Civil Engineering and Architecture 13(3): 1433-1445, 2025 http://www.hrpub.org
DOI: 10.13189/cea.2025.130301

Optimization of U-Enclosure Courtyard (UEC) Design Factors in Tropical Climate: Energy Assessment

Abdulbasit Almhafdy[1], Norhati Ibrahim[2], Sabarinah Sh Ahmad[2], Essam Almahmoud[1,*], Ali Alashwal[3]

[1]Department of Architecture, College of Architecture and Planning, Qassim University, Saudi Arabia
[2]Centre of Studies for Architecture, Faculty of Architecture, Planning and Surveying, Universiti Teknologi MARA, Malaysia
[3]School of Built Environment, Western Sydney University, Australia

Received May 21, 2024; Revised February 22, 2025; Accepted March 17, 2025

Cite This Paper in the Following Citation Styles

(a): *[1] Abdulbasit Almhafdy, Norhati Ibrahim, Sabarinah Sh Ahmad, Essam Almahmoud, Ali Alashwal , "Optimization of U-Enclosure Courtyard (UEC) Design Factors in Tropical Climate: Energy Assessment," Civil Engineering and Architecture, Vol. 13, No. 3, pp. 1433 - 1445, 2025. DOI: 10.13189/cea.2025.130301.*

(b): *Abdulbasit Almhafdy, Norhati Ibrahim, Sabarinah Sh Ahmad, Essam Almahmoud, Ali Alashwal (2025). Optimization of U-Enclosure Courtyard (UEC) Design Factors in Tropical Climate: Energy Assessment. Civil Engineering and Architecture, 13(3), 1433 - 1445. DOI: 10.13189/cea.2025.130301.*

Abstract Recently, many researchers have investigated the environmental performance of courtyards for thermal and energy improvement in buildings and urban spaces. For microclimate modification, achieving optimal benefits from courtyards depends on several design factors: the plan aspect ratio, number of floors, area, cantilevered roof, and orientation. This study assessed the energy performance of the U-enclosure courtyard (UEC) attached built volume in a tropical climate using these design factors. The UEC configuration was chosen for investigation through a parametric analysis using integrated environmental solutions virtual environment (IESVE) simulation software. The results highlight the significant energy-saving potential of an optimized courtyard design. A square plan aspect ratio improves energy performance, saving 13.10% annually compared to a rectangular design due to reduced solar radiation exposure. Increasing the building height to six floors achieved the best energy savings per square meter, reducing energy consumption by 41.35% compared to a single-floor courtyard. Similarly, decreasing the courtyard area from 900 m^2 to 400 m^2 resulted in an energy saving of 28.90%. Adding a cantilevered roof covering 60% of the courtyard opening further reduced energy consumption by 14.78%. While orientation had a negligible impact overall, the west orientation performed slightly better, with an annual energy reduction of 0.4%. The study also highlights the interaction among these design factors and their cumulative effect on energy efficiency. These insights provide valuable guidelines for designing courtyards in tropical climates, harnessing their potential to lower energy consumption and enhance the energy performance of buildings. By understanding the relationship between courtyard design factors and energy performance, architects and urban planners can develop more sustainable building practices, contributing to the broader goal of environmental conservation and energy efficiency in urban development.

Keywords Courtyard Design, Energy Assessment, Optimization, Tropical Climate, Energy Consumption, IESVE

1. Introduction

Malaysia has a hot, humid, uncomfortable climate for most of the year, which requires active intervention to provide suitable living conditions. Concerning the built environment, the unpleasant climate in tropical regions is one of the hardest to overcome through design [1]. This is due to the high humidity and daytime sun exposure resulting in indoor temperatures exceeding the upper limit of thermal comfort for most of the year. Since Malaysia is a tropical area, it is undeniable that designers and architects are confronted with difficult building challenges.

Solar heat gain through the building walls causes overheating, which is exacerbated by radiant solar penetration through openings [2]. The courtyard is usually an area partially enclosed by buildings or walls but exposed to the sky [3]. The courtyard design was primarily developed from the historical architecture of Europe and the Middle East, and this historical aspect created barriers to the implementation of the new courtyard [4], [5].

According to architectural history, the courtyard form was eventually modified and changed in response to the surrounding environment, influenced by climate, site restrictions and orientation. This led to the creation of a new and modern form of courtyard designed in the shape of a ‘U’, an ‘L’, or a ‘Y’ [5]. The application of these forms meant that the courtyard need not be fully enclosed (four-sided or enclosed by the four directions). This led to the investigation of new forms like the semi-enclosed courtyard in terms of orientation and aspect ratio, because such changes could have a significant effect on thermal performance in a tropical climate [6], [7].

Numerous studies have identified the primary purpose of incorporating a courtyard in a building is to create more congenial living conditions [6]. For that reason, the courtyard design can be modified according to several factors [8] such as length-to-height ratio [9], wall envelope [10], orientation [11], courtyard configuration [12] and height or number of floors [13].

For example, Kubota et al. [14] investigated the thermal properties of courtyards in traditional Chinese storefronts in Malaysia’s hot-humid climate. Field experiments in 16 shophouses identified five courtyard types and recommended cross-ventilated courtyards and staggered V-shaped roofs for better thermal comfort and cooling. Zhu et al., [15] investigated how courtyard geometry and orientation influenced shading and ventilation. Results showed that in hot climates, north-south courtyards with high aspect ratios (>2) provided excellent shading, while temperate zones benefited from square or round courtyards with aspect ratios near 1 for seasonal balance.

Mahmoud & Abdallah, [16] investigated strategies for improving outdoor thermal comfort (OTC) in school courtyards in hot, arid climates. Results showed that hybrid staggered shading with trees reduced physiological equivalent temperature (PET) values up to 18.6 ℃, with the most comfortable thermal conditions achieved in wide courtyards (H/W = 0.4). Diz-Mellado et al. [17] assessed shading and misting systems in a Seville courtyard, and found a temperature reduction of up to 11.7 ℃ and a 100% increase in comfort hours during heat waves, highlighting the effectiveness of passive cooling strategies in adapting building designs to extreme heat.

Wen et al. [18] evaluated the impact of roofed courtyards (CBR) on building energy efficiency in Hebei, China. Results showed that light-transmitting (T-CBRT) and non-light-transmitting (NT-CBRT) roofs reduced energy consumption by 19.97% and 15.41%, respectively.

Almumar [11] analysed traditional courtyard house designs to find ways of achieving optimal solar orientation with random plot layouts. Most houses were oriented to maximize summer shading and winter sunlight. Testing with a simulated model confirmed that spaces aligned with desired directions, could be compatible with energy-efficient modern designs.

As an extension of the work outlined above, this paper focused on the courtyard as a micro climate regulator, especially within tropical environments. The argument is that while many researchers have investigated courtyards, gaps remain in evaluating how well their design actually worked and in determining how courtyard designs affect the energy consumption of adjacent buildings, the attached built volume. Therefore, in this study, we explored the energy performance of a selected U-enclosure courtyard (UEC) as an architectural feature across diverse design contexts, including plan aspect ratio, orientation, area, cantilevered roof, and number of floors. As shown in **Figure 2**, the evaluation of energy performance was conducted using a parametric analysis of different UEC scenarios.

2. Methods

The methodology comprises two main phases.

2.1. Modelling Approach

A simulation model of a UEC was constructed using IESVE simulation software. As shown in

Attached built volume		Measured in KWY/m^2 (energy consumption)
		Adiabatic area
Inside the courtyard		Semi-outdoor

Figure 1, the target of this energy investigation included only the adjacent built-up areas of the courtyard. The area of the attached built volume is graphically illustrated in brown. The other indoor areas were specified as adiabatic, and were shown in green. All the UEC design factors (**Figure 2**) reflect the existing design factors of courtyards in government buildings in Malaysia [19].

The model was further expanded to generate six different models of the courtyard, which were tested in a parametric study using IESVE software. **Figure 3** shows the UEC design factors of all six models.

ModelIT, in the IESVE software suite, was used for geometry verification, checking for issues like non-planar surfaces, holes, zoning errors, and overlaps that could cause simulation problems. ApLocate then applied site-specific data for Kuala Lumpur, using weather data in *.fwt format provided by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). The SunCast module was utilized to perform solar insolation and shading studies, calculating shadows and internal heat gain based on sun position, date, time, orientation, and location. In this study, SunCast was used to determine the solar insolation for alternative courtyard designs, contributing to thermal performance assessments in the simulation. For systematic comparison, the adjacent built-up indoor areas under investigation were temperatures controlled fully to 22 ℃.

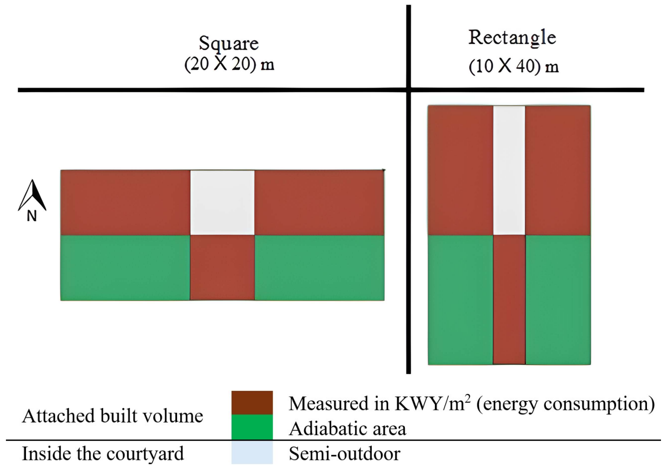

Figure 1. Energy observations during the parametric study of the UEC

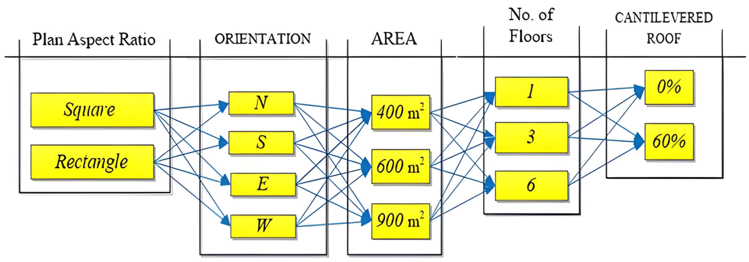

Figure 2. Design factors of the UEC

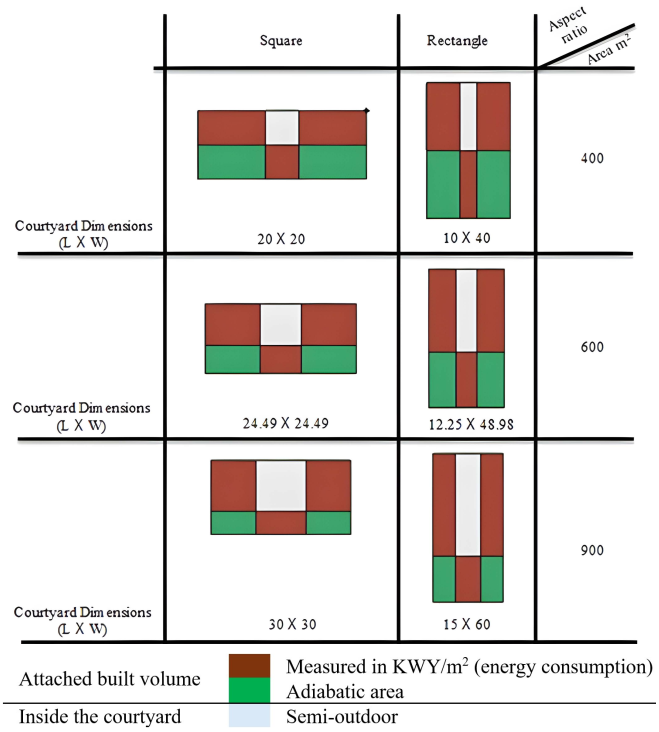

Figure 3. UEC design factors, plan aspect ratio and area

2.2. Analysis

The energy consumption of the attached built volume of indoor areas that faced the courtyard directly (2000 m^2 in all cases) was evaluated for the whole year, and the results were normalised based on MWY/m^2 for comparison and analysis of all design factors. The results were also expressed in terms of min, max and summed total.

2.2.1. Plan Aspect Ratio

Two types of UECs were considered in these factors. As illustrated in

Attached built volume		Measured in KWY/m^2 (energy consumption)
		Adiabatic area
Inside the courtyard		Semi-outdoor

Figure 1, the square and the rectangle were selected by varying the UEC length and width.

2.2.2. Number of Floors

Three different heights (number of floors) of the courtyard were constructed for energy assessment. The number of floors was chosen to correspond with what is currently used for government buildings in Malaysia: one, three or six floors (**Figure 4**).

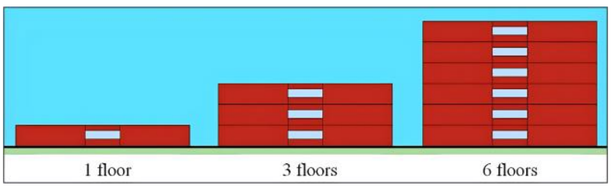

Figure 4. Height factor of courtyard design (number of floors)

2.2.3. Area

Three different areas were selected for the generated models: 400 m^2, 600 m^2 and 900 m^2 (**Figure 3**). The areas of the attached buildings in all types of the courtyard were 2000 m^2.

2.2.4. Cantilevered Roof

As part of the simulation, we assessed the effect of including a cantilevered roof covering 60% of the courtyard area compared with one without (0%) (**Figure 5**). Since the simulation examined three different courtyard sizes, the cantilevered roof, as a shading device, was calculated as a percentage of each courtyard's area. The lengths of the cantilevered roofs varied depending on the courtyard size, with values corresponding to either 0% or 60% coverage of the courtyard area.

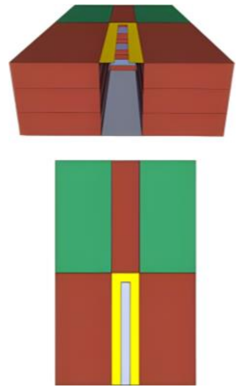

Figure 5. The UEC with three floors and 60% coverage by the cantilevered roof

2.2.5. Orientation

All cases of the generated models of the UECs were oriented to the four main directions, namely, north (N), south (S), west (W) and east (E). In the simulation process, the courtyards were three-sided, and, as illustrated in **Figure 6**, the models were oriented according to the opening side.

2.3. Calibration Process for Software Reliability

In this study, data collection was performed each week to accurately measure the thermal performance in the courtyard. The mean radiant temperature (MRT) was measured within the enclosure of the selected courtyard (UEC) at the University Technology MARA (UiTM). This fieldwork was done for more accurate calibration between the actual measurements and the IESVE simulation data. This phase contained the justifications of courtyard selections, description of the equipment that was used, calibrations process and correlation analysis.

2.3.1. Courtyard Selection

The UEC is located on the Civil Engineering campus at UiTM, Shah Alam. As shown in **Figure 7**, it is oriented in a SE to NW direction. The courtyard is enclosed on three sides with the fourth side open to the SE. The courtyard is rectangular in plan aspect ratio, with a varying number of floors on each of its three sides as shown in **Figure 8**.

The Faculty of Civil Engineering has allowed one week and 24 hours of data collection. The data collection was performed to collect the MRT as it will be used for the calibration process.

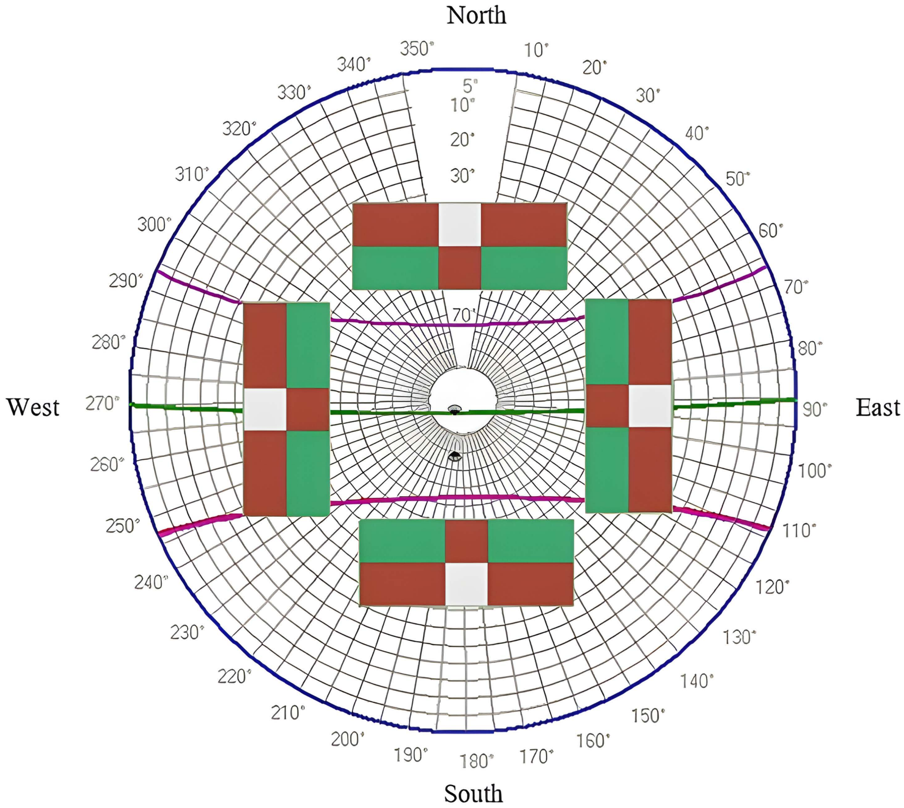

Figure 6. Sun path in Kuala Lumpur relative to courtyard orientation

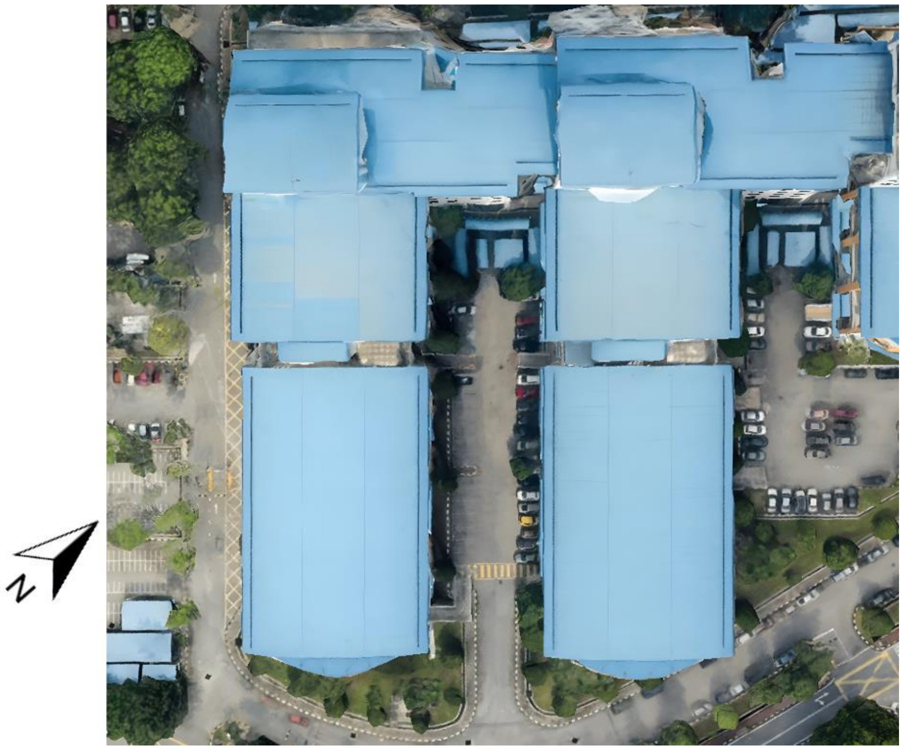

Figure 7. Google image of the UEC at the UiTM civil engineering facility

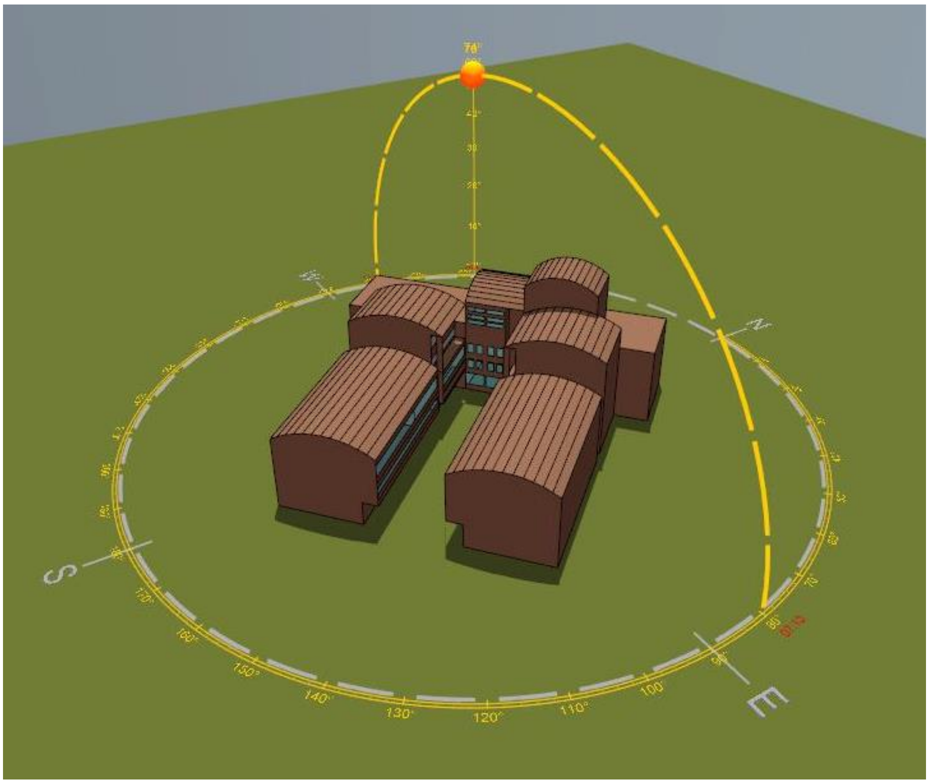

Figure 8. The UEC Courtyard in Modell viewer (IESVE) Source: [20]

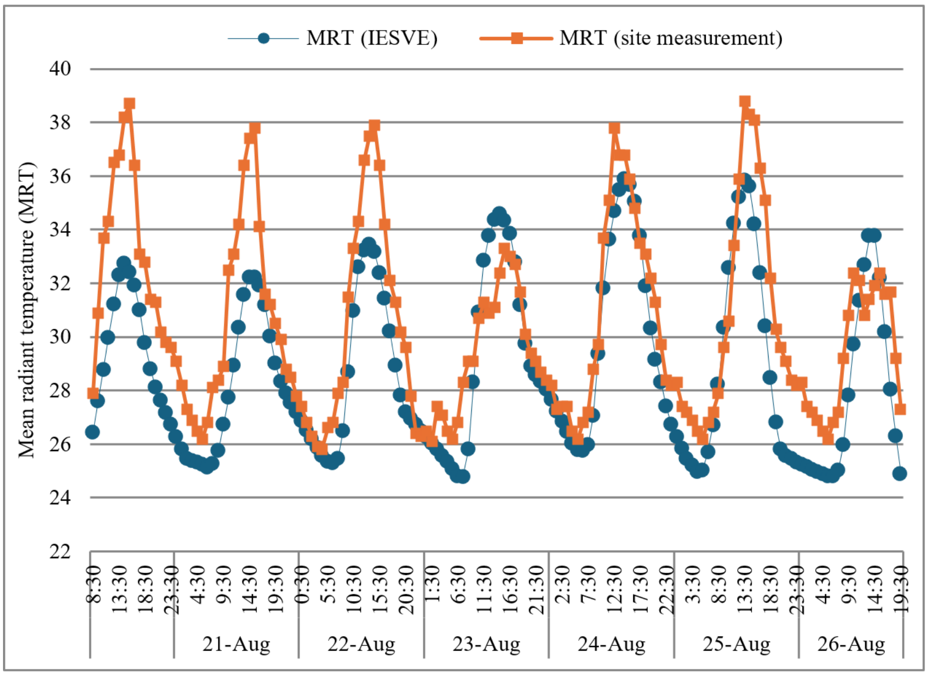

Figure 9. Comparison of MRTs obtained through field measurement and simulation (IESVE) with hourly readings taken over a one-week period Source: [20]

2.3.2. Equipment

The heat stress wet bulb globe temperature (WBGT) meter was used for collecting accurate temperature data. This meter measures the heat stress index, which is displayed on the device as TG, and indicates how hot it feels when the temperature is combined with humidity, sunlight and air movement. The MRT indicates the effects of direct solar radiation on exposed faces.

2.3.3. Calibration of the Case Study Model

The IESVE simulation results were compared to the fieldwork data collection. Using the passive approach, the courtyard simulation results were calibrated by matching the semi-outdoor MRT of the courtyard with the fieldwork data for the selected days. The simulation data for the UiTM courtyard were recorded hourly for seven days from 8:30 on 20 August until 19:30 on 26 August. The building materials closely reflect those of the actual construction and are kept constant for all the simulations. The internal environment of the attached built volume (surrounding rooms) was modelled at a constant air-conditioned temperature of 22 ℃.

Figure 9 and ****.** Correlation is significant at the 0.01 level (2-tailed).

show the MRT obtained through measurement and simulation for the simulation day at the central point of the UEC in UiTM. The simulation data shows a strict correlation with the field measurements.

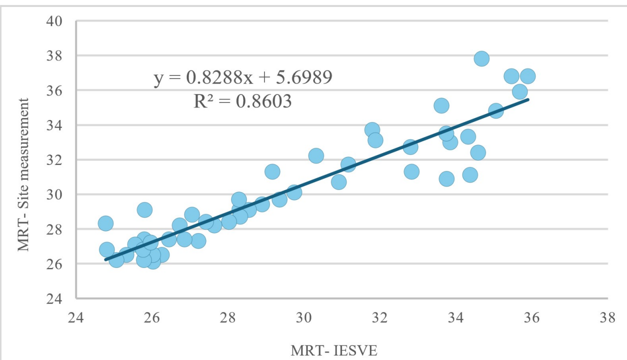

Figure 10. Correlations between the simulation MRTs (IESVE) and site measurement data for the UEC at UiTM

Table 1 shows a significant correlation between the field measurement readings and courtyard simulated results with an R^2 value of 0.86. Hence, the findings confirmed the accuracy and reliability of IESVE to be used for subsequent simulations for the courtyard alterations.

Table 1. Pearson correlation analysis between simulation data of case study model and site measurements in the UEC at UITM

MRT		IES<VE>	Site Measurement
Simulation	Pearson Correlation	1	.882**
	Sig. (2-tailed)		.000
	N	168	168
Site Measurement	Pearson Correlation	.882**	1
	Sig. (2-tailed)	.000	
	N	168	168

**. Correlation is significant at the 0.01 level (2-tailed).

3. Findings

Six design cases of courtyard models were generated to perform the parametric study. The results of the fieldwork established that the thermal conditions of the courtyard could be significantly improved by choosing the optimal design factors. Accordingly, in this parametric study, we simulated the energy performance of the attached built volume of the courtyard under alternative design conditions (square vs rectangular, number of floors and area).

3.1. Plan Aspect Ratio

As shown in **Figure 11**, the peak energy consumption occurred in March for the rectangular courtyard and in May for the square courtyard. A rectangular UEC generally shows lower energy performance than a square UEC. For example, in **Figure 11**, during the peak time (March), the energy consumption of the rectangular courtyard was increased by 1.12 KWh/m^2 relative to the square courtyard. In terms of annual energy performance, the square courtyard performed better than the rectangular courtyard, with a savings of 13.10% in energy consumption (**Table 2**).

Because the orientation of the attached built volume of the rectangular courtyard is north, the façades of the attached sections are expected to receive more solar radiation per day than the façades of the square courtyard.

3.2. Number of Floors in Rectangular UEC

The results show that the change in energy performance by varying the number of floors has the same pattern during the whole year (**Figure 12 and Table 3**). The simulation results show that the peak time is during March while the lowest value was recorded in December.

Results in **Table 3** show that the annual total energy consumption increased with the number of floors. However, when the energy consumed per m^2 is calculated (KWh/m^2), the energy performance of the six-floor configuration becomes the best in energy saving. A courtyard with one floor and an attached built volume with an indoor area of 2000 m^2 consumed the most energy per m^2 (**Figure 12**).

Table 3 clearly shows that percent energy consumption is significantly reduced by adding more floors. A courtyard with three floors in the attached building has an area of 6000 m^2 (2000 m^2/floor × three floors) and reduces the energy consumption by 30.83% compared to the courtyard with one floor.

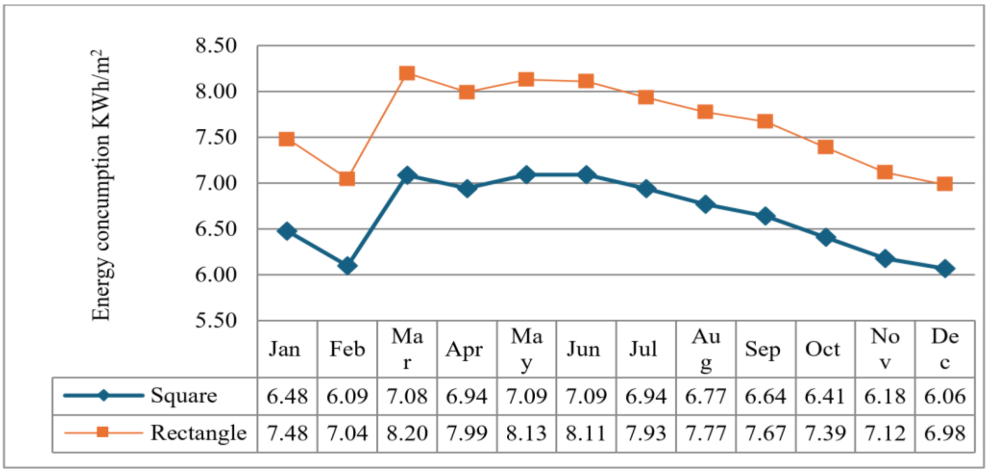

Figure 11. Effect of courtyard plan aspect ratio on energy consumption

Table 2. Effect of courtyard plan aspect ratio on energy consumption

Plan Aspect Ratio	Min. Val./month	Max. Val./month	Summed Total MWh	MWh/m^2	Reduction in Energy Consumption (%)
Rectangle	41.90 / Dec	49.18 / Mar	550.82	0.092	
Square	36.38 / Dec	42.56/ May	478.67	0.080	13.10

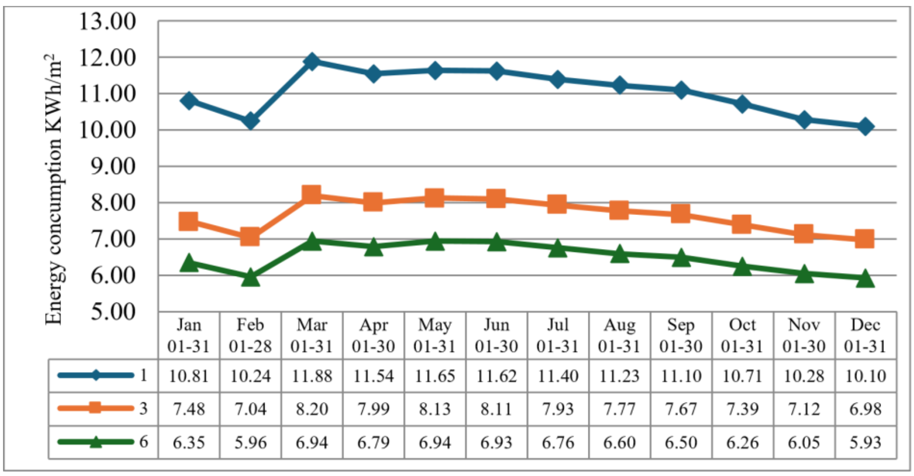

Figure 12. Effect of the number of floors on the energy consumption of the rectangular form of the UEC

Table 3. Summary of the effect of the number of floors on the energy performance of the rectangular form of the **UEC**

No. of floors	Min. Val./month	Max. Val./month	Summed Total MWh/Y	MWh/m^2	Reduction in Energy Consumption (%)
1 floor	20.20 / Dec	23.77 / Mar	265.11	0.13	
3 floors	41.90 / Dec	49.18 / Mar	550.82	0.09	30.83%
6 floors	71.21 / Dec	83.30 / Mar	936.06	0.08	41.35%

Similarly, a design with six floors, covering an area of 12,000 m^2 (2,000 m^2 per floor × 6 floors), achieved a 41.35% reduction in energy consumption.

3.3. Area

Figure 13 presents the effect of the courtyard area on energy consumption. The energy performance of the courtyard with 900 m^2 was the worst compared to the others with a total sum of 775.4 MWh. Nevertheless, the reductions of energy consumption in the 600 m^2 and the 400 m^2 courtyards were only 128.68 MWh and 224.54 MWh respectively.

The reduction in energy consumed in the 900 m^2 courtyard is more than double when compared with the courtyard with 400 m^2 area. However, the reduction of energy consumption for the 400 m^2 is only 28.90% compared to the 900 m^2. Moreover, although the 900 m^2 area of the courtyard is 33.33% bigger than the 600 m^2 area of the courtyard, the reduction of energy consumption for the 600 m^2 is only 16.60% compared to the 900 m^2 area of the courtyard.

Table 4 shows the energy performance of the three sizes of the courtyard (400 m^2, 600 m^2 and 900 m^2).

3.4. Cantilevered Roof

The energy performance is clearly influenced by the installation of a cantilevered roof. However, as seen in **Figure 14**, the decrease in energy consumption (14.78%) is not as high as the ratio of the area of the cantilevered roof to the total top opening area of the courtyard (60%). The reduction in energy consumption is compared to the courtyard without a cantilevered roof.

Results in **Table 5** show a summary of the effect of the cantilevered roof on the energy performance of a rectangular form of UEC with an area of 400 m^2. The annual total energy consumption is decreasing when applying the cantilevered roof. However, the maximum reduction in energy consumption is 15.28% during March while the minimum reduction is 14.62% during December.

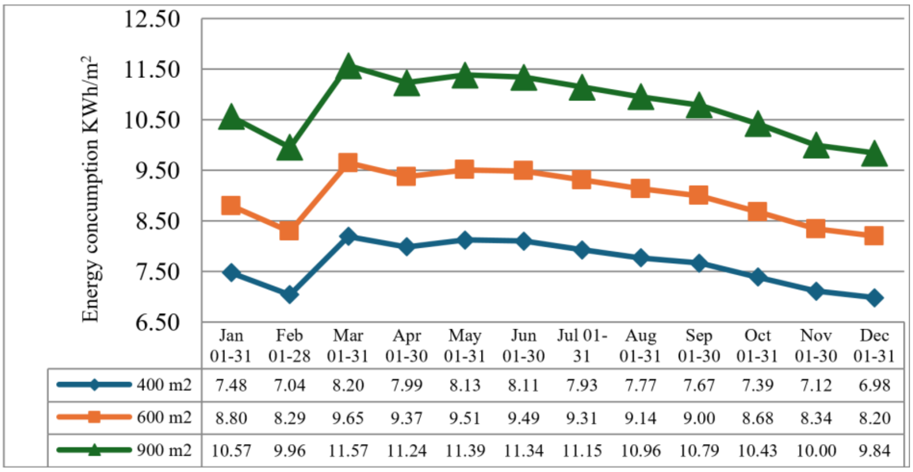

Figure 13. Effect of the courtyard area on the energy consumption in a rectangular courtyard with three floors

Table 4. Effect of the courtyard area on energy performance in a rectangular courtyard with three floors

Courtyard Area (m^2)	Min. val./mo	Max. val./mo	Summed Total MWh	MWh/m^2	Reduction in Energy Consumed (%)
900	59.05 / Dec	69.45 / Mar	775.36	0.13	
600	49.21 / Dec	57.88 / Mar	646.68	0.10	16.60%
400	41.90 / Dec	49.18 / Mar	550.82	0.09	28.90%

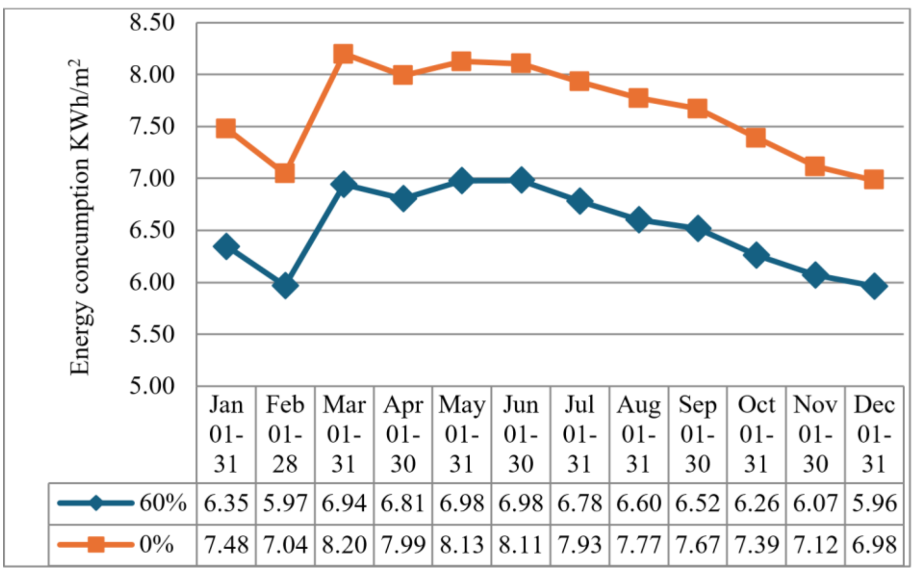

Figure 14. Effect of a cantilevered roof on energy consumption of a rectangular courtyard

Table 5. Effect of a cantilevered roof on energy performance of a rectangular courtyard with an area of 400 m^2

Cantilevered-roof (%)	Min. Val./month	Max. Val./month	Summed Total MWh/Y	MWh/m^2	Reduction in Energy Consumption (%)
0%	41.89/Dec	49.18/Mar	550.82	0.09	
60%	35.77/Dec	41.66/Mar	469.41	0.08	14.78%

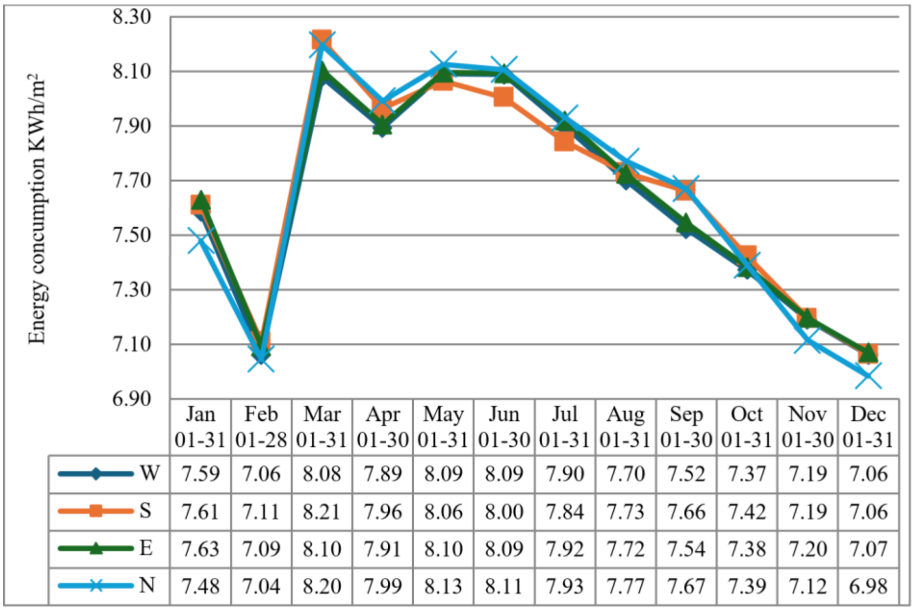

Figure 15. Effect of orientation on energy consumption in a rectangular UEC

3.5. Orientation

Regarding the energy consumption of the courtyard attached built volume, we found that the effect of orientation on the energy consumption was negligible. **Figure 15** and **Table 6** show that the peak month of energy consumption was recorded in March for the north, south and east directions; for the west direction, the peak time was found in May. The lowest energy consumption was recorded in December and February, but, the overall results show only slight differences among the main four directions.

In **Table 6**, the energy consumption of the courtyard oriented to the west was the highest compared to the other directions. However, based on the summed total of annual energy consumption, the average annual reduction of the orientation, with the same UEC condition, was only 0.4%, 0.2% and 0.3% for the south, east and north respectively. The lowest annual energy consumption was found in the courtyard oriented to the north followed by the west, while the highest annual energy consumption was in the courtyard oriented to the south followed by the north.

3.6. Overall Impact of Courtyard Design Factors

Figure 16 shows the energy performance of the attached built volume of the courtyard based on the design factors that were simulated. The results of energy consumption in **Figure 16** and **Figure 17** are presented in MWh/m^2 for compression purposes and to show the effects of all the courtyard design factors on energy performance. **Figure 16** shows the energy performance of the attached built volume in all design scenarios, while **Figure 17** focuses on the UEC with an area of 900 m^2.

In **Figure 16**, the results show that orientation has no significant effect on energy consumption. For the height design factor, the results in **Figure 16** and **Figure 17** show that the energy performance was decreased by increasing the number of floors of the attached buildings. However, some courtyard energy performance simulations showed little differences among the models with different numbers of floors. For example, the differences in energy consumption of the 400 m^2 square courtyard (s-400) among the three models that vary in the number of floors were smaller than the differences in energy consumption of the 900 m^2 rectangular courtyard (r-900). The s-400 courtyard with six floors reduced the energy consumption by 28% and 39% compared to one floor and three floors, respectively. **Figure 16** and **Figure 17** show that the differences in UEC design factors were further decreased with the application of the cantilevered roof as a shading device. The cantilevered roof plays a significant role in improving the energy performance of the attached built volume of the courtyard. In **Figure 17**, despite the significant differences in energy consumption between the courtyard with one floor and courtyards with three floors, the differences were decreased by the addition of the cantilevered roof to the courtyard. Therefore, the energy consumption of the courtyard with three floors without a cantilevered roof was almost the same as the energy consumption of the UEC of one floor with a cantilevered roof. In addition, the square courtyard, s-900, performed better than the rectangular courtyard, r-900 (**Figure 17**), but the differences were less with increasing numbers of floors as well as with the addition of a cantilevered roof.

Table 6. Yearly effect of orientation on energy consumption in a 400 m^2 rectangular courtyard

Orientation	Min. Val./month	Max. Val./month	Summed Total MWh	MWh/m^2	Reduction in Energy Consumption (%)
W	42.37 / Dec	48.55 / May	549.28	0.09155	
S	42.38 / Dec	49.29 / Mar	551.26	0.09188	0.4%
E	42.42 / Dec	48.62 / Mar	550.53	0.09176	0.2%
N	41.90 / Dec	49.19 / Mar	550.82	0.09180	0.3%

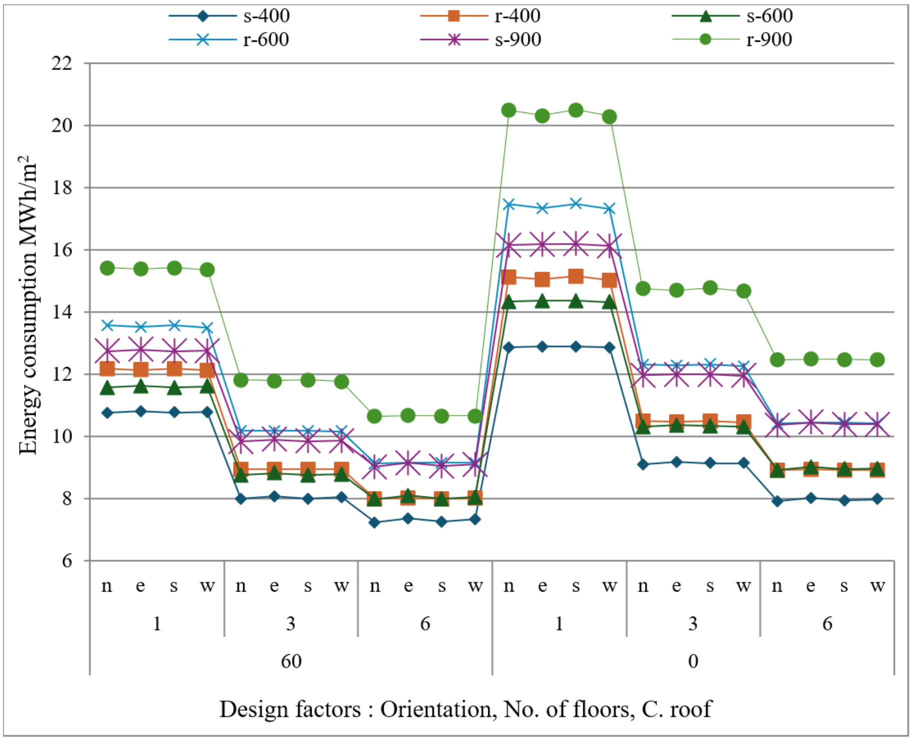

Figure 16. Overall UEC design factors and their effects on energy consumption of the UEC attached built volume

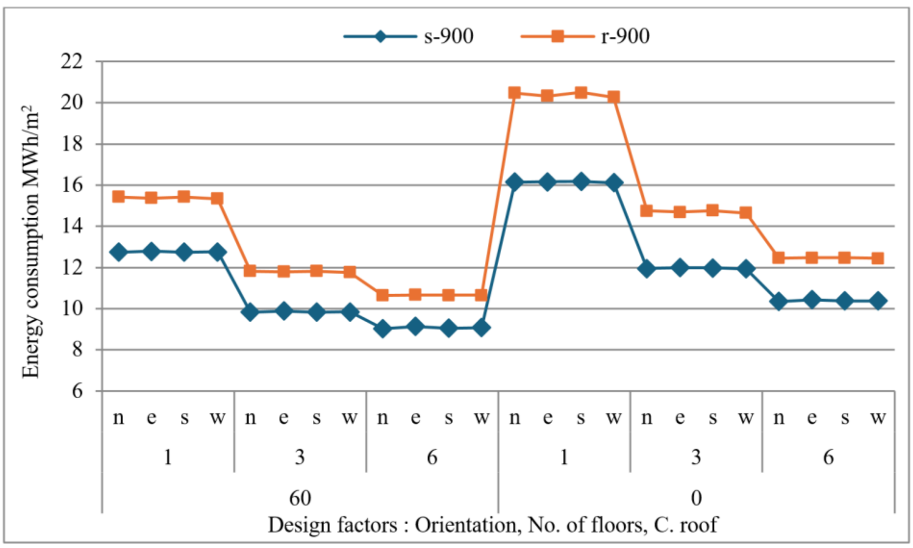

Figure 17. Overall UEC design factors and their effects on the energy consumption of the UEC attached built volume with the area of 900 m^2

4. Conclusions

The present paper focuses on courtyard design factors and their effect on energy performance in a hot, humid climate. The methodology was based on parametric modeling in IES<VE>. This method allowed us to achieve the main goal of the paper, which was to provide recommendations for optimising the energy performance of courtyards with attached built volume in a tropical climate. The results show that courtyards can improve the energy performance of the attached built volume when they are properly designed.

The comparison of energy performances of the attached built volumes of courtyards with different design factors will help architects design them for lower energy consumption. The following recommendations are based on interpretations of the simulation results.

- The courtyard should be designed with a square plan aspect ratio, especially when it is necessary to save energy in the courtyard attached built volume.
- The relationship between area and height (number of floors) should be adjusted in tandem. If the area is increased, the height should be increased in order to provide more shading within the courtyard.
- A cantilevered roof should be installed in the courtyard when the height of the courtyard attached building to width or length is shallow (height to plan ratio is 1:1 or less). This is to ensure that the courtyard will be sufficiently shaded. The cantilevered roof has a negative relationship with height (number of floors). If the attached built volume height of the courtyard is increased, the advantage of a cantilevered roof becomes negligible.
- The effect of courtyard orientation on energy consumption is negligible. The west orientation showed the highest annual energy consumption, while changing to the south, east, or north reduced it by 0.4%, 0.2%, and 0.3%, respectively.

Acknowledgments

The Researchers would like to thank the Deanship of Graduate Studies and Scientific Research at Qassim University for financial support (QU-APC-2024).

REFERENCES

[1] A. Aflaki, N. Mahyuddin, Z. Al-Cheikh Mahmoud, and M. R. Baharum, "A review on natural ventilation applications through building façade components and ventilation openings in tropical climates," *Energy and Buildings*, vol. 101, pp. 153-162, 2015, doi: 10.1016/j.enbuild.2015.04.033.

[2] I. Rajapaksha, H. Nagai, and M. Okumiya, "A ventilated courtyard as a passive cooling strategy in the warm humid tropics," *Renew Energy*, vol. 28, no. 11, pp. 1755–1778, Sep. 2003, doi: 10.1016/S0960-1481(03)00012-0.

[3] B. Edwards, M. Sibley, P. Land, and M. Hakmi, *Courtyard housing: past, present and future*. Taylor & Francis, 2006.

[4] J. Reynolds, *Courtyards: aesthetic, social, and thermal delight*. John Wiley & Sons, 2002.

[5] T. A. Saeed, "Studies on the geometrical properties of courtyard house form considering natural ventilation in hot-dry regions," Illinois Institute of Technology, 2007.

[6] I. A. Meir, D. Pearlmutter, and Y. Etzion, "On the microclimatic behavior of two semi-enclosed attached courtyards in a hot dry region," *Build Environ*, vol. 30, no. 4, pp. 563–572, Oct. 1995, doi: 10.1016/0360-1323(95)00018-2.

[7] H. Safarzadeh and M. N. Bahadori, "Passive cooling effects of courtyards," *Build Environ*, vol. 40, no. 1, pp. 89–104, Jan. 2005, doi: 10.1016/j.buildenv.2004.04.014.

[8] A. Forouzandeh, "Parametric analysis of influence of courtyard microclimate on diminution of convective heat transfer through building's envelope," *Build Simul*, pp. 1–21, Apr. 2019, doi: 10.1007/s12273-019-0528-2.

[9] Z. Zamani, S. Heidari, and P. Hanachi, "Reviewing the thermal and microclimatic function of courtyards," *Renewable and Sustainable Energy Reviews*, vol. 93, pp. 580-595, 2018. doi: 10.1016/j.rser.2018.05.055.

[10] W. Lili, Y. Zheng, and Y. Lipei, "The research on environmental facility of traditional Residence based on modern residence pattern—Takes the Dali courtyard traditional folk house as an example," in *2011 International Conference on Electric Technology and Civil Engineering (ICETCE)*, IEEE, 2011, pp. 1751–1756.

[11] M. M. S. Almumar, "Understanding the environmental performance of the Iraqi traditional courtyard house, Is there an order of façades orientation in randomly oriented land plots?," *Journal of Building Engineering*, vol. 22, pp. 140–146, Mar. 2019, doi: 10.1016/J.JOBE.2018.12.004.

[12] P. W. Tien and J. K. Calautit, "Numerical analysis of the wind and thermal comfort in courtyards 'skycourts' in high rise buildings," *Journal of Building Engineering*, vol. 24, p. 100735, Jul. 2019, doi: 10.1016/j.jobe.2019.100735.

[13] A. Aldawoud, "Thermal performance of courtyard buildings," *Energy Build*, vol. 40, no. 5, pp. 906–910, Jan. 2008, doi: 10.1016/j.enbuild.2007.07.007.

[14] T. Kubota, M. A. Zakaria, S. Abe, and D. H. C. Toe, "Thermal functions of internal courtyards in traditional Chinese shophouses in the hot-humid climate of Malaysia," *Build Environ*, vol. 112, pp. 115–131, Feb. 2017, doi: 10.1016/J.BUILDENV.2016.11.005.

[15] J. Zhu *et al.*, "A review of the influence of courtyard geometry and orientation on microclimate," *Build Environ*, vol. 236, p. 110269, May 2023, doi: 10.1016/J.BUILDENV.2023.110269.

[16] R. M. A. Mahmoud and A. S. H. Abdallah, "Assessment of outdoor shading strategies to improve outdoor thermal comfort in school courtyards in hot and arid climates," *Sustain Cities Soc*, vol. 86, p. 104147, Nov. 2022, doi: 10.1016/J.SCS.2022.104147.

[17] E. Diz-Mellado, V. P. López-Cabeza, C. Rivera-Gómez, E. Naboni, and C. Galán-Marín, “Optimizing a courtyard microclimate with adaptable shading and evaporative cooling in a hot mediterranean climate,” *Journal of Building Engineering*, vol. 88, p. 109167, Jul. 2024, doi: 10.1016/J.JOBE.2024.109167.

[18] B. Wen, Q. Yang, F. Xu, J. Zhou, and R. Zhang, “Phenomenon of courtyards being roofed and its significance for building energy efficiency,” *Energy Build*, vol. 295, p. 113282, Sep. 2023, doi: 10.1016/J.ENBUILD.2023.113282.

[19] A. Almhafdy, N. Ibrahim, S. S. Ahmad, and J. Yahya, “Analysis of the Courtyard Functions and its Design Variants in the Malaysian Hospitals,” *Procedia Soc Behav Sci*, vol. 105, pp. 171–182, Dec. 2013, doi: 10.1016/j.sbspro.2013.11.018.

[20] A. Almhafdy, “Optimization of courtyards design factors in the hot humid climate: Energy and thermal assessment,” The Doctoral Research Abstracts, IGS Biannual Publication, Institute of Graduate Studies, UiTM, vol. 11, no. 11, 2017.