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RESEARCH PAPER

Sustainable building: Achieving thermal comfort in hot and humid climate using building performance simulation

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Abstract. The scientific community has established a clear link between the built environment and various environmental problems. Various strategies have been implemented to mitigate the negative impacts of buildings and to address broader environmental challenges. One such strategy is the adoption of sustainable building practices. Among the factors contributing to the environmental impacts of buildings, efforts to achieve thermal comfort play significant role. Particularly due to the energy consumption involved. At the same time, thermal comfort is also a critical factor influencing human productivity, including academic performance. Comfortable learning environments are known to enhance students' learning outcomes. This research presents a case analysis conducted at State Elementary School 91 Sipatana, Gorontalo City, Indonesia. Measurements were carried out on December 24, 2022, from 06.00 to 18.00. Room temperature was recorded using an Elitech GSP-6 data logger, and further simulations were carried out using Ladybugs and Honeybees. The purpose of this study is to evaluate building performance in achieving thermal comfort by considering solar radiation exposure, roof surface temperature, room temperature, and Predicted Mean Vote (PMV) values. Comparisons were made across different building materials, including variation in roofing, wall types, and ventilation systems. The wall in the existing structure are composed of concrete with a fiber wall. The findings highlight the impact of roofing materials, wall construction, and ventilation on the PMV, roof surface temperature, and indoor air temperature. Based on-site measurements, the average classroom temperature was 30.5°C. Among the simulation configurations, Model 3 which featured a metal roof with a cool roof technology, concrete walls, and added ventilation demonstrated the best thermal performance. It maintained a roof surface temperature just above 25°C and an indoor air temperature close to 30°C, showing the effectiveness of cool roof technology and adequate ventilation in reducing heat accumulation.

Keywords: Building Performance Simulation; Educational building; PMV; Thermal comfort; sustainable building.

1. Introduction

Researchers have identified a connection between the built environment and environmental issues (Smith et al., 1998). Various strategies have been implemented to mitigate the adverse effects of buildings and combat environmental challenges, one of which is the adaptation of

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sustainable building practices. Sustainable buildings are gaining global popularity due to their potential to reduce resource consumptions. However, their implementation also presents administrative, strategic, and operational challenges (Lima et al., 2021) .

Effort to achieve thermal comfort are among the main contributors to the environmental impacts of buildings, particularly in terms of carbon emissions. According to the Energy Consumption Survey in commercial buildings, air conditioning (AC) is the largest consumer of energy, accounting over 62% of average total energy use. Other significant contributors include lighting, electrical outlets, elevators, escalators, and various other electrical devices (Hermanto, 2005). In the modern context, the ability of a product or system to provide comfort is a critical consideration. Beyond offering physical ease, comfort can improve well-being, concentration, efficiency, and overall effectiveness (Pratiwi & Attaufiq, 2024).

One of the primary activities in school is teaching and learning. Learning requires cognitive abilities and sustained concentration, because it involves processes such as reasoning, memory, perception, thinking, and information processing (Sativa & Adilline, 2021). On average, students spend approximately 15,600 hours in the classrooms before earning a school diploma, making classroom time second only to time spent at home (Brager, 2001). A significant relationship exists between classroom indoor environmental quality (IEQ) and students' learning outcomes, psychosocial development, problem-solving skills, and health. Poor indoor air temperatures, inappropriate relative humidity, and unacceptable radiant temperatures negatively affects students' academic performance (Lala & Hagishima, 2022). Therefore, maintaining a thermally comfortable environment in schools and classrooms is essential to support student well-being and academic achievement.

Thermal comfort is defined in the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 55 standard as the "that condition of mind which expresses satisfaction with the thermal environment' (ASHRAE, 2020). The concept of comfort is complex, because it applies both psychological and physiological aspects of overall environment (Gagge & Stolwijk, 1967). Thermal comfort refers to a mental state in which individual feels content with the surrounding thermal conditions. The primary physical variables influencing thermal comfort include air temperature, mean radiant temperature, relative humidity, and air movement or wind speed (Latifah et al., 2013). According to Lippsmeier, the acceptable thermal comfort range for equatorial regions spans from 19°C effective temperature (TE) as the lower limit to 26°C TE as the upper limit. At approximately of 26°C TE, individual typically begin to perspire. Human endurance and work performance start to decline in the range of 26°C TE to 30°C TE. Discomfort becomes more pronounced at 33.5°C TE to 35.5°C TE, and temperatures between 35°C TE and 36°C TE are generally intolerable. Human productivity tends to decrease under uncomfortable air conditions, whether too cold or too hot, while it improves under thermally comfortable (thermic) conditions (Talarosha, 2005).

Building performance simulation is critical tool in addressing sustainable building design and achieving thermal comfort. Such simulations assist in evaluating and improving building designs to optimize performance and reduce energy consumption. Parametric design software emerged in 2008 and since been further developed by various companies and software developers. One of the most commonly used software in this domain is Grasshopper, a graphical algorithm editor integrated with Rhinoceros 3D. It enables users, especially those without formal programming experience, to efficiently generate parametric models (Eltaweel & SU, 2017; Lagios et al., 2010). Grasshopper provides robust operations in design and optimization processes, thereby facilitating the development of environmentally responsive architectural designs (Qingsong & Fukuda, 2016).

The purpose of this study was to assess Predicted Mean Vote (PMV), Field Surface Temperature (FST), and Classroom Air Temperature (CAT) in relation to thermal comfort standards for tropical regions, by modifying roofing materials, wall types, and ventilation systems.

Modifying roofing materials is particularly important, as rooftops can represent approximately 20–25% of the overall urban surface area and up to 30–50% in high-density metropolitan areas, making them a key target for passive cooling strategies (Duan et al., 2025).

To minimize heat absorption by the roof, passive cooling technology was applied using reflective approach. Replacing dark- colored alternatives roofs with lighter-colored alternatives can dramatically reduce heat absorption (Akbari et al., 2006). The use of light-colored cool paints has increased over the past decade, highlighting the effectiveness of cool coating in enhancing roof performance. For instance, applying cool paint to the roof of a single-story house in Jamaica reduced the surface temperature by 2.5-5.5°C and resulted in energy savings approximately 7.5% (Kolokotroni et al., 2018).

Model simulations have shown that on sunny days, a cool coating with a solar reflectance of 0.74 can reduce peak roof surface temperature by up to 14.1°C, indoor air temperature by 2.4°C, and daily heat gain through concrete roofs by 0.66 kWh/m^2 (or 54%). These model predictions closely align with experimental observations, which resulted a surface temperature reduction of 5.4°C and energy savings of 54% (Zingre et al., 2015). In tropical climates, cool roofs have been found to deliver energy savings ranging from 15% to 35.7% (Rawat & Singh, 2022). Additionally, coatings have been shown to lower roof surface temperatures by approximately 20°C and improve ambient air temperatures at ground level by an average of 0.8°C (Djafar et al., 2024).

2. Method

The research was conducted on December 24, 2022, from 06.00 to 18.00 at State Elementary School 91 Sipatana in Gorontalo City, Indonesia, with the objective of measuring both indoor and outdoor temperatures. Indoors, the measuring instrument was placed at the center of the 6th-grade classroom, using Elitech GSP-6 device (Figure 1). Outdoors, the instrument was positioned in the middle of the school field, where a dry-bulb thermometer was employed (Figure 2). The measurement tools used in the study are shown in Figure 3.

After the measurements were completed, simulations were performed using Ladybug and Honeybee, focusing on the thermal properties of roof and wall materials. The input parameters for simulation, including the thermal properties of the selected materials, are presented in Table 1. A total of nine simulation models were developed under four different conditions: variations in roof materials, wall materials, natural ventilation, and the absence of ventilation, as summarized in Table 2.

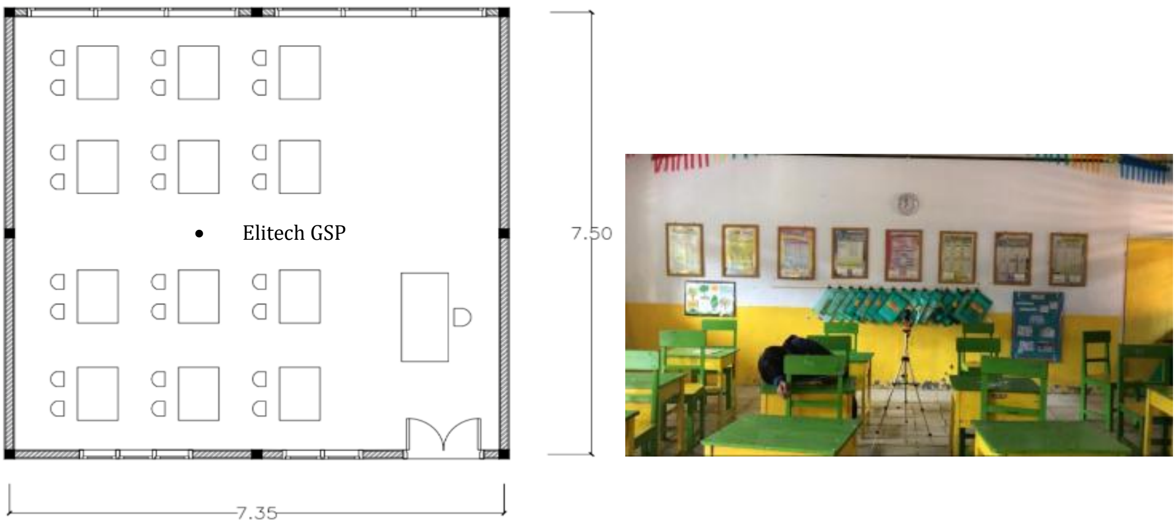


Figure 1. Placement of measuring devices in indoor

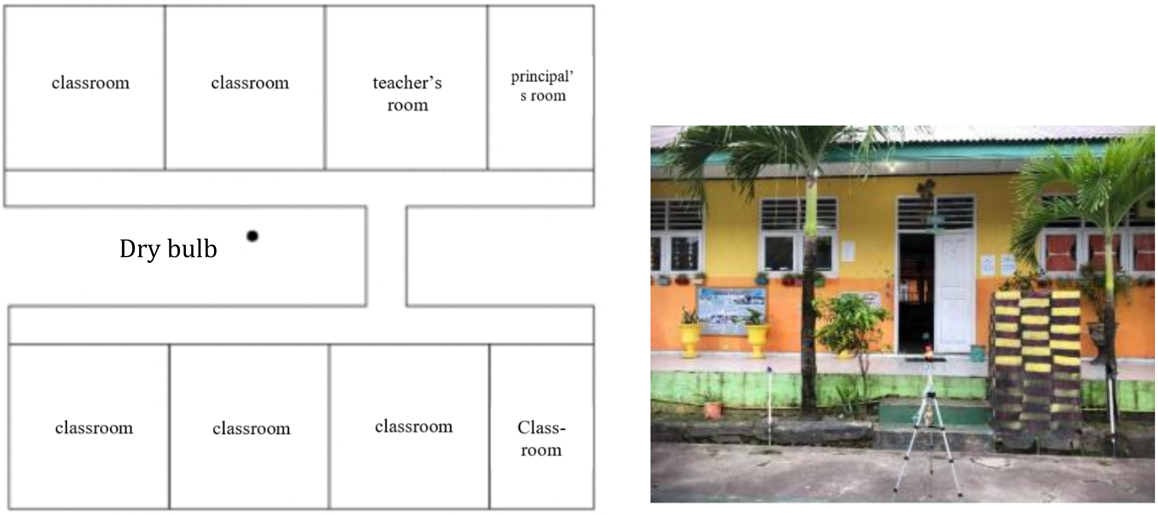


Figure 2. Placement of measuring devices in outdoor

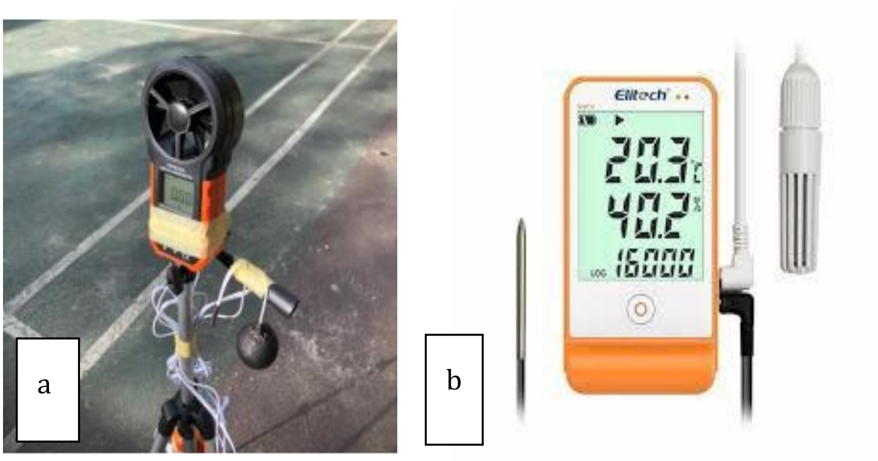


Figure 3. Measurement tools used (a) Dry bulb, (b) Elitech GSP-6

Table 1. Thermal properties of the selected materials

Properties	Roof		Wall	
	Metal	**Plastic/Polymer**	**Stone/Concrete**	**Fiber Composite**
Thickness	0.001	0.004	0.15	0.15
Conduct	13	0.04	0.1	0.1
Density	1700	100	400	1000
Spec. Heat	130	800	800	300
Thermal abs	0.9	0.9	0.9	0.9
Solar abs	0.7	0.7	0.7	0.7
Vis abs	0	0	0	0

Source: (Johra, 2021)

Table 2. Varieties of simulation condition

Variants	Simulation condition			
	Roof	Wall	Naturally ventilated	Unventilated
Model 1	Metal without cool roof	Concrete	-	✓
Model 2	Metal without cool roof	Concrete	✓	-
Model 3	Metal with cool roof	Concrete	✓	-
Model 4	Plastic	Concrete	-	✓
Model 5	Plastic	Concrete	✓	-
Model 6	Plastic	Fiber	-	✓
Model 7	Plastic	Fiber	✓	-
Model 8	Metal with cool roof	Fiber	-	✓
Model 9	Metal with cool roof	Concrete	-	✓

3. Result and discussion

According to the measurements taken on December 24, 2022, the outdoor temperature was quite fluctuating. It began to rise at 7:30 a.m. from 26°C, reached its peak at 12:30 p.m. at over 45°C, and gradually declined by 4:30 p.m. The average outdoor temperature during the observation period was approximately 36°C. In contrast, the indoor temperature remained relative stable. It gradually increased from just over 25°C at 8:00 a.m., peaking at nearly 35°C around 1:00 p.m., and then gradually decreased to approximately 30°C by 5:00 p.m.. The average classroom temperature was around 30°C, as illustrated in Figure 4.

Before conducting simulation for the nine conditions, the baseline condition was established and used for comparison. In this initial condition, the roof was made of metal without a cool roof coating, the wall was constructed from concrete, and the room was naturally ventilated, as shown in Figure 5. Under these conditions, the average indoor temperature was approximately 35°C. The result indicates that the combination of a bare metal roof and limited passive cooling strategies leads to high indoor temperatures, potentially exceeding thermal comfort thresholds and negatively affecting learning productivity.

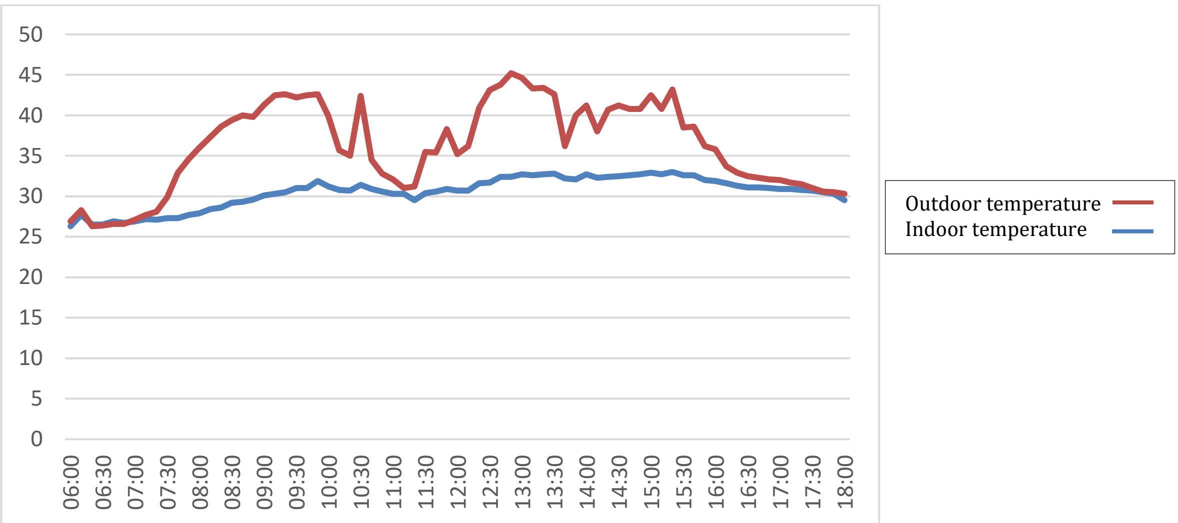


Figure 4. Measurement results in the classroom of State Elementary School 91 Sipatana, Gorontalo City on 24 December 2022.

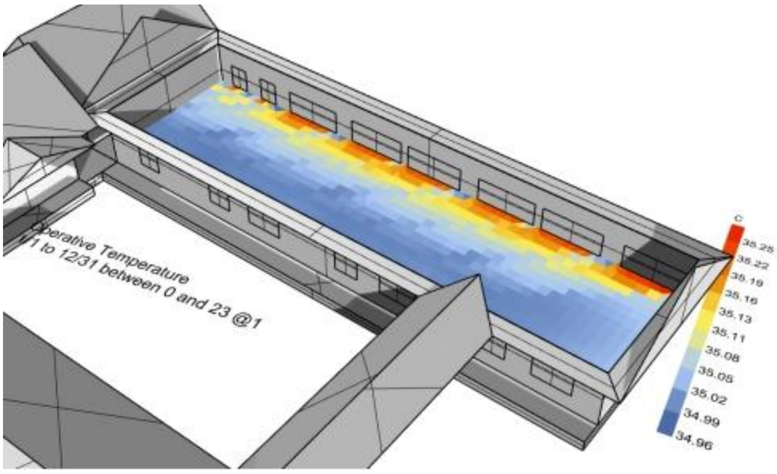


Figure 5. Initial condition of State Elementary School 91 Sipatana

The simulation results are presented in Table 3, which includes three key indicators: PMV, FST, and CAT. The PMV data reflect thermal sensation based on seven comfort levels, while the FST and CAT are measured in degrees Celsius. The corresponding measurement results are listed in Table 4.

According to the measurement results, Model 3, which uses metal roof with cool coating, concrete walls, and ventilation, shows the best thermal performance among all models listed in Table 2. The FST is recorded ate 26.6°C, and CAT is 28.5°C, both which are the lowest across all simulations. In contrast, Model 4 (plastic roof, concrete wall, no ventilation) and Model 6 (plastic roof, fiber wall, no ventilation) show the highest temperatures, with classroom temperatures exceeding 35°C, making them the least thermally comfortable designs.

Among roofing materials, those using cool roof coating consistently shows lower surface temperatures, as seen in Models 3, 8, and 9, which recorded surface temperatures of 26.6°C, 28.3°C, and 28.32°C, respectively. These results reinforce finding from previous studies. For example, it has been reported a surface temperature reduction of by approximately four times the surface temperature reduction (Kolokotroni et al., 2018). A cool coating with a solar reflectance of 0.74, as used in the study by Zingre et al. (2015), also demonstrated a notable reduction in roof temperature. Furthermore, a cool roof with higher solar reflectance of 0.84 was shown to significantly reduce roof surface temperature by 21.1°C (Djafar et al., 2024).

The simulation results also indicate that lack of ventilation significantly contribute to elevated classroom air temperatures. This particularly evident in Models 4 and 6, where the absence of ventilation results in highest indoor temperatures, reaching 35°C and 34.4 °C, respectively (Table 4).

Moreover, the PMV values are closely aligned with the classroom temperature readings. Following the thermal comfort scale proposed by Lippsmeier, neutral comfort lies between 19-26°C, slightly warm between 26-30°C, warm between 30-35°C, and hot at 35-36°C. This classification helps explain why Model 3 (28.5°C) is rated as “slightly warm”, while Model 4 and 6 (≥ 35°C) are rated as “hot”.

4. Conclusion

This study highlights the impact of roofing materials, wall types, and ventilation on PMV, FST, and CAT. Field measurements showed an average indoor temperature of 30.5°C. Based on the simulation results, Model 3 (metal roof with cool coating, concrete walls, and natural ventilation) demonstrates the best thermal performance, maintaining a FST just above 25°C and a CAT near

Table 3. The simulation result

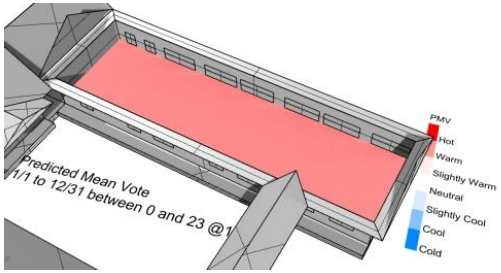
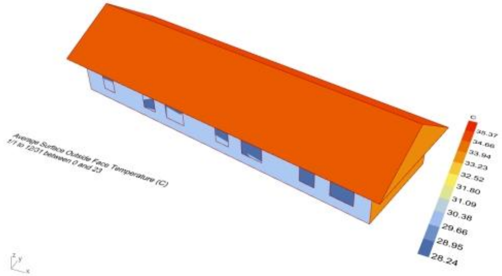
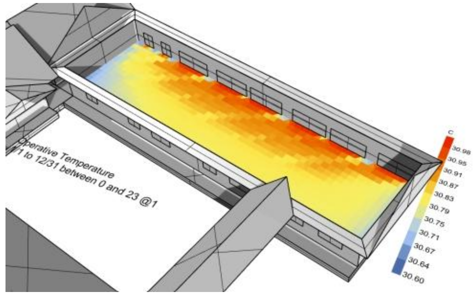
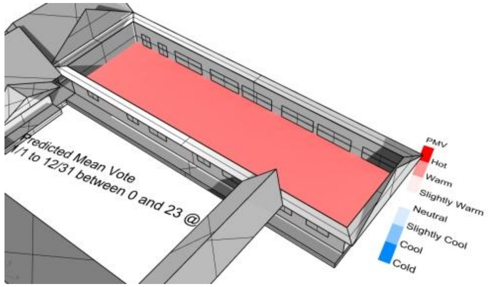
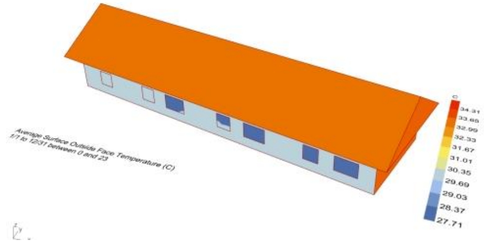
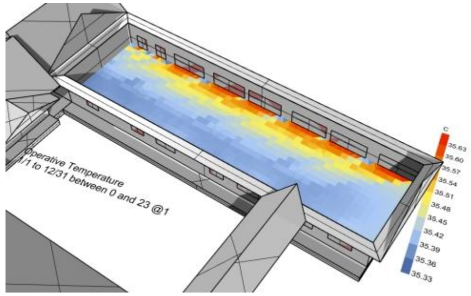
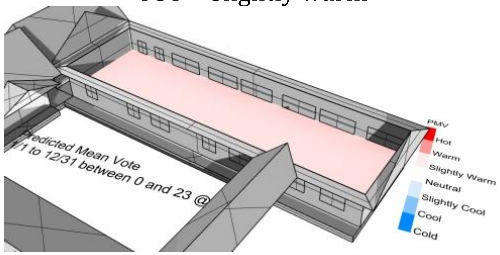
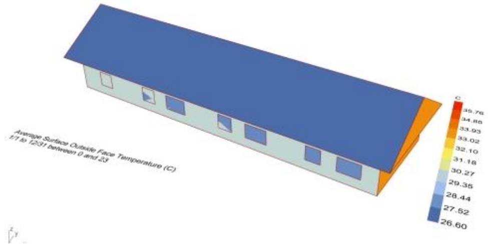
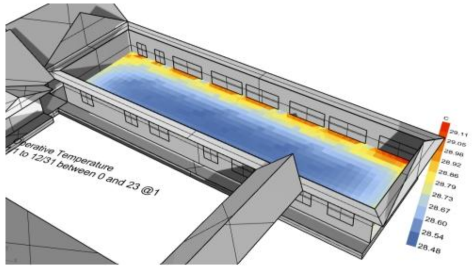
Variants	Result visualization		
	PMV	**FST**	**CAt**
Model 1	FST = Warm 	FST = 33.23°C 	CAT = 30.8°C 
Model 2	FST = Warm 	FST = 32.9°C 	CAT = 30.5°C 
Model 3	FST = Slightly warm 	FST = 26.6°C 	CAT = 28.5°C 

Table 3. The simulation result (cont'd)

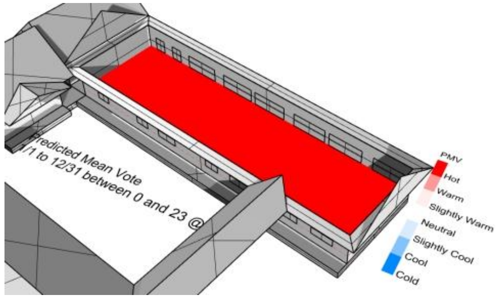
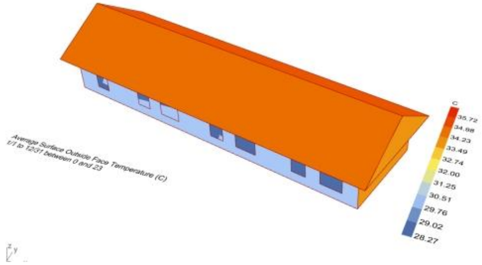
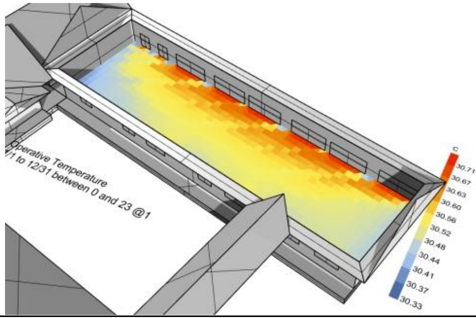
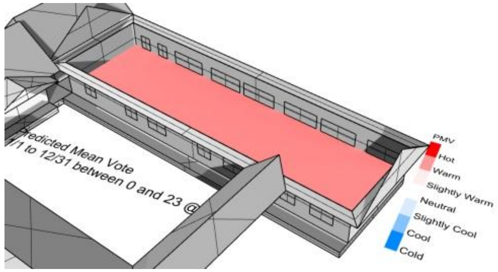
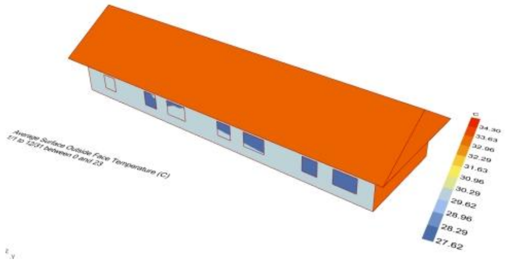
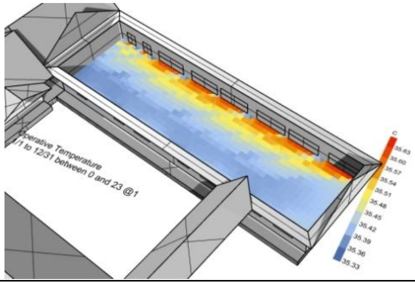
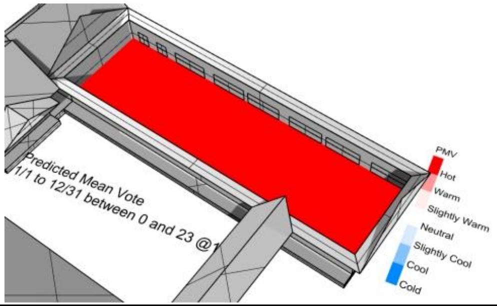
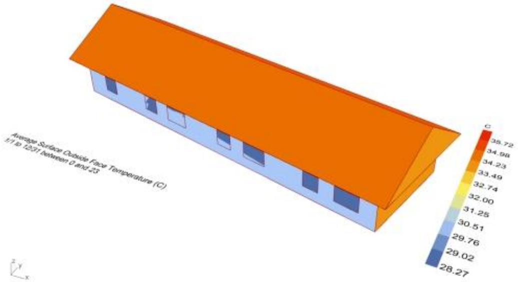
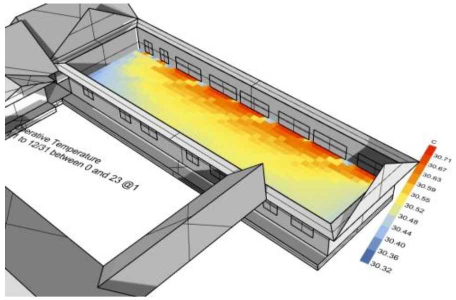
Variants	Result visualization		
	PMV	**FST**	**CAT**
Model 4	FST = Hot 	FST = 34.23°C 	CAT = 35°C 
Model 5	FST = Warm 	FST = 32.9°C 	CAT = 30.5°C 
Model 6	FST = Hot 	FST = 34.23°C 	CAT = 35.4°C 

Table 3. The simulation result (cont'd)

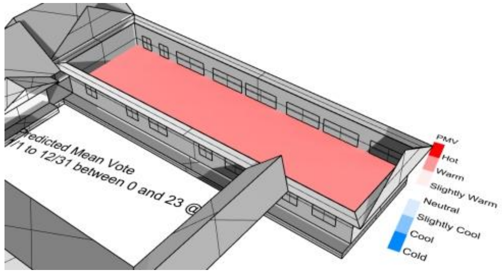
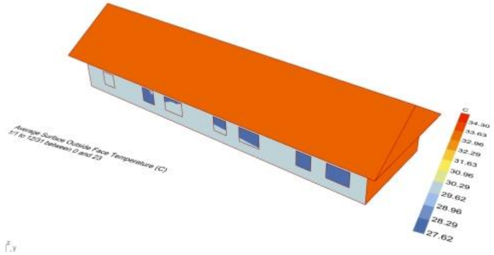
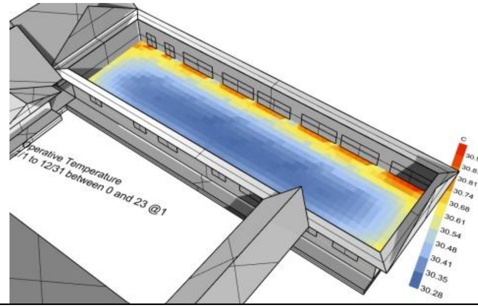
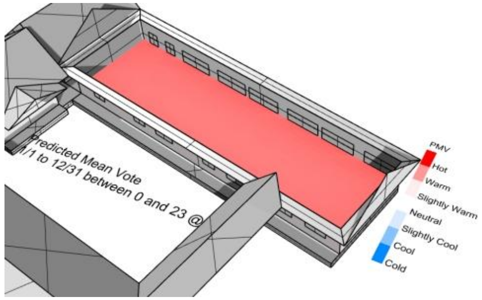
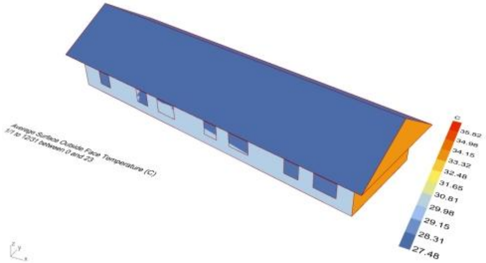
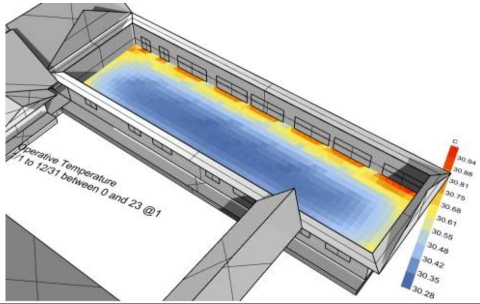
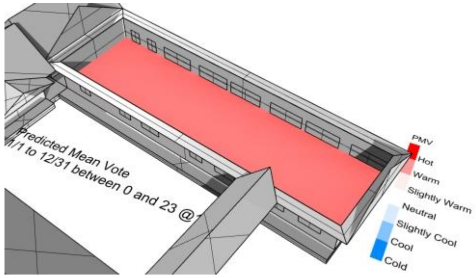
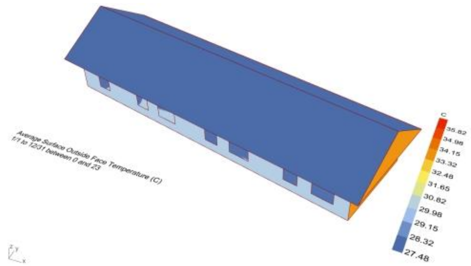
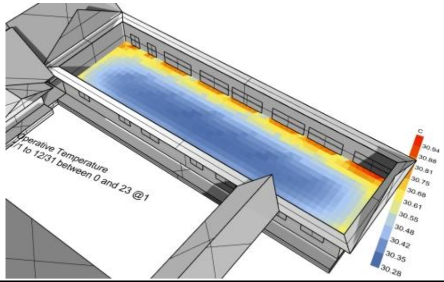
Variants	Result visualization		
	PMV	**FST**	**CAT**
Model 7	PMV = Warm 	FST = 32°C 	CAT = 30.4°C 
Model 8	PMV = Warm 	FST = 28.3°C 	CAT = 30.4°C 
Model 9	PMV = Warm 	FST = 28.32°C 	CAT = 30.4°C 

Table 4. Simulation result of FST and CAT

Model	Roof type and condition	Wall type	Ventilation	FST (°C)	CAT (°C)
Model 1	Metal (no cool roof)	Concrete	No	33.23	30.8
Model 2	Metal (no cool roof)	Concrete	Yes	32.90	30.5
Model 3	Metal (with cool roof)	Concrete	Yes	26.60	28.5
Model 4	Plastic	Concrete	No	34.23	35.0
Model 5	Plastic	Concrete	Yes	32.90	30.5
Model 6	Plastic	Fiber	No	34.23	35.4
Model 7	Plastic	Fiber	Yes	32.00	30.4
Model 8	Metal (with cool roof)	Fiber	No	28.30	30.4
Model 9	Metal (with cool roof)	Concrete	No	28.32	30.4

30°C. The result shows the effectiveness of the cool roof technology and ventilation in reducing heat loads. Cool roofs have consistently been shown to reduce rooftop heat absorption, as supported by previous studies (Kolokotroni et al., 2018; Zingre et al., 2015; Djafar et al., 2024).

In contrast, Models 4 and 6 (plastic roofs without ventilation) recorded the highest temperatures, exceeding 35°C for both FST and CAT, indicating significant heat retention and poor thermal performance. Models using cool roof materials, such as Models 3, 8, and 9, maintained lower FST (26.6°C, 28.3°C, and 28.32°C, respectively), confirming their role in reducing heat absorption. Ventilation also proved critical, as non-ventilated models (4 and 6) experienced the highest indoor temperatures, classified as "hot" on the PMV scale, indicating considerable thermal discomfort. These findings emphasize the importance of cool roofing materials and adequate ventilation in achieving thermal comfort in classroom environments, particularly in hot and humid climates.

Acknowledgment

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