Unveiling the Thermal Comfort Dynamics of Asymmetrical Buildings Configurations in Malaysia’s Public School Courtyard Design

Muhammad Arif Harun
Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia

Sheikh Ahmad Zaki
Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia

Ng Wai Tuck
Tunku Abdul Rahman University of Management and Technology

Samsol Faizal Anis
Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia

他

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Muhammad Arif Harun[1], Sheikh Ahmad Zaki[1], Ng Wai Tuck[2], Samsol Faizal Anis[1], Elmira Jamei[3], Hom Bahadur Rijal[4]

[1] Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, 54100 Kuala Lumpur, Malaysia,

[2] Tunku Abdul Rahman University of Management and Technology, Jalan Genting Kelang, Setapak, 53300 Kuala Lumpur, Malaysia,

[3]Institute for Sustainable Industries and Liveable Cities, Victoria University, Australia,

[4]Tokyo City University, 3 Chome-3-1 Ushikubonishi, Tsuzuki Ward, Yokohama, Kanagawa 224-8551, Japan

Corresponding author email: sheikh.kl@utm.my

Abstract: *Most public schools in Malaysia have courtyards for assemblies and outdoor activities, but the hot and humid climate limits their comfortable usage hours. This study investigates how optimising building configurations with asymmetrical building configurations can effectively enhance comfort hours in school courtyards by taking advantage of sun orientation. This study used a simulation method involving five scenarios with a different aspect ratio from 0.4 to 0.8. Simulations tested five different building arrangements surrounding the courtyard with B1 (East and West buildings) and B2 (North and South buildings). Furthermore, the software was validated with field measurements from a school in Kuala Lumpur. The validation result shows a low root mean square error of 1.4˚C in air temperature. Results indicate that building configuration significantly impacts thermal comfort, with Design 5, the highest buildings (aspect ratio = 0.8) on all sides, providing 4 out of 7 hours of comfort and 30% of the area below a Physiological Equivalent Temperature (PET) value of 42.0˚C.*

Keywords: Thermal Comfort; Asymmetrical Building Configurations; Courtyards; Physiological Equivalent Temperature

1. INTRODUCTION

Based on the Environment Statistic 2020 from the Department of Statistics Malaysia [1], the average mean temperature typically ranges from 25°C to 28°C while the highest mean temperature that Malaysia can achieve is up to 33.9°C. Therefore, achieving good outdoor thermal comfort is very challenging. In Malaysia, public schools commonly feature courtyards intended for assemblies and outdoor activities. These courtyards serve as multifunctional spaces, playing crucial roles in students' physical and social development. Based on a previous study by Lu and Hazril [2], the central courtyard was used for recreation purposes and easy supervision for juvenile schools. The design of a courtyard is commonly an enclosed or semi-enclosed space exposed to the sky and surrounded by buildings or walls [3].

However, the equatorial climate, characterized by high temperatures and humidity, significantly limits the comfort hours and usability of these courtyards to specific times of the day with low solar radiation exposure. Previous studies showed that the temperature of climate Malaysia has a constant trend where the temperature for early morning and late evening (25.0˚C) is lower than in the afternoon (33.0˚C) [4, 5].

Consequently, public schools in Malaysia typically hold assemblies in the early morning and physical education classes in the late evening. However, during events such as school marathons or sports days, they sometimes use the courtyard for assemblies at noon when solar radiation exposure is high. The impact of climate change further worsens these challenges, with increasing cases of extreme weather conditions, including heat waves, which pose serious risks to student health and well-being [6]. A study by Lala and Hagishima [7] underscores the adverse effects of heat stress on students, noting that high temperatures can reduce comfort levels, hinder productivity, and cause various health problems. This issue creates an urgent need for innovative architectural solutions that can mitigate heat stress and improve the thermal comfort of school environments.

Meteorological factors (such as air temperature, relative humidity, wind speed, and mean radiant temperature) and personal factors (such as clothing type and activity level) influence outdoor thermal comfort [8]. Typical input data used in software to evaluate comfort indexes include air temperature, wind speed, relative humidity, and albedo [9]. Most research utilized these data to calculate comfort indexes such as the Predicted Mean Vote (*PMV*), Physiological Effective Temperature (*PET*), Mean Radiant Temperature (*MRT*), and Universal Thermal Climate Index (*UTCI*). Software commonly used for simulating microclimates include ENVI-met, Computational Fluid Dynamics (CFD), RayMan, and EnergyPlus.

A review by Zhu et al. [10] indicates that optimizing courtyards to create favorable microclimates is feasible when considering key design variables. Factors such as geometry [11], orientation [12], wall materials [13], and landscape elements (e.g., ponds, trees, grass) significantly influenced the microclimate within a courtyard [14, 15]. Among these factors, geometry is crucial as it affects solar radiation reception and airflow, playing a decisive role in shaping the microclimate [11]. Proper orientation can also effectively reduce heat gain, while an appropriate airflow distribution can enhance air quality [16]. The right combination of these design elements can make courtyards more energy-efficient in hot and humid climates compared to temperate and cold climates [10].

However, it is important to note that there is a significant gap in the current body of research regarding the impact of asymmetrical design on courtyard microclimates. While existing studies extensively explore symmetrical designs, focusing on factors like geometry and orientation in standard courtyard layouts, they do not address how asymmetrical configurations might influence thermal comfort. Understanding how to optimize non-standard, innovative designs for better microclimate control is particularly critical. Investigating how these designs affect key microclimate parameters could lead to novel strategies for enhancing the environmental performance of courtyards, thereby contributing to more sustainable and resilient urban spaces.

The previous study on asymmetrical buildings only involves on-street urban canyons. A study by Rodríguez-Algeciras et al. [17] on asymmetrical street canyon profiles in the historical center of Camagüey, Cuba, reveals that high façades on specific sides of streets can reduce thermal stress. Asymmetrical profiles serve as adaptable geometric variations within urban canyons, effectively managing urban microclimates and walkability in warm-humid environments by altering airflow and exposure to solar radiation.

This study seeks to explore how asymmetrical building configurations can enhance thermal comfort in school courtyards, thereby maximizing their usability throughout the day. By examining the thermal dynamics of these configurations, this study aims to identify design strategies that can be employed to create more comfortable and sustainable outdoor spaces in Malaysian public schools. The study will utilize advanced simulation tools, specifically ENVI-met 5.5.1 and Design Expert 11, to model and analyze different asymmetrical designs and their impact on thermal comfort.

The exploration of asymmetrical building configurations as a solution to thermal discomfort in school courtyards is both timely and essential. With the growing awareness of the impacts of climate change and the importance of sustainable design, this research contributes to the broader discourse on creating healthier, more resilient educational environments. By optimizing courtyard designs for thermal comfort, we can ensure that these spaces remain functional and beneficial for students throughout the year, enhancing their overall educational experience.

2. METHODOLOGY

2.1 Selection of the study area

The study centered on the courtyard of Padang Tembak Secondary School in Kuala Lumpur, Malaysia, chosen for its representativeness and importance as a communal space for students. The school is located at coordinates 3.1817° N, 101.6891° E, within a tropical rainforest climate (*Af*).

The site was selected to capture the prevalent challenges posed by the region's hot and humid climate, which can significantly impact students' thermal comfort and overall well-being. The courtyard, designed in a square shape and enclosed by buildings on all four sides, creates a unique microclimate that amplifies heat and humidity effects. This configuration, as illustrated in Fig. 1 and Table 1, provides a controlled environment for studying how architectural design influences thermal comfort in educational settings. By focusing on this specific courtyard, the research aims to generate insights applicable to similar school environments across Malaysia, contributing to the development of more comfortable and sustainable school designs.

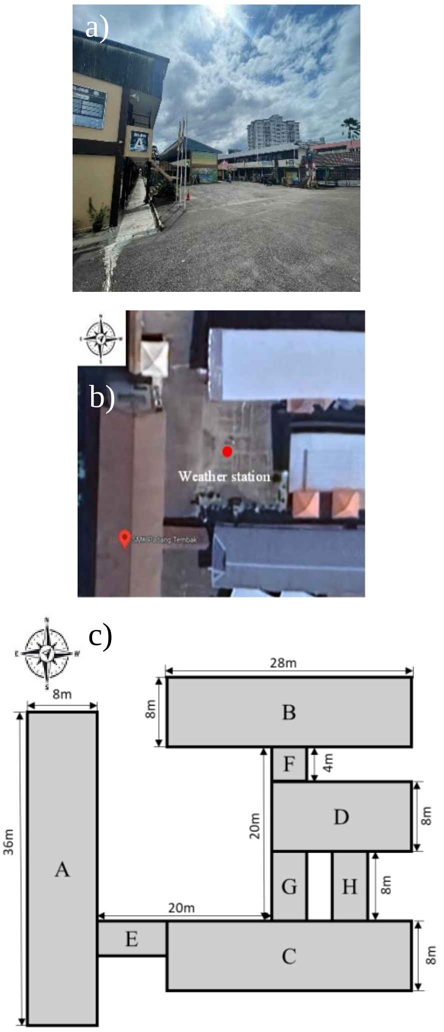


Fig. 1. Description of the study area (a) school courtyard area; (b) Google Map view; (c) school layout with building name and dimensions

Table 1. Details of building configuration

Building	Description
A	4-storey with 1st semi-indoor hall
B, C, D	2-storey
E, F, G, H	1-storey

2.2 Field measurement

This research conducted field measurements using a weather station strategically set up in the central part of the chosen school courtyard. This location was selected to accurately capture the area's microclimate, encompassing sun exposure and wind patterns essential for the study. The weather station recorded real-time micrometeorological data such as air temperature (T_a), wind speed (*WS*) and direction (*WD*), relative humidity (*RH*), and solar radiation (*SR*), ensuring a detailed and precise understanding of the courtyard's environmental conditions.

Measurements were taken over three days (7th, 12th, and 14th March 2023) from 9:00 to 16:00, aligning with school hours to reflect the daily climatic variations experienced by students and staff. This research chose a specific time frame to encompass the peak hours of school activity and to observe the most significant fluctuations in temperature and weather patterns throughout a typical school day. By covering different days within the same month, the study accounted for potential variations in weather conditions, providing a robust dataset for validating the ENVI-met simulations.

This approach helped ensure the simulation's accuracy by providing a comprehensive overview of the courtyard's dynamic weather conditions, thereby enhancing the study's reliability and the relevance of its findings. The recorded data included temperature, relative humidity, wind speed and direction, and solar radiation, among other parameters. These variables were critical in validating the ENVI-met model's predictions and ensuring that the simulated environment closely matched the actual conditions.

Fig. 2 and Table 2 show the details of the specifications of the weather station used in the study, including the types of sensors, their accuracy, and the data logging frequency. This information is crucial for understanding the precision and reliability of the field measurements and for replicating the study in future research.

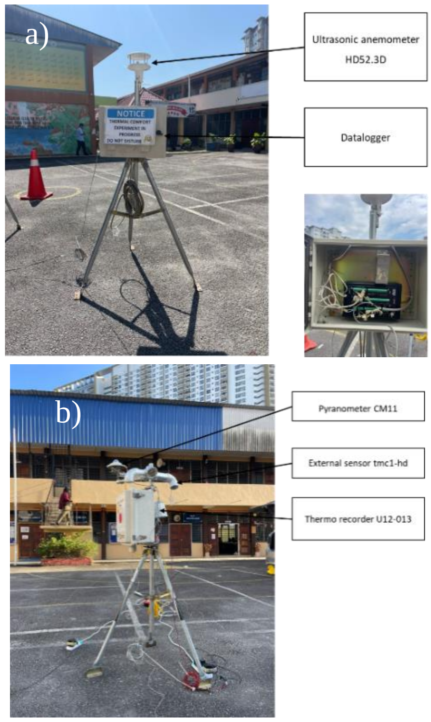


Fig. 2. Weather station equipment setup consists of (a)T_a, *WD*, *WS* equipment, (b) *RH and SR* equipment

Table 2. Weather station equipment specification

Instrument	Parameter	Manufacture, Country	Sensor type	Accuracy	Interval
Thermo recorder U12-013	T_a, *RH*	Onset, USA	External sensor tmc1-hd, Internal sensor	± 0.4 °C (0 to 50 °C); ± 2.5% *RH* (10% to 90%)	5 minutes
Ultrasonic anemometer HD52.3D	*WS*, *WD*	Deltaohm, Italy	Ultrasonic	±0.2 m/s or ±2% (0 to 35 m/s), ±2% (>35 m/s)	1 minute
Pyranometer CM11	*SR*	Kipp & Zonen, Netherlands		7 to 14 µV/W/m²	5 minutes

2.3 Numerical simulation

The simulation process used climate data from a nearby weather station within a 5-kilometer radius of the selected school courtyard to ensure accuracy and relevance [18]. This data included T_a, *WS*, *WD*, *RH*, and *SR*, all crucial for simulating the courtyard's microclimate under various conditions using ENVI-met 5.6.1 software. These inputs allowed a detailed analysis of the dynamic environmental factors affecting thermal comfort. Table 3 shows the ENVI-met boundary conditions, which details the measured meteorological data, instruments, sensor accuracy, and range used in the simulation.

Specifically, the simulation was conducted on the 7th, 12th, and 14th of March 2023, with each simulation lasting 7 hours, starting from 9 am. The model's dimensions were set with x-Grids of 12 units, y-Grids of 11 units, and z-Grids of 32 units, ensuring a comprehensive representation of the courtyard's spatial configuration. The grid size was determined to be 4 meters for both X-axis and Y-axis and 1 meter for Z-axis. The initial surface temperature was set at 30.0˚C to reflect the typical conditions of the area.

This research applied a simple forcing method for meteorological boundary conditions to incorporate the average wind speed and direction for each simulation day. Additionally, this research fine-tuned the solar adjustment factor to accurately match field measurement data, ensuring that the solar radiation input was realistic and precise. These parameters collectively enabled a robust simulation of the courtyard's microclimate, facilitating an in-depth analysis of thermal comfort under varying environmental conditions.

Table 3. ENVI-met software boundary condition

Items	Description/Value
Simulation day	March 7th, March 12th, and March 14th, 2023
Simulation duration	7 h, from 9:00
Model dimensions (m)	x-Grids: 12 units, y-Grids: 11 units, z-Grids: 32 units
Size of the grid (m)	X-axis=4, Y-axis=4, Z-axis=1
Initial surface temperature (˚C)	30.0
Meteorological boundary condition method	Simple forcing
Average wind speed (constant)	2.3 m/s (Standard Deviation = 0.2)

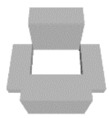
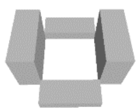
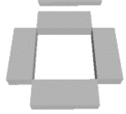
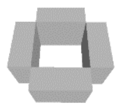
Items	Description/Value
Average wind direction (constant)	223˚ (Standard Deviation = 22.5)
Solar adjustment factor	1.5 (Adjust according to match with weather station data accurately)

Next, this research simulated five scenarios with different building configurations to study the impact of asymmetrical buildings on comfort hours, as shown in Table 4. These scenarios are crucial for examining how building configuration affects solar radiation exposure in the courtyard, considering sun orientation. *B1* consists of buildings on the East and West sides, while *B2* consists of buildings on the North and South sides. Equation 1 defined the aspect ratio where H is the height of buildings, and W is the width between two buildings, which is constant at 20m. Throughout this study, only H is varied.

$$Aspect\ ratio = \frac{H}{W} \tag{1}$$

This research utilised Design Expert 11 software for experimental design and statistical analysis. The factors are B1 and B2, while the response is comfort hours. The definition of comfort hours is 30% of the area having a PET value below 42.0˚C.

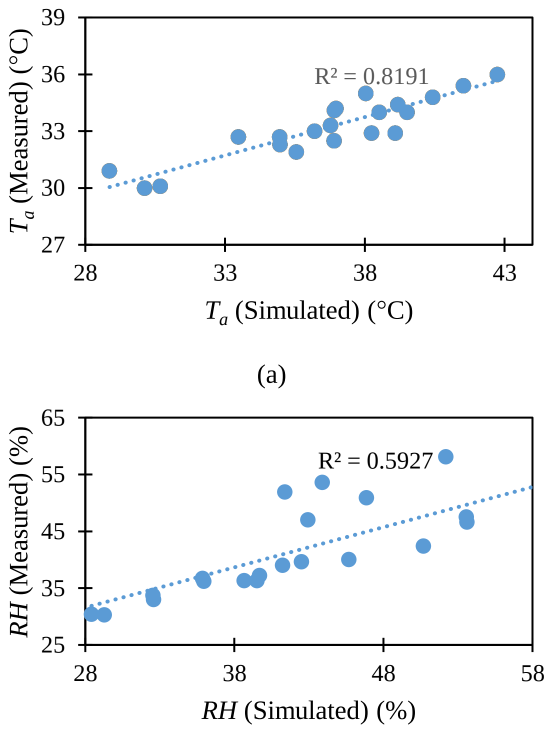
Table 4. List of scenarios

Design	Aspect ratio of *B1* *(Building in East & West)*	Aspect ratio of *B2* *(Building in North & South)*	Model
1	0.4	0.4	
2	0.2	0.8	
3	0.8	0.2	
4	0.2	0.2	
5	0.8	0.8	

2.4 Validation of simulation

This research tested two variables to validate the ENVI-met simulations: T_a and *RH*. Validation techniques included the Coefficient of variation Root Mean Squared Error (CvRMSE) and Mean Biased Error (MBE). Employing a combination of these methods ensures a comprehensive and reliable validation process [19]. The validation results show that the CvRMSE is 13.3% and 13.5%, while MBE is 10.5% and 1.5% for T_a and *RH*, respectively. This result is highly accurate as CvRMSE and MBE fall below 30% and 10%, respectively, based on US Department of Energy M&V Guidelines and ASHRAE Guideline 14 [20]. By using CvRMSE and MBE, the validation process provides a comprehensive overview of the model's performance, confirming that the ENVI-met simulations are both precise and minimally biased. This robust validation approach ensures the reliability of the simulation results for assessing thermal comfort in school courtyards.

This scatter plot in Fig. 3 illustrates the relationship between simulated and experimental values of T_a and *RH*. Each blue dot represents a data pair, with the dotted line indicating the linear regression fit. The R^2 values are 0.82 and 0.60 for T_a and *RH*, respectively, which signifies that the simulated data explains the variability in the experimental data. The strong positive linear trend suggests a good agreement between the simulated and experimental values. The scatter of the measured and simulated data can be explained by the coarse grid cell setting in the ENVI-met [21]. Although ENVI-met can simulated with smaller grid sizes, this will cost more RAM and time. Furthermore, the deviation is partly attributed to weather conditions due to the variability of cloud conditions during field measurement [22].



(b)

Fig. 3. Scatter plot for (a) T_a and (b) *RH*

3. RESULTS AND DISCUSSIONS

3.1 Comparison of thermal comfort across different building designs

The results show that the proposed building configuration enhances thermal comfort than the actual design up to 40%. Fig. 4 illustrates the comfort hours (in hours) for five different designs measured on three different dates: March 7th, March 12th, and March 14th, 2023.

For Design 1, the comfort hours have remained relatively low across all three dates, with 1 hour on all days. Design

2 showed the variability, peaking at approximately 2 hours on March 7th but showing no comfort hours on the other two dates. Design 3 achieved peak comfort hours on two days with four comfort hours, similar to Design 5. Design 4 has one day with comfort hours at 1 hour only and the other days with no comfort hours.

In summary, the graph indicates that the comfort hours varied notably across different designs and dates. Design 3 and Design 5 stand out with high comfort hours, which is four hours. Furthermore, on March 14th, Design 3 and Design 5 showed more comfort hours than the other designs despite not achieving four comfort hours. This finding confirms that higher aspect ratios in buildings on the east and west sides of the courtyard are significantly important for improving comfort hours. This finding is due to the taller buildings on the East and West sides reducing solar radiation exposure to the courtyard due to the shading from sun orientation from East to West.

A study by Rodríguez-Algeciras et al. [23] supports these results where a square courtyard with 0˚ orientation similar to the current study school courtyard design and higher aspect ratio has more comfort hours with PET>30.0˚C compared to 45˚ orientation and low aspect ratio buildings. Furthermore, a study by Abd Elraouf et al. [24] on urban street canyon thermal comfort shows that the presence of buildings on the East-West side provides better thermal comfort than the North-South side due to the least exposure to solar radiation.

Analyzing these variations could help identify the optimal conditions or features contributing to increased comfort in these designs. Therefore, instead of achieving good thermal comfort with typical high buildings on all sides, as in Design 5, Design 3 can also achieve similar thermal comfort performance.

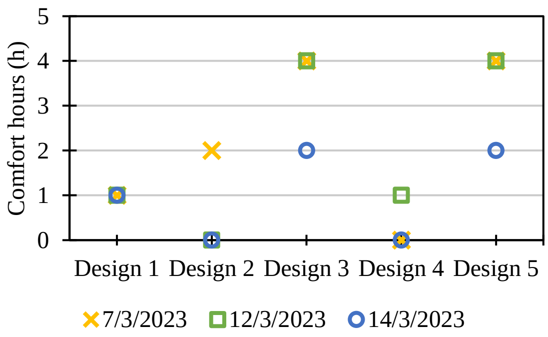


Fig. 4. Overall results of all scenarios based on comfort hours

3.2 Statistical Analysis and Optimization of Building Configurations for Thermal Comfort

Next, statistical analysis is done based on the simulation results of all designs. Table 5 shows the ANOVA and Fit statistics analysis based on the simulation results. P-values less than 0.05 indicate that model terms are significant. In this case, *B1* is a significant model term. Furthermore, the R^2 is high, which shows the accuracy of the results obtained.

Table 5. Analysis of variance and fit statistics based on buildings' height of B1 and B2

Source	Sum of squares	df	Mean square	F-Value	p-value
Model	25.8	2	12.9	16.9	< 0.05
A-B1	25.5	1	25.5	33.5	< 0.05
B-B2	0.2	1	0.2	0.2	0.7
Std. Dev.	0.9				
Mean	1.7				
R^2	0.7				

Based on the statistical analysis, Equation 2 shows the equation in terms of actual factors that can be used to make predictions about the response for given levels of each factor. The levels should be specified in the original units for each factor.

$$Comfort\ hours = -0.75 + 0.24(B1) + 0.02(B2) \quad (2)$$

Fig. 5. and Fig. 6. show the effect of B1 and B2 on the comfort hours. Based on Fig. 5, the X-axis (A: B1) and Y-axis (B: B2) represent variables B1 and B2, respectively, with values ranging from 4 to 16 meters. The higher the height, the higher the aspect ratio. This axis is crucial for understanding how changes in B1 and B2 influence comfort hours. Together, these axes provide a framework for analyzing how variations in these two variables affect the outcome. The Z-axis (Comfort hours) displays the comfort hours, ranging from 0 to 4 hours, and is key to interpreting the level of comfort achieved under different conditions of B1 and B2.

The surface plot uses color gradients to represent different levels of comfort hours. Warmer colors (yellow to red) indicate higher comfort hours, while cooler colors (blue to green) indicate lower comfort hours. This visual cue helps quickly identify areas of high and low comfort in the plot. The general trend observed in the graph shows that comfort hours significantly increase as the height of B1 increases along the X-axis. However, there is no significant change in comfort hours as the height of B2 increases from back to front along the Y-axis. This finging indicates that B1 has a more significant influence on comfort hours than B2.

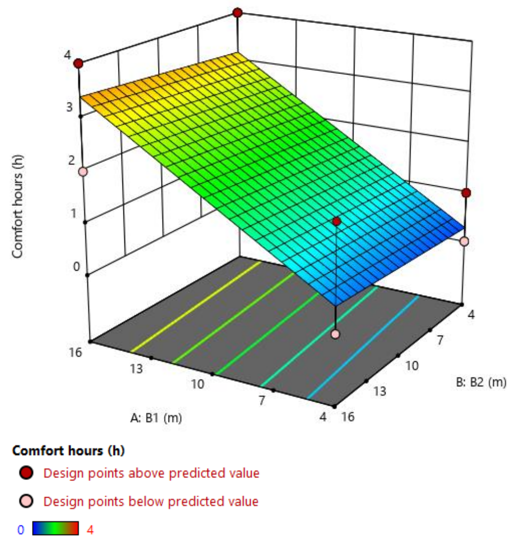


Fig. 5. 3D surface graph of the effect of B1 and B2 on the comfort hours

Figure 6 provides a contour graph illustrating the interplay between variables B1 and B2 concerning comfort hours. The horizontal axis (A) denotes B1 in meters, ranging from 4 to 16, while the vertical axis (B) represents B2 in meters, also ranging from 4 to 16. The higher the height of buildings, the higher the aspect ratio. The color gradient from blue to yellow depicted the contour levels that transition, where blue signifies lower comfort hours and yellow indicates higher comfort hours. Red dots scattered across the graph mark specific design points where experimental data were collected.

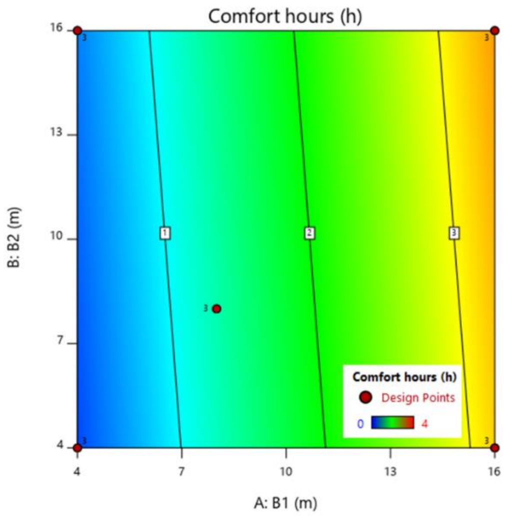


Fig. 6. Contour graph of the effect of B1 and B2 on the comfort hours

Key observations from the graph include the following points. Firstly, the gradient analysis reveals a more pronounced color change along the B1 axis compared to the B2 axis. This finding suggests that B1 exerts a more significant effect on comfort hours than B2. As B1 increases from 4 to 16 meters, the color shifts from blue to yellow, indicating a substantial increase in comfort hours, demonstrating that higher B1 values considerably enhance comfort hours.

In contrast, the effect of B2 is less pronounced. The color transition along the B2 axis is more gradual, suggesting a smaller impact on comfort hours relative to B1. As B2 increases, the comfort hours change, but not as steeply as with B1. The graph also highlights the combined effect of B1 and B2 on comfort hours, showing that the finding achieves the highest comfort hours when both B1 and B2 are at their maximum values. This finding underscores the combined positive effect of these variables.

The overall results indicate that the aspect ratio of B1 primarily influences the optimal building configuration. The significant impact of B1 on comfort hours is greater compared to B2. This finding suggests that adjusting B1 has a more pronounced effect on improving comfort hours than adjusting B2. A study by Rodríguez-Algeciras et al. [17] supports these findings, emphasizing the significant influence of tall buildings in providing shade along the sun's orientation. Their research highlights that the strategic placement and height of buildings can create shaded areas, which are crucial for reducing heat exposure and improving thermal comfort in urban environments. By blocking direct sunlight, these structures help mitigate the urban heat island effect, thereby enhancing the overall livability and sustainability of cityscapes.

4. CONCLUSIONS

The objectives of this study to investigate the impact of asymmetrical building configurations on thermal comfort in school courtyards in Malaysia was achieved with some significant findings as follows:

1. The results demonstrated that higher aspect ratios on the East and West sides significantly enhanced thermal comfort hours.
2. Instead of Design 5, which featured higher buildings on all sides and achieved the highest comfort hours up to four hours, Design 3, with a high aspect ratio on the East and West sides only also provided a similar comfort hour performance with Design 5 illustrating the importance of building height and orientation in optimizing courtyard microclimates.
3. The statistical analysis confirmed the significant influence of the East and West building configurations (B1) on comfort hours, with a p-value less than 0.05, indicating strong model significance. Additionally, the contour graph analysis reinforced the significant role of B1 over B2 in enhancing thermal comfort. This insight underscores the potential of strategic asymmetrical designs in mitigating solar radiation exposure and improving the usability of courtyards throughout the day.

In conclusion, this study provides valuable guidelines for architects and planners aiming to improve thermal comfort in school courtyards. By adopting optimal building configurations, it is possible to create more comfortable and usable outdoor spaces, thereby enhancing the overall learning environment for students. However, this research has certain limitations. The study focused on a specific climatic region, and the findings may not be directly applicable to other climates without additional validation. Furthermore, the simulations were based on idealized conditions that might differ from real-world scenarios. Future research should aim to explore the impact of asymmetrical building configurations in different climatic contexts and validate the findings through long-term field studies. Additionally, examining the influence of vegetation, materials, and other microclimatic factors on thermal comfort could provide a more comprehensive understanding of courtyard design optimization.

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