THERMAL PERFORMANCE AND BEHAVIOURAL DIVERSITIES OF WORKERS AT MIXED-MODE OFFICE BUILDINGS IN MANNAR: A FIELD INVESTIGATION

KANISTAN A.A.[1]* & RAJAPAKSHA I.G.P[2]
[1, 2]Department of Architecture, University of Moratuwa, Moratuwa, Sri Lanka
[1]*antony.kanistan@gmail.com*, [2]*indrika@uom.lk*

Abstract: Sri Lanka faces escalating electricity consumption, with buildings contributing significantly. Indoor overheating, exacerbated by inadequate sustainable design, compromises occupant comfort and amplifies energy demand in both air-conditioned and naturally ventilated buildings. This study investigates the impact of building design and occupant behaviour on thermal comfort in government office buildings in Mannar City. Case study was analysed based on orientation and height. Objective assessment and subjective assessment were collected. Thermal comfort was analysed using ASHRAE scales, PMV, and AMV. Occupant behaviour, including window opening, fan usage, and clothing adjustments, was examined. Results indicate a disparity between occupant comfort and building performance. While occupants employed adaptive strategies, the buildings exhibited thermal discomfort. The study highlights the need for integrating occupant-centered design and sustainable strategies to optimize energy efficiency and enhance occupant well-being. Future research should explore retrofitting strategies to improve overall building performance.

Keywords: *Thermal comfort, Behavioural adaptation, Office Buildings, Mixed mode ventilation, Dry zone*

1. Introduction

The IPCC report emphasizes the urgent need for accelerated building renovations and the construction of ultra-efficient buildings in order to limit global warming to 1.5°C. Achieving this goal necessitates a 43% reduction in global greenhouse gas emissions by 2030, compared to 2019 levels (Calvin et al., 2023). Sri Lanka, like many countries worldwide, is currently grappling with an energy crisis. Attalage and Wijetunge (1997) highlighted that the demand for energy in Sri Lanka has been growing at an annual rate of 8%. During the first half of 2019, energy demand surged by 1.9%, with a peak demand of 2,616 watts. In 2020, the Ceylon Electricity Board utilized 6,460 GWh out of the total 7,308 GWh produced, further stressing the energy sector. The high energy consumption in office buildings is largely due to indoor overheating, with occupants relying on air conditioning to achieve thermal comfort.

Sri Lanka's dry zone, which is one of the main climate zones of the country, is characterized by hot and dry weather. In such regions, it is crucial to consider the climate when designing buildings that are thermally efficient and energy conscious. Achieving thermal comfort in these buildings requires either removing excess heat or retaining heat when necessary. The adoption of the right design strategies is essential for creating energy-efficient buildings. Building typologies that align with the local climate conditions are key to fostering a sustainable built environment.

Mannar, located in the Northern Province of Sri Lanka, falls under the hot and dry climate category, with temperatures soaring high and severe drought conditions prevailing from March to September. The existing government office buildings in Mannar do not adequately respond to the local climate, which results in indoor spaces becoming excessively hot. Consequently, this leads to a high reliance on air conditioning to ensure thermal comfort, contributing to an increase in energy consumption. This study aims to investigate the thermal performance of mixed-mode ventilated office buildings in Mannar. It seeks to assess the thermal conditions of these buildings and analyze how occupants' behaviors influence and respond to the thermal environment.

2. Literature Review

2.1. THERMAL COMFORT AND ENERGY USE FOR THERMAL COMFORT

Temperature comfort, as described by Ferrari and Zanotto, (2012) refers to the state of mind that is content with the surrounding temperature conditions. Improved thermal comfort would be beneficial for individuals in any setting and would enhance their overall well-being. The fundamental components impacting thermal comfort are both human and

*Corresponding author: Tel: +94771845309 Email Address: antony.kanistan@gmail.com
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environmental features. The environmental factors include air temperature, radiant temperature, air velocity, and humidity. Personal factors to consider include clothing insulation and metabolic heat. A crucial factor that influences the thermal comfort of a location is the circulation of air. The inhabitants' effectiveness and production decline when the heat conditions inside are not sufficiently comfortable. Extreme deviations from normal temperature can cause discomfort or anxiety to the occupier (Holopainen et al., 2014).

Buildings consume a significant quantity of energy to attain thermal comfort. In tropical regions with warm and humid climates, buildings mostly consume energy for mechanical ventilation and cooling, namely for air conditioning. In colder regions, the primary energy source is predominantly utilized for heating applications. The disparity between indoor and exterior temperatures is the crucial determinant in minimizing energy usage for cooling or heating purposes. As stated in Nicol et al., (2012) in the UK, roughly 10% of the heating energy used in winter is typically saved by a reduction of 1K in the indoor temperature. According to Holopainen et al., (2014) from an environment point of view, the environmental impacts and the use of resources are associated to maintain certain thermal comfort levels mainly caused by the production, installation operation and maintenance of HVAC systems.

Traditional structures exhibit a range of temperature conditions, as documented by Nicol et al., (2012). It offers options to increase the happiness levels of individuals occupying the space. Kwok and Rajkovich, (2010) stated that, thermal environments that promote productivity and do not induce undue stress on the occupant are part of responsible building design. Currently, people are striving to design buildings that integrate passive design strategies to reduce the amount of energy needed for their operation. Additionally, they are employing adaptive ways to ensure optimal thermal comfort within these structures. Givoni, 1998 stated that, "design principles aim at maximizing comfort and minimizing the use of energy for heating and cooling".

Janda, (2011) stated that, "Occupants, not buildings are the primary consumers of energy because they behave protectively within their indoor environments to seek comfortable personal conditions and to perform energy related tasks. Accordingly, they consume energy for the purpose of heating, ventilation, air conditioning, lighting, plugin loads/appliances and domestic services. If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort". When occupants engage in energy consumed adaptive behaviours, they can either modify their surrounding environment to align with their thermal preferences and needs (such as opening or closing doors and windows, turning off fans and lights) or adjust their clothing to adapt to the changing thermal conditions. According to Sonderegger, (1978) The behaviour of occupants has a significant impact on the energy performance of a building. Study done by Maier et al., (2009) further reveals that the changing patterns of the occupant behaviour have a huge impact on the energy consumption of buildings. As stated in Sardianou, (2008) the age of the occupant, family size, annual income and the size and ownership of dwelling can be found as the determinants of energy consumption of buildings. This indicates that the socioeconomic status has an impact on the behaviour patterns of occupants thus has an impact on the energy consumption.

2.2. THE 'HEAT BALANCE APPROACH' FOR DEFINING THERMAL COMFORT

As cited in Nicol et al., (2012) thermal comfort, defined as a state of mind reflecting satisfaction with the thermal environment (ASHRAE, 2004), has been extensively researched. Two primary modelling approaches have emerged: empirical models based on occupant surveys and heat balance models grounded in human physiology. Fanger's static model, relying on PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) indices, is widely used. PMV quantifies the average thermal sensation, while PPD estimates the proportion of dissatisfied individuals. These indices are calculated using six parameters: metabolic rate, clothing insulation, air temperature, air velocity, humidity, and mean radiant temperature.

However, the static model's universal applicability has been questioned due to its neglect of psychological, physiological, and behavioural factors. Consequently, the adaptive model was developed, acknowledging human adaptability to varying thermal conditions. This model emphasizes the role of occupants in achieving thermal comfort through physiological adaptation, psychological habituation, and behavioural adjustments, such as clothing changes, window operation, and fan use.

Overheating is a critical issue in tropical regions, primarily caused by inadequate building design. Passive design strategies and the integration of adaptive comfort principles are essential for mitigating overheating. By understanding the interplay between building design, climate, and occupant behaviour, buildings can be designed to optimize energy efficiency and occupant well-being. While the adaptive model offers potential for energy savings, further research is needed to explore its implementation in different climatic regions and building typologies. Additionally, the impact of cultural factors on thermal comfort preferences and adaptive behaviours warrants investigation.

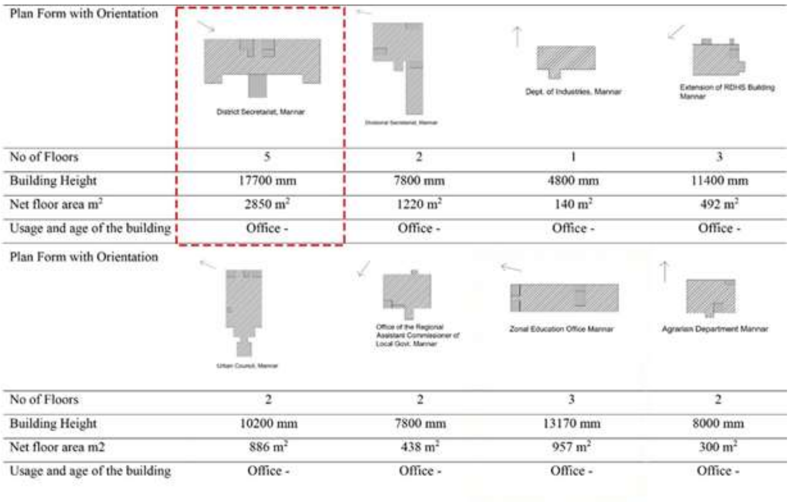
3. Research Methodology and Data Collection

The sampling process involves selecting one critical case study building from eight office buildings based on set criteria for field investigation, divided into objective and subjective methods. The objective investigation examines the thermal performance of the building using instruments like Hobo loggers and thermocouples, with data analysed alongside ambient temperature records from the Meteorological Department to identify key thermal trends across mixed-mode, air-conditioned, and non-air-conditioned zones, as well as surface and perimeter temperatures. The subjective investigation assesses occupants' thermal comfort and behavioural patterns through questionnaires, complemented by airspeed measurements using a VelociCalc anemometer. The results from both investigations are then analysed together to evaluate the building's thermal performance, comfort levels, and occupant behaviour.

3.1. SELECTION OF CRITICAL CASE STUDY OFFICE BUILDINGS

Eight Mannar office buildings were chosen for the sampling process. Only eight buildings were taken into consideration due to data constraints and city limits. One case study was chosen for this research because of time and weather constraints. The investigation was restricted to a week due to the difficulty in locating hot days caused by rainy days. Typical hot days made up the bulk of the investigation week's heat index. After the mapping of Office buildings, case studies on the following criteria. Height of the building: Maximum height building chosen with the assumption of highest energy consumption and average height building selected.

Figure 1, Method of data collection & analysis (Source: Author1*)

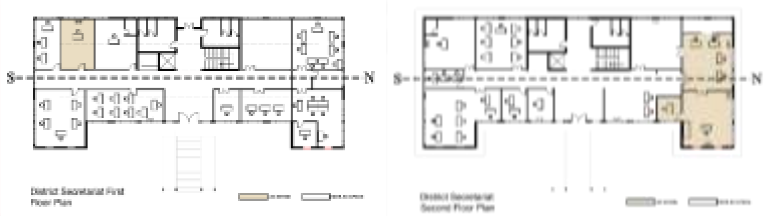


Plan Form with Orientation				
No of Floors	5	2	1	3
Building Height	17700 mm	7800 mm	4800 mm	11400 mm
Net floor area m^2	2850 m^2	1220 m^2	140 m^2	492 m^2
Usage and age of the building	Office -	Office -	Office -	Office -
Plan Form with Orientation				
No of Floors	2	2	3	2
Building Height	10200 mm	7800 mm	13170 mm	8000 mm
Net floor area m2	886 m^2	438 m^2	957 m^2	300 m^2
Usage and age of the building	Office -	Office -	Office -	Office -

Figure 2, Analysis of eight buildings in Mannar (Source: Author1*)

3.2. DESCRIPTION OF CRITICAL CASE STUDY OFFICE BUILDINGS

Table 1, Description of Selected case study building

	Case Study
Morphology	
Orientation	South-North Orientation (Long Axis)
Number of Storey	5
Composition	Detached
A/C Area	Yellow coloured Hatch areas mechanically ventilated areas, others are naturally ventilated
A/C Set Point	26 C
Building Envelope	Sealed – Airtight
Number of Occupants	141

Working Hours	08:30 to 16:30 | Monday to Friday
Wall to Window Ratio	33%
Material Composition of Front Façade	

3.3. FIELD INVESTIGATION: OBJECTIVE ASSESSMENT

The Pilot study is conducted consecutively for a period of 7 days, commencing at 12 PM on December 12, 2023, and concluding at 12 PM on December 18, 2023. The indoor temperature was assessed, specifically in spaces that were naturally ventilated and spaces that were air-conditioned. Due to the scarcity of Thermocouple Loggers, only the surface temperature of the East and South Façade on the First Floor was recorded. To accurately assess the real indoor temperature of the air-conditioned spaces, the Thermal loggers were consistently placed in the same spot throughout the entire weekend.

Hobo Loggers were positioned in the perimeter zone of all four facades. The vertical distance from the floor to the ceiling is 3 meters. Hence, the perimeter zone extends up to a distance of 6 meters from the façade. Due to the significant solar heat gain in the East and West perimeter zone, the Hobo loggers were consistently active for the entire duration of 7 days. Due to limitations of Thermal Hobo Loggers, it was necessary to temporarily position one in the North perimeter before moving it to the South perimeter. Thermocouple placed in East.

3.4. FIELD INVESTIGATION: SUBJECTIVE ASSESSMENT

The indoor temperature was measured using both Hobo loggers and Thermocouple devices. In addition, a survey was conducted among all staff members working on the selected floors of the building. These individuals possess extensive knowledge of the current climatic conditions for a minimum of six months and are aged between 25 and 60. Every participant was surveyed once they had become accustomed to the surveying environment for a period of time that was longer than 20 minutes. The mean metabolic rate observed was 1 Met for writing and 1.1 Met for typing. The conversion rate for 1 meter is 58.2 W/m^2.

The indoor air temperature is a crucial factor required for conducting thermal sensation analysis. Survey conducted of the subjects while measuring indoor temperature. The office staff members were present during office hours, which were from Monday to Friday, starting at 08:30 and ending at 16:30. Consequently, participants were surveyed from the specific date when thermal equipment (Hobo Loggers and Thermocouple) were placed. A comprehensive survey was conducted on 50 individuals during weekdays. During the survey, the air velocity is determined using a “Velocicalc Anemometer”. The anemometer is positioned close to the subject and securely attached to a tripod in order to minimize any potential errors.

Given that case study office building, it is customary for the employees to adhere to a dress code that includes formal attire, such as trousers and long or short sleeve shirts for males, and sarees for females. Data regarding clothing insulation, metabolic rate, thermal sensation vote, health conditions, and physical attributes of office space were collected by employing a structured questionnaire and conducting observations.

4. Analysis and Results

4.1. INDOOR AVERAGE TEMPERATURE IN MIXED MODE SPACES

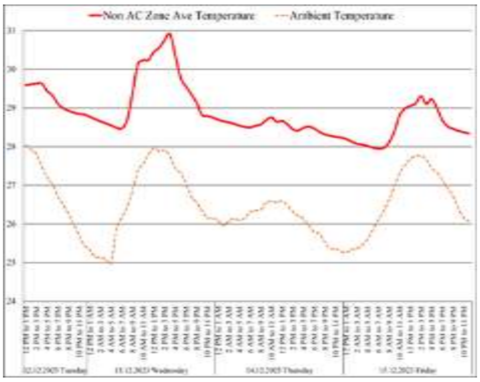


Figure 3, Weekdays Indoor average temperature profile in non-AC Zone

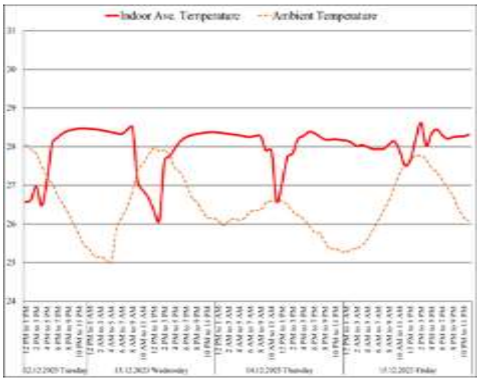


Figure 4, Weekdays Indoor average temperature profile in AC Zone

Indoor temperatures in the non-AC zone are usually higher than in the AC zone. This is expected as the AC zone is artificially cooled. The non-AC zone averages 29°C, whereas the AC zone averages 26°C. Afternoon and evening temperatures are higher in non-AC and AC zones. Due to the lowest solar heat gain both zones have the lowest morning temperatures. Non-AC zone indoor temperatures peak at 31°C on Wednesday, December 13th. This is much higher than the AC zone's max temperature of 26°C that day.

Figure 5 and Figure 6 shows the same pattern of line. Non-AC Zone mean temperature is 28.1 °C, AC Zone mean temperature is 27.81 °C. ΔT = 0.29 °C Both zones have approximately identical indoor temperatures without air conditioning. All the perimeter zones are overheated according to the weekend. This indicates the real situation of indoor of all the perimeter zones.

4.2. INDOOR AVERAGE HUMIDITY PROFILE IN NON-AC AND AC ZONES IN WEEKDAY AND WEEKEND DAYS

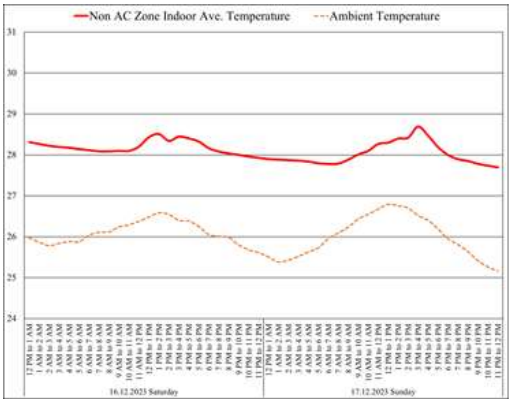


Figure 5, Weekend Indoor average temperature profile in non-AC Zone

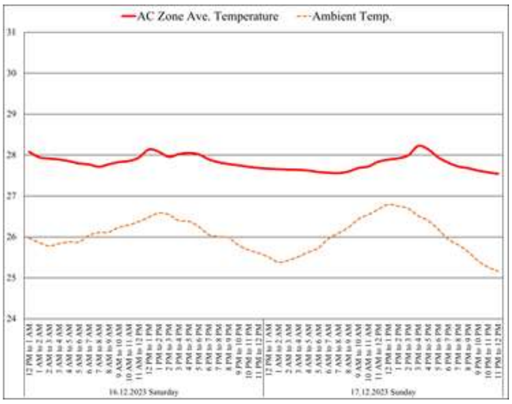


Figure 6, Weekend Indoor average temperature profile in AC Zone

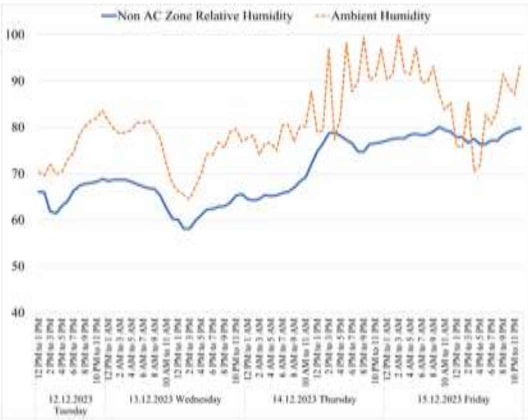


Figure 7, Non-AC Zone Humidity Profile in Weekdays

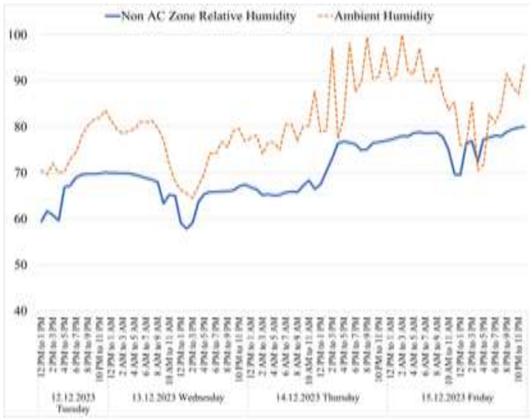


Figure 8, AC Zone Humidity Profile in Weekdays

In Weekdays and Weekend, both zone in Figure 7 and Figure 8 appears with similar pattern of Humidity. Therefore, there is no any major changes in Humidity in Both zones.

4.3. INDOOR TEMPERATURE PROFILE IN PERIMETER ZONES

The figure 9 shows North Perimeter Zone and South Perimeter has highest value of indoor temperature than other perimeter zone temperatures. North Perimeter Zone shows the higher value of indoor temperature in Weekend. East Perimeter Zone, which is AC Zone, has lowest value of indoor temperature. West Perimeter Zone indoor temperature falls between East Perimeter Zone and South, North Perimeter Zone. West Perimeter Zone which is AC Zone minimum temperature is 24.9 °C, maximum is 28.9 °C. All the perimeter zones' indoor temperatures above the ambient temperature in weekend without AC.

All the perimeter zones are overheated according to the weekend. This indicates the real situation of indoor of all the perimeter zones. West Perimeter Zone in weekend shows the same pattern of temperatures with other perimeter zones. In weekdays West Perimeter Zone uses AC to reduce the indoor temperature in warmest day 12:00 pm to 2:00 pm. Ambient temperature on that period is 28 °C, West Perimeter Zone indoor temperature is 24.9 °C. Can be seen the difference 3.1 °C which causes high energy cooling demand. Since the North Perimeter zone and South Perimeter zone are overheated, these perimeter zones are discomfortable environments. East Perimeter zone's minimum temperature is 25.9 °C, Ambient temperature on that time is 27.7 °C. Difference can be seen 1.8 °C. West Perimeter zone demanding for cooling is higher than East Perimeter zone demanding.

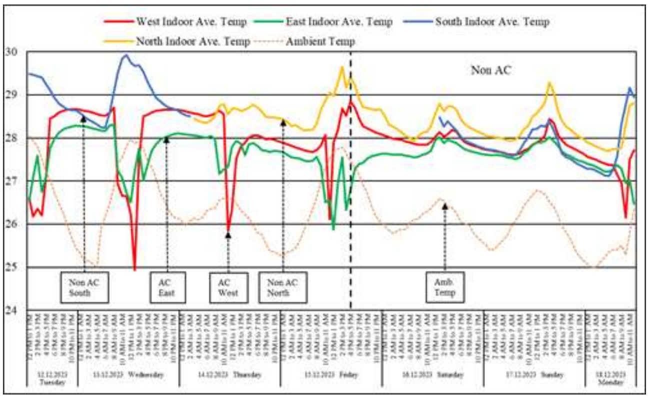


Figure 9, Indoor temperature profile in perimeter zones

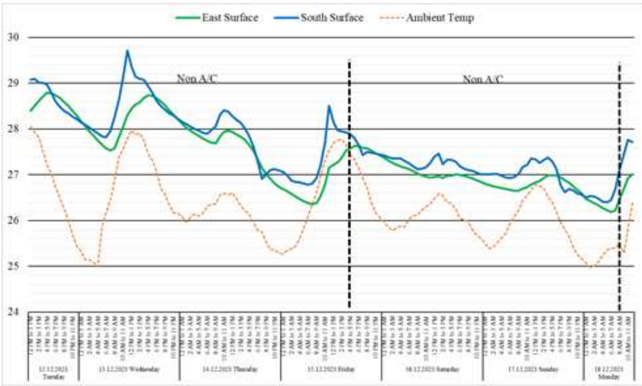


Figure 10. Indoor Surface temperature profile of Case

The rise in overall indoor wall surface temperature than the ambient temperature can be clearly seen during the office hours. South Façade indoor wall surface temperature is higher than the East Façade indoor wall surface temperature.

4.4. THERMAL SENSATION ANALYSIS

In this study, sensations and preferences of occupants were accessed by using questions “How do you feel right now?” and “How would you prefer to feel?” based on temperature. Following figures show the distribution of sensation votes and preference votes of temperature across Non-AC Zone and AC Zone. This evaluation only focuses on Thermal sensation of occupants. PMV and PPD values were computed utilizing the CBE thermal comfort online tool. The online tool requires the following input data: relative humidity (RH), indoor velocity (V), operating temperature (To), metabolic rate (Met), and insulation provided by clothing (Clo).

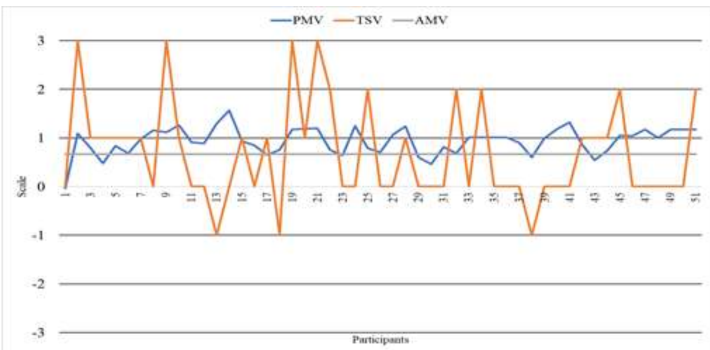


Figure 11. Case study PMV, TSV, AMV Comparison

According to Figure 11, the majority of the individuals perceive the atmosphere to be warmer. The Actual Mean Vote (AMV) is closer to +1, indicating that the overall inhabitants perceive an average level of warmth. However, the thermal perception varies depending on the climatic periods, adaptation behaviours. According to this assessment, the warmest day of the entire week is determined to be December 13th. Hence, the initial 26 individuals responded to the thermal sensation inquiries on December 13th. According to Figure 11, the residents on December 13th experience a higher level of warmth compared to other days. The TSV (Thermal Sensation Vote) exceeds the PMV (Predicted Mean Vote), indicating that the inhabitants in Case study building experience a higher level of discomfort which clearly indicates the overheated environment from occupants perspective.

4.5. THERMAL ADAPTATION BEHAVIOURS

Adaptive thermal comfort is founded on the underlying assumption that when a change causes discomfort, individuals respond in ways that aim to regain their comfort (Auliciems, 1981). In a building with natural ventilation, inhabitants utilize various behavioral and control measures, such as movable windows, doors, blinds, curtains, fans, and fan regulators, to modify the air velocity and ensure their comfort in response to the changing temperature conditions. The utilization of these adaptive controls is also influenced by changes in indoor climatic conditions. This study focuses on the behavioral adaptations of office workers who are confined to their working environment. Specifically, it analyzes the effects of two methods that occupants can use to make themselves comfortable: opening windows and utilizing a fan.

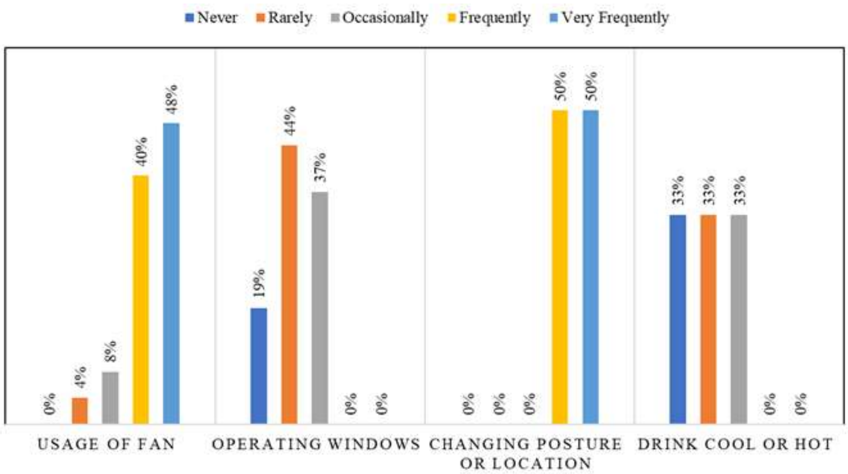


Figure 12. Adaptation behaviour of Occupant in Case study

Use of controls: windows, external door and fan: In the questionnaire, the adaptive behavior of occupants for use of controls such as opening windows, external door and use of fan was recorded. The majority of occupants utilize fans to create a comfortable environment, indicating a high usage of fans that results in high energy consumption. Additionally, Figure 24 demonstrates a low frequency of window openings. This is due to the presence of glare, which indirectly suggests a lack of shading.

4.6. ANALYSIS

The thermal study of the building shows a clear difference in indoor temperatures in different zones, affecting energy use and comfort. Non-air-conditioned (non-AC) zones are much warmer, with an average temperature of 29°C, compared to 26°C in air-conditioned (AC) zones. On the hottest day, December 13th, non-AC zones reached 31°C, while AC zones stayed at 26°C. This shows how AC zones depend on artificial cooling, while non-AC zones don't have enough passive cooling to keep them comfortable.

The perimeter zones have noticeable differences in temperature. The North and South Perimeter zones are the hottest, especially on weekends when no cooling systems are used. The West Perimeter Zone, which has AC, needs a lot of cooling because it has a temperature difference of 3.1°C from the outside air during the hottest times. In comparison, the East Perimeter Zone, also with AC, needs less cooling due to better design features. Indoor wall surface temperatures in all zones are higher than outside temperatures, with the South Façade being hotter than the East Façade. This shows the need for better shading, insulation, and materials to reduce heat gain.

Occupants feel the heat clearly, especially on December 13th, the warmest day. Their Thermal Sensation Vote (TSV) shows more discomfort than what the Predicted Mean Vote (PMV) expected. Most people rated the space as warm (closer to +1 in the Actual Mean Vote). Many use fans to stay cool, but this increases energy use. Windows are rarely opened because of glare, showing a need for better shading to reduce discomfort and improve natural ventilation.

5. Discussion and Conclusion

The findings of this study show that office buildings in Mannar, Sri Lanka, experience significant thermal discomfort, especially in non-air-conditioned zones. The comparison between air-conditioned and non-air-conditioned spaces highlights a noticeable difference in temperature control. Non-AC zones, with an average temperature of 29°C, often exceed

30°C, while the air-conditioned zones maintain a more comfortable 26°C. This temperature difference not only reflects the dependency on mechanical cooling to achieve thermal comfort, but also emphasizes the need for passive cooling strategies in naturally ventilated spaces to reduce energy consumption and enhance occupant well-being. The study underscores the importance of designing buildings that are responsive to the hot and dry climate conditions to optimize thermal performance.

The analysis of perimeter zones further demonstrates the influence of building design on indoor temperatures. The North and South perimeter zones, which are directly exposed to intense solar radiation, experience higher temperatures, particularly on weekends when air conditioning is not used. The West perimeter zone, although air-conditioned, requires more cooling due to the greater temperature difference from the outside air, while the East perimeter zone benefits from design features that reduce heat gain. These findings suggest that enhancing building insulation, improving shading, and selecting suitable materials are essential for lowering thermal loads and improving energy efficiency in these buildings.

The study also highlights the role of occupant behavior in the building's overall energy performance. The discrepancy between the Predicted Mean Vote (PMV) and the Actual Mean Vote (AMV) indicates that occupants feel warmer than was anticipated, with many relying on fans and seldom opening windows for ventilation. This suggests the need for better shading strategies to enhance natural ventilation and minimize energy use. The results further confirm that occupant behaviors, driven by both thermal discomfort and energy-saving habits, significantly impact energy consumption. This shows that building energy performance can be greatly influenced by the thermal preferences and actions of its occupants.

Further this study highlights the need to address indoor overheating issues in existing office buildings. Retrofitting these buildings with proper insulation, shading systems, and better natural ventilation will be necessary. These changes will not only improve the comfort levels for the occupants but also reduce the heavy reliance on air conditioning systems. By adopting these improvements, the office buildings in Mannar can respond better to the hot and dry climate, creating indoor spaces that are comfortable for occupants while reducing energy use.

6. Acknowledgement

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