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Droning Sustainability: Advancing Thermal Analysis of GBI-Certified Buildings in Putrajaya, Malaysia, Through Drone Technology

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ABSTRACT

Buildings have played a crucial role in shaping the environmental space of sustainability. In Malaysia, the introduction of the Green Building Index (GBI) represents a significant effort to advocate for sustainable building designs, with a focus on energy efficiency and technological advancement. Against this backdrop, this paper explores the potential of emerging drone technology in assessing and enhancing the environmental sustainability of building designs. It utilizes drone-assisted imagery modelling to analyse thermal performance in two GBI-certified buildings in Putrajaya: the Z10 Tower and the Ministry of Science, Technology, and Innovation (MOSTI) building. The study is conducted with the objective of utilizing drone technology for thermal pattern inspections. In response to this objective, four methodological procedures are employed: site selection, drone equipment identification, mapping technique planning, and aerial imaging documentation. The findings reveal varied responses in terms of the buildings' compositions and materiality to sun heat exposure, illustrating the intricate interplay between architectural design and environmental spaces. For instance, the Z10 Tower's metal roof reaches 53°C by noon, whereas its concrete roof attains 45°C, and its north-facing glass window cools significantly by 4 p.m. Similarly, the MOSTI building exhibits temperature variations based on orientation, with the roof peaking at 51°C and the solar panel at 49°C. These temperature variations inform the targeted design interventions proposed in this study, specifically the installation of louvres to enhance the building's sustainable design. As an exploratory investigation, this study calls for more interdisciplinary collaboration between design thinking, architecture, and engineering studies.

Keywords: Buildings; design interventions; drone technology; energy efficiency; environmental sustainability; Green Building Index (GBI).

INTRODUCTION

Buildings have played a crucial role in shaping the environmental space of sustainability. The relationship between buildings and sustainability encompasses a complex interplay of factors that extend from initial construction to eventual demolition or repurposing (Akadiri et al. 2012; Hafez et al. 2023). In this regard, energy efficiency stands as a benchmark, addressing substantial energy consumption inherent in heating, cooling, lighting, and operational systems in a building. Through strategic design choices, such as incorporating renewable energy sources like solar and wind power and implementing energy-saving technologies like insulation and smart management systems, buildings aim to minimize their carbon footprint and reliance on natural resources. Moreover, material selection plays an important role in determining a building's impact on the environment. Sustainable building prioritizes materials that are renewable, locally sourced, and possess low embodied energy. By minimizing carbon emissions associated with construction, sustainable buildings strive to create a more ecologically balanced built environment (Zuo & Zhao 2014; Mousa 2015).

Energy certification and rating systems are specific approaches adopted to further promote energy efficiency and sustainability in building design (Hafez et al. 2023). While this approach encourages the systematic adoption of energy-efficient design, construction, and operational practices, it concurrently leads to reduced energy consumption, lower operating costs, and minimized environmental impact. Throughout the world, the implementation of building energy certifications and rating systems varies in scope due to differences in climate, building practices, regulatory frameworks, and cultural preferences. These include LEED, which is widely used in the United States; BREEAM, predominantly in the United Kingdom and European countries; and Green Star in Australia and New Zealand. With the emergence of new technologies, there is a growing push to incorporate digitalization and big data analytics to enhance the effectiveness and scalability of energy certification and rating systems. Real-time monitoring, predictive modeling, and adaptive control strategies are being leveraged to drive efficiency and sustainability in building operations.

BACKGROUND

In Malaysia, the Green Building Index (GBI) was introduced in 2009 as a building energy certification scheme to promote sustainable construction practices and reduce environmental impact (Wan Yusoff and Wen 2014; Sim & Putuhena 2015). As a significant step toward sustainable architecture, the GBI serves as a benchmark for developers, architects, and builders committed to eco-friendly construction. It evaluates various aspects of building design, from site planning and design innovation to material usage and energy efficiency. The primary objective is to recognize and incentivize green practices, with effective thermal management becoming a critical consideration given Malaysia's tropical climate, characterized by high humidity, intense solar radiation, and heavy rainfall (Wan Yusoff and Wen 2014; Harun et al. 2017; Pandey 2018). As a result, achieving commendable GBI ratings requires a comprehensive approach to thermal inspections, ensuring that buildings not only meet energy efficiency standards but also enhance occupants' well-being.

Traditionally, thermal inspections relied heavily on manual assessments and basic tools. Early advanced techniques, like infrared thermography, revolutionized this field by allowing architects and builders to visualize and quantify thermal irregularities (Martin et al. 2022). However, these physical methods had limitations in terms of accessibility and comprehensiveness, often requiring substantial time, manpower and resources while exposing to high risk of safety challenge (Zakaria & Singh 2021; Albeaino et al. 2023; Zhu et al. 2023). Responding to these shortcomings, the environmental design community has sought more efficient approaches. The integration of advanced technologies, such as drone-based thermal imaging, has emerged as a promising solution, offering faster, more precise, and cost-effective means of assessing thermal efficiency (Wågø and Berker 2014; Eiris et al. 2021; Elghaish, 2021; Kaamin et al. 2022; Abd Manan and Abd Halin 2023; Bayomi and Fernandez 2023; Bogue 2023).

Recent studies have highlighted the potential of drone technology within building practice, particularly in proactive maintenance and energy assessment. For instance, Rakha et al. (2022) demonstrated the adaptability of drones equipped with state-of-the-art thermal cameras in capturing intricate thermal data of diverse building structures, aiding in identifying thermal anomalies and areas of heat loss. Furthermore, Rodríguez et al. (2021) and Nooralishahi et al. (2021) emphasized the transformative potential of drone technology in revolutionizing thermal inspections on building structures. By generating detailed thermal imagery, drones facilitate a comprehensive understanding of heat generation characteristics, aiding in identifying thermal irregularities and areas requiring attention.

From these perspectives, exploring the utilization of drones within the GBI framework and thermal inspections is essential for advancing environmental design strategies while demonstrating a commitment to harnessing technological advancements. Moreover, the potential of drone-assisted thermal inspections remains relatively untapped in real-time assessment and optimization, particularly in addressing challenges posed by Malaysia's tropical climate (Sim and Putuhena 2015; Lim et al. 2016; Solla et al. 2022). Thus, the promise of drone-assisted thermal inspections holds significant prospects for enhancing the GBI, emphasizing its importance in elevating sustainable environmental practices in Malaysia.

Against this backdrop, this paper aims to narrow the existing gap in leveraging drone technology for assessing thermal inspections of GBI-certified buildings. The study seeks to provide a broad perspective on how building designs interact with real-time environmental conditions. Specifically, it aims to clarify the practical applications of drone technology in assessing building performance, emphasizing its potential to enhance the evaluation and optimization of sustainable environmental designs. The objective of this paper thus revolves around addressing the following two key questions:

1. How can drone technology be effectively utilized for the analysis and evaluation of thermal performance in buildings?
2. In what ways can insights gathered from drone-assisted assessments be leveraged to inform design interventions aimed at enhancing sustainable building performance?

METHODOLOGY

Responding to the above questions, this methodology section outlines the utilization of drone mapping as an innovative method for acquiring detailed visuo-spatial data for architectural design analysis. This approach involves employing unmanned aerial vehicles (UAVs) equipped with cameras and sensors to capture high-resolution imagery and related data from various angles as they traverse the targeted terrain within a designated study area (Falamarzi et al. 2021; Fox et al. 2014). The collected images are then meticulously processed using specialized software, such as DroneDeploy, to perform point cloud techniques, ultimately resulting in the creation of detailed thermal models of specific buildings within the study area.

The significance of drone mapping lies in its ability to provide rich visual and spatial insights, which are crucial for scientific analysis and informed decision-making processes (Kleinschroth et al. 2022). Inspired by the methodology proposed by Rakha et al. (2022), our study adopts a systematic approach consisting of four procedural phases: site selection, setup of appropriate drone equipment, implementation of mapping techniques, and aerial imaging. These phases will be further elaborated in the subsequent sections.

PHASE 1: DETERMINING SITE STUDY

For this research, our site study specifically focuses on Putrajaya, the well-planned administrative capital of Malaysia, established in 1995. From its inception, Putrajaya was envisioned as a sustainable urban center embracing the concept of a city garden (Norhisham et al. 2013). The city's strategic location at approximately 2.9264° N latitude and 101.6964° E longitude places it centrally within Peninsular Malaysia. Such positioning effectively addresses the congestion and overcrowding challenges of Kuala Lumpur. Throughout the year, Putrajaya experiences warm to hot temperatures, with daily averages ranging from 25°C to 32°C (77°F to 90°F) (Qaid et al. 2016). Its tropical setting contributes to high humidity levels, often exceeding 80%, particularly during the rainy season. Despite frequent rainfall, Putrajaya enjoys ample sunshine, although cloud cover may vary. While there is not a distinct dry season, the months between April and October typically see less rainfall compared to the monsoon months, albeit sporadic showers persist even during drier periods.

Situated a mere 25 kilometers from Kuala Lumpur International Airport, a prominent regional aviation hub in Southeast Asia, and harmoniously integrated into modern public transportation networks, Putrajaya boasts exceptional accessibility and connectivity. Its location approximately 40 kilometers from Kuala Lumpur emphasizes its role as a modern, environmentally conscious city (Morshidi and Rahim, 2011). Notably, Putrajaya showcases sustainable architecture with numerous iconic buildings designed to be energy-efficient, earning prestigious GBI certification as a testament to its commitment to ecological responsibility. Building upon this dedication to sustainable architecture, our inquiry delves into two GBI-certified buildings in Putrajaya, namely, Z10 Tower office building and the Ministry of Science, Technology, and Innovation (MOSTI) building (Putrajaya Corporation 2022: 7).

During the initial phase of our research, we sought permission from the respective building managements to conduct our investigation, which involved drone mapping activities. Obtaining permits for such activities in Putrajaya is a meticulous process due to the presence of government offices. Therefore, we diligently secured approvals from various relevant authorities, including the Prime Minister's Office, the Putrajaya Corporation (PjC), the Department of Survey and Mapping Malaysia (JUPEM), and the Civil Aviation Authority of Malaysia (CAAM). These regulatory bodies oversee the research activities to ensure they adhere to safety protocols and respect the privacy of the surrounding areas.

PHASE 2: IDENTIFYING DRONE EQUIPMENT

After thorough comparison of various drone models, the DJI Mavic 2 Enterprise Dual emerged as the suitable choice for the study. Renowned for its exceptional thermal imaging capabilities, this drone is perfectly suited for capturing thermal data in urban settings. Equipped with a dual-camera system, the Mavic 2 Enterprise Dual seamlessly combines a high-resolution visual camera with a radiometric thermal camera, enabling us to capture both visual and thermal data simultaneously with precision (Flir 2019).

One of the standout features of the Mavic 2 Enterprise Dual is its integration of Multi-Spectral Dynamic Imaging (MSX) technology. This innovative approach overlays visual orthophoto images onto key details extracted from thermal images, replacing traditional composite images with a significantly more detailed and interpretable representation. By providing a comprehensive depiction of objects and elements visible in the thermal images alongside visual support, we are equipped to perceive structures, identify anomalies, and clarify underlying temperature distributions with discernible clarity.

The integration of MSX technology in thermal scanning offers several advantages. Firstly, it facilitates the generation of more comprehensive and easily understandable graphical representations of thermal data. This enables precise and efficient thermal mapping, allowing us to detect temperature variations across physical features with greater accuracy. This capability is particularly beneficial for identifying issues such as thermal visualizations and distribution within the selected two buildings.

PHASE 3: PLANNING MAPPING TECHNIQUES

Performing a drone flight for the three selected buildings requires the careful selection of an open space, crucial for ensuring the safety and effectiveness of the operation. This involves securing an appropriate area for mapping that offers ample room for the drone to take off, fly, and land within its flight range. Moreover, it is essential to ensure the absence of obstacles such as trees, power lines, or any other obstructions to prevent collisions and maintain the integrity of the data collection.

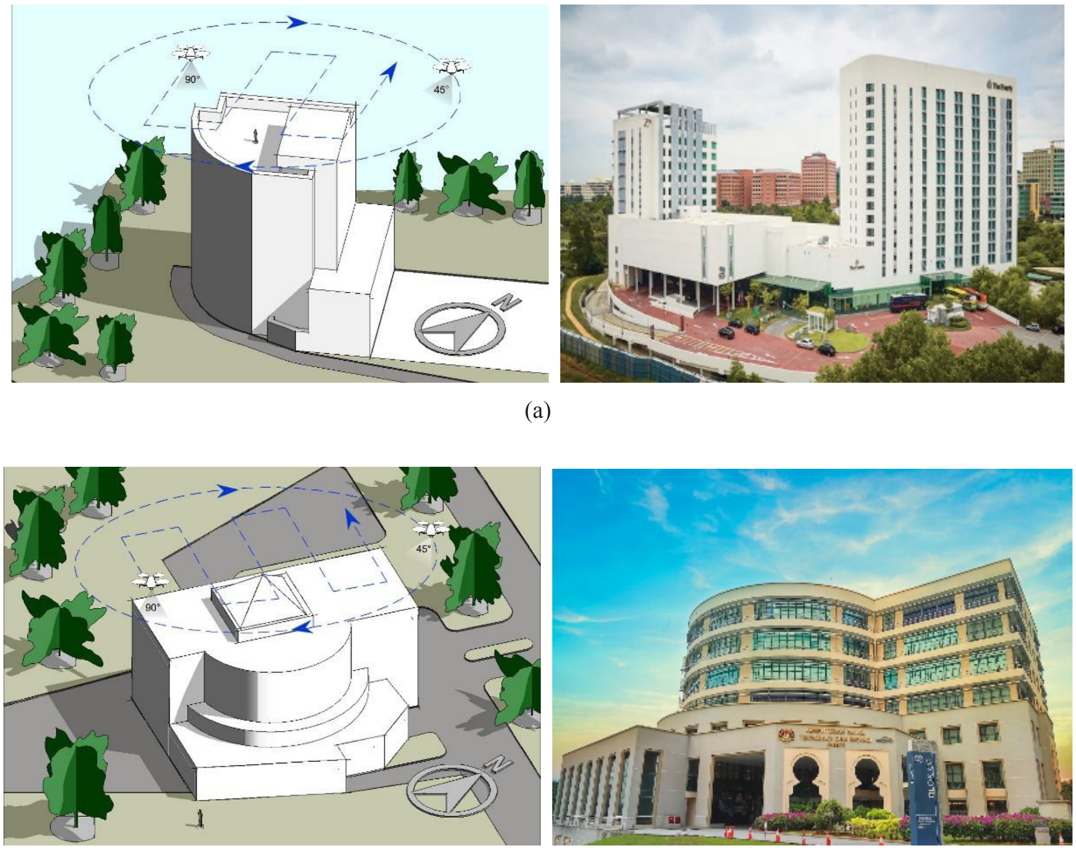
In this research, we employ a synergistic approach, combining oblique and grid mapping techniques, to enhance the acquisition of reliable data from the two buildings (see Figure 1). The oblique method, utilizing a 45-degree camera angle, captures images from multiple viewpoints, enabling the creation of detailed three-dimensional models that elucidate thermal distribution across building surfaces. This approach yields intricate insights into the thermal dynamics of the buildings' facades and structural components.

Concurrently, the grid pattern, employing a 90-degree camera angle, entails systematic drone flight in a grid-like trajectory, capturing thermal imagery at regular intervals to ensure comprehensive coverage of the study area. This systematic approach facilitates the generation of precise 3D thermal maps, revealing temperature differentials across larger spatial domains.

The mapping process incorporates three distinct flight intervals: at 9 a.m., 12 p.m., and 4 p.m., strategically capturing the dynamic temperature fluctuations throughout the day. This temporal diversity is instrumental in capturing the thermal performance of the buildings under varying environmental conditions. To maintain data integrity, ambient conditions surrounding each flight, such as weather, temperature, wind speed, humidity, dew point, and air pressure, are attentively recorded before drone takeoff and throughout the mapping process (Table 1).

TABLE 1. Ambient conditions readings surrounding the buildings (AccuWeather 2023)

Building	Z10 Tower		
Time	9.00 am	12.00 pm	4.00 pm
Temperature	26 °C	30 °C	31 °C
Wind Speed	0 km/h	2 km/h	7 km/h
Humidity	73 %	54 %	57 %
Dew Point	21 °C	20 °C	22 °C
Air pressure	1014 hPa	1014 hPa	1011 hPa
Visibility	16 km	16 km	16 km
Building	**MOSTI Building**		
Time	9.00 am	12.00 pm	4.00 pm
Temperature	26 °C	32 °C	30 °C
Wind Speed	11 km/h	11 km/h	7 km/h
Humidity	73 %	51 %	69 %
Dew Point	21 °C	21 °C	24 °C
Air pressure	1013 hPa	1013 hPa	1010 hPa
Visibility	16 km	16 km	16 km



(a)

(b)

FIGURE 1. The drone flight path for each building: a) Z10 Tower, and b) MOSTI Building. (Author 2023)

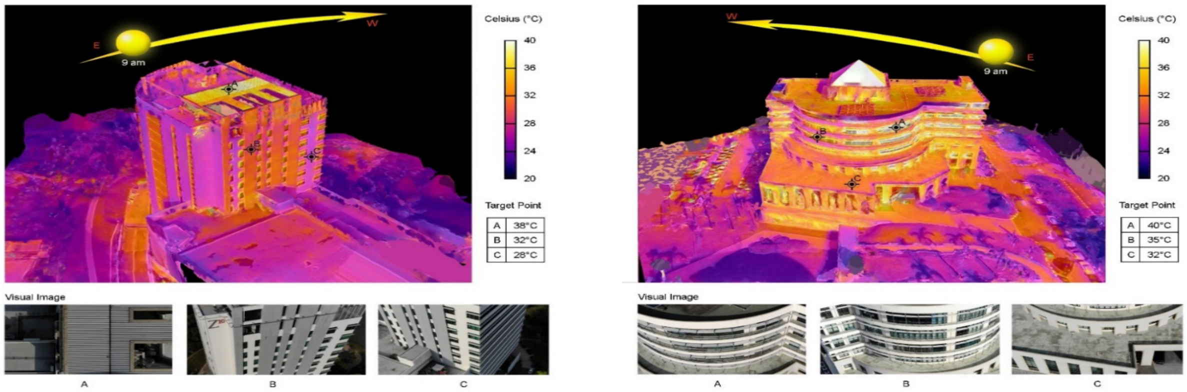
PHASE 4: DOCUMENTING AERIAL IMAGING

In this phase, our focus lies on the careful documentation of aerial imaging, particularly emphasizing the surfaces of buildings significantly exposed to direct sunlight, as indicated by the orientation outlined in the sun path diagram. Following the completion of the drone's flight and the acquisition of numerous images across the study area, the subsequent step involves processing these images to generate a comprehensive visual representation. This process entails the merging of orthomosaic images to form a point cloud—a dataset of spatially distributed points representing the surfaces and structures within the area of interest. Additionally, we utilize these images to construct three-dimensional models, offering insight into the spatial arrangement of buildings and their surroundings.

Our primary objective centers on the analysis of thermal patterns exhibited by the buildings. To achieve this, we develop two thermal models to observe temperature fluctuations throughout various intervals of the day. Initiating this process involves uploading all captured images to DroneDeploy, a cloud-based software platform. Utilizing advanced techniques, DroneDeploy smoothly merges these images to produce a high-resolution map, facilitating detailed analysis of buildings and their surroundings. Moreover, the software aids in the creation of 3D thermal models by extracting temperature data from the thermal images captured during the aerial survey. These models afford us the opportunity to examine temperature differentials, pinpointing areas exhibiting abnormal thermal behavior, whether it be excessive heat or cold.

RESULTS AND DISCUSSION

The analysis of the aerial imaging has produced substantial findings for this study, revealing important insights that contribute significantly to our understanding of the relationship between building designs and real-time environmental data. We organize the results of the findings to align closely with the two key questions of this paper, as outlined earlier in the preceding section.The initial focus explores the utilization of drone technology as a means to assess the thermal patterns of the studied buildings. By closely monitoring the temperature of the buildings at various times in Figure 2, we identified the value of temperature based on three different time intervals. This helped us gain insights into how they adapt to the local climate through each of the thermal models. The findings were later analyzed using descriptive statistics, presented through a series of line graphs. This study primarily focuses on visualizing how temperature trends change over time, based on real-time mapping data collected on-site. The descriptive analysis of these graphs highlights the buildings' performance concerning sun heat exposure, taking into account factors such as building orientation and materiality. This is crucial for exploring design interventions enabled by the insights gained from the thermal pattern findings. By closely examining the data obtained from aerial imaging, potential areas for improvement can be identified.



(a) (b)

FIGURE 2. The 3D thermal model of the buildings: a) Z10 Tower, and b) MOSTI Building.
Source: Author (2023)

THERMAL PERFORMANCE ANALYSIS OF Z10 TOWER

The temperature variations across different sides of the Z10 Tower reveal interesting patterns regarding time, building material, and orientation (Figure 3). Across most materials and orientations, there is a noticeable increase in temperature from 9 a.m. to 12 p.m., highlighting the sun's heating effect reaching its peak around noon. However, by 4 p.m., many materials exhibit a decrease in temperature, indicating a natural cooling effect as the day progresses. A remarkable exception is the glass window on the north side, experiencing a significant temperature drop by evening.

Differences also arise when comparing building materials. The metal louver, particularly on the north and south sides, tends to attain higher temperatures around noon than other materials, suggesting its capacity to retain more heat. In contrast, the substantial temperature decrease observed for the north-facing glass window by 4 p.m. implies external factors such as shading or reflection are influencing its thermal behavior.

When examining the effects of building orientation, the east side displays a consistent temperature trajectory for all materials, rising from morning to afternoon and stabilizing or dropping by evening. The south elevation exhibits a similar pattern but with elevated midday temperatures, indicating more direct sunlight exposure during these hours. Meanwhile, the west elevation experiences a steady temperature increase throughout the day, suggesting prolonged sun exposure.

At 9 a.m., the temperature of the metal roof reaches 38°C. By noon, the thermal has increased up to the peak temperature of 53°C, due to the heating effect from direct sunlight. This substantial rise can be attributed to metal's inherent property of retaining heat. However, by 4 p.m., the temperature sees a downturn, settling at 33°C, suggesting a combination of reduced solar exposure and the metal's capacity to dissipate the day's accumulated heat.

The concrete roof of the building follows a different temperature trajectory. It begins the morning cooler at 32°C and warms up to 45°C by midday. Interestingly, unlike the metal roof, the concrete maintains this temperature into the evening, indicating its slower thermal response and propensity to retain the heat it absorbs. This extended warmth highlights concrete's thermal inertia, which could be both advantageous and challenging depending on the desired indoor climate.

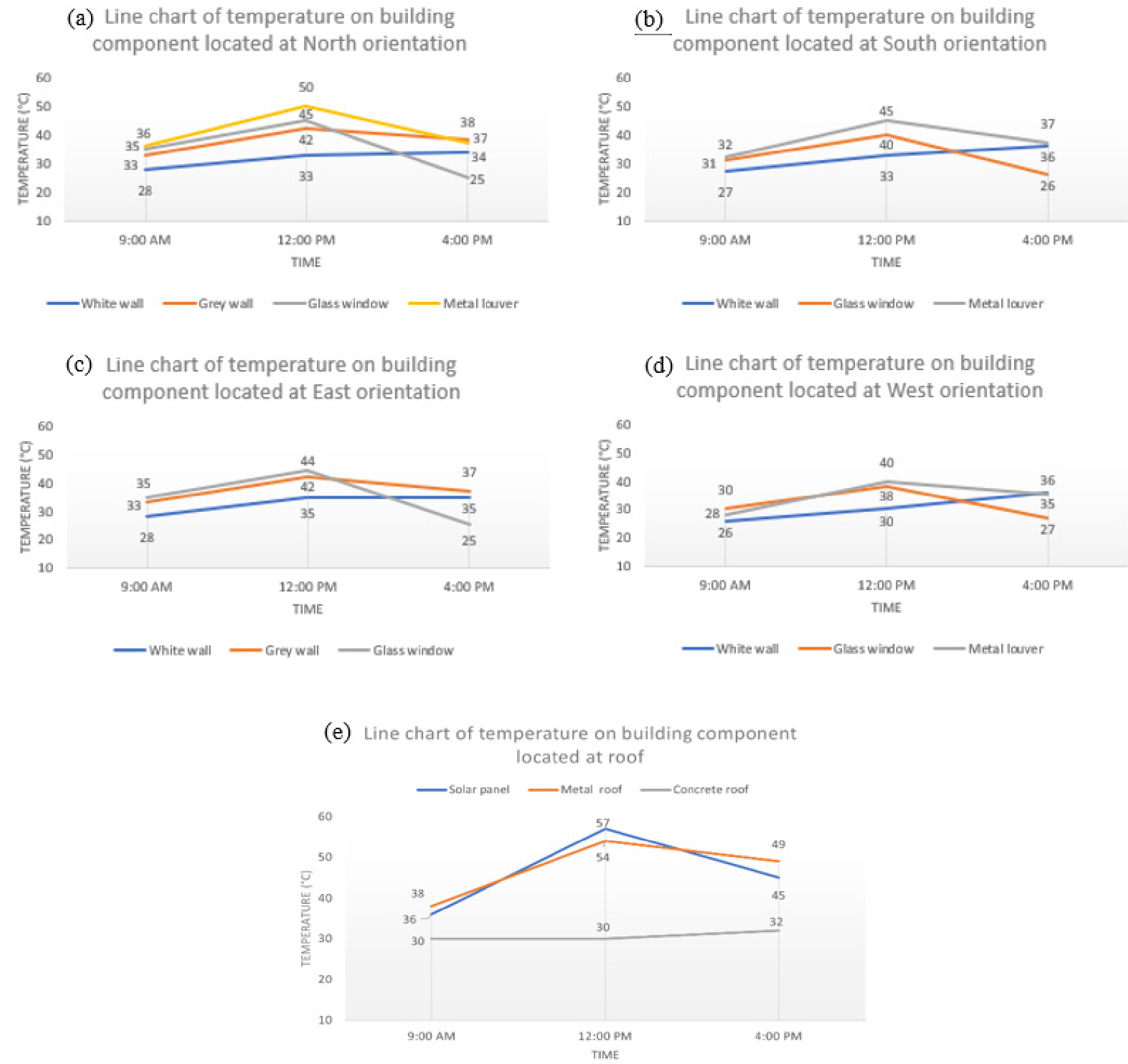


FIGURE 3. Thermal performance analysis of Z10 Tower according to orientation: (a) North, (b) South, (c) East, (d) West, and (e) Roof.
Source: Author (2023)

DESIGN INTERVENTIONS FOR Z10 TOWER

The thermal performance analysis discussed above serves as a precursor to specific design interventions aimed at enhancing the sustainability of the Z10 Tower. The incorporation of aluminum vertical louvers, especially on the northern and eastern facades as depicted in Figure 4, effectively tackles several issues concerning the building's comfort and energy efficiency. These orientations are particularly susceptible to direct sunlight exposure in the morning hours, contributing to the building's thermal load. The strategic placement of louvers mitigates this by obstructing a portion of the direct sunlight, thereby maintaining cooler indoor temperatures and diminishing reliance on air conditioning systems.

Aluminum emerges as a prime material choice for the louvers due to its robustness and high reflectivity, deflecting a significant portion of the sun's rays. This feature aids in safeguarding the building's interior from excessive heat and harmful ultraviolet radiation, thus extending the longevity of furnishings and interior finishes. Moreover, the design of the louvers ensures optimal diffusion of natural light, reducing the need for artificial lighting and consequently lowering energy consumption and associated costs.

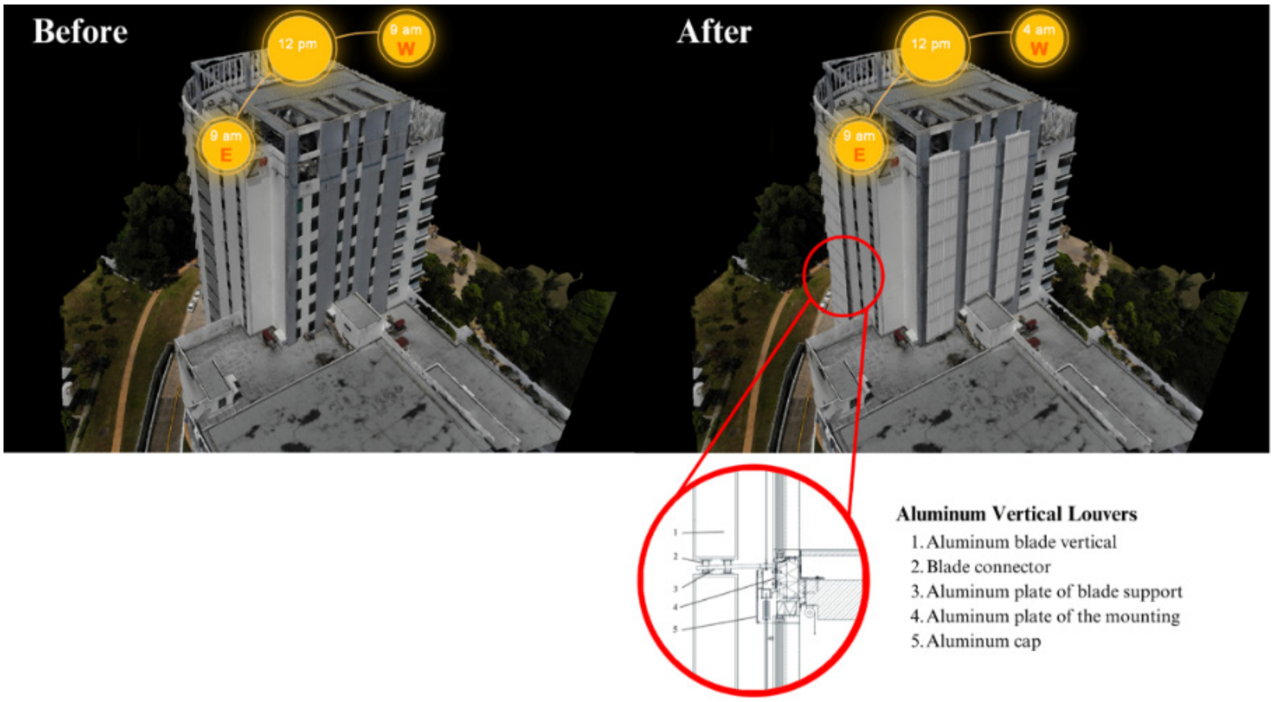


FIGURE 4. Comparison of the Z10 Tower before (left) and after (right) the installation of aluminum overhang louvers.
Source: Author (2023)

THERMAL PERFORMANCE ANALYSIS OF MOSTI BUILDING

The second building studied is the MOSTI Building. On the north side of the building in the early morning, the temperatures of the different materials vary slightly: the concrete wall registers at 35°C, while the glass window and metal roof both measure 37°C, and the metal louver is the coolest at 34°C, as depicted in Figure 5. However, as noon approaches, an intriguing shift occurs: the concrete wall's temperature escalates to 43°C, contrasting sharply with the glass window, which cools down to 35°C. Simultaneously, the metal louver and metal roof experience a considerable increase in temperature, reaching 47°C and 48°C respectively. By late afternoon, while the concrete wall and glass window stabilize at 34°C and 35°C respectively, the metal louver and metal roof remain relatively hot at 45°C and 48°C.

On the west side of the building in the morning, the temperatures are slightly cooler: the concrete wall reads 32°C, the glass window measures 35°C, the metal louver stands at 31°C, and the metal roof registers the coolest at 30°C. By noon, all the materials experience a rise in temperature, with the concrete wall reaching 39°C, the glass window maintaining 35°C, the metal louver rising to 45°C, and the metal roof climbing to 46°C. In the late afternoon, the metal louver and metal roof intensify in heat, reaching 49°C and 52°C, while the concrete wall and glass window measure 37°C and 40°C, respectively.

On the south side of the building, the morning temperatures are recorded at 35°C for the concrete wall, 37°C for the glass window, 33°C for the metal louver, and 32°C for the metal roof. By noon, the concrete wall heats up to 42°C, the glass window cools down to 34°C, while the metal louver and metal roof both soar to 47°C and 48°C respectively. In the late afternoon, the temperatures remain relatively stable, except for the glass window, which rises to 38°C.

Finally, on the east side and the roof of the building, the temperatures start off warm in the morning, particularly for the concrete wall at 39°C, the glass window at 42°C, the metal louver at 37°C, and the metal roof at 40°C. By noon, the concrete wall and glass window cool down to 35°C, while the metal louver and metal roof heat up to 46°C and 50°C. By 4 p.m., the concrete wall and glass window cool down even further to 33°C, while the metal louver and metal roof maintain 45°C. On the roof, the solar panel begins at 38°C, rises to 49°C by noon, and then slightly decreases to 47°C by late afternoon, while the concrete roof starts at 30°C, peaks at 50°C by noon, and then increases slightly to 51°C by late afternoon.

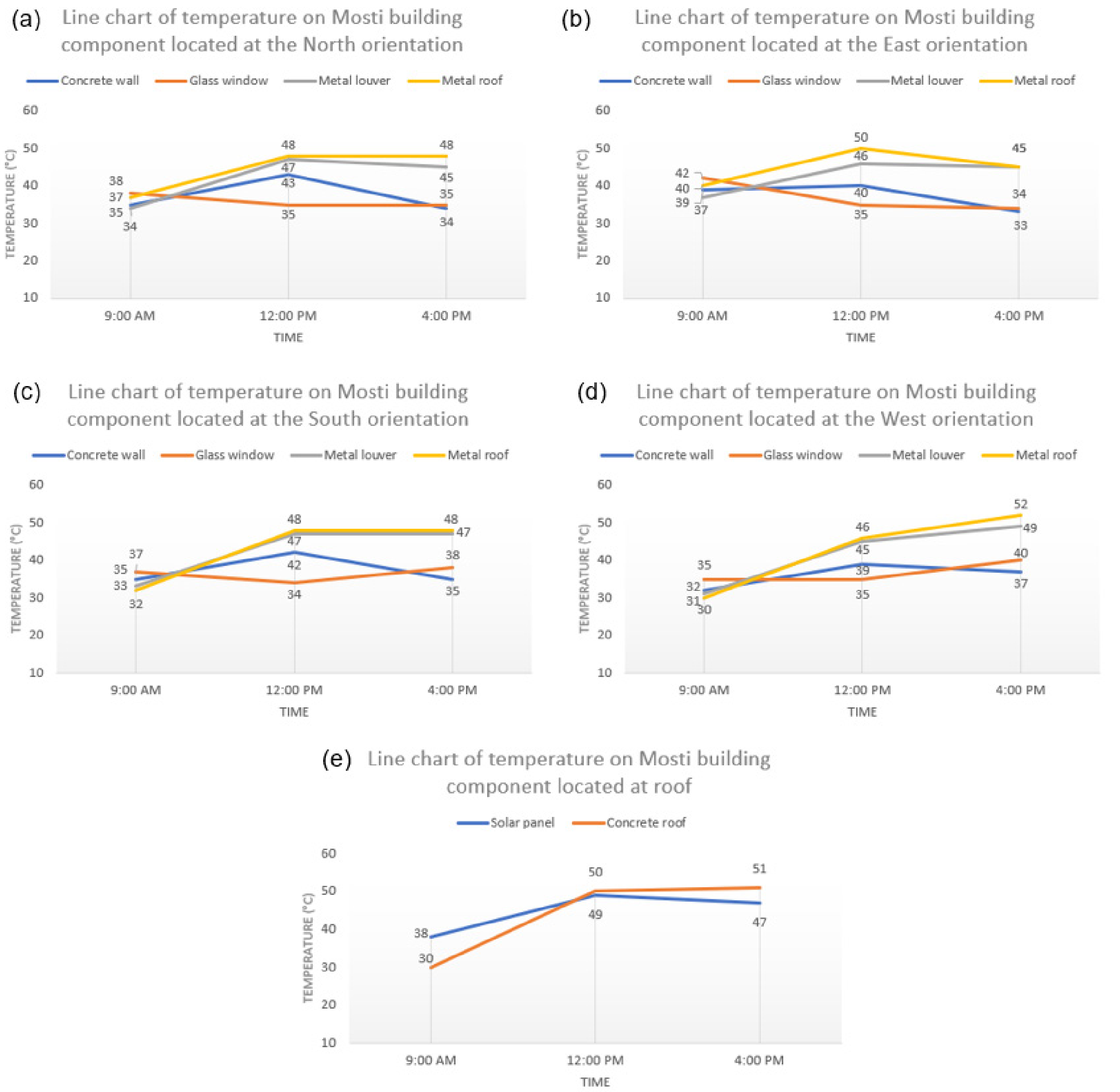


FIGURE 5. Thermal performance analysis of MOSTI Building according to orientation: (a) North, (b) East, (c) South, (d) West, and (e) Roof.
Source: Author (2023)

DESIGN INTERVENTIONS FOR MOSTI BUILDING

The thermal performance analysis indicates the necessity for specific design interventions. The proposal suggests implementing metal vertical louvers on the east side of the building to mitigate heat exposure from the sun, as depicted in Figure 6. Structures facing east in tropical regions are particularly vulnerable to the morning sun, which, although less intense than its afternoon counterpart, can significantly elevate indoor temperatures. Metal's reflective properties offer effective protection by deflecting a substantial portion of sunlight, thereby minimizing solar heat absorption on the building's facade. These louvers allow controlled natural light penetration while acting as a shield against heat, thus ensuring a comfortable indoor climate for occupants.

Furthermore, the decision to incorporate additional solar panels on the roof signifies a forward-looking commitment to sustainability. Given Putrajaya's geographical proximity to the equator, it benefits from ample sunlight throughout the year. Expanding the solar panel array enhances the MOSTI building's capability for clean energy generation and reduces its reliance on non-renewable sources, delivering both environmental and sustainable energy advantages. The design interventions also enrich the aesthetic outlook of the MOSTI building. The sleek lines and geometric patterns of the louvers create a contemporary touch and visually dynamic effect, enhancing the texture of the building's facade.

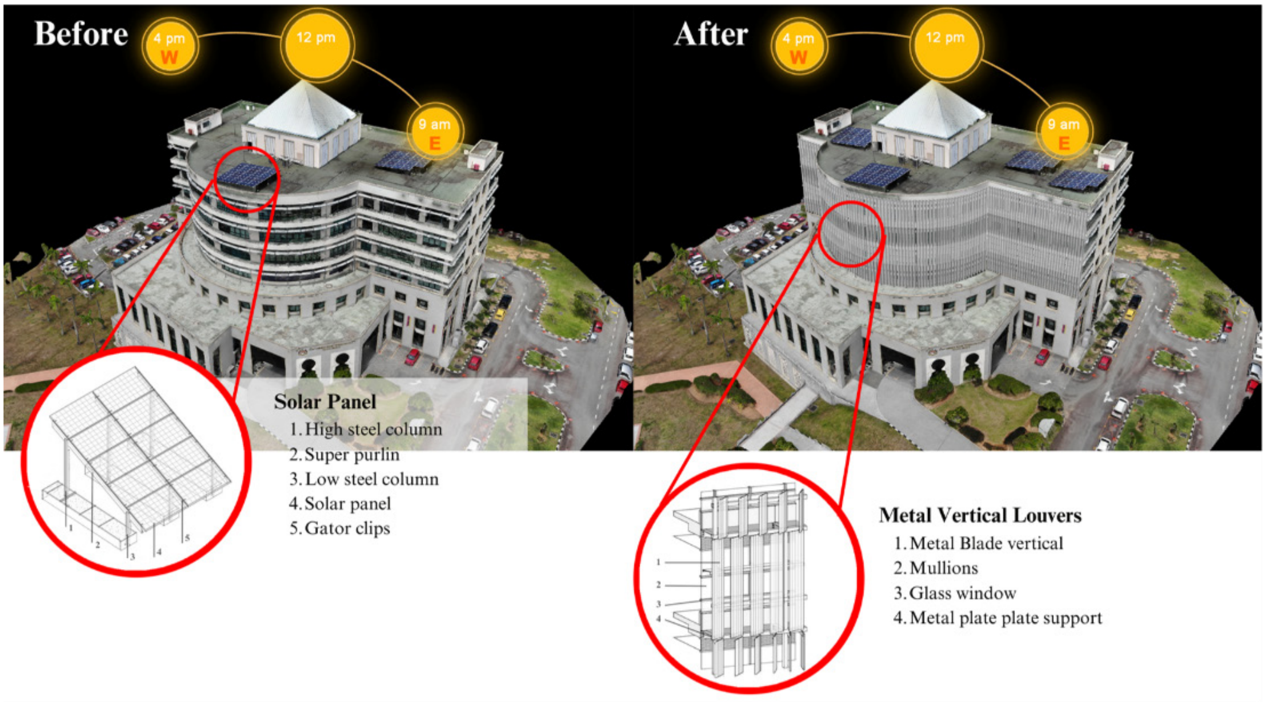


FIGURE 6. Comparison of the MOSTI Building before (left) and after (right) the installation of metal louvers.
Source: Author (2023)

CONCLUSION AND RECOMMENDATIONS

This paper highlighted the pivotal role that drones played in exploring the environmental space of sustainability. The exploration was made possible through harnessing the interplay between building designs and real-time environmental data. Beginning with an examination of the importance of building designs vis-à-vis green certifications as a means to advance sustainability, the paper established a foundation for the deployment of drones in analyzing the thermal performance of two selected GBI-certified buildings in Putrajaya city.

While focusing on the tectonic physicality of building designs, the study emphasizes the necessity of integrating dynamic environmental factors to enhance the functionality and sustainability of building structures. The integration of drone technology not only facilitates precise measurements but also offers insights into how the surrounding environment interacts with the built environment, guiding the implementation of design interventions such as passive solar design, daylighting optimization, and shading techniques.

LIMITATIONS OF THE STUDY

While the study has revealed the promising capabilities of drone technology in advancing environmental design, it is essential to acknowledge the constraints that frame its exploration. Primarily, the study takes an exploratory stance, which requires a limited timeframe for its execution. This temporal constraint inevitably affects the depth and breadth of the investigation. Furthermore, the case studies conducted in this research are intentionally focused on two exemplary buildings known for their sustainable design principles. While this approach offers valuable insights, it inherently limits the scope of inquiry to the specific characteristics of these buildings. Specifically, the study examines the material composition of these buildings, closely analyzing particular features and their implications for design innovation. Moreover, the interventions explored in this study mainly revolve around the potential of louvers in building design. While this avenue presents interesting possibilities, it also sets boundaries for creative exploration.

To overcome these limitations, we envision several promising directions for expanding the scope of inquiry in subsequent studies. These include prolonging the study's duration to allow for a more thorough examination of drone technology's impact on building design over an extended period. In this context, we are excited to integrate thermal drone mapping with datalogger procedures. While each method serves different purposes and offers unique strengths, combining them could yield significant benefits. Dataloggers provide continuous, localized data, while thermal drones can periodically map larger spatial areas to detect broader trends or changes. By establishing a hybrid system that incorporates both drone mapping and ground-based dataloggers, we can achieve more comprehensive data collection. To enhance this integration, further advancements in drone battery life, data storage, transmission capabilities, and the development of more sophisticated sensors and cameras will be crucial. These improvements could pave the way for better-integrated and longer-term data monitoring.

Additionally, augmenting the monitoring analysis with comprehensive indoor thermal comfort assessments, post-occupancy evaluations, and detailed material building specifications could significantly enhance the depth and breadth of the findings. This approach could potentially facilitate the integration of drone technology into green auditing practices. Furthermore, broadening the range of case studies to include a more diverse selection of building typologies beyond sustainable design exemplars would encompass a wider spectrum of environmental design approaches and challenges.

Furthermore, beyond focusing solely on specific features of building materiality, future studies could diversify exploration into design interventions beyond louvers. This could encompass a broader range of building elements, environmental features, and strategies enabled by drone technology. Incorporating feedback and insights from diverse experts such as architects, engineers, and environmental scientists would further enrich the understanding of these interventions and broaden the perspective on their potential applications. By embracing these multidimensional approaches, future studies can offer more holistic insights into the transformative role of drone technology in environmental design. From this perspective, the paper calls for more interdisciplinary collaboration between design thinking, architecture, and engineering studies. Such collaboration is essential to fully leverage the emerging capabilities of drone technology as a means to address the pressing issues of environmental crisis and climate change.

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DECLARATION OF COMPETING INTEREST

None.

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