RESEARCH ARTICLE

Bioclimatic Architectural Intervention on the Traditional Roof Design to Improve Building Thermal Performance

Ratih Widiastuti[1*], Kharizma Aulia Syarifiyah[1], Previari Umi Pramesti[1], Juliana Zaini[2], Dina Shona Laila[3]

[1]Civil Infrastructure Engineering and Architectural Design, Department of Civil and Planning, Vocational School, Diponegoro University, Semarang, 50275, Indonesia

[2]Faculty of Integrated Technologies, Universiti Brunei Darusssalam, Jalan Tungku Link, Gadong BE1410, Brunei Darussalam

[3]Department of Computer Science, Electrical & Space Engineering, Luleå University of Technology, SE-971 87, Luleå, Sweden

*Corresponding author: ratihwidiastuti@lecturer.undip.ac.id

Abstract

Bioclimatic architecture is currently gaining interest among architect and building designers. In response to this trend, a study using bioclimatic design was conducted in Universitas Diponegoro (UNDIP) Mosque. Modeling simulation using Autodesk Ecotect was carried out to simulate the alternative design of joglo roof. Field measurement were done to validate the difference on the thermal performance between the existing and reccomendation design. Result from field measurement showed the highest room temperature was obtained on the second floor area of the mosque by 28°C. Meanwhile according to the simulation, the bioclimatic roof could decrease the indoor temperature of the mosque around 4.3°C - 5.2°C or to the level of 24.5°C. Moreover, compared to the existing design, the bioclimatic design had higher temperature difference with outdoor temperature by 7.5°C. It means, if an air conditioning system is installed inside the mosque with bioclimatic roof, it would require a lower energy consumption. Thus, the application of bioclimatic roof on the UNDIP Mosque can be a prospective solution to improve its indoor thermal comfort and provide an environmentally friendly design.

Keywords: *Autodesk Ecotect; Bioclimatic design; Building thermal performance; Field measurement; Modelling and simulation*

Citation:
Widiastuti, R., Syarifiyah, K. A., Pramesti, P. U., Zaini, J., & Laila, D. S. (2025). Bioclimatic architectural intervention on the traditional roof design to improve building thermal performance. *Alam Cipta*, 18(3), [Article 7]. https://doi.org/10.47836/AC.18.3.PAPER07
Received:
09 November 2024
Accepted:
05 November 2025
Published:
December 2025

Introduction

Data from Intergovernmental Panel on Climate Change (IPCC) reported the building sector consumes approximately 40 % of global energy, a proportion that surpasses both the transportation and industrial sectors (Korkas et al., 2015). These global and local energy consumption are often affected by buildings design and operation (Tungnung, 2025). Previous research has shown that incorporating passive design strategies during the early stages of building design can significantly reduce energy consumption (Alghamdi et al., 2022). Decisions made at this stage have a decisive impact on the building's ultimate energy performance (Chi & Xu, 2022) and (Gaber et al., 2024).

Passive cooling design is a key element of traditional architecture, uses natural elements like sunlight, wind, and materials to minimize reliance on artificial climate control. Buildings with traditional architecture often incorporate strategies like shading, natural ventilation, and materials with high thermal mass to achieve comfortable indoor temperatures without using intensive energy for cooling systems. Therefore, adopting traditional architecture to improve passive cooling can assist in developing zero energy buildings (Izadpanahi et al., 2021).

Indonesia is known for its rich and diverse traditional architecture, which reflects the cultural and historical heritage of the country. Even though modernization often reduces the magnificence of local wisdom and diminishes the meaning of culture, the existence of traditional buildings is still widely found in society. This includes Arsitektur Joglo (local named). Joglo which is the name of traditional roof is one of the local wisdoms that comes from traditional Javanese Architecture. There are various designs of joglo roofs that distinguish them from one another which highlights the component that containing values, convictions, and standards of Javanese traditions (Idham, 2018). The unique design of joglo roof is not only applied on the traditional buildings but also on the modern buildings. The philosophical value and the positive contribution to the environment become the main preference (Ashadi, 2020).

Meanwhile, due to the growing attention to the relationship between architecture and ecosystems (Hart, 2011), promoting bioclimatic architectural concepts (Yeang & Hamzah, 2003) has been proposed as a suitable solution to improve building thermal performance. The principles of bioclimatic architecture involve minimizing loads through the use of passive cooling techniques in building design. The design approach combines health and safety, landscape configuration, taking into account the adverse impacts of natural disasters and climate change (Bera & Nag, 2022), and also enhanced passive systems of microclimate and active systems (Stasi et al., 2020). Bioclimatic architecture also considers the integration between technology and materials in the building cycle system in order to minimize the environmental damage from the use of materials to the recycling process (Talarosha, 2005). This emphasizes the integration concept of local ecological conditions, climate responsive design, site conditions, and building programs. According to (Handoko & Ikaputra, 2019), the concept of bioclimatic architecture has three main principles i.e. energy saving, referral to local climate conditions, and environmentally friendly.

Despite the interesting topic of bioclimatic architecture, only a few papers have attempted to comprehensively examine the effects of bioclimatic architecture on the building thermal performance. Recently highlighted in a review paper by (Pan et al., 2024), some researchers have begun exploring current and future climates in terms of bioclimatic potential for enhancing the energy performance of building refurbishments. This approach aims to provide a comprehensive insight into the effectiveness of bioclimatic strategies.

As studied by (Azmi et al., 2023) numerical study was conducted to investigate the use of bioclimatic design approach to achieve comfortable condition during low occupancy daily prayer times without using HVAC system. The results confirmed surface temperature on the Qiblah wall and the value of PMV-PPD (Predicted Mean Vote and Predicted Percentage of Dissatisfied) were considered as indicator to evaluate the efficiency of passive design approach from bioclimatic architecture. A study conducted by (Stasi et al., 2020) investigated potential technological and bioclimatic strategies to achieve Zero Energy Buildings through building energy simulation discovered with the aim of improving energy efficiency and indoor thermal comfort. The findings of the study emphasized to meet the zero energy buildings, combination between solar screen, earth to air heat exchangers, and heat recovery mechanism in HVAC systems were needed. A related study conducted by (De León et al., 2023) highlighted the key factors to ensure the thermal comfort and achieve energy efficiency for bioclimatic design. It confirmed building morphology, orientation, glazing properties, shading techniques, wall materials, and HVAC systems configurations were parameters to assess energy consumption reduction through dynamic energy simulations. (Tamaskani Esfehankalateh et al., 2022) explored thermal comfort by examining twelve solutions across fourteen houses in cold climate, in Tabriz. Locally bioclimatic architectural strategies highlighted building orientation, design of overhangs, wall openings, and transitional space between the yard and building were strategies of traditional houses to utilize passive soar design and prevention of heat transfer and loss. (Khalili & Amindeldar, 2014) highlighted thermal comfort compatible solutions used in traditional Iranian architecture. Unfortunately, according to this study, people were less interested to apply the contemporary architecture for lifestyle adaptation. (Shaeri et al., 2018) conducted a study with the aim to identify the passive elements and to assess the indoor thermal comfort of two old houses in Bushehr. The results showed natural ventilation as passive cooling technique was able to significantly provide adequate indoor thermal comfort. A recent study conducted by (Syarifiyah et al., 2024) confirmed the bioclimatic design can be a prospective solution for improving indoor thermal comfort through reducing indoor temperature and providing an environmentally friendly design.

Although there have been numerous studies of bioclimatic architectural design, yet the discussions mainly only focused on the middle parts of the building. There were very limited studies that discuss the impact of bioclimatic design on the roof. Therefore, in this study, a thermal evaluation was conducted on the Universitas Diponegoro (UNDIP) Mosque that uses the iconic joglo roof as the symbol of the bioclimatic architecture. The purpose of this study was to evaluate the thermal impact of bioclimatic architectural design on the on the Universitas Diponegoro (UNDIP) Mosque. Several thermal parameters were measured to observe the indoor thermal performance of the mosque. Simulation using Autodesk Ecotect software was conducted to strengthen the research method and also to simulate the recommendation model of the traditional joglo roof from the earliest stages of conceptual design.

Methods

Study object

The object of this study is the Universitas Diponegoro (UNDIP) Mosque located in Semarang City, Indonesia at 6°58'S 110°25'E (Figure 1.a). Established in 2004, UNDIP Mosque is one of Universitas Diponegoro public facilities that are surrounded by open space areas and trees (Figure 1.b). There is a void inside of the mosque creating easier air circulation between the floor and the roof (Figure 1.c). A corridor was placed outside of the mosque for the people access and to optimize natural ventilation for the room (Figure 1.d).

The specific design of the mosque can be seen from its iconic joglo roof. Different from the style of the roof of other vernacular houses in Indonesia, the design of a joglo roof is almost like forming a pyramid. The architect modified the roof design by adding small windows on the lower and upper parts for natural lighting and air circulation (Figure 1.c). The roof material utilizes metal without insulation.

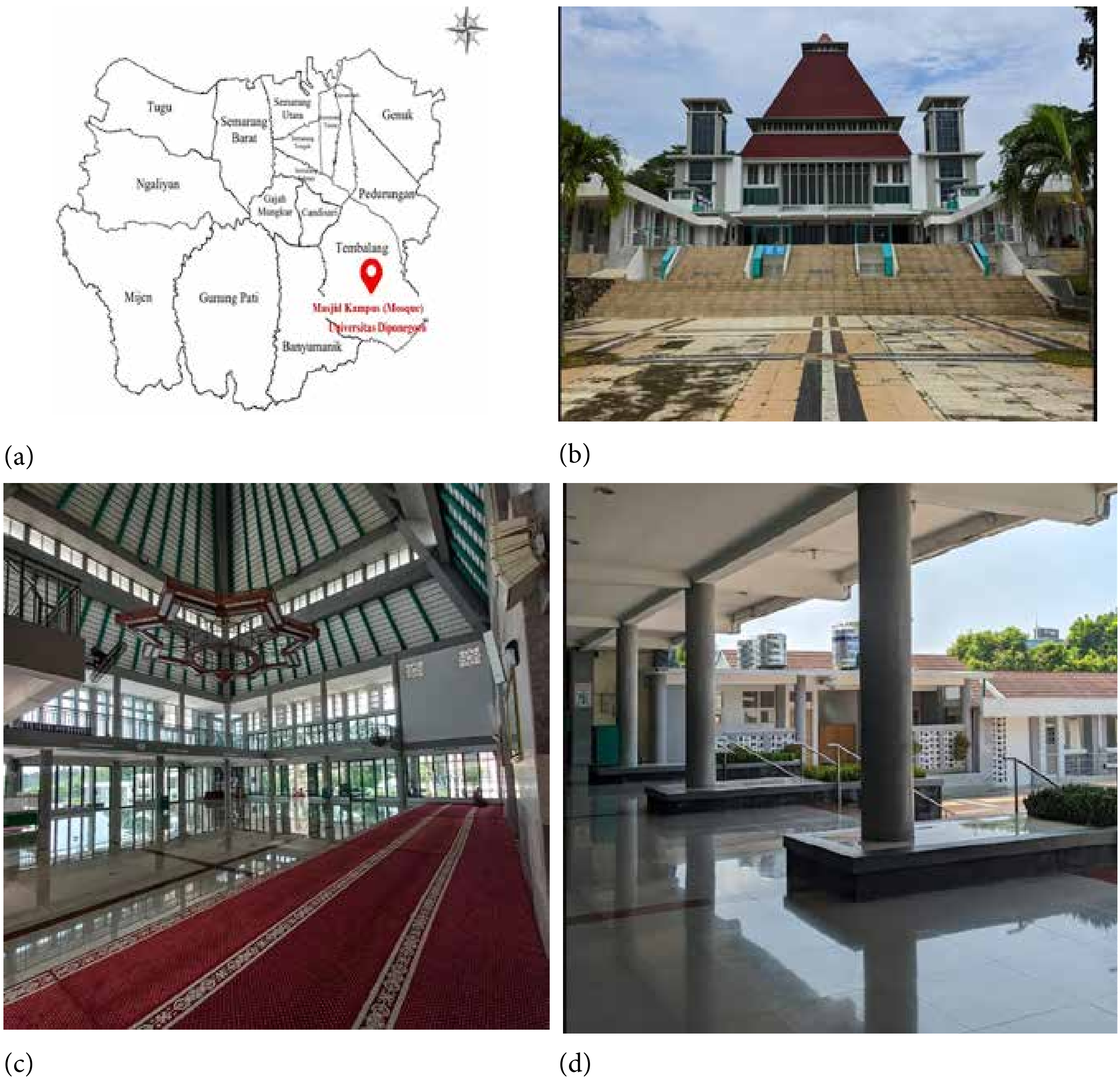


Figure 1: Detail of Study Object (a) Location of Universitas Diponegoro (UNDIP) Mosque; (b) Design of Universitas Diponegoro (UNDIP) Mosque; (c) Void and Small Windows on the Joglo Roof of Universitas Diponegoro (UNDIP) Mosque; and (d) Corridor of Universitas Diponegoro (UNDIP) Mosque

Research method

This study combined two methods i.e. field measurement to obtain building thermal parameters and modeling simulation using Autodesk Ecotect to prove the thermal effect of bioclimatic roof design.

Field measurement

In order to evaluate the impact of the roof design, field measurements were conducted to obtain data of the thermal parameters i.e. room temperature and humidity. The measurement campaigns were carried out during the transition of pandemic era on 12th November 2022. The data were obtained from measurements done in the morning (7:50 a.m. and 09:00 a.m.), afternoon (1:00 p.m. and 3:00 p.m.), and evening (7:30 p.m.) in a very restricted procedure. Due to safety aspect, the study excluded human parameter.

Table 1: Parameters, Type, Accuracy, and Range of Measurement Devices

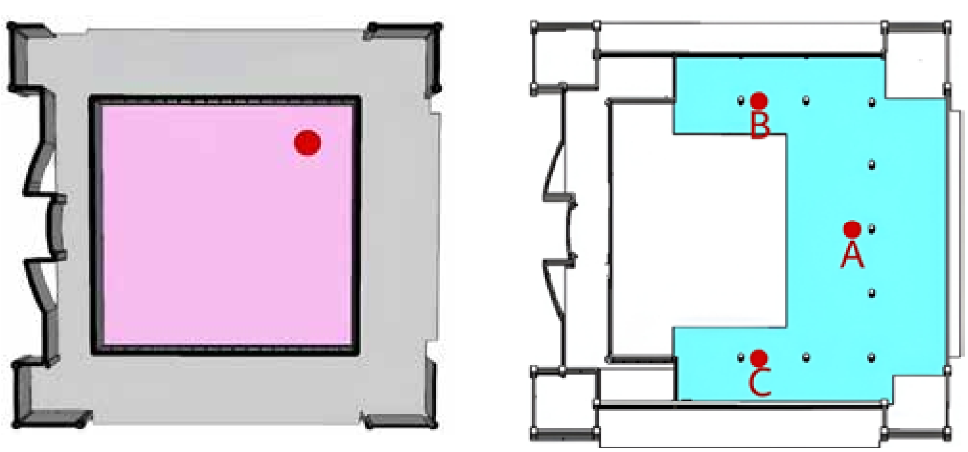
Devices	Manufacturer	Model	City, Country	Parameters	Accuracy	Range
Digital Thermometer TPM-10	Airmend	LR44	Guangzhou,China	• T_{ia}	±1°C (±2°F)	-50°C~110°C (-58°F~+158 °F)
HTC-1 Clock Hygrometer Thermometer	Heybits	AAA xl	Guangzhou,China	• T_{ea} • T_{ia} • RH	±1°C (1-8 °F) ±5% RH (40% -80%)	-50~+70°C (-58~+154°F) 10%-99% RH

Note: : Humidity; : External air temperature; : Indoor air temperature

Several instruments were installed to collect measurement data for the building thermal performance. Table 1 presents the type and specifications of instruments used for the measurement of each parameter. Room thermometer (Digital Thermometer TPM-10) was used to measure the indoor temperature. The room humidity was obtained using Hygrometer (HTC-1 Clock Hygrometer Thermometer). Figure 2 shows the instruments for measurement campaign. The measurements were conducted in the prayer areas on the first floor (male prayer area) and the second floor (female prayer area) during the clear sunny weather condition. Samples were taken at several points with the interval of data collection of the two location about 1 – 5 minutes. The sample points and the position of the measurement instruments can be seen in Figure 3.

(a) (b)

Figure 2: Measurement Instruments (a) Thermometer (b) Hygrometer Tools



(a) (b)

Figure 3: Position of Measurement Instruments (a) 1st Floor Measuring Point (b) 2nd Floor Measuring Point

Ecotect Simulation

Apart of field measurement, this study also utilized computer simulation using Autodesk Ecotect software to simulate the model of bioclimatic roof. Being the most user friendly, Autodesk Ecotect allows to simulate building performance from the earliest stages of conceptual design. It combines analysis functions with an interactive display that presents the analytical results directly within the context of the building model. Furthermore, Ecotect was acquired by Autodesk from Square One Research and adds to an array of tools that augment to the other Autodesk software (Autodesk, 2015).

Before running the simulation using Autodesk Ecotect, the 3D model of bioclimatic roof was imported from SketchUp. Several parameters such as building geometry, materials property, building thermal condition, and climatic data were inputted to run the simulation. Geometric and physical descriptions of the bioclimatic roof such as wall, roof, floor, and windows were added to the models. The material properties include specific heat capacity, thermal conductivity, and density of materials. Results from the field measurement and the bioclimatic model simulation were compared to evaluate the thermal effect of bioclimatic design on the building. Figure 4 shows the simulation and comparison procedure.

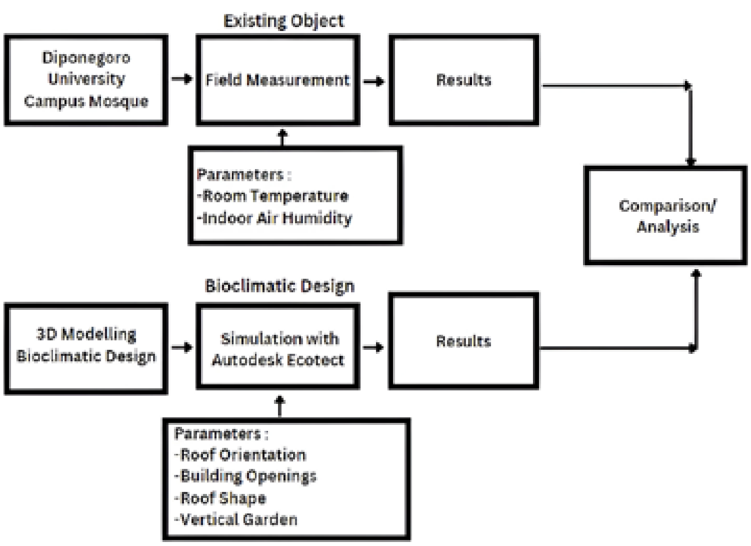


Figure 4: The Simulation and Comparison Procedure Between the Existing Roof and the Bioclimatic Design

Result and Discussion

Local Climate Condition

As informed in Subsection about the Study Object, the location of the Diponegoro University (UNDIP) Mosque is in Semarang City. According to Köppen climate classification, this city has tropical rain forest and tropical monsoon climate (Ǩoppen et al., 2011). Furthermore, data from Maritime Meteorology Station of Semarang City stated that the average daily temperature from 2021 to 2022 was around 31.75°C, while the lowest and the highest temperatures were 26°C and 37°C, respectively. The range of relative humidity was from 73% to 100% (Youlanda & Cherish, 2022). Most of the time, the daily climatic condition was hot and humid with minor temperature variation. The average rainfall was from 1500 mm to 3000 mm per year. Figure 5 shows the monthly temperature and precipitation of Semarang City.

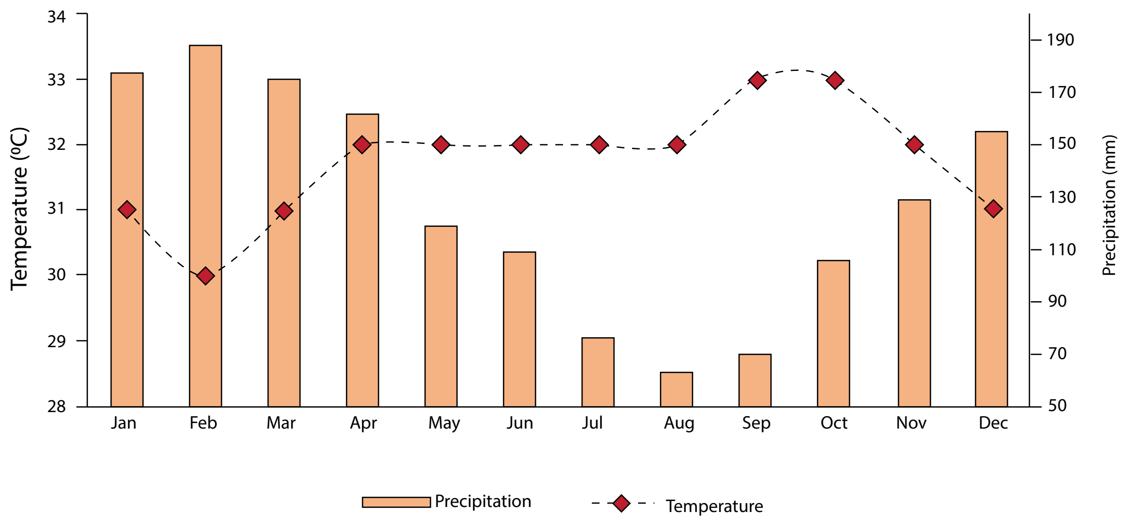


Figure 5: Monthly Average Temperature and Precipitation of Semarang City

Building Thermal Profile

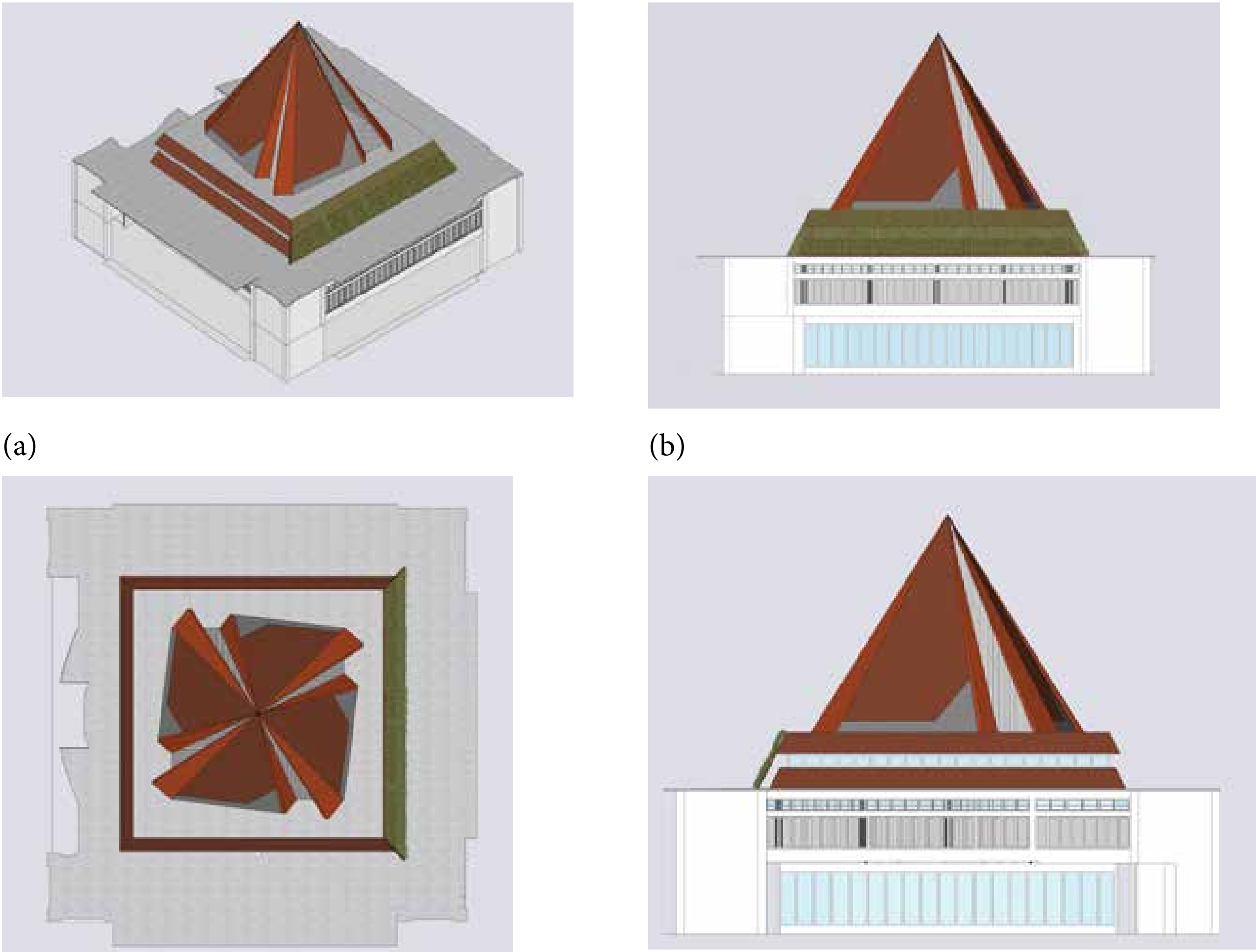
A summary on the statistical calculation of the room temperature variations was presented in Table 2. The results showed the average temperature and relative humidity on the first floor were 28.8°C and 77.2%, respectively. On the second floor, the average temperature and humidity in each measurement point were 28.9 °C and 76.4% (point A), 28.9 °C and 77% (point B), and 28.9 °C and 76.8% (point C), respectively. Compared to the first floor area, the second floor had higher thermal performance, as can be seen from the temperature of points A, C, and B. Therefore, the implementation of bioclimatic design of the roof was focused on the area of the second floor, particularly at point A and point C.

Table 2: Results of Temperature Data Collection on the First and the Second Floors

First floor		Second floor					
Time	**Temperature [°C]**	**Time**	**Temperature (point A) [°C]**	**Time**	**Temperature (point B) [°C]**	**Time**	**Temperature (point C) [°C]**
07:53 a.m.	27.6	07:57 a.m.	27.8	07:59 a.m.	27.8	08:00 a.m.	27.7
09:03 a.m.	28.1	09:00 a.m.	28.1	08:56 a.m.	28.3	08:58 a.m.	28.2
01:01 p.m.	29.7	01:03 p.m.	29.8	01:04 p.m.	29.9	01:06 p.m.	29.9
03:09 p.m.	29.6	03:02 p.m.	29.9	03:06 p.m.	29.8	03:07 p.m.	29.8
07:31 p.m.	29.2	07:34 p.m.	29.2	07:36 p.m.	29.1	07:38 p.m.	28.9

Implementation of Bioclimatic Design on the Joglo Roof

As mentioned in Section on Methods, Autodesk Ecotect was utilized for the simulations in this study. Results from field measurements were used as the input for the simulation. Several elements of bioclimatic design, such as orientation, form, opening, and selected materials were applied on the roof model during the simulation process (Melanira, 2022). Figure 6 showed the elements of bioclimatic design that are applied on the roof model.



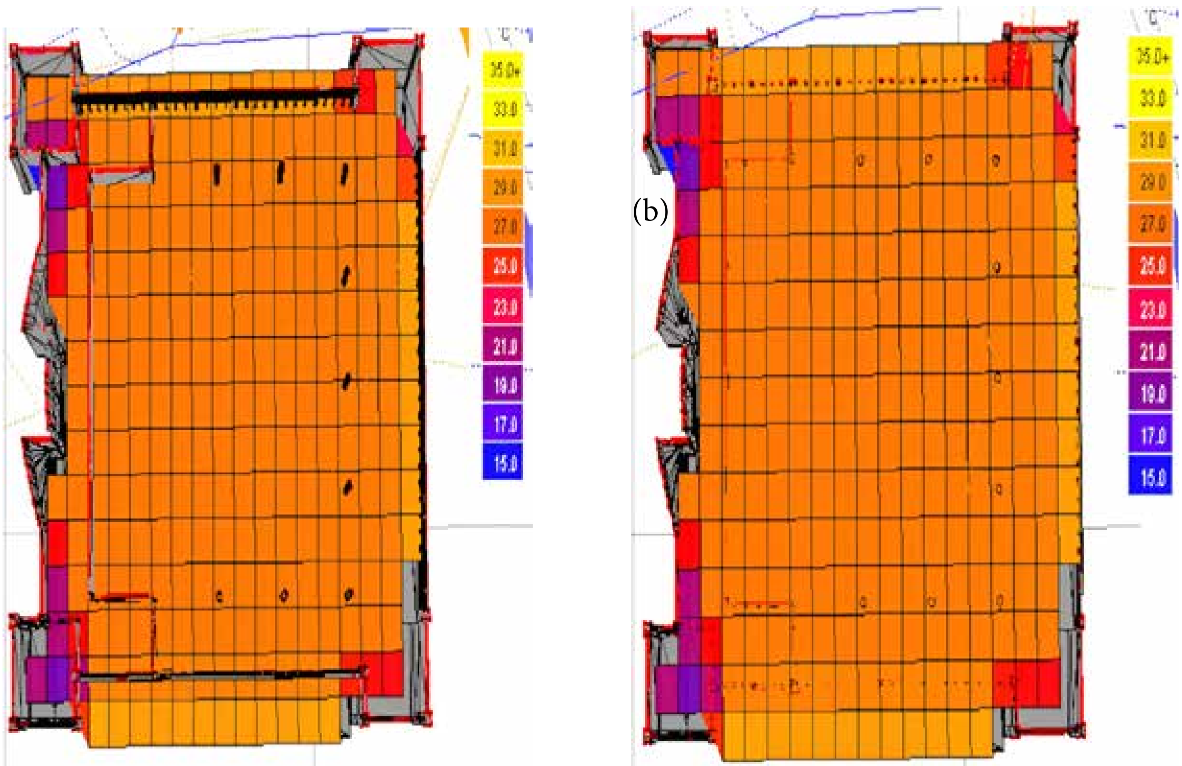
(a) (b) (c) (d)

Figure 6: Elements of Bioclimatic Design that Applied on the Roof Model (a) Implementation of Bioclimatic Design in Response to the Sunlight Orientation; (b) Implementation of Bioclimatic Design in Response to the Materials; (c) Implementation of Bioclimatic Design in Response to the Forms; and (d) Implementation of Bioclimatic Design in Response to the Openings.

The orientation of the building was facing east and according to the field measurement, the east area showed the highest temperature profile, since most of the time sunlight came from this side (Figure 6.a). To minimize the negative effect of solar radiation, a vertical greenery system was applied on the roof model (Figure 6.b). The greenery system is very useful to reduce the heat transfer from solar radiation to the indoor environment, especially in the morning (Widiastuti et al., 2022). According to (Kalani C. Dahanayake et al., 2017), suitable plant species are vital to improve the thermal effect of vertical greenery system. Therefore, study on the plant types that are suitable to use was needed in order to know the maximum cooling effect from that the greenery.

In response to wind circulation and to optimize the indoor air circulation, slanted roof was applied in the design of the joglo roof (Figure 6.c). On each part of the slanted roof, an opening design was applied on the roof ridge to provide cross ventilation (Figure 6.d). In bioclimatic design, the application of an opening system can be realized in the form of cross ventilation, chimney ventilation, and wind tower (Lockhart-Ball, 2012). The opening system is very beneficial to provide more air circulation inside the roof ceiling. It produces cooler air temperature and creates cooler indoor environment (Hildayanti & Wasilah, 2022). The opening system can also be applied on the wall as windows.

Figure 7 shows the results of the bioclimatic design in Autodesk Ecotect. Clearly the indoor temperatures on the first and second floor were lower compared to the result from the field measurements. According to this simulation, after the bioclimatic roof was fit in to the building design, the indoor temperature on the first and the second floors were reduced to 21.0°C and 24.5°C, respectively.



(a)

Figure 7: Simulation Results of Bioclimatic Design Using Autodesk Ecotect (a) Bioclimatic Design Simulation of First Floor; (b) Bioclimatic Design Simulation of Second Floor

Table 3 presents the comparison between the results from the field measurement and the simulation. Referring to the data from field measurements, the indoor temperature range was from 28.8°C to 28.9°C. The highest temperature profiles were found on the second floor, as that area is close to the roof area and tend to get a direct solar radiation. The average indoor temperature was 28.9°C. It can be seen from the data in Table 3 that the simulation results showed lower indoor temperature profiles. The temperature range obtained from simulation was between 21.0°C and 24.5°C with the average temperature of 23.6°C. The average temperature difference between the measurement and the simulation is 5.3°C. Therefore, according to this simulation, the application of bioclimatic design on the roof of the mosque can decrease the indoor temperature around 4.3°C - 5.2°C or to the level of 24.5°C.

Moreover, compared to the average outdoor temperature, the existing design had a smaller difference at 3.1°C, while the simulation results provide higher temperature difference at 7.5°C. It means, if an air conditioning system was installed inside the mosque with bioclimatic design, potentially lower energy consumption can be achieved. Thus, the application of bioclimatic design on the roof of UNDIP Mosque can be a promising solution to improve indoor thermal comfort and provide environmentally friendly design.

Table 3: Comparison Between Field Measurement and Simulation

Locations	Temperature (°C)	
	Field Measurement	Simulation
First floor	28.8	21.0
Second floor (point A)	28.9	24.5
Second floor (point B)	28.9	24.5
Second floor (point B)	28.9	24.5
Average	28.9	23.6

However, uncertainties of simulation result due to the modelling and simulation process was possible and led to the deviations in the predicted of building thermal performance. The uncertainties could emerged from incomplete weather data, since the input of environmental parameter was only temperature. The material properties could be induced to the uncertainties of the simulation results. As mentioned in the sub section of Ecotect simulation, the material properties were adopted from literatures. Even though the type of building materials was the same, yet material testing from laboratory was more recommended. Also, the simulation model itself could cause the uncertainties in the results. It was due to the simplifications in representing the complex building systems. Therefore, in the future works, model validation and calibration should be performed to improve the reliability and accuracy of simulation results.

Conclusion

Traditional architecture is still popular in Indonesia, due to its magnificent cutural meaning, local wisdom and artistical value. The traditional iconic joglo roof of Universitas Diponegoro (UNDIP) Mosque holds this purpose. It is not only giving philosophical values but also improves the aesthetic of the mosque. This study has applied bioclimatic architecture design to create the simulation model of the mosque's joglo roof using Autodesk Ecotect. Several thermal parameters were measured to observe the thermal performance of the mosque before and after the bioclimatic design applied.

According to the simulation, installing bioclimatic roof on the mosque can decrease the indoor temperature around 4.3°C or from the level of 28.8°C to the level of 24.5°C. Compared to the existing standard design, the bioclimatic design had a higher temperature difference with outdoor temperature by 7.5°C. It means, if an air conditioning system was installed inside the mosque with bioclimatic design, potentially lower energy consumption can be achieved.

The findings led to the conclusion that through the modelling simulation, bioclimatic design on the traditional roof proved a significant reduction to the indoor temperature of the mosque. The practical implication is possible to be adopted and implemented for other tropical buildings. Adjustment might be needed since the environmental condition and the building design are specific, especially the roof section. It can be adapted and reinterpreted through modifications by incorporating local or traditional symbols. Moreover, field implementation of the bioclimatic roof on the real building is needed for the future study in order to validate the thermal benefit.

Acknowledgement

The authors would like to thank the Management of Universitas Diponegoro (UNDIP) mosque for providing and facilitating the license to conduct this research during the pandemic era.

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