EVALUATING ADAPTIVE THERMAL ACCEPTABILITY IN A RIVERINE TRADITIONAL BUILDING: PASSIVE TROPICAL DESIGN AT ISTANA GUNUNG SAHILAN

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ABSTRACT

Traditional Malay buildings in riverine settings reflect long-term adaptation to hot-humid tropical conditions. However, the relationship between their architectural and spatial characteristics and measured thermal conditions remains insufficiently examined, particularly in traditional palaces. This study evaluates the adaptive thermal acceptability of measured conditions at Istana Gunung Sahilan, Riau, Indonesia, in relation to its passive tropical design characteristics. A single-building case study combined architectural analysis with quantitative field measurements. Architectural observation, photographic documentation, and three-dimensional modelling identified features related to solar and rainfall protection, natural ventilation, and transitional and raised-floor spaces. Air temperature, relative humidity, and air velocity were measured sequentially at 23 points across two floors during four observation periods on a single cloudy day. Point 1, located outdoors in an unobstructed area, served as the outdoor reference. The 22 indoor points were assessed using the ASHRAE Standard 55 adaptive framework, with instantaneous outdoor air temperature used as an approximate model input. Operative temperatures increased from 24.7–28.0°C at 11:00 to 28.9–30.5°C at 15:00. All indoor points met the 80% acceptability range throughout the survey. Within the narrower 90% range, acceptable points decreased from 100% at 11:00 and 13:00 to 90.9% at 14:00 and 50% at 15:00. Locations with measurable airflow were generally more likely to remain within the narrower range during warmer periods, although airflow was unevenly distributed. The findings indicate an association between spatial configuration, air movement, and model-based adaptive thermal acceptability, highlighting the relevance of opening distribution and connections between interior and transitional spaces. As measurements covered only one cloudy day and no occupant surveys were conducted, the results represent a preliminary assessment of measured conditions rather than actual occupant comfort or performance across different weather conditions.

Keywords: *Adaptive Thermal Acceptability, Riverine Traditional Architecture, Passive Tropical Design, Istana Gunung Sahilan*

INTRODUCTION

Indonesia has a tropical climate characterized by high levels of solar radiation, rainfall, and humidity. These conditions influence how buildings are designed to provide protection from the weather and maintain a comfortable thermal environment. In traditional architecture, adaptation to local climatic and environmental conditions is reflected in building forms and architectural elements developed through accumulated community knowledge (Rahim et al., 2023; Redden and Crawford, 2021; Al Shaikhli and Al Shafie, 2020). Various architectural features, including pitched roofs, wide overhangs, openings on multiple sides, upper ventilation openings, verandas, and raised-floor construction, form part of passive tropical design strategies. Pitched roofs and wide overhangs provide protection from solar exposure and rainfall, while appropriately positioned openings can facilitate natural ventilation. Verandas and raised floors also shape the relationship between indoor spaces and the outdoor environment. These features may influence indoor thermal conditions by affecting solar exposure, heat transfer, and air movement (Muqoffa et al., 2025; Zain and Oktafiansyah, 2023). In naturally ventilated buildings, air movement is particularly relevant because it can enhance heat loss from the human body and potentially improve thermal acceptability under warm conditions (Pratiwi et al., 2025). However, the presence of passive design features alone does not establish whether the resulting indoor conditions fall within an acceptable thermal range.

In riverine areas, the relationship between buildings and the surrounding water environment introduces additional considerations for architectural design. The physical conditions of a river influence how nearby settlements develop and adapt (Hamidah et al., 2016). Outdoor air temperature, humidity, and wind conditions may vary across locations and observation periods, while building orientation, opening arrangement, and spatial configuration can influence how outdoor air interacts with indoor spaces. Research along the Martapura River has reported variations in air temperature and humidity, with wind direction influencing the distribution of these conditions (Febrita, 2024). These findings highlight the relevance of examining outdoor environmental conditions alongside the architectural configuration of naturally ventilated buildings. In addition, fluctuating water levels and flood risk can influence the relationship between traditional buildings and the ground, making raised-floor construction relevant to the broader environmental context. A study in Palembang examined building design for flood-prone areas (Wahyu et al., 2022), while research near the Lambidaro River found that flood hazard levels varied among settlement locations (Al Amin et al., 2020). These environmental considerations provide a context for understanding how traditional riverine buildings respond to their surroundings through features such as raised floors and transitional spaces. However, the presence of these features and the building's riverside setting alone does not establish their relationship with indoor thermal conditions. Examining this relationship therefore requires consideration of the building's spatial configuration alongside field measurements of temperature and air movement.

Istana Gunung Sahilan is located on the banks of the Kampar Kiri River in Kampar Regency, Riau Province. This building provides a relevant case for

examining these relationships. As a surviving building of the Gunung Sahilan Kingdom, it holds historical and cultural significance for the local community (Mayval et al., 2021). Previous research has documented its hipped roof, timber construction, and Malay decorative elements (Masrita et al., 2016). Field observations for this study further identified layered roof forms, wide overhangs, openings on multiple sides, verandas, upper ventilation openings, and partially raised construction. The palace complex also consists of two closely positioned building masses connected by an intermediate circulation space. The original palace and the later addition differ in their spatial arrangements and connections with surrounding spaces, creating variations in enclosure, opening distribution, and proximity to the roof. These characteristics provide a basis for examining differences in measured thermal conditions and air movement across the building. The palace's architectural features, spatial configuration, and riverine setting therefore make it a relevant case for investigating the relationship between passive tropical design and model-based adaptive thermal acceptability. However, the potential contribution of individual architectural features cannot be established solely from their physical presence.

Research on Istana Gunung Sahilan has largely focused on its history and descriptive accounts of its architecture. Existing studies have examined the history of the kingdom (Mayval et al., 2021) and the building's form and the meanings of its decorative elements (Masrita et al., 2016). Meanwhile, studies of traditional Malay houses have investigated climatic considerations and building thermal comfort (Zain and Oktafiansyah, 2023; Zain and Nadiya, 2025). More specifically, a study of the Kobuang Limo House in Riau used field measurements to examine tropical architectural elements and assess thermal comfort using effective temperature (Mulfakli et al., 2025). These studies provide a foundation for understanding the architectural and environmental characteristics of traditional Malay buildings. However, the relationship between architectural and spatial characteristics, measured thermal conditions, and model-based adaptive thermal acceptability has not been specifically examined at Istana Gunung Sahilan. In particular, the relationship between passive tropical design features, spatial variations in air movement, and adaptive thermal acceptability within a traditional palace in a riverine setting remains insufficiently understood. Addressing this gap requires an approach that considers both the physical characteristics of the building and measured environmental conditions, rather than inferring thermal performance from architectural features alone.

To address this research gap, this study aims to evaluate the adaptive thermal acceptability of the measured conditions at Istana Gunung Sahilan and examine how its spatial variations relate to the building's passive tropical design characteristics. The study combines architectural and spatial analysis with field measurements and a model-based assessment using the adaptive framework of ASHRAE Standard 55 and the CBE Thermal Comfort Tool. The resulting acceptability classifications are interpreted in relation to the architectural characteristics and spatial configuration of the palace to identify observed patterns in thermal conditions and air movement. By integrating architectural and spatial analysis with model-based adaptive thermal evaluation, this study provides a field-based examination of passive tropical design

in a traditional riverine palace. The findings contribute to understanding the environmental performance of traditional architecture and may inform considerations of architectural conservation and future use.

THEORY / RESEARCH METHODS

Passive Tropical Design in Riverine Traditional Architecture

Passive design utilizes local climatic conditions and architectural characteristics to maintain indoor environmental quality while reducing dependence on mechanical cooling (Elaouzy and El Fadar, 2022). In hot-humid tropical environments, this approach primarily seeks to limit solar heat gain, provide protection from heavy rainfall, and facilitate natural air movement. Research on Indonesian vernacular houses shows that these strategies can take different forms according to a building's construction and environmental setting (Nugroho et al., 2026). These strategies are therefore better understood as an integrated system of architectural features rather than as the independent performance of individual elements (Rivaldy and Utomo, 2024; Kalu Arachchi et al., 2026).

Solar and rainfall protection is generally provided by the roof and building envelope. Pitched roofs facilitate the drainage of rainwater, while overhangs shade walls, openings, and adjoining spaces from direct solar exposure and wind-driven rain. Their environmental contribution, however, depends on roof geometry, material properties, orientation, and exposure to solar radiation. In traditional buildings, these features operate together with the arrangement of interior and transitional spaces, influencing the extent to which indoor areas are exposed to outdoor conditions (Shofie and Prianto, 2025).

Natural ventilation strategies concern the arrangement of openings and the continuity of airflow through occupied spaces. Cross-ventilation is a form of wind-driven natural ventilation in which outdoor air enters through an inlet opening, passes across the interior, and exits through another opening as a result of pressure differences across the building. Openings on opposite or adjacent façades may facilitate this process, while appropriately positioned high-level openings may support air movement near the roof. However, ventilation performance depends on opening size and position, building orientation, and the continuity of internal airflow paths (Zhang et al., 2022; Aflaki et al., 2015). In large timber buildings with multiple rooms and interconnected spaces, the presence of openings does not necessarily produce uniform airflow throughout the building. Internal partitions, differences in enclosure, and connections between adjoining spaces may influence how air moves from one area to another. Field studies of Indonesian vernacular buildings similarly indicate that ventilation strategies should be interpreted in relation to room configuration, opening distribution, and local air movement, rather than the presence of ventilation features alone (Muqoffa et al., 2025; Mulfakli et al., 2025). These considerations are particularly relevant to Istana Gunung Sahilan, which comprises multiple building masses and spaces with different degrees of enclosure.

Transitional spaces and raised floors further shape the relationship between a building and its surroundings. Verandas can provide shaded intermediate areas, whereas elevated floors may reduce direct contact with ground moisture and potentially allow air movement beneath the building when the underfloor area remains open. In riverine environments, these elements may also reflect adaptation to local ground and water conditions (Rahman et al., 2022). Their potential contribution to indoor environmental conditions nevertheless depends on their physical configuration and the surrounding conditions at the time of observation.

Solar and rainfall protection, natural ventilation, and transitional and raised-floor spaces provide an analytical framework for examining passive tropical design at Istana Gunung Sahilan. They are not used to establish the isolated thermal performance or causal effect of individual elements. Instead, the framework supports interpretation of spatial variations revealed by the field measurements and adaptive thermal comfort evaluation.

Adaptive Thermal Comfort

Adaptive thermal comfort theory recognizes that thermal perception is influenced not only by indoor environmental conditions but also by occupants' previous thermal experiences, expectations, and opportunities to adapt. In naturally conditioned buildings, occupants may respond to changes in temperature by adjusting clothing, opening or closing windows, changing their activity, or moving to a different location within the building. Consequently, the indoor temperatures considered acceptable may vary according to outdoor climatic conditions rather than remaining within a fixed temperature range throughout the year (ASHRAE, 2023).

The adaptive comfort model is particularly applicable to naturally ventilated buildings whose indoor environments maintain a direct relationship with outdoor climatic conditions. Unlike heat-balance-based models that assess comfort through combinations of personal and environmental parameters, the adaptive approach relates acceptable indoor operative temperature to the prevailing mean outdoor air temperature. This relationship reflects the tendency of occupants in naturally conditioned buildings to accept warmer indoor conditions when they have experienced warmer outdoor temperatures and have opportunities to make behavioral adjustments. Research in tropical buildings also indicates that comfort conditions may differ according to the building's ventilation mode and the degree of interaction between indoor and outdoor environments (Mohammadpourkarbasi et al., 2022).

ASHRAE Standard 55 provides adaptive acceptability ranges based on the relationship between indoor operative temperature and prevailing mean outdoor air temperature. The standard distinguishes between 80% and 90% acceptability ranges. The 80% range represents a broader interval of acceptable operative temperatures, whereas the 90% range provides a narrower criterion associated with a higher expected level of thermal acceptability. These percentages refer to the expected proportion of occupants who would find the thermal conditions acceptable rather than the proportion of measurement points that must satisfy the model (ASHRAE, 2023).

The CBE Thermal Comfort Tool provides a graphical and computational interface for applying thermal comfort models, including the adaptive method specified in ASHRAE Standard 55 (Tartarini et al., 2020). In this study, the model was used as a reference for comparing measured indoor conditions against the 80% and 90% acceptability ranges. However, the use of instantaneous outdoor temperature and indoor air temperature as proxies for the required model inputs limits the assessment; the resulting classifications should therefore be interpreted as preliminary indicators rather than evidence of full compliance with the standard. As the palace was unoccupied during measurements, the assessment did not capture occupants' thermal sensations or adaptive behaviours. The results thus provide a basis for comparing model-based acceptability across locations and observation periods, rather than representing actual occupant comfort.

Architectural Characteristics of Istana Gunung Sahilan

Istana Gunung Sahilan is located in Gunung Sahilan District, Kampar Regency, Riau Province, Indonesia, within a settlement developed along the Kampar Kiri River. Its location on the riverine area places the palace within a riverine environment in which the development of buildings and settlements has historically been connected to local environmental conditions. Rivers have played an important role in shaping the spatial development and adaptation of traditional settlements in parts of Indonesia (Hamidah et al., 2016; Rahman et al., 2022). The location of the palace and its relationship with the Kampar Kiri River are presented in Figure 1.

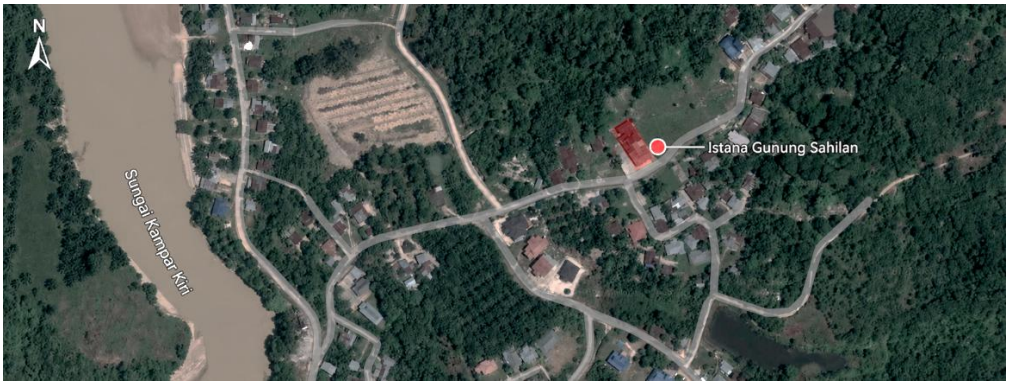


Figure 1. Location and Riverine Setting of Istana Gunung Sahilan
Source: Google Maps, annotated by the authors, 2026

As a surviving building associated with the Gunung Sahilan Kingdom, the palace has historical and cultural significance for the local Malay community (Mayval et al., 2021). Previous architectural documentation identifies characteristics such as hipped roofs, timber construction, and Malay decorative elements (Masrita et al., 2016). Field observations conducted for this study further recorded layered roof forms, wide overhangs, semi-raised construction, verandas, upper ventilation openings, and doors and windows distributed across several façades.

The palace complex consists of two closely positioned building masses (Figure 2). The front mass is the original royal palace, while the rear mass was added in 1940 and formerly accommodated kitchen and bathing functions. A pool was previously located behind the palace. The two masses are connected by an intermediate space that provides circulation between the original and additional sections of the complex. This configuration produces a sequence of interior, transitional, and exterior spaces across the building.



Figure 2. Spatial Arrangement of the Original Palace and Rear Addition at Istana Gunung Sahilan
Source: Field documentation and 3D model, 2026

The palace has two floors, although the upper-floor spaces occupy a substantially smaller area than the first floor (Figure 3). The floor structure is elevated above the surrounding ground and supported by umpak lesung stone foundations, but several parts of the underfloor area have subsequently been enclosed. Hipped roofs at varying heights follow the arrangement of the building masses. Their sloping surfaces and wide overhangs cover portions of the walls, openings, and spaces around the building. Doors, windows, and ventilation openings are distributed across several façades. Verandas provide transitional spaces between the interior and exterior. Timber is used extensively in the floors, walls, doors, windows, and upper structure, while some elements at ground level use heavier materials.



Figure 3. Exterior Architectural Elements of Istana Gunung Sahilan

These physical characteristics, such as roofs, overhangs, openings, verandas, and raised floors, establish the spatial context for the field measurements. Their possible relationship with the measured conditions is examined through the spatial classification of the measurement points and the adaptive thermal comfort evaluation.

Research Method

This research employed a single building case study design combining qualitative analysis of architectural elements with quantitative evaluation of measured thermal conditions. The qualitative component used the passive tropical design framework to identify the architectural and spatial characteristics relevant to solar and rainfall protection, natural ventilation, and transitional and raised-floor spaces. The quantitative component examined spatial and temporal variations in the measured environmental conditions and assessed the adaptive thermal acceptability of the measured conditions using the ASHRAE Standard 55 adaptive framework. The two components were subsequently interpreted together to identify possible relationships between spatial characteristics and thermal conditions.

Architectural data were collected through direct observation, photographic documentation, aerial recording, and three-dimensional modelling. A Nikon D300 DSLR camera was used to document roof forms, overhangs, doors, windows, ventilation openings, verandas, materials, and semi-raised construction. Drone imagery documented the arrangement of the two building masses and their relationship with the surrounding site. The resulting documentation was used to prepare a three-dimensional model and schematic visualizations of the building. These materials supported the identification of architectural elements and the classification of spaces according to their degree of enclosure, connection with openings, relationship with transitional areas, and position within the building. The identified features were subsequently interpreted using three analytical categories: solar and rainfall protection, natural ventilation, and transitional and raised-floor spaces.

Environmental measurements were conducted on 30 July 2026 under cloudy weather conditions. The palace was unoccupied during the survey, and no mechanical cooling system was operating. All accessible doors and windows were kept open throughout the measurement periods. This configuration allowed the indoor spaces to interact with outdoor air through natural ventilation. However, it was treated as the survey condition rather than assumed to represent the building's usual operation during occupancy or ceremonial use. As the measurements were conducted on a single day, the results characterize the environmental conditions observed during the survey and should not be interpreted as representative of the building's thermal performance across different weather conditions or seasons.

A total of 23 measurement points were established across the building and its immediate surroundings. Point 1 was located outdoors on the southeastern to southern side of the palace, in an unobstructed area without trees or buildings providing shade directly in front of the measurement location. It was used to record outdoor air temperature, relative humidity, and air velocity during each observation period and served as the outdoor reference point for the field measurements. The air temperature recorded at Point 1 was subsequently used as an approximation of the prevailing outdoor temperature input in the CBE Thermal Comfort Tool. However, because preceding daily outdoor temperature records were unavailable, this instantaneous measurement was not equivalent to a prevailing mean outdoor temperature calculated in accordance with ASHRAE Standard 55.

Points 2–21 were distributed across the first floor, including the entrance veranda, relatively open interiors, more enclosed rooms, transitional spaces, and the connection between the original and additional building masses. Points 22 and 23 were located in the upper floor spaces of the additional and original palace masses, respectively. The measurement points were selected to capture spatial differences in enclosure, opening configuration, connection with transitional spaces, floor level, and proximity to the roof. The distribution included relatively open interiors, more enclosed rooms, verandas, transitional areas, and upper-floor spaces across the two building masses. This arrangement enabled a comparative examination of measured environmental conditions in spaces with different architectural and spatial characteristics. Their locations are presented in Figure 4.

Measurements were undertaken during four observation periods beginning at approximately 11:00, 13:00, 14:00, and 15:00 WIB. These periods were selected to examine changes in environmental conditions from late morning to the warmer afternoon period. Because one portable set of instruments was moved between the locations, the points were measured sequentially rather than simultaneously. The stated times therefore represent measurement rounds and not identical recording times for all points within a period.

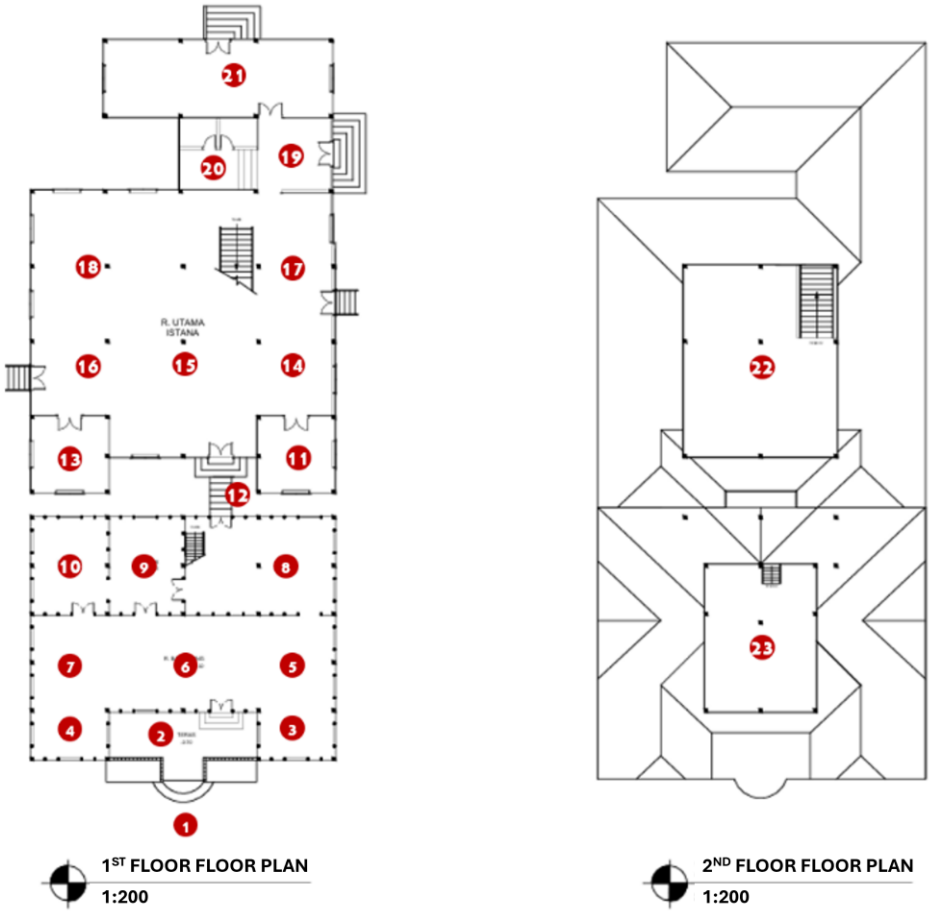


Figure 4. Distribution of Measurement Points on the First and Second Floors of Istana Gunung Sahilan

At each point, the instruments were positioned approximately 1 m above the floor to represent environmental conditions within the occupied zone. Measurements were observed for approximately one minute at each location before the values were recorded. Air temperature and relative humidity were measured using a UNI-T UT333 temperature–humidity meter. Air velocity was measured using a Benetech GM8903 hot-wire anemometer. The specifications of the instruments are presented in Table 1. These specifications describe the manufacturers' stated measurement accuracy and should not be interpreted as the total uncertainty of the field measurements.

Table 1. Specifications of the Field-measurement Instruments

Parameter	Instrument	Measurement range	Accuracy	Resolution
Air temperature	UNI-T UT333 Temperature Humidity Meter	−10 - 60 °C	±1.0 °C	0.1 °C
Relative humidity	UNI-T UT333 Temperature Humidity Meter	0 - 100% RH	±5% RH	0.1% RH
Air velocity	Benetech GM8903 Hot Wire Anemometer	0.0–30.0 m/s	±(3% of reading + 0.1 m/s)	0.001 m/s

Source: Manufacturer specifications for the UNI-T UT333 and Benetech GM8903

The adaptive approach was selected because Istana Gunung Sahilan relies on natural ventilation, no mechanical cooling was operating, and the open doors and windows provided a direct connection between indoor and outdoor conditions during the field measurements. Nevertheless, because the building was unoccupied and no occupant questionnaire was administered, the analysis assessed the adaptive thermal acceptability of the measured conditions rather than occupants' reported thermal sensations or satisfaction.

The measured conditions at Points 2–23 were evaluated using the Adaptive Method in the CBE Thermal Comfort Tool, following the adaptive framework of ASHRAE Standard 55. Point 1 was excluded from the indoor acceptability classification because it represented the outdoor reference location. Air temperature was used as an approximation of operative temperature. The operative temperature assigned to each indoor point was assessed against the model's 80% and 90% adaptive acceptability limits, using the outdoor air temperature recorded at Point 1 during each observation period as the outdoor reference input. Air velocity was included in the assessment, with elevated-air-speed cooling adjustments applied where permitted by the adaptive method. Relative humidity was recorded to characterize the indoor environmental conditions. The outdoor reference temperatures were instantaneous measurements rather than prevailing mean outdoor temperatures (PMOTs) calculated from the preceding 7–30 days of daily outdoor temperatures

An exploratory one at a time sensitivity analysis was conducted to examine the effect of changes in the outdoor reference temperature on adaptive acceptability classifications. Five scenarios were tested by varying the original CBE outdoor reference input by −2°C, −1°C, 0°C, +1°C, and +2°C. For each scenario, the operative temperature and air-speed settings were held constant, and the 80% and 90% acceptability classifications were recorded for all 22 indoor measurement points across the four observation periods. The results were compared by calculating the number and percentage of points within each acceptability range and identifying classification changes across scenarios. The scenarios represented hypothetical variations for exploratory testing rather than measured PMOT variability, and the

analysis did not replace the PMOT calculation specified in ASHRAE Standard 55-2023. The baseline scenario (0°C) was checked against the original CBE classifications for consistency.

The analysis was completed in three stages. First, the measured air temperature, relative humidity, and air velocity were compared across the points and observation periods to identify spatial and temporal variations. Second, the adaptive acceptability classifications and sensitivity results were examined to identify changes across observation periods and outdoor reference-temperature scenarios. Third, these results were interpreted in relation to spatial enclosure, opening distribution, connections with transitional spaces, floor level, and proximity to the roof. This integrated analysis identified observed associations between architectural and spatial characteristics, air movement, and adaptive thermal acceptability without attributing the results to individual architectural elements alone (Figure 5).

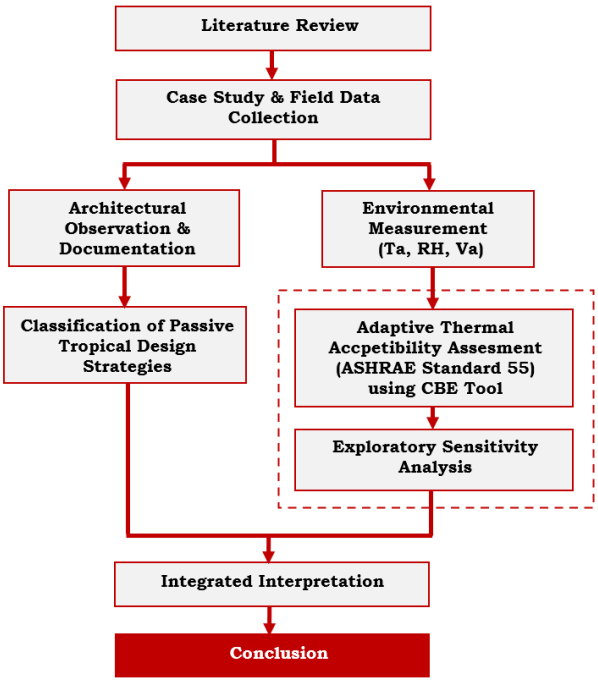


Figure 5. Research Design and Data Analysis Framework

RESULTS AND DISCUSSION

Architectural and Spatial Context of the Measurement Points

The spatial configuration of Istana Gunung Sahilan creates different levels of openness, enclosure, and connection among the measurement points. The palace consists of an original building mass at the front and an additional mass at the rear, separated by a transitional spFace. As illustrated in Figure 6 (a), the first floor

contains relatively open interiors, more enclosed rooms, open or transitional spaces, and service areas. This spatial classification provides a basis for interpreting variations in temperature and air movement recorded throughout the building.

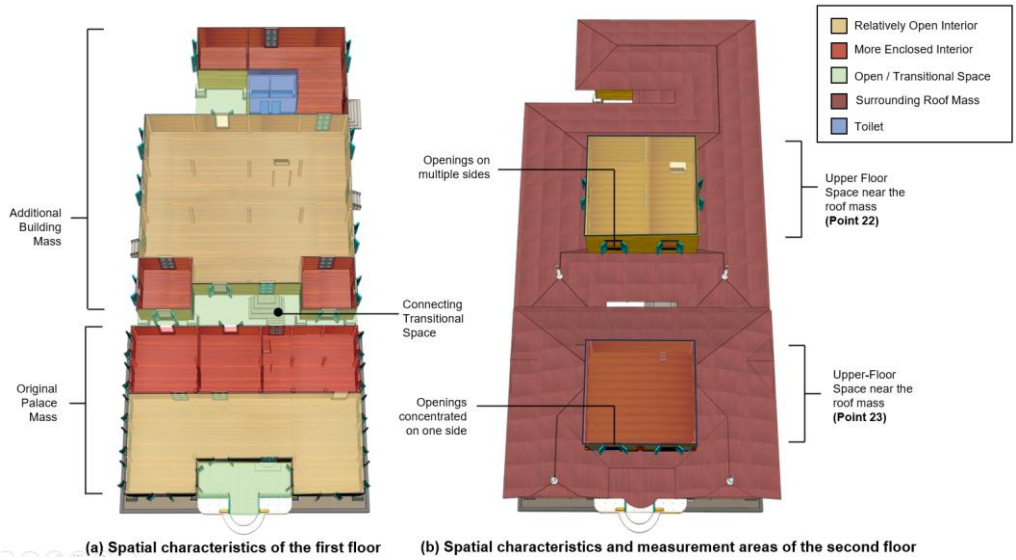


Figure 6. Architectural and Spatial Context of the Measurement Areas at Istana Gunung Sahilan

The original palace mass contains a large, relatively open main hall adjoining several more enclosed rooms. The main hall has openings distributed along its outer walls and is connected to the entrance veranda, which acts as a transitional space between the exterior and interior. The rooms behind the main hall have a greater degree of enclosure because they are divided by internal partitions and have less direct connection with the exterior. The arrangement therefore creates different potential relationships with outdoor conditions, even among points located within the same building mass.

The additional building mass also contains a large, relatively open interior surrounded by smaller enclosed rooms and service spaces. Openings are distributed on several sides of the main space, while the adjoining rooms differ in their number of openings and connection with surrounding areas. A transitional space between the original and additional masses creates an intermediate area that links the two parts of the palace. This space is directly connected with adjacent openings and outdoor conditions, distinguishing it from the enclosed rooms on either side.

The second-floor measurement areas are illustrated in Figure 6 (b). Point 22 is located in an upper-floor space within the additional mass. This space is classified as a relatively open interior because it has openings on multiple sides. Point 23 is located in the upper-floor space of the original palace mass. Its openings are concentrated on one side, resulting in a more enclosed spatial character and more limited opportunities for cross-ventilation. Both upper-floor spaces are surrounded

by extensive roof surfaces, placing them in a different vertical and architectural context from the first-floor measurement points.

Istana Gunung Sahilan also uses semi-raised construction, although parts of the underfloor area have been enclosed. Consequently, the potential for air movement beneath the floor may differ across the building. The classifications shown in Figure 6 do not independently demonstrate the thermal performance of each space. Instead, they describe the architectural context used to interpret spatial and temporal variations in the field measurements.

Spatial and Temporal Variations in Measured Thermal Conditions

The field measurements revealed temporal changes in environmental conditions from late morning to afternoon. At the outdoor reference location, air temperature increased from 26.2°C at 11:00 to 27.7°C at 13:00 and 28.0°C at 14:00, reaching 30.0°C at 15:00. The highest measured outdoor air temperature therefore occurred during the final observation period. Indoor air temperatures generally followed this increasing pattern, although the values differed among measurement points within each period.

Because mean radiant temperature was not measured separately, air temperature was used as a representative for operative temperature in the adaptive assessment. As shown in Figure 7, the values at Points 2–23 ranged from 24.7°C to 28.0°C at 11:00. The range subsequently increased to 27.1–28.7°C at 13:00 and 27.9–29.2°C at 14:00. At 15:00, operative temperatures reached their highest range of 28.9–30.5°C. These measurements indicate that higher temperatures were generally recorded during the afternoon observation periods, while differences between measurement points show that thermal conditions varied within the building. Because measurements were taken sequentially, these results describe the observed conditions at each period rather than simultaneous temperature changes across all spaces.

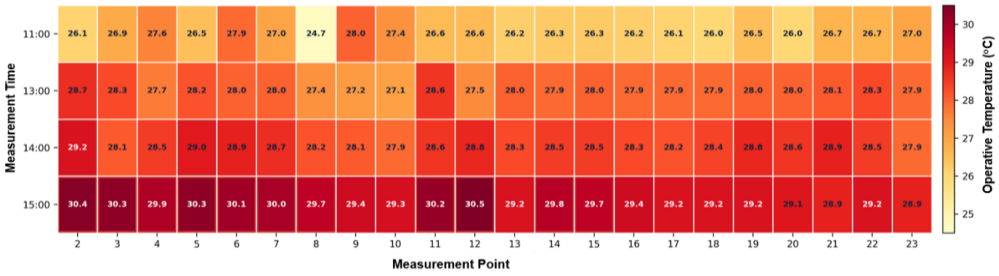


Figure 7. Spatial and Temporal Distribution of Operative Temperature Across Measurement Points 2–23 at Istana Gunung Sahilan

Relative humidity also varied spatially and temporally, as presented in Figure 8. Across the indoor points, the recorded values ranged from approximately 69.0% to 79.0% at 11:00. The range was 72.0–77.1% at 13:00 and 69.7–75.0% at 14:00, before decreasing to approximately 67.9–72.8% at 15:00. Thus, relative humidity

generally declined during the afternoon as air temperature increased. Although relative humidity was not used directly to establish the adaptive acceptability limits, these values describe the hot-humid environmental conditions under which the temperature and airflow measurements were obtained.

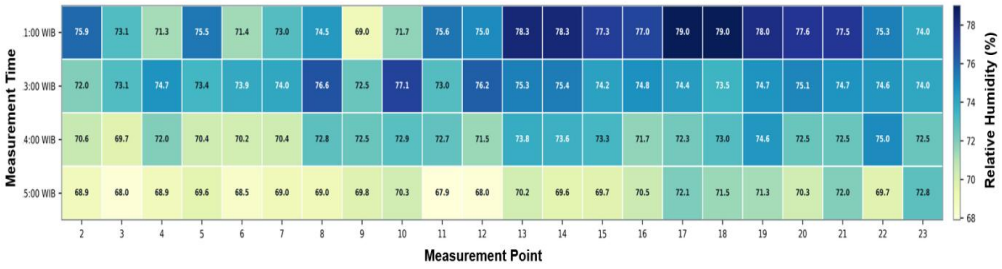


Figure 8. Spatial and Temporal Distribution of Relative Humidity Across Measurement Points 2–23 at Istana Gunung Sahilan

Air velocity displayed greater spatial variability than temperature and relative humidity (Figure 9). Measurable air movement occurred only at certain locations and observation periods, while several points recorded zero or very low values. At 11:00, the highest recorded air movement occurred at Point 2, followed by Point 3. At 13:00, comparatively high values were recorded at Points 7, 10, and 12. At 14:00, Point 10 recorded the highest air velocity of the survey, at 2.384 m/s, while measurable airflow was also observed at Points 7 and 9. At 15:00, air movement was recorded at several locations, including Points 8, 10, 19, and 22, with Point 10 recording the highest value during that period at 0.800 m/s. This pattern indicates that air movement was not evenly distributed throughout the palace during the survey. Although the doors, windows, and ventilation openings were kept open, their presence did not result in measurable airflow at every point. Differences in spatial enclosure and connections between rooms may help explain this variation. However, the measurements show an association between spatial characteristics and air movement rather than the isolated effect of individual architectural elements.

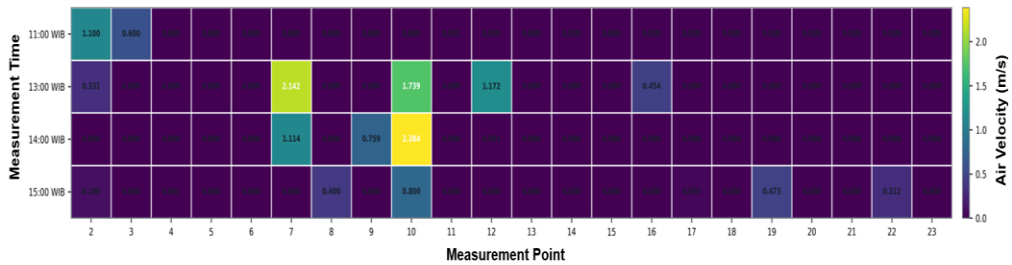


Figure 9. Spatial and Temporal Distribution of Air Velocity Across Measurement Points 2–23 at Istana Gunung Sahilan

The air-velocity measurements were interpreted with consideration of the instrument's minimum starting velocity of approximately 0.3 m/s. Values below the stated minimum starting velocity were treated as indicating minimal or undetectable airflow, rather than as precise measurements of low air speed. The analysis therefore focused on distinguishing points with airflow detected above the threshold from those where air movement remained below the instrument's reliable measurement level. Furthermore, higher velocities occurred only at certain points and observation times, indicating an uneven and fluctuating distribution of airflow throughout the building.

Overall, the measurements reveal three temporal and spatial patterns. First, outdoor and indoor temperatures increased toward the afternoon. Second, relative humidity generally decreased as temperature increased, although the indoor environment remained humid. Third, air movement varied substantially between locations and periods, including among points within the same building mass. These measured variations provide the environmental basis for the adaptive thermal acceptability assessment presented in the following section.

Adaptive Thermal Comfort Evaluation

The adaptive thermal acceptability assessment was conducted for Points 2–23, while Point 1 served as the outdoor reference. The measured conditions were evaluated against the 80% and 90% adaptive acceptability ranges using the CBE Thermal Comfort Tool. As described in the Research Method, the outdoor air temperature recorded at Point 1 was used as the model's outdoor reference input rather than a prevailing mean outdoor temperature (PMOT) calculated from preceding daily records. The results should therefore be interpreted as a preliminary assessment of the measured conditions using this reference input.

All 22 evaluated points remained within the 80% acceptability range during the four observation periods. A different pattern emerged under the narrower 90% criterion, as shown in Figure 10. At 11:00 and 13:00, all points remained within the 90% range. At 14:00, the proportion decreased to 90.9%, with 20 of the 22 points satisfying the criterion. At 15:00, only 11 points, or 50% of the evaluated locations, remained within the 90% range, while the other 11 points exceeded its upper limit. These percentages represent the proportion of measurement points meeting the model's acceptability criteria.

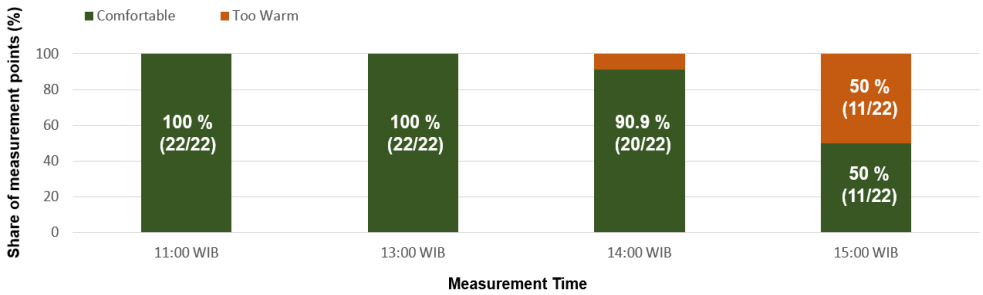


Figure 10. Distribution of Points Under the 90% Adaptive-comfort Criteria

The difference between the two acceptability levels is important for interpreting the thermal performance of the building. The 80% range represents a broader interval of acceptable operative temperatures, whereas the 90% range represents a narrower thermal expectation. Accordingly, all measured points remained within the broader acceptability range throughout the observation period. However, the declining proportion of points within the 90% range indicates reduced spatial consistency in meeting the more stringent criterion toward the afternoon. Thus, the conditions recorded at 15:00 should not be interpreted as complete thermal failure. Instead, the results indicate that fewer locations met the narrower adaptive thermal acceptability range as temperatures increased.

The point-level results reveal an association between air movement and the classifications. At 14:00, Points 2 and 5 exceeded the upper limit of the 90% range and recorded no detectable air movement. By comparison, Points 7, 9, and 10 remained within the narrower range while receiving measurable airflow. A similar contrast was observed at 15:00. Points 2–8, 11, 12, 14, and 15 exceeded the 90% upper limit, whereas several other locations remained within the range. Among the latter, Points 10 and 19 recorded air velocities of 0.800 m/s and 0.473 m/s, respectively.

This comparison suggests an association between measurable air movement and a greater likelihood of satisfying the narrower acceptability criterion during the warmer afternoon periods. Increased air movement can improve convective and evaporative heat loss and extend the upper acceptable temperature limit under applicable conditions (Zhou et al., 2023). However, air velocity cannot be regarded as the only factor responsible for the classifications. The result at each point was also associated with its operative temperature, degree of enclosure, proximity and orientation to openings, connection with adjoining spaces, and exposure to surrounding building surfaces. In addition, the adaptive calculation itself permits an elevated-air-speed adjustment only under specified conditions. The observed pattern should therefore be interpreted as an association rather than direct evidence that airflow alone determined thermal acceptability.

This spatial variation is relevant to the interpretation of the palace's passive tropical design. Although doors, windows, and ventilation openings were open during the survey, measurable airflow was not detected at every point. The pattern is

consistent with research on Indonesian vernacular buildings, which indicates that natural ventilation depends not only on the presence of openings but also on their position, orientation, relationship with adjacent spaces, and the continuity of airflow paths (Muqoffa et al., 2025). At Istana Gunung Sahilan, the results suggest that the arrangement and connection of spaces may be important in understanding why some locations experienced measurable air movement while others did not. This interpretation is also consistent with research on naturally ventilated buildings in hot-humid climates, where thermal conditions are influenced by outdoor climatic variation and opportunities for adaptation (Adnan et al., 2026). Nevertheless, the present measurements establish associations between spatial characteristics, air movement, and model classifications; they do not isolate the effect of any individual architectural element.

An exploratory sensitivity analysis was conducted to examine how changes in the outdoor reference-temperature input affected the classifications. Five scenarios were assessed by varying the baseline input by −2°C, −1°C, 0°C, +1°C, and +2°C, while keeping operative temperature and air-speed settings constant. The results are presented in Table 2.

Table 2. Sensitivity of Adaptive Thermal Acceptability Classifications to Outdoor Reference-Temperature Scenarios Hypothetical Outdoor Reference Temperature Scenarios

Scenario	Criterion	11:00	13:00	14:00	15:00
- 2°C	80%	22 (100%)	22 (100%)	22 (100%)	15 (68.2%)
- 2°C	90%	20 (90.9%)	19 (86.4%)	9 (40.9%)	4 (18.2%)
- 1°C	80%	22 (100%)	22 (100%)	22 (100%)	18 (81.8%)
- 1°C	90%	22 (100%)	20 (90.9%)	16 (72.7%)	9 (40.9%)
0°C (baseline)	80%	22 (100%)	22 (100%)	22 (100%)	22 (100%)
0°C (baseline)	90%	22 (100%)	22 (100%)	20 (90.9%)	11 (50.0%)
+1°C	80%	22 (100%)	22 (100%)	22 (100%)	22 (100%)
+1°C	90%	22 (100%)	22 (100%)	22 (100%)	15 (68.2%)
+2°C	80%	22 (100%)	22 (100%)	22 (100%)	22 (100%)
+2°C	90%	22 (100%)	22 (100%)	22 (100%)	18 (81.8%)

The sensitivity analysis shows that the classifications, particularly under the 90% criterion, changed with the outdoor reference-temperature input. At 15:00, the number of points within the 90% range varied from 4 under the −2°C scenario to 18 under the +2°C scenario. Under the 80% criterion, the classifications were comparatively stable, except when the reference input was reduced. These scenarios illustrate the influence of the selected model input on the classifications. They do not

represent measured changes in the building's physical conditions or substitute for the prevailing mean outdoor temperature calculation specified in ASHRAE Standard 55-2023.

Overall, the findings show that adaptive thermal acceptability at Istana Gunung Sahilan varied across measurement locations and observation periods. The association between airflow and the narrower acceptability criterion highlights the importance of considering the relationship between spatial configuration and air movement when interpreting passive tropical design. The results do not establish the isolated performance of individual architectural elements, but indicate that their potential contribution to thermal conditions should be understood in relation to the airflow and spatial conditions observed throughout the building.

CONCLUSIONS

This study examined the relationship between passive tropical design features, measured thermal conditions, and model-based adaptive thermal acceptability at Istana Gunung Sahilan. By combining architectural documentation with field measurements, the study shows how differences in spatial configuration and air movement can help explain variations in thermal conditions within a traditional riverine building. This approach provides a basis for examining the environmental performance of traditional architecture in relation to its physical and spatial characteristics.

The results showed that all 22 indoor measurement points remained within the 80% adaptive acceptability range during the four observation periods. Under the narrower 90% criterion, all points met the criterion at 11:00 and 13:00, decreasing to 20 points at 14:00 and 11 points at 15:00. Locations with measurable air movement were generally more likely to remain within the 90% range during the warmer periods. This pattern suggests that air movement and the connection between spaces are important considerations when evaluating passive tropical design. Although Istana Gunung Sahilan has features such as wide roof overhangs, openings on several sides, upper ventilation openings, verandas, and raised-floor construction, their individual effects on thermal conditions could not be determined from this study.

These findings may support the conservation and future use of traditional riverine buildings by highlighting the importance of maintaining their architectural features and understanding how their spaces connect with the outdoor environment. However, the thermal acceptability results should be interpreted as preliminary. Measurements were conducted sequentially over a single cloudy day while the palace was unoccupied. Mean radiant temperature was not measured separately, and the instantaneous outdoor air temperature recorded at Point 1 was used as the model's outdoor reference input instead of a prevailing mean outdoor temperature (PMOT) calculated from preceding days. The sensitivity analysis also showed that changes in this input could affect the classifications, particularly under the 90% criterion. Therefore, the results represent a model-based adaptive thermal

acceptability assessment and do not directly establish occupants' thermal comfort or demonstrate full compliance with ASHRAE Standard 55-2023.

Future research should include longer monitoring periods under different weather conditions, outdoor temperature records for calculating PMOT, and direct measurement of mean radiant temperature. Simultaneous measurements at selected locations could help clarify differences between spaces, while surveys of occupants or visitors could provide information about their actual thermal experiences. These additional data would strengthen the assessment of passive tropical design and provide a more reliable basis for conservation and adaptive reuse decisions.

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