure that the AC is off. A similar trend is also reported in dwellings (Rijal et al. 2019), which is effective to heat up and cool down the space more efficiently. Occupants' awareness of the energy use was observed much higher in the Japanese MM offices than in the Norwegian MM building. This suggests that occupant awareness of the building system and energy use of the building is very important in saving energy in an MM building.

Conclusions

Overall, MM office buildings are better suited for future resilient comfort, as compared to fully HVAC sealed offices. Considering the future energy challenges, potential pandemics, and higher expectation of thermal comfort, MM buildings are more adaptable and suitable options. The availability of thermal control or adaptive opportunity for occupants is another great advantage of MM buildings. This is particularly important, as the building industry is moving away from providing occupant control and it tries to "simplify" the building performance through centrally operated control systems, such as a fully HVAC office with no openable windows or user control. This is not align with the current users' expectation and experience of control at the tip of their fingers through technologies. It appears that rather than acknowledging this need, the building industry moves away from it creating a further gap between building performance and end users. This work showed that MM buildings performed better and provided a much higher user experience, as compared to fully HVAC offices. The work concludes with the following key findings:

- *Future Resilience:* MM offices are more resilient regarding both energy and comfort, as compared to HVAC office buildings. They have higher levels of occupant comfort, satisfaction, and health levels overall, while they have the potential for a low energy use. Also during a power outage, an MM building takes advantage of natural ventilation and end user control.

- *Thermal Comfort:* The indoor temperatures of the MM buildings were more dynamic and connected to outdoor temperatures and seasonal conditions. Also, the temperature differences throughout the year reached 12.5°C. On the contrary, HVAC buildings provided a uniform and consistent thermal environment all year round with a narrow indoor temperature band of 2°C. The Norwegian MM building had 16% higher overall comfort and 28% higher satisfaction levels, as compared to the Swedish HVAC office.

- *Thermal Control:* Variety of adaptive opportunities were provided in the MM offices, while the HVAC buildings lacked any thermal control. Seasonal variations in the use of different systems were observed. The adaptive opportunities were well used in the MM buildings, particularly openable windows, pedestal fans and local heaters, responding well to individual differences in perception and preference of the thermal environment.

- *Healthy Buildings:* MM buildings are more suited to future proofing the buildings against potential pandemics, due to lower number of occupants sharing a space as well as encouraging fresh air through openable windows to reduce the risks of catching a virus, such as COVID-19 (WHO, 2020). In this work, building related symptoms were observed up to 23.3% higher in the Swedish HVAC building, as compared to the Norwegian MM office, suggesting greater health conditions in the MM building.

- *Energy:* Contradictory findings were observed in this work, as the MM building used five times more energy than the HVAC building; potentially due to the complexity of the thermal control unit and the simultaneous use of openable windows with cooling and heating. Other studies demonstrated that a well designed MM building has the potential to reduce the energy, particularly that of cooling load (Emmerich, 2006, Brager and Borgeson, 2007). However, careful design of the system is needed to either turn off the AC or to minimise it, when the windows are open to avoid unnecessary energy loss. Also, in the Japanese buildings, 20% less cooling was used in the MM buildings, as compared to the HVAC buildings. It indicated that significant energy can be saved by the appropriate design of an MM building.

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