Leveraging drone technology for enhanced thermal performance analysis in sustainable architecture: a case study of GBI-certified buildings in Malaysia

Mohd Shahrudin Abd Manan & Al-Fhaliq Naabil Abd Halin

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Leveraging drone technology for enhanced thermal performance analysis in sustainable architecture: a case study of GBI-certified buildings in Malaysia

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Mohd Shahrudin Abd Manan Al-Fhaliq Naabil Abd Halin

Faculty of Design and Architecture, Universiti Putra Malaysia, Serdang, Malaysia

CONTACT Mohd Shahrudin Abd Manan am_shahrudin@upm.edu.my Faculty of Design and Architecture, Universiti Putra Malaysia, Serdang, Malaysia

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ABSTRACT

In recent years, the realm of architecture has witnessed a significant transformation marked by a notable surge in focus on sustainable practices and energy efficiency. Architects and engineers increasingly recognize the innovative role of thermal efficiency in enhancing building performance. Such recognition emphasizes the critical importance of thermal analysis in understanding the thermal attributes of building materials and structures. Against this backdrop, this paper aims to bridge a current gap in architectural practices and sustainable design within the Malaysian context. It proposes a case study leveraging drone thermal mapping techniques on Green Building Index (GBI)-certified buildings. The study seeks to examine how architectural designs interact with environmental conditions and identify areas for improvement in sustainable building practices, particularly within Malaysia's tropical climate context. The primary objective is to assess the effectiveness

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of drone technology in analysing building thermal performance and to explore how the findings can inform design interventions to enhance sustainability. To achieve this, a structured methodology comprising five procedural phases is employed in a case study focused on three iconic GBI-certified buildings in Putrajaya, namely Putrajaya Holdings Tower, Energy Commission Building, and Heriot-Watt University Malaysia. By integrating thermal imaging with visuospatial data and 3D modeling techniques, the study demonstrates the effectiveness of drones in analysing heat patterns, highlighting their potential as a tool for strategic design interventions. As an exploratory study, this paper serves as a catalyst for further investigations into the integration of drone technologies with architectural design, particularly within the context of tropical climates , thereby highlighting opportunities for advancement within the field [Q1].

KEYWORDS

- Sustainable architecture
- Green Building Index (GBI)
- drone technology
- thermal mapping
- energy efficiency
- tropical climates

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1. Introduction

The realm of architecture has undergone significant changes in recent years, with a heightened focus on sustainability and energy conservation. Recognized as a pivotal aspect for enhancing building performance in terms of energy utilization and indoor environmental quality, thermal efficiency has garnered increasing attention from architects and engineers (Birgonul, 2021; Ebbini & Al-Assaf,2023; Eslamirad, Malekpour Kolbadinejad, Mahdavinejad, & Mehranrad,2020; Sibilla & Manfren, 2021; Sijakovic & Peric, 2021; Stremke & Schöbel, 2019; Winarto, Purwani, Setyaningsih, & Triratma, 2023). Within this paradigm shift, thermal analysis methods have played a crucial role by furnishing valuable insights into the thermal characteristics of building materials, structures, and their collective behavior (Akadiri, Chinyio, & Olomolaiye,2012; Soares et al., 2017; Zuo & Zhao, 2014).

Traditionally, thermal inspections in architecture heavily relied on manual assessments and rudimentary tools to assess the thermal efficiency of buildings (Kohansal, Akaf, Gholami, & Moshari,2021). Among the early advanced techniques introduced was infrared thermography, which enabled architects and builders to visualize and quantify thermal anomalies on building surfaces (Martin, Chong, Biljecki, & Miller,2022). Despite its historically revolutionary impact, this method had limitations in terms of accessibility and comprehensiveness, often requiring extensive time and resources for thorough inspections (Nooralishahi et al., 2021; Ortiz-Sanz, Gil-Docampo, Arza-García, & Cañas-Guerrero, 2019).

In response to the shortcomings of traditional methods, the architectural field has sought more efficient and updated approaches to thermal inspections. 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 (Abd Manan & Abd Halin,2023; Bayomi & Fernandez, 2023; Bogue, 2023; Challa, Al-Hmoud, Islam, Gokaraju, & Tesiero, 2023; Eiris, Albeaino, Gheisari, Benda, & Faris,2021; Elghaish et al., 2021; Kaamin et al., 2022; Wågø & Berker, 2014). Time considerations for drone-based methods include minimal setup time compared to traditional methods, rapid data capture as drones can cover large areas quickly, and automated data processing, which reduces the time required for analysis (Grosso, Mecca, Moglia, Prizzon, & Rebaudengo,2020; Tkáč & Mésároš, 2019). Comparing the estimated time required for both traditional and drone-based methods for a hypothetical multi-story building shows that for preparation and setup, traditional methods take 2-3 hours (scaffolding and safety checks) versus 30 minutes (flight planning and setup) for drone-based methods; for data collection, traditional methods take 1–2 days (manual inspection) versus 1-2 hours (automated drone flight) for drone-based methods; and for data processing, traditional methods take 1–2 days (manual analysis) versus 2-3 hours (automated processing) for drone-based methods. This results in a total time of 3–4 days for traditional methods versus 4-5 hours for drone-based methods.

The studies by Rakha and Gorodetsky(2018), as well as Entrop and Vasenev (2017), specifically highlight procedures for engaging drones in thermal-infrared inspection of buildings. In a similar vein, Hou, Volk, Chen, and Soibelman(2021) investigate the configuration of drone flights to establish efficient procedures for assessing energy performance. Drones have proven effective in implementing thermal modeling and corrective measures to improve energy efficiency in building design. Expanding on these findings, Rakha, El Masri, Chen, Panagoulia, and De Wilde(2022) conducted a thorough

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investigation illustrating the adaptability of drones equipped with state-of-the-art thermal cameras. Their research meticulously inspected diverse building structures, capturing intricate thermal data that vividly depicted the thermal properties of construction materials. The approach was instrumental in pinpointing areas prone to heat loss, insufficient insulation, and other thermal anomalies, offering invaluable insights into overall thermal performance.

Furthermore, Rodríguez, Melgar, Cordero, and Marquez(2021) contributed to the discourse by highlighting the myriad potentials of drone technology in revolutionizing the process of thermal inspections on building structures. Similarly, the study by Nooralishahi et al. (2021) showcased the extensive capabilities of employing leading thermal cameras attached to drones for comprehensive building structure inspections. This technique facilitated the generation of detailed thermal imagery of various building materials and components, thereby providing a comprehensive understanding of their heat generation characteristics. The critical insights derived from these images aided in identifying areas of heat loss, inadequate insulation, and other thermal irregularities, thus furnishing invaluable insights into overall temperature performance.

Bayomi, Nagpal, Rakha, and Fernandez(2021) underscored the transformative impact of drone thermal imaging in the domains of preventative maintenance and energy auditing. The technology not only identifies thermal anomalies but also enables prompt corrective actions to optimize energy efficiency. By precisely pinpointing areas of concern, building owners and facility managers gain the capacity to enact targeted interventions, resulting in significant enhancements to a building's energy performance and sustainability. The utilization of drones for thermal inspections also mitigates logistical challenges associated with conventional methods. With their ability to access inaccessible areas and provide comprehensive aerial perspectives, drones facilitate a more thorough and less intrusive inspection process (Seo, Duque, & Wacker, 2018). This, in turn, streamlines workflows, conserves time and resources, and minimizes disruption to occupants.

These studies collectively highlight the pivotal role of drone technology in addressing thermal imaging and energy efficiency imperatives. Moreover, they exemplify how technological innovations can revolutionize thermal inspection protocols and contribute to the overarching objective of sustainable architecture. This shift heralds a new paradigm wherein architects and builders are equipped with the requisite tools to elevate building thermal performance while striving for heightened green certifications (Alkaabi, Senghore, & Rhman El Fawair, 2023).

2. Background

In the realm of green certifications, effectively managing thermal efficiency emerges as a crucial factor in advancing sustainable architecture. In Malaysia, the Green Building Index (GBI) serves as the national green certification, developed to evaluate the environmental design and performance of buildings. This certification focuses on energy efficiency, sustainable site planning, and the use of materials and natural resources. Launched in 2009, the GBI framework assesses the design and performance of buildings with an emphasis on thermal effectiveness (Harun, Samah, Majid, Yusoff, & Lim,2017; Pandey, 2018; Wan Yusoff & Wen, 2014). Achieving commendable GBI ratings requires a holistic approach to thermal analysis, ensuring that buildings not only meet energy efficiency benchmarks but also positively impact occupants' well-being.

GBI's mission to enhance building sustainability and energy efficiency in Malaysia highlights the critical role of technological progress (Lim, Sediadi, Shahsavari, & Azli,2016; Sim & Putuhena, 2015; Solla et al., 2022). The adoption of drone technology for thermal inspections represents a significant advancement, smoothly aligning with global efforts to integrate innovative solutions and smart technologies into construction practices. Building upon this foundation, exploring the utilization of drones in thermal inspections is essential for advancing architectural methodologies, indicating a conscious commitment to leveraging technological innovations for enhanced thermal efficiency and sustainability. Furthermore, the potential of drone-assisted thermal inspections to enhance GBI ratings underscores its relevance and importance in the contemporary discourse on architecture.

However, despite these strides, there exists a noticeable gap in Malaysia regarding the integration of drone technology into local architectural practices. While GBI certification emphasizes sustainability metrics such as energy efficiency and indoor environmental quality, the utilization of drone technology remains relatively untapped in assessing and optimizing these aspects in real-time. This gap is particularly pronounced in addressing architectural adjustments required to mitigate the challenges posed by Malaysia's tropical climate, such as high humidity, intense solar radiation, and heavy rainfall.

Within this context, this paper aims to narrow the knowledge gap by conducting a case study that employs drone thermal mapping on GBI-certified buildings. By leveraging drone technology, this study seeks to provide an analysis of how architectural designs interact with environmental conditions, shedding light on potential areas for improvement in sustainable building practices. The primary aim is to examine architectural adjustments in response to the tropical climate, clarifying how drone technology can enhance understanding of sustainable practices within the local environment.

Moreover, this research effort aims to clarify the practical applications of drone technology in assessing building performance, emphasizing its potential to enhance the evaluation and optimization of sustainable architectural designs. The objective of this paper thus revolves around addressing the following two key questions to facilitate the preliminary investigation:

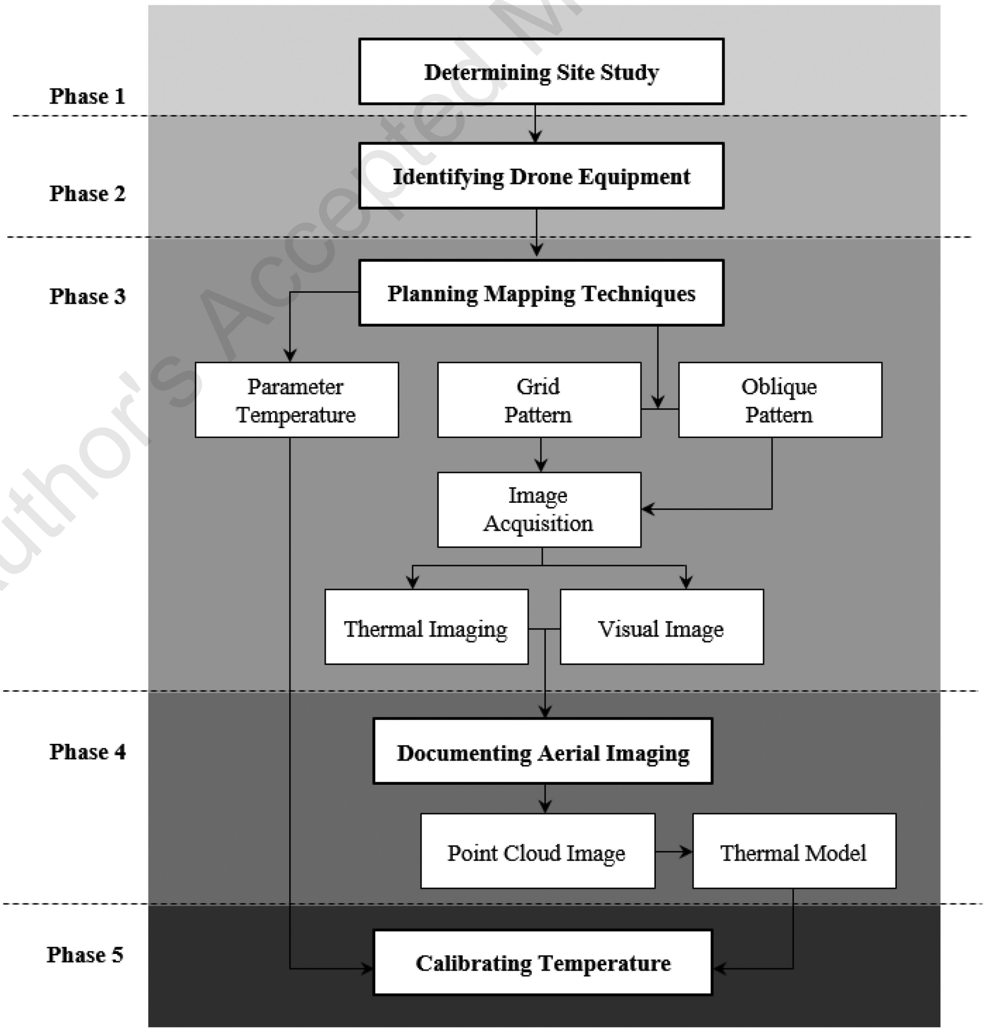
1 How can drone technology be effectively employed to analyze and assess the thermal performance of buildings?
2 In what ways can the findings obtained through drone-assisted investigation be utilized to inform and guide design interventions aimed at enhancing sustainable building performance?

3. 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 (Fox, Coley, Goodhew, & De Wilde, 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 Rakha et al. (2022) from drone mapping strategy, our study adopts a systematic approach consisting of five procedural phases, where one additional step were design as to calibrating the temperature from primary source: site selection, setup of appropriate drone equipment, implementation of mapping techniques, aerial imaging, and calibrating temperature (see Figure 1). These phases will be further elaborated in the subsequent sections.

Figure 1. **[Q4]**Flowchart of the methodology for the drone-mapping procedure, divided into five phases [1].



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3.1. 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 (Samsudin et al., 2022). 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 metropolitan Kuala Lumpur. According to the Köppen-Geiger system, Putrajaya has a tropical rainforest climate (Af), characterized by consistently high temperatures ranging from 25°C to 30°C and significant year-round rainfall exceeding 2000mm annually (Peel, Finlayson, & McMahon, 2007). 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 no distinct dry season, the months between April and October typically experience less rainfall compared to the monsoon months, albeit sporadic showers persist even during these 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 & 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 three GBI-certified buildings in Putrajaya, namely, Putrajaya Holdings Tower (PjH Tower), Energy Commission Building (ECB), and Heriot-Watt University Malaysia (HWUM) (Putrajaya Corporation, 2022, p. 7).

These selected buildings are architectural icons, each showcasing a unique blend of geometric forms and structural configurations that harmonize with the local climate. The PjH Tower's design exudes captivating minimalism, characterized by an innovative facade adorned with overlapping blinds, while the ECB stands out with its distinctive 'diamond' appearance. On the other hand, the HWUM's architecture embraces fluidity, accentuated by a captivating green roof feature.

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, the Department of Survey and Mapping Malaysia, and the Civil Aviation Authority of Malaysia. These regulatory bodies oversee the research activities to ensure they adhere to safety protocols and respect the privacy of the surrounding areas.

3.2. Phase 2: Identifying drone equipment

After a thorough comparison of various drone models, the DJI Mavic 2 Enterprise Dual emerged as the suitable choice for this study due to its affordable thermal-infrared sensor. The visual camera includes a 1/2.3″ CMOS sensor with 12 megapixels, capable of capturing 4 K video at 30 frames per second, and offers a 3x digital zoom for detailed inspections (Flir, 2019). Renowned for its minimal thermal imaging capabilities at the entry level, the drone can capture basic thermal detection for visual thermal settings. Equipped with a dual-camera system, the drone effectively combines a high-resolution visual camera with a radiometric thermal camera, enabling it to capture both visual and thermal data simultaneously with precision.

Despite its lower resolution thermal camera compared to the DJI Mavic 2 Enterprise Advanced (DJI M2EA), the Mavic 2 Enterprise Dual features Multi-Spectral Dynamic Imaging (MSX) technology (Flir, 2019). This innovative approach overlays visual orthophoto images onto key details extracted from thermal images, offering a balanced combination of features suitable for many types of surveys and inspections, especially when budget constraints are considered. Its thermal imaging capabilities, combined with a high-quality visual camera and modular accessories, make it a versatile tool for various applications, including basic thermal assessments and visual inspections. 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 three buildings (Provost, Butcher, Coleman, Bloom, & Kelaher, 2020; Zhang & Zhu, 2023).

3.3. 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 three buildings (see Figure 2). The oblique method, utilizing a 45-degree camera angle, captures images from multiple viewpoints circulating on building, enabling the creation of detailed three-dimensional models that reveal thermal distribution across building surfaces. This approach yields intricate insights into the thermal patterns 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 (Jiang, Jiang, Huang, & Yang, 2017).

Figure 2. The drone flight path for each building: a) Putrajaya Holdings Tower (PjH Tower), b) Energy Commission Building (ECB), and c) Heriot-Watt University Malaysia (HWUM).

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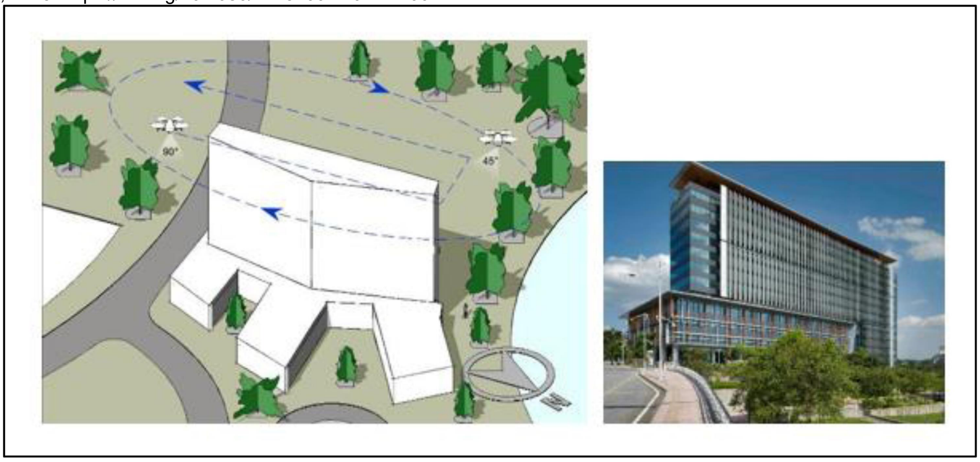

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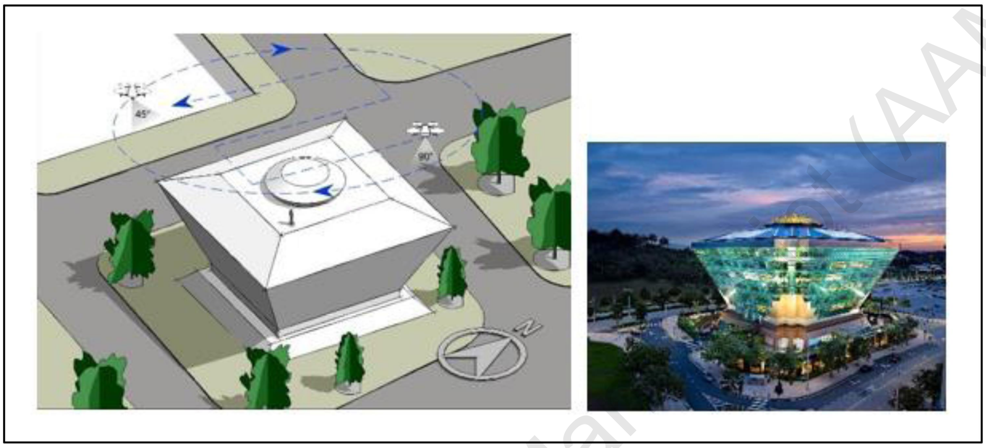

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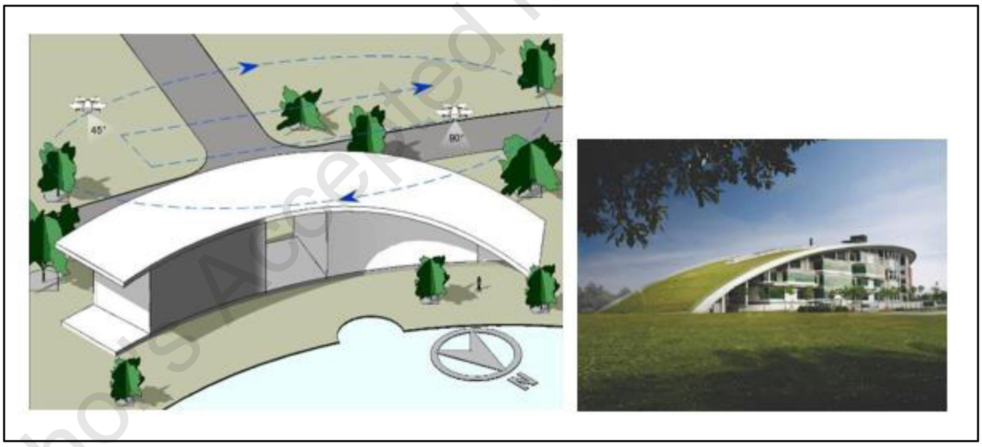

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The mapping process involves three distinct flight intervals: at 9 am, 12, and 4 pm in March, strategically capturing the dynamic temperature fluctuations throughout the day. These three time intervals were chosen due to drone battery limitations requiring recharging after each flight. This time-specific thermal imaging study, conducted at different intervals throughout the day, can effectively identify and analyze thermal performance (Rakha, El Masri, Chen, & De Wilde,2021). Collecting temperature data of the surrounding environment before each drone flight helps establish a baseline and calibrate the thermal sensors, ensuring accurate readings. This process considers external factors and enhances thermal analysis in the targeted building (Lehmann, Wakili, Frank, Collado, & Tanner, 2013; Ostańska, 2018) (see Table 1).

Table 1. Ambient conditions readings surrounding the buildings: a) PjH Tower on 7 March 2023; b) ECB on 9 March 2023; c) HWUM on 10 March 2023. (AccuWeather, 2023).

Building	a) PjH Tower

Time	9.00 am	12.00 pm	4.00 pm
Temperature	26 °C	31 °C	34 °C
Wind Speed	9 km/h	9 km/h	9 km/h
Humidity	73%	48%	47%
Dew Point	21 °C	19 °C	22 °C
Air pressure	1012 hPa	1013 hPa	1011 hPa
Visibility	16 km	16 km	16 km
Building	b) ECB		
Time	9.00 am	12.00 pm	4.00 pm
Temperature	28 °C	32 °C	34 °C
Wind Speed	11 km/h	9 km/h	13 km/h
Humidity	65%	58%	53%
Dew Point	21 °C	23 °C	24 °C
Air pressure	1011 hPa	1011 hPa	1009 hPa
Visibility	16 km	16 km	8 km
Building	c) HWUM		
Time	9.00 am	12.00 pm	4.00 pm
Temperature	27 °C	32 °C	34 °C
Wind Speed	6 km/h	5 km/h	11 km/h
Humidity	73%	51%	54%
Dew Point	22 °C	21 °C	24 °C
Air pressure	1012 hPa	1012 hPa	1007 hPa
Visibility	16 km	16 km	8 km

3.4. 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 developed a total of nine 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, as the software aids in the creation of 3D thermal models, we further calibrating the temperature data of model from the screenshot images. These models afford us the opportunity to examine temperature differentials, pinpointing areas exhibiting abnormal thermal behavior, whether it be excessive heat or cold.

3.5. Phase 5: Calibrating temperature

To ensure accuracy in thermal imaging, the first step involves collecting temperature data from both primary resources, such as screenshots of the temperature parameter from remote controls, and the surrounding environment. This primary resource data provides a baseline for environmental temperature conditions, which are captured at multiple times of the day to account for diurnal variations and ensure a comprehensive understanding of environmental temperature influences. This data is crucial for calibration, distinguishing between normal environmental temperature variations and genuine thermal parameters in the targeted building (Lehmann et al., 2013).

Once the primary resource data is collected, it is processed using ImageJ, an image processing software recommended for handling thermal images due to its capability to support various image formats and perform complex analyses. The collected screenshots are imported into ImageJ, where each image is assigned a specific temperature value based on the baseline data. This step involves using ImageJ's calibration function to map pixel intensity values to actual temperature readings. By applying this calibration curve to all thermal images, discrepancies are corrected to ensure that the thermal data accurately reflects true temperature conditions (Schneider, Rasband, & Eliceiri, 2012).

The final step in the methodology involves validating the accuracy of the calibrated thermal images by comparing them with the thermal model's expected results. Any significant deviations are carefully analyzed, and adjustments to the calibration curve are made if necessary. This iterative process ensures that the thermal images are as accurate as possible, accounting for environmental influences and sensor inaccuracies. Once validated, these thermal images can be used for detailed thermal analysis of the targeted building, providing reliable data for further studies (Abràmoff, Magalhães, & Ram, 2004).

4. Results and discussion

The analysis of aerial imaging has yielded substantial findings for the study, revealing important insights that contribute significantly to our understanding of the subject matter. In acknowledgment of this, we have organized our discussion to center on these findings, ensuring that our analysis aligns closely with the objectives set forth in this paper. Specifically, we will concentrate on addressing the two key questions outlined earlier in the preceding section.

Our initial focus will delve into the utilization of drone technology as a means to assess the thermal dynamics of the studied buildings. Drones capture aerial imagery, which is instrumental for creating detailed thermal models. The models will assist us in analyzing and understanding how heat is absorbed and distributed within the buildings. To enhance the analysis, we use ImageJ software to calibrate temperatures extracted from the aerial thermal images. This calibration process ensures measurement accuracy, enabling us to precisely map variations in thermal behavior across different parts of the buildings.

Subsequently, we explore the design interventions made possible through the insights acquired from the drone-assisted investigation. By closely examining the data obtained from aerial imaging, we can identify potential areas for improvement in the design and construction of these buildings. This analysis opens up opportunities for implementing innovative solutions aimed at enhancing energy efficiency and their overall sustainability.

4.1. Employing drone technology for assessing the thermal performance of buildings

We conducted a comprehensive drone analysis focusing on the thermal dynamics of the three buildings: the PjH Tower, ECB, and HWUM. The investigation centerd on their thermal models, with the objective of understanding their resilience in the face of the tropical weather patterns. Through careful monitoring of temperature variations across different time intervals, we aimed to uncover how the buildings respond to the fluctuating climatic conditions prevalent throughout the day.

Figure 3 depicts the 3D model visualization showcasing the thermal patterns exhibited by each building. The visualization vividly portrays the distinct reactions of the buildings to solar exposure over the course of a day. The deliberate manipulation of building geometries, coupled with the choice of construction materials, significantly influences the thermal comfort levels within the buildings. Notably, while the PjH Tower experiences pronounced heat exposure, the ECB and HWUM effectively mitigate this through their thoughtful building design strategies.

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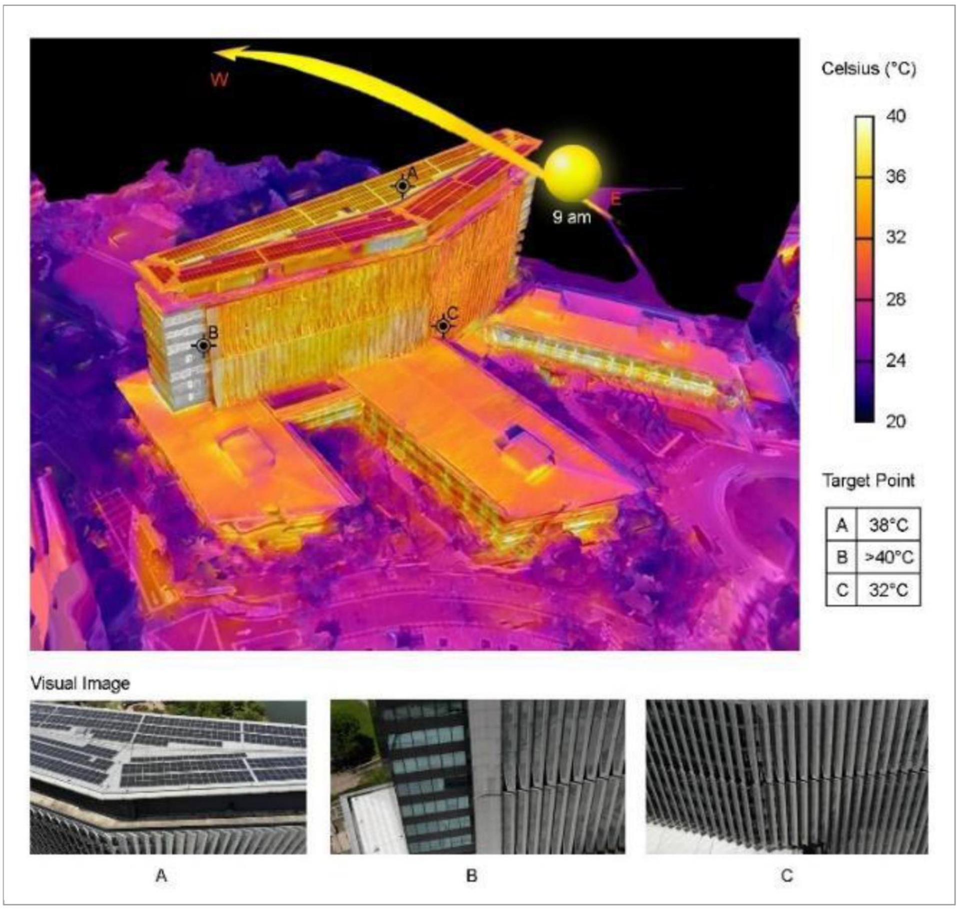
Figure 3. The 3D model visualization illustrates the thermal patterns exhibited by the buildings: a) PjH Tower, b) ECB, and c) HWUM.



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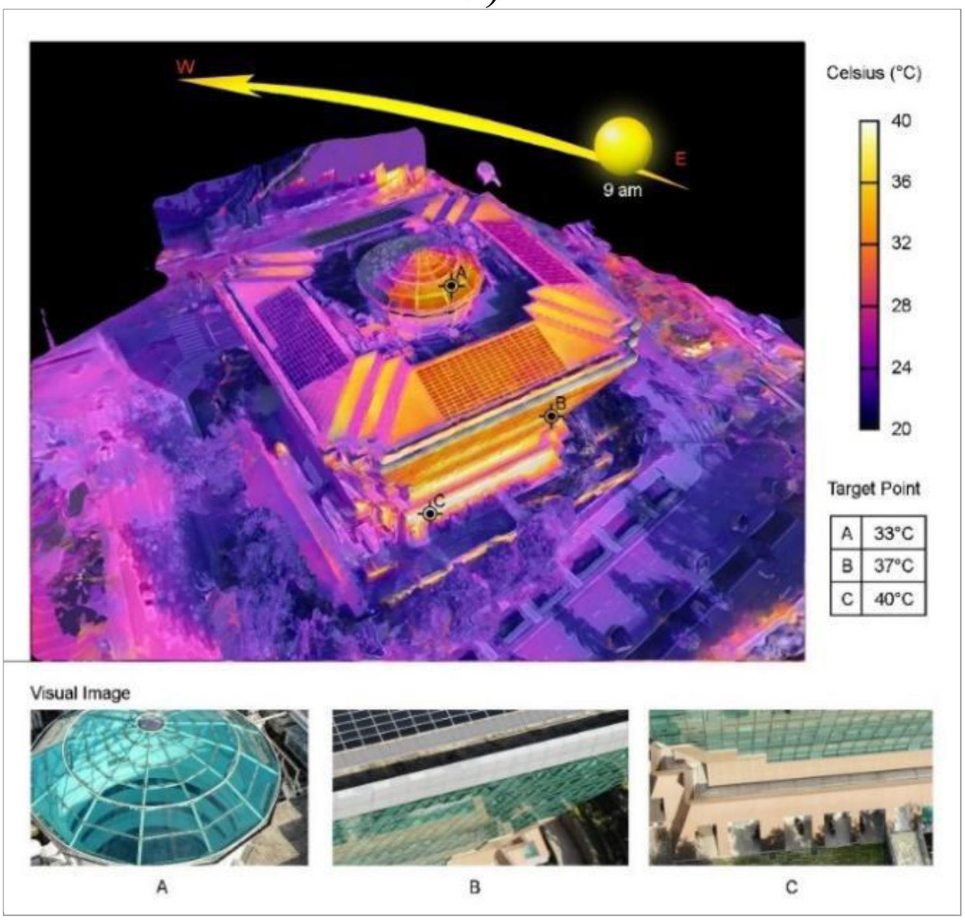

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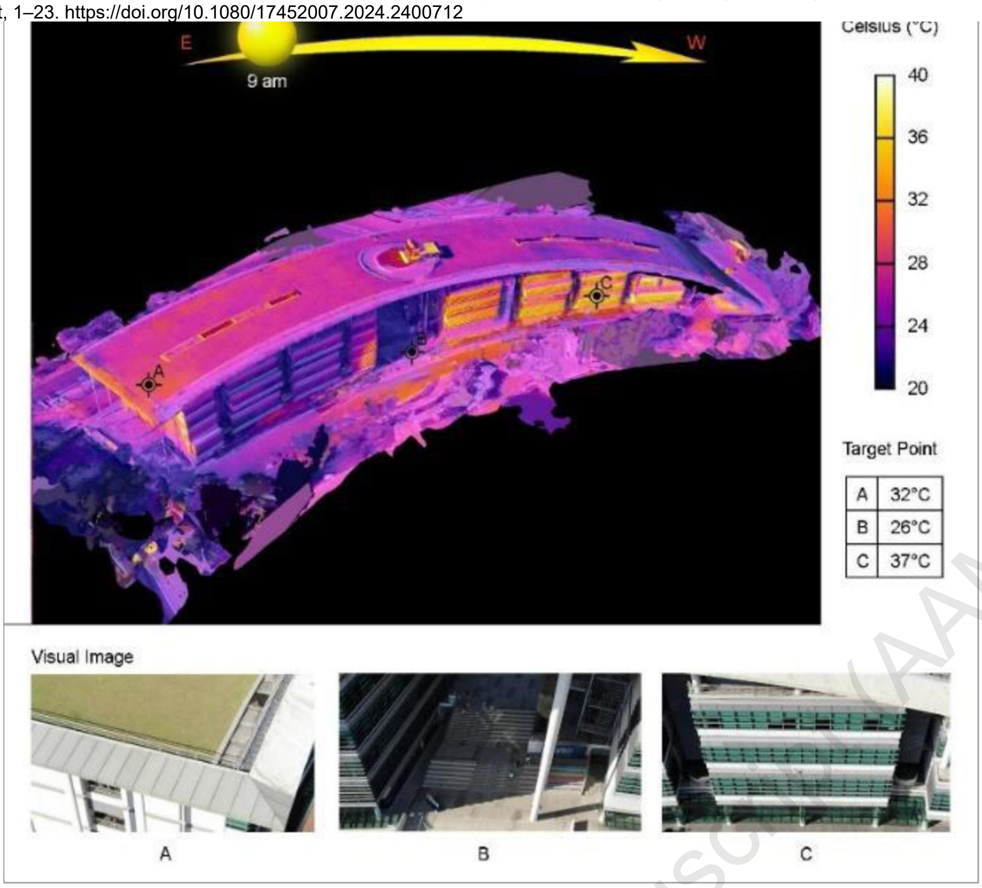

c)

To delve deeper into these observations, we pinpoint three specific areas on the building surfaces directly impacted by solar radiation. These areas, denoted as target points A, B, and C, are crucial for precise analysis in understanding the thermal variations experienced by the buildings. The analysis culminates in the presentation of temperature trends over time, conveyed through a series of informative line graphs. These graphs illustrate the temporal evolution of thermal conditions within each building.

4.1.1. Thermal performance analysis of PjH tower materialities

In this section, we explore the thermal behavior of the materials utilized in the construction of the PjH Tower, specifically examining grey walls, glass windows, metal louvers, and roofing, across four distinct geographical orientations: north, south, east, and west.

Beginning with the north orientation, noticeable differentials in temperature responses between the grey wall and glass window are observed throughout the day. Starting at 35°C and 38°C, respectively, in the morning, both materials experience a midday surge to 45°C for the grey wall and a slightly higher 47°C for the glass window. By 4 pm, a minor cooldown is evident, with the grey wall registering 43°C and the glass window at 45°C, consistently maintaining a 2-3°C variance (see Figure 4).

Figure 4. Thermal performance analysis of PjH Tower materialities according to the north orientation.

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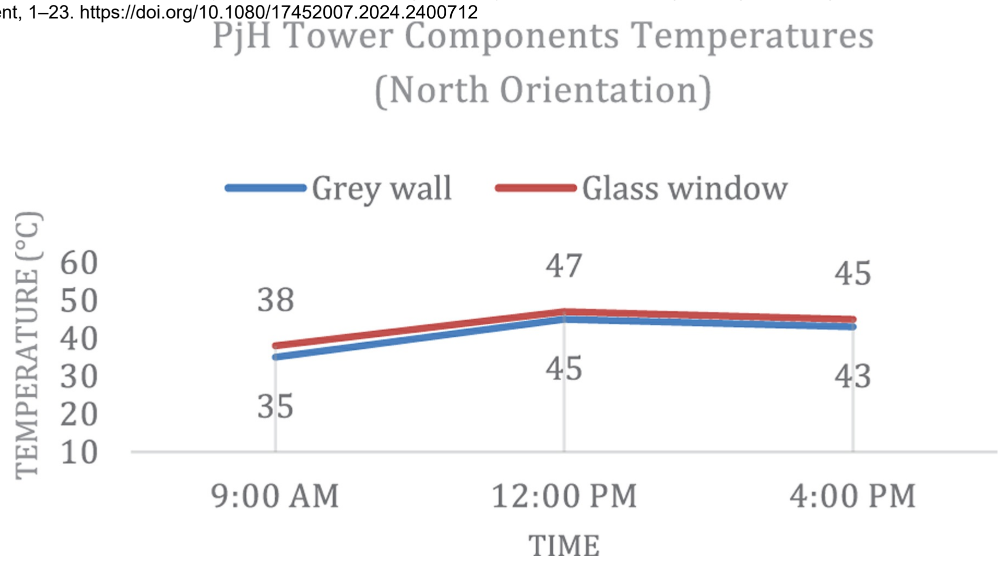
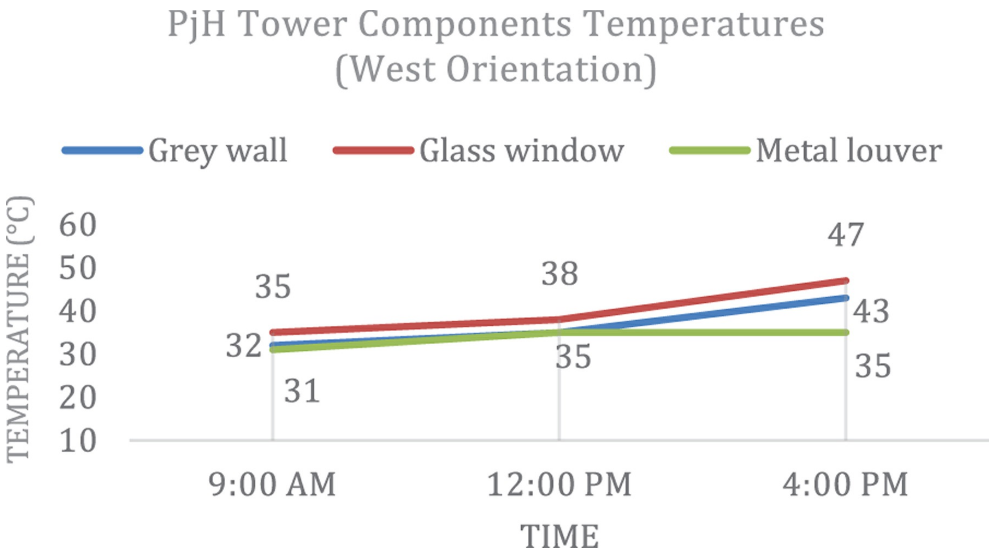


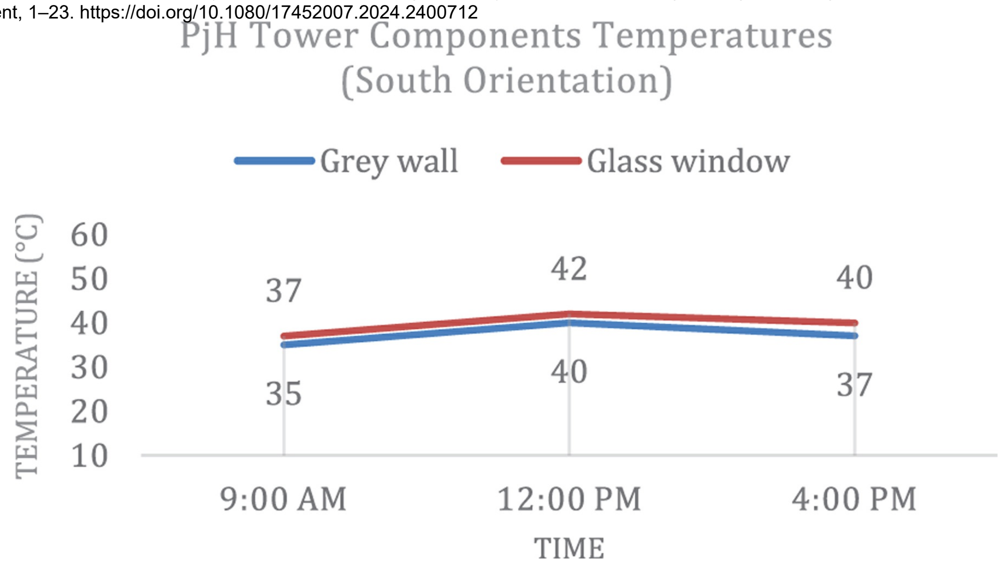
Moving to the western face of the building, intriguing temperature dynamics among the metal louver, grey wall, and glass window come to light. At dawn, the metal louver stands at 31°C, the grey wall slightly higher at 32°C, and the glass window peaking at 35°C. By noon, stabilization occurs with the metal louver and grey wall plateauing at 35°C while the glass window escalates to 38°C. Come late afternoon, substantial changes manifest: the metal louver remains constant, the grey wall ascends to 43°C, and the glass window further rises to 47°C, indicating significant afternoon heat exposure (see Figure 5).

Figure 5. Thermal performance analysis of PjH Tower materialities according to the west orientation.



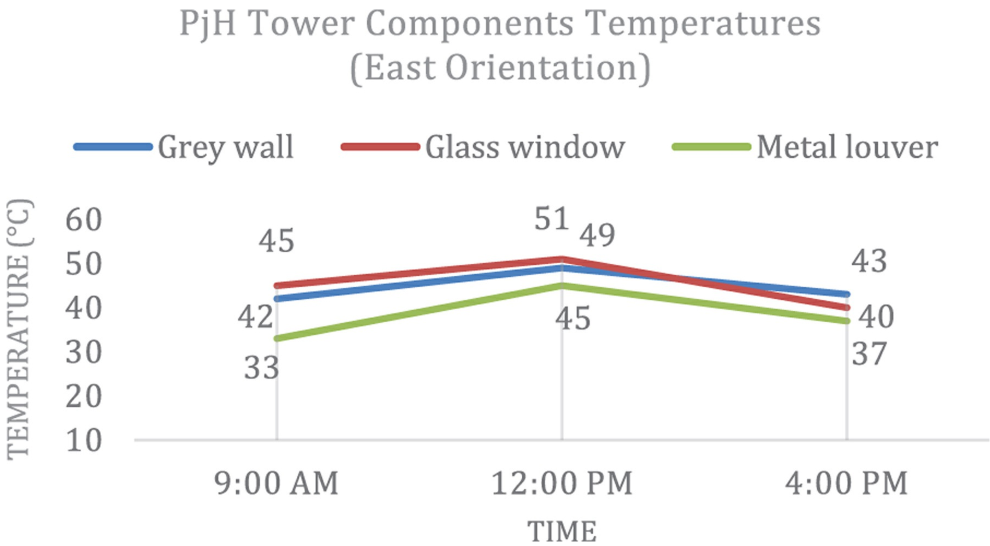
In the southern orientation, the grey wall and glass window begin at 35°C and 37°C, respectively, at 9 am, escalating to 40°C and 42°C by noon, before slightly cooling to 37°C and 40°C around 4 pm The temperature rise on this side exhibits a more gradual and balanced trajectory, with commensurate evening cooldowns, illustrating a harmonious temperature pattern throughout the day (see Figure 6).

Figure 6. Thermal performance analysis of PjH Tower materialities according to the south orientation.



Conversely, focusing on the eastern exposure in the morning reveals elevated temperatures, with the metal louver at 33°C, grey wall at 42°C, and glass window at 45°C. Midday intensifies the heat, pushing temperatures to 45°C, 49°C, and 51°C, respectively, owing to direct sunlight exposure. Come late afternoon, a decline sets in, with readings dropping to 37°C, 43°C, and 40°C, respectively, with the glass window exhibiting a noteworthy temperature decrease (see Figure 7).

Figure 7. Thermal performance analysis of PjH Tower materialities according to the east orientation.



Lastly, examining the roofing materials, initial temperatures are noted: the solar panel starts at 36°C, the metal roof at 38°C, and the concrete roof at the coolest 30°C. Noon brings considerable heat accumulation, with the solar panel reaching an extreme 57°C, the metal roof at 54°C, while the concrete roof maintains its cool at 30°C. Late afternoon sees a moderated cooldown, with the solar panel and metal roof descending to 45°C and 49°C, respectively, while the concrete roof experiences a slight uptick to 32°C. These observations highlight the disparate reactions of materials to sunlight and thermal fluctuations throughout the day (see Figure 8).

Figure 8. Thermal performance analysis of components of the PjH Tower located on the roof.

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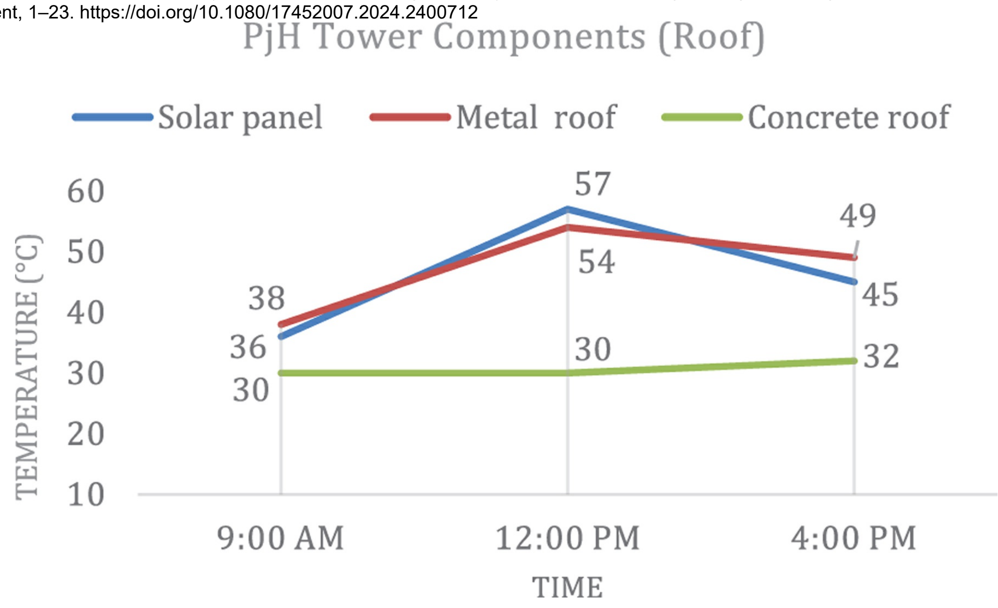
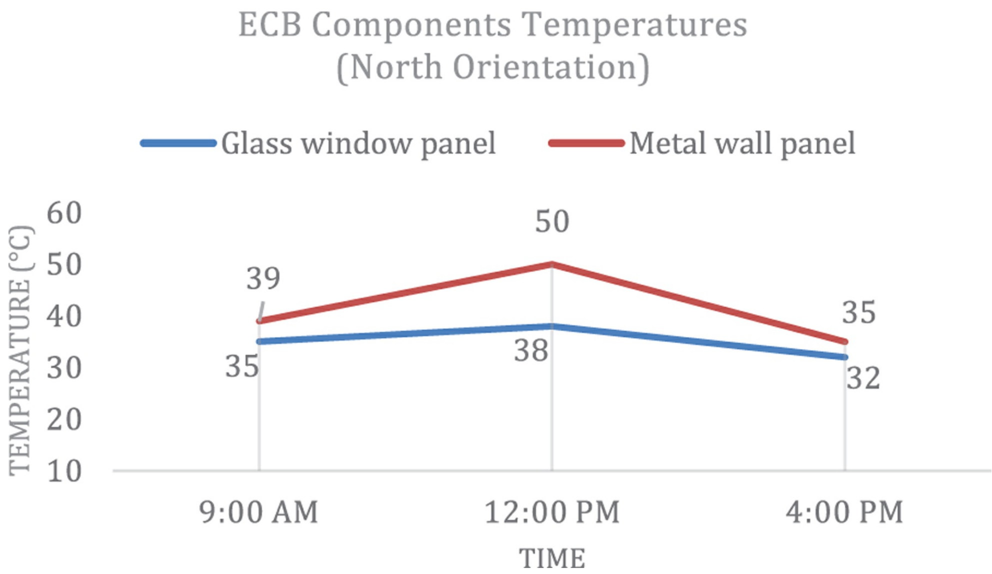


In short, the thermal analysis of materials used in the construction of the PjH Tower – grey wall, glass window, metal louvers, and its roofing materials – reveals significant variations in temperature response across different orientations. The materials exhibit distinct behaviors in response to sunlight exposure and thermal fluctuations. This emphasizes the importance of orientation-specific design considerations and material selection in optimizing thermal performance and enhancing occupant comfort within the building.

4.1.2. Thermal performance analysis of ECB materialities

This section presents a comprehensive analysis of the thermal performance of the ECB with respect to different building orientations and materials, including glass window panels, metal wall panels, and various roofing materials. In the context of the north-facing orientation of the ECB, at 10 am, the glass window panel registers a temperature of 35°C, while the metal wall panel is slightly warmer at 39°C. As noon approaches, the metal wall panel heats up significantly to 50°C, while the glass window panel experiences a modest increase to 38°C. Towards late afternoon, both materials begin to cool down, with the glass window panel dropping to 32°C and the metal wall panel to 35°C (see Figure 9).

Figure 9. Thermal performance analysis of ECB materialities according to the north orientation.



Shifting attention to the west-facing orientation, during the early hours, the glass window panel records 30°C, with the metal wall panel slightly cooler at 28°C. By noon, the glass window panel maintains its temperature at 30°C, while the metal wall panel rises to 33°C. However, by 4 pm, both materials experience substantial heating, with the glass window panel peaking at 46°C and the metal wall panel at 43°C, indicating the pronounced impact of afternoon sun exposure on this side of the building (see Figure 10).

Figure 10. Thermal performance analysis of ECB materialities according to the west orientation.

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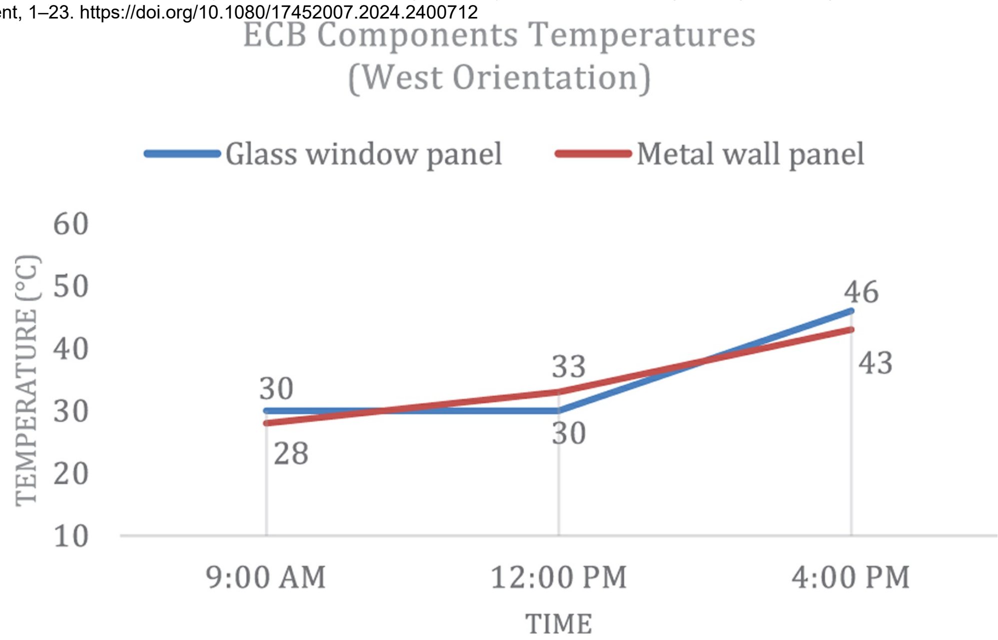
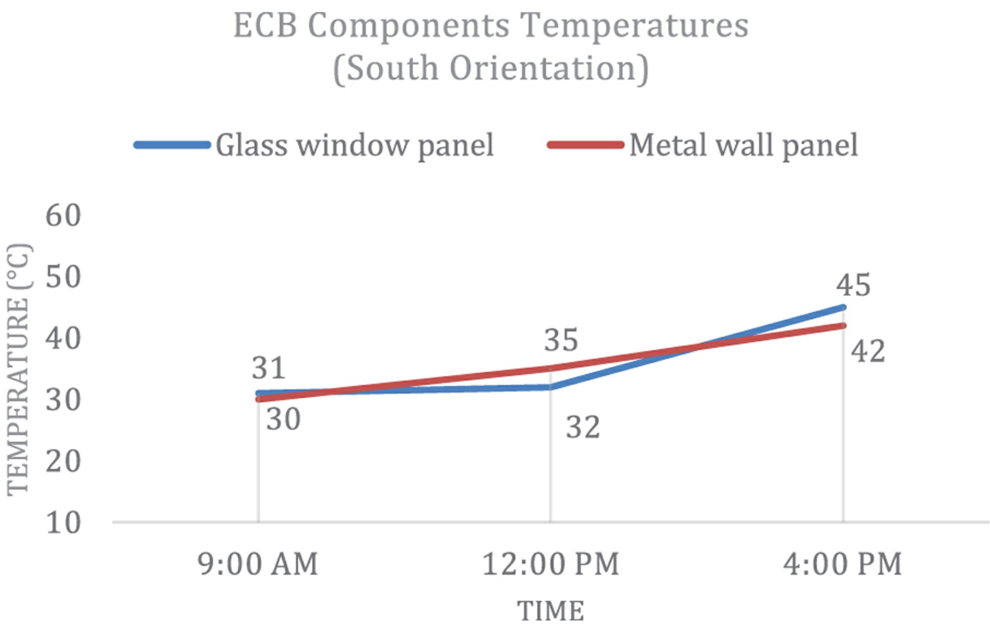


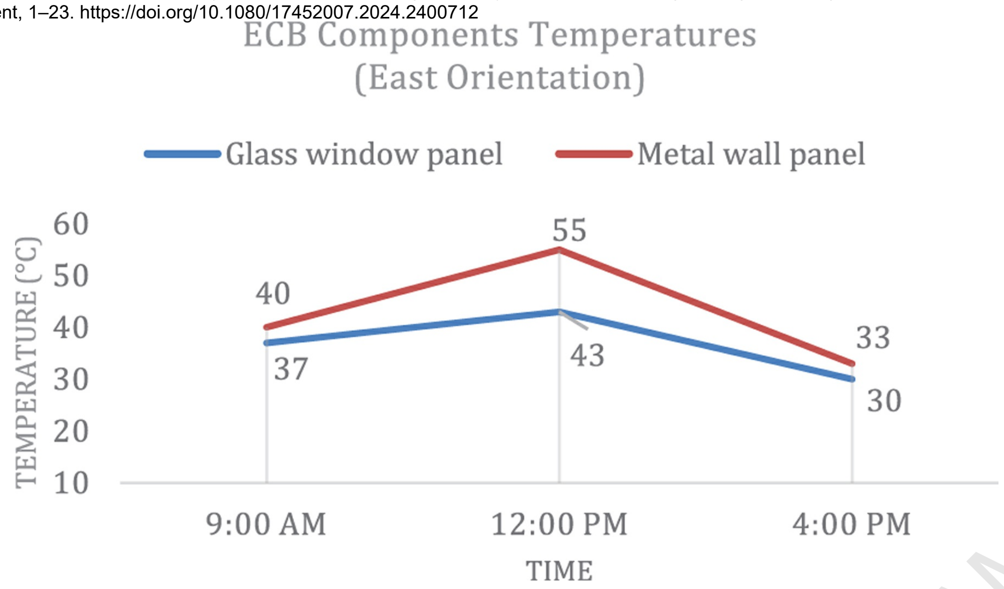
For the south-facing orientation, the glass window panel measures 31°C, while the metal wall panel records 30°C. At noon, both materials exhibit a slight increase in temperature, with the glass window panel at 32°C and the metal wall panel at 35°C. Notably, there is a sharp rise in temperature, particularly for the glass window panel, reaching 45°C, and the metal wall panel, reaching 42°C, in the late afternoon (see Figure 11).

Figure 11. Thermal performance analysis of ECB materialities according to the south orientation.



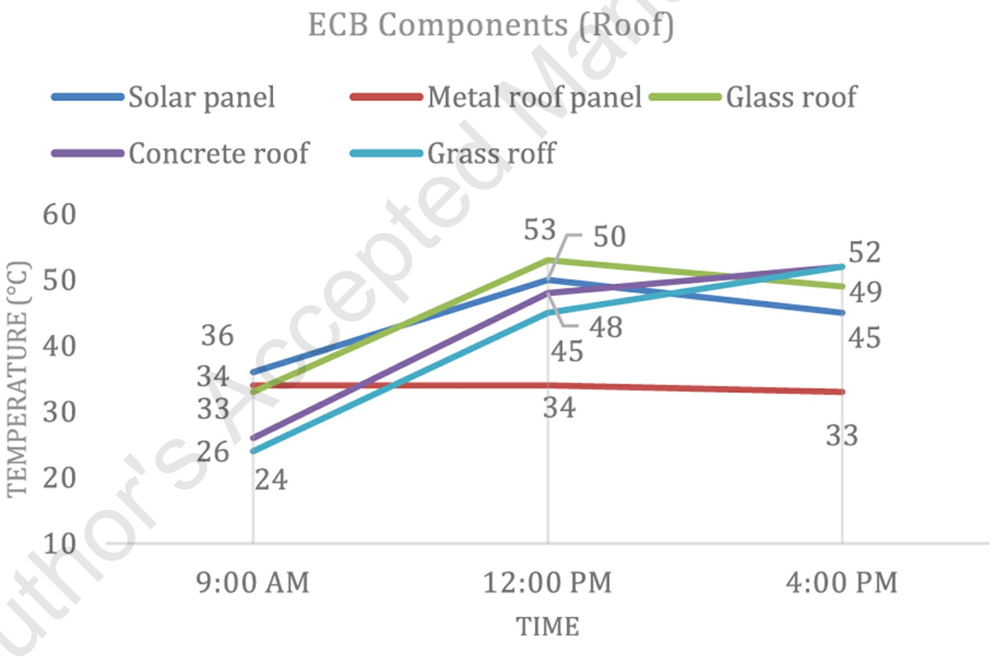
Moving to the east-facing orientation, in the morning, the glass window panel measures 37°C, with the metal wall panel slightly warmer at 40°C. By noon, the metal wall panel's temperature escalates to 55°C, while the glass window panel also rises to 43°C. Towards late afternoon, there is a slight cooling trend, particularly for the metal wall panel, dropping to 33°C, aligning with the temperature of the glass window panel (see Figure 12).

Figure 12. Thermal performance analysis of ECB materialities according to the east orientation.



Regarding the roofing materials, in the morning, the solar panel and grass roof both measure 36°C, the metal roof records 34°C, the glass roof registers 33°C, and the concrete roof is the coolest at 26°C. By noon, most materials experience significant heating, with the glass roof peaking at 53°C, the solar panel at 50°C, the concrete roof at 48°C, and the grass roof at 45°C, while the metal roof remains stable at 34°C. In the late afternoon, the concrete roof and grass roof both reach high temperatures of 52°C, the glass roof cools slightly to 49°C, the solar panel decreases to 45°C, and the metal roof maintains a temperature of 33°C (see Figure 13).

Figure 13. Thermal performance analysis of components of the ECB located on the roof.

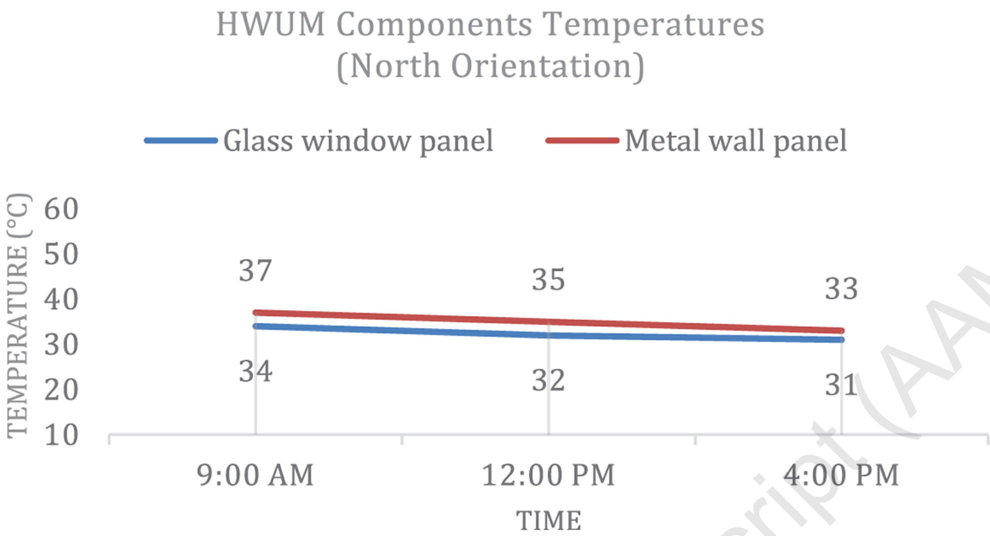


In general, the thermal analysis of the ECB across different orientations and building materials reveals distinct temperature patterns throughout the day. Specifically, west-facing orientations tend to experience the highest temperatures in the afternoon, while east-facing orientations exhibit significant heating by noon. Moreover, south-facing orientations also demonstrate pronounced temperature rises in the late afternoon. Furthermore, roofing materials exhibit varying heat absorption capacities, with concrete roofs consistently maintaining cooler temperatures in comparison. These findings emphasize the critical importance of considering building orientation and strategic material selection in optimizing thermal performance and enhancing energy efficiency in building design, as exemplified in the careful design approach applied to the ECB.

4.1.3. Thermal performance analysis of HWUM materialities

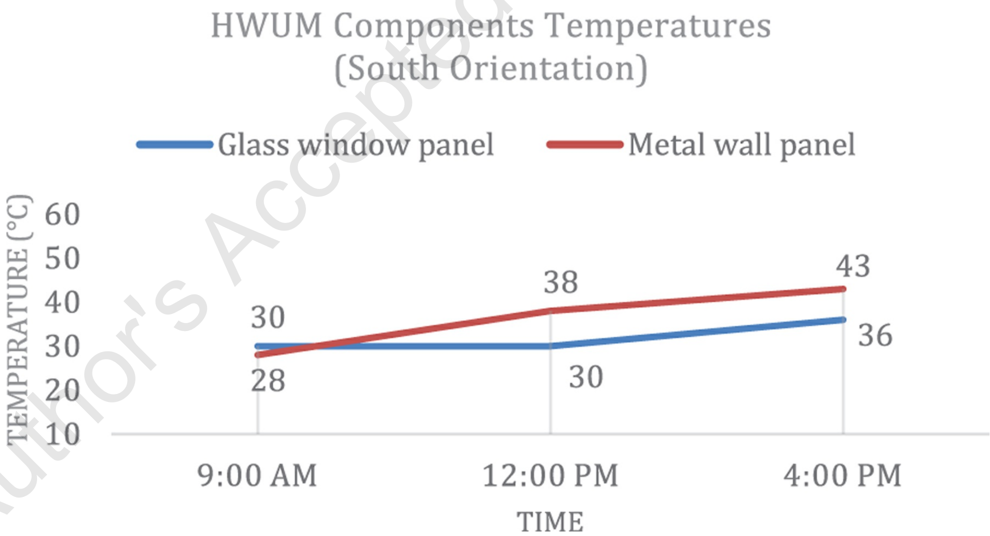
This section discusses an examination of HWUM's thermal dynamics across varied building materials, encompassing glass window panels, metal wall panels, and roofing materials, notably its distinctive green roof aspect. On the northern facade of the HWUM building, the day begins with the glass window panel registering 34°C, slightly warmer than the metal wall panel at 37°C. As the day progresses toward noon, both materials experience a marginal decrease in temperature, with the glass window panel at 32°C and the metal wall panel at 35°C. This trend continues into the late afternoon, with temperatures declining to 31°C for the glass window panel and 33°C for the metal wall panel, indicating effective shading from the intense midday sun and sustained cooling over the day (see Figure 14).

Figure 14. Thermal performance analysis of HWUM materialities according to the north orientation.



Conversely, the southern orientation exhibits a cooler start in the morning, with the glass window panel at 30°C and the metal wall panel even cooler at 28°C. By midday, the glass window panel maintains its temperature at 30°C, while the metal wall panel significantly warms up to 38°C. By 4 pm, temperatures escalate further, with the glass window panel at 36°C and the metal wall panel at 43°C, revealing substantial exposure to afternoon sunlight (see Figure 15).

Figure 15. Thermal performance analysis of HWUM materialities according to the south orientation.



Analysis of the eastern orientation reveals comparatively warmer temperatures at the outset, with the glass window panel at 36°C and the metal wall panel at 39°C. By noon, the glass window panel remains stable at 36°C, while the metal wall panel experiences a slight drop to 37°C. By 4 pm, both materials further cool down to 33°C and 34°C, suggesting reduced solar exposure as the day progresses (see Figure 16). It is noteworthy to mention that for this drone mapping analysis, the western section of the building is excluded due to complete coverage by the sloped grass roof, resulting in a uniform exposure.

Figure 16. Thermal performance analysis of HWUM materialities according to the east orientation.

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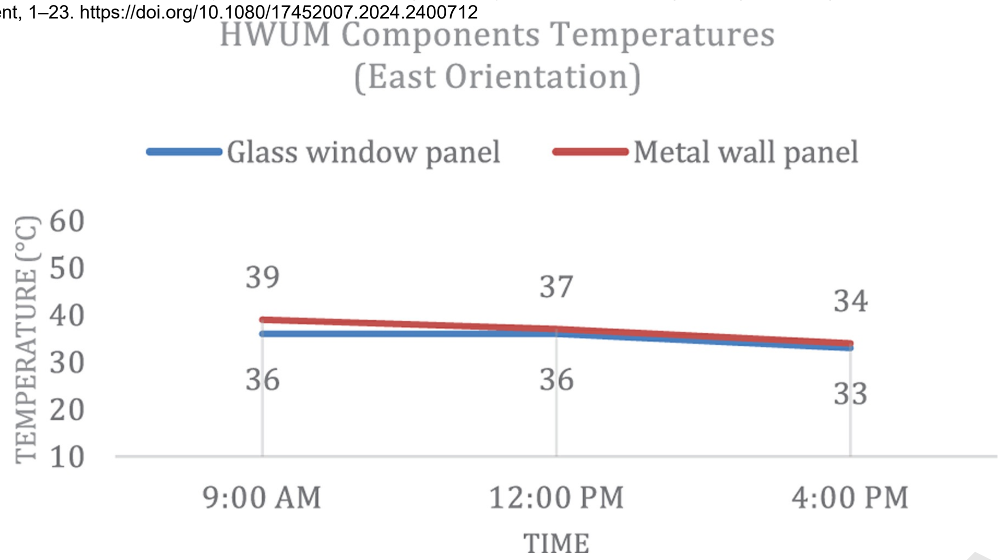
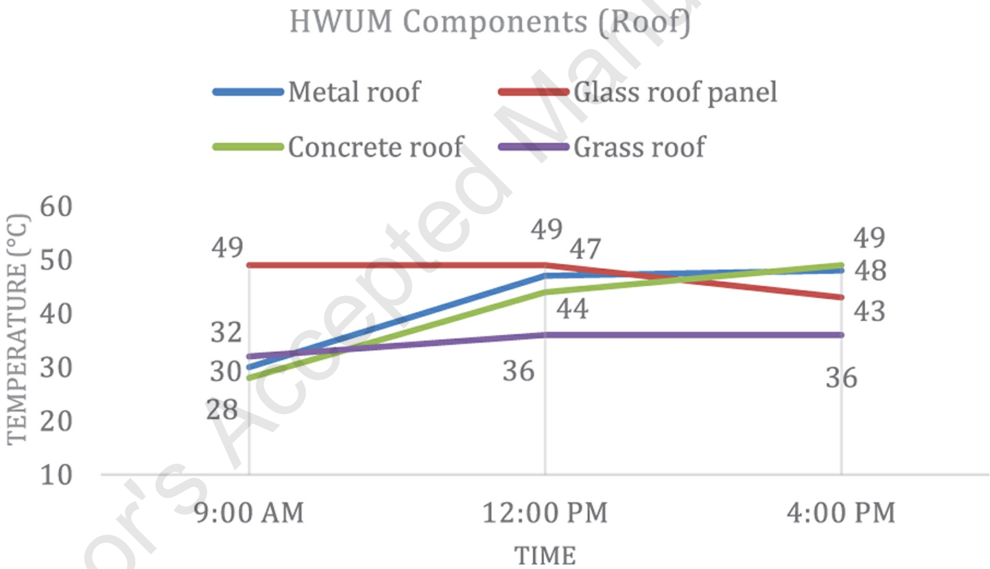


Regarding the roof, distinct material responses to sunlight are observed. In the morning, the glass roof exhibits high temperatures at 49°C, while the grass roof, metal roof, and concrete roof maintain cooler temperatures at 32°C, 30°C, and 28°C, respectively. By midday, the concrete roof experiences a significant heat increase to 44°C, the metal roof rises to 47°C, and the grass roof and glass roof reach 36°C and 49°C. In the late afternoon, the concrete roof becomes the hottest at 49°C, closely followed by the metal roof at 48°C. The glass roof sees a slight cooling to 43°C, while the grass roof remains constant at 36°C (see Figure 17).

Figure 17. Thermal performance analysis of components of the HWUM located on the roof.



Overall, the analysis of HWUM's thermal dynamics across different building materials reveals distinct temperature patterns influenced by solar exposure. Glass window panels and metal wall panels show effective shading from intense midday sun, resulting in gradual temperature decreases throughout the day. However, southern orientations experience significant temperature escalation by the afternoon due to prolonged sunlight exposure. Conversely, eastern orientations display relatively warmer mornings but cooler afternoons, indicating reduced solar exposure as the day progresses. The analysis of roofing materials demonstrates varied responses to sunlight. Remarkably, the grass roofs of HWUM consistently maintain cooler temperatures, highlighting the significance of material choice in mitigating solar heat gain and optimizing building thermal performance.

4.2. Design interventions through drone-assisted investigation

The thermal performance analyses highlight the importance of design interventions aimed at mitigating temperature fluctuations, thereby ensuring optimal comfort for building occupants. In the realm of building material temperature management, the interventions prioritize enhancing comfort within structures while upholding their eco-friendly attributes. By synergizing traditional architectural approaches with cutting-edge technological innovations, these interventions tackle challenges such as passive cooling techniques, the creation of shaded areas, and the integration of reflective and insulating

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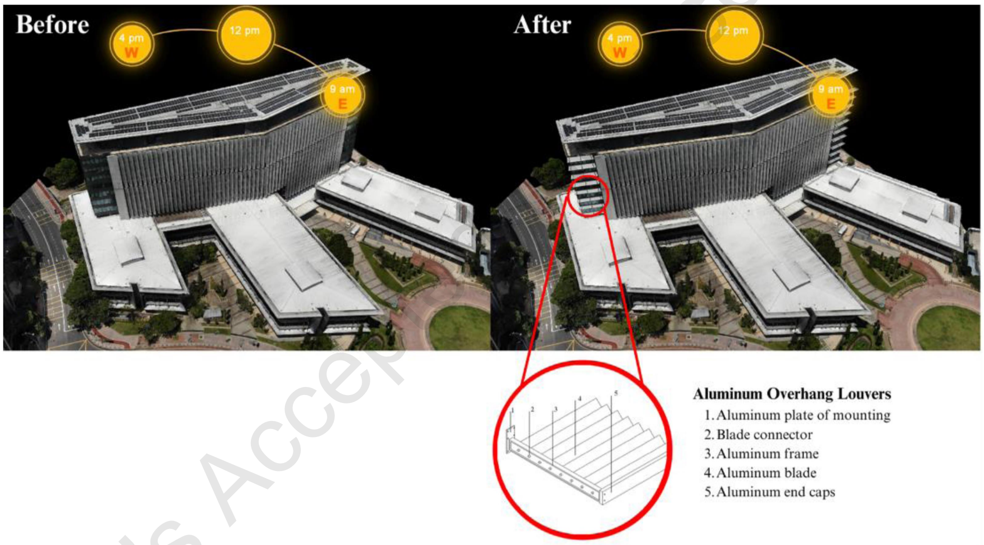
materials, among others.

Through strategic retrofitting and redesign, the objective is to preserve optimal cooling properties, reduce reliance on mechanical cooling systems, and cultivate a tranquil indoor environment for occupants. This approach not only aligns with the sustainability goals of Putrajaya's vision for a livable city but also contributes to the ongoing realization of its green building initiatives. For this study, our primary emphasis is on implementing louvers strategically within the designs of three selected buildings in Putrajaya: PjH Tower, ECB, and HWUM. The aim is to effectively counteract heat gain from direct sunlight exposure, as identified through drone mapping imagery. The interventions are limited to simulations for positioning the specified louvers based on the identification of heat exposure from prior thermal analyses, considering the buildings' orientations.

4.2.1. Design interventions for PjH Tower

For the purpose of this analysis, the drone images captured of the PjH Tower have been processed using DroneDeploy software to present a realistic portrayal of the building's features. The proposed addition of aluminum overhang louvers on the western and eastern facades, illustrated in Figure 18, represents a significant advancement toward augmenting comfort and energy efficiency. Aluminum has been selected as the optimal material for these louvers due to its robustness and capacity to reflect a substantial portion of sunlight. By deflecting sunlight, these louvers mitigate direct solar heat absorption by the building's exterior, thereby fostering cooler internal temperatures, reducing the demand for air conditioning, and cultivating a more hospitable indoor environment.

Figure 18. Comparison of the PjH Tower before (left) and after (right) the installation of aluminum overhang louvers.



The installation of these louvers is especially advantageous on the eastern facade, which is exposed to the morning sun. Although morning sunlight may not be as intense as its afternoon counterpart, it still contributes to a perceptible rise in indoor temperatures. Through strategic placement, the louvers allow ample natural light while curbing associated heat, achieving a harmonious equilibrium between illumination and thermal regulation.

Beyond their functional advantages, the aluminum overhang louvers enhance the contemporary aesthetic appeal of the PjH Tower. They amplify the visual allure of the building, highlighting the idea that modern architectural solutions can effortlessly marry style with practicality.

4.2.2. Design interventions for ECB

The drone-captured images of the ECB, processed through DroneDeploy, provide a captivating portrayal of the building's actual presence (see Figure 19). Since its inception, the ECB has embraced a bioclimatic and passive design approach to address the complexities of maintaining a pleasant indoor environment. A key focus has been mitigating the impact of sunlight exposure on its windows, achieved through the distinctive diamond geometrical architecture. This commitment extends to a broader initiative aimed at minimizing the building's environmental footprint while simultaneously elevating the Energy Commission's image as the premier authority in environmental stewardship.

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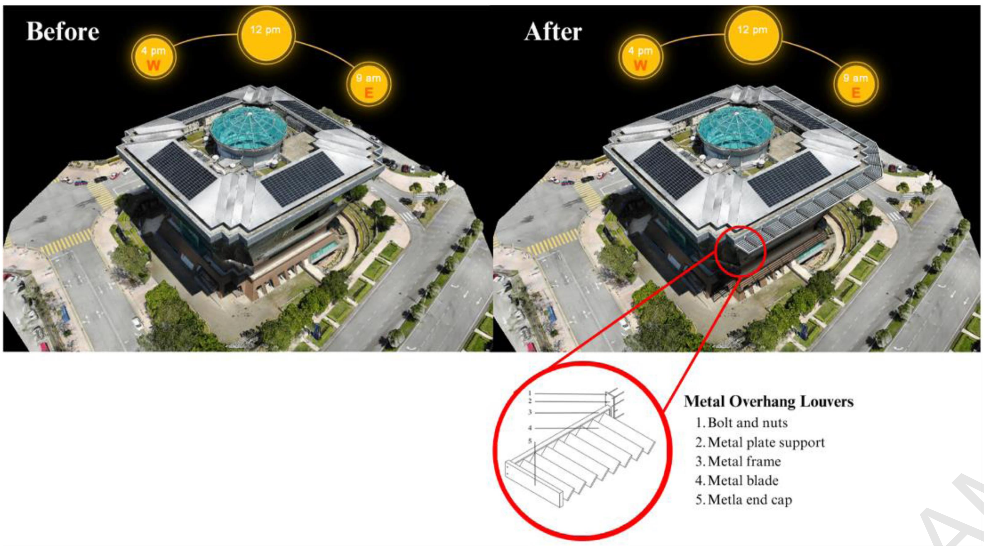
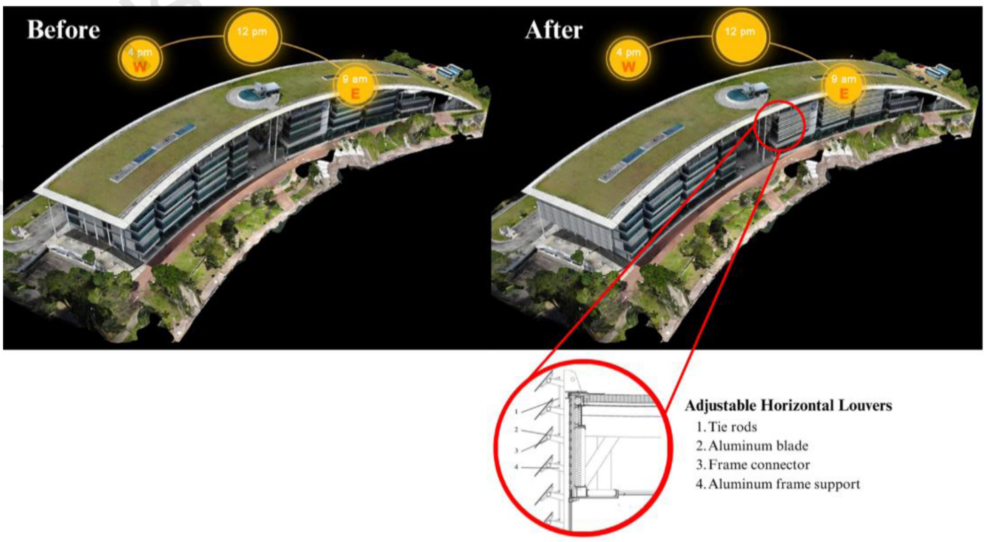


A recent addition to the building exemplifies this dedication: the integration of metal overhang louvers on its east and north elevations. The east-facing side, vulnerable to morning sunlight, now benefits from these louvers' dual functionality. By effectively reflecting a significant portion of incoming sunlight, they alleviate heat ingress, while their intelligently designed overhang structure ensures ample ambient daylight permeates indoor spaces. This balance maintains a bright, inviting atmosphere without compromising on temperature control. On the north side, where direct sunlight is less intense, the louvers still provide consistent shading, ensuring a uniform temperature distribution throughout the building. This proactive approach mitigates the risk of any area becoming uncomfortably warm, particularly in tropical climates like Malaysia.

The introduction of metal overhang louvers represents more than just a functional upgrade; it signifies a commitment to occupant comfort and environmental responsibility. It serves as a prime example of how modern architecture can meet the challenge of creating spaces that are not only visually striking but also genuinely comfortable and sustainable for habitation.

The drone-captured images of the HWUM campus, processed through DroneDeploy, provide a strikingly realistic portrayal of the institution's architectural features (see Figure 20). Notably, the recent upgrade to the HWUM building stands out as a testament to the university's steadfast commitment to enhancing environmental responsibility and sustainability.



the sun's rays, mitigating heat gain and ensuring a more comfortable indoor atmosphere.

While the north-facing orientation of the building receives less direct sunlight, the inclusion of these louvers still yields considerable benefits. They offer consistent shading, promoting stable indoor temperatures and preventing the formation of uncomfortably warm zones within the building. Moreover, beyond mere comfort, these enhancements result in tangible energy savings by reducing the reliance on air conditioning systems. In addition to their functional advantages, the horizontal louvers contribute to the HWUM's aesthetic appeal, lending a contemporary and sleek demeanor to its exterior with a distinctive green roof. This synthesis of functionality and visual charm exemplifies the university's dedication to creating an optimal learning environment that marries comfort, sustainability, and aesthetic sophistication.

In essence, the exploration of these design interventions – in projects like the PjH Tower, ECB, and HWUM – highlights a significant stride in architectural innovation through the integration of drone technology. This integration not only unleashes a myriad of possibilities but also sets a pioneering benchmark for sustainable local architecture, not just within the confines of Putrajaya city but on a national scale.

5. Conclusion

This paper discussed the integration of drone technology within architectural design, presenting a promising avenue for enhancing thermal efficiency and sustainability. Employing a methodology based on five distinct phases, the study focused on a case study encompassing three GBI-certified buildings located in Putrajaya, namely PjH Tower, ECB, and HWUM. By leveraging thermal imaging in conjunction with visuo-spatial data and 3D modeling techniques, the study demonstrated the efficacy of drone technology in evaluating the thermal performance of the buildings. This evaluation served as a basis for implementing strategic design interventions aimed at mitigating heat gain induced by direct sunlight exposure, as evidenced through the drone mapping imagery.

While the study has revealed the promising capabilities of drone technology in advancing architectural design, it is essential to acknowledge the constraints, particularly regarding the cost estimation of the drone mapping operation for this study. Primarily, the study takes an exploratory stance, which requires a limited timeframe for 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 three 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 architectural innovation. Moreover, the design interventions explored in this study mainly revolve around the potential of louvers in architectural 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 architectural design over an extended period. Augmenting this analysis with comprehensive indoor thermal comfort assessments could enhance the depth and breadth of findings, potentially paving the way for the integration of drone technology into green auditing practices. In this regard, it would be beneficial to study the green market for the costs associated with the proposed installation of louvers, including potential power savings and whether the expenses saved from reduced power consumption will cover the installation costs. Additionally, broadening the range of case studies to include a more diverse selection of architectural typologies beyond sustainable design exemplars would capture a wider spectrum of design approaches and challenges. Furthermore, beyond focusing solely on specific features of building materiality, future studies could diversify exploration into passive design strategies. This could encompass a broader range of architectural elements and strategies enabled by drone technology, such as adaptive facades, kinetic structures, or modular construction methods. Incorporating feedback and insights from industry experts, including architects, builders, building surveyors, and engineers 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 architectural design.

Disclosure statement

No potential conflict of interest was reported by the author(s **[Q2]**).

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Attachment Files

1 Figure 1.png *: Flowchart of the methodology for the drone-mapping procedure, divided into five phases.*

2 Figure 3 (a).png *: The 3D model visualization illustrates the thermal patterns exhibited by the buildings: a) PjH Tower, b) ECB, and c) HWUM.*

3 Figure 3 (b).png *: The 3D model visualization illustrates the thermal patterns exhibited by the buildings: a) PjH Tower, b) ECB, and c) HWUM.*

4 Figure 3 (c).png *: The 3D model visualization illustrates the thermal patterns exhibited by the buildings: a) PjH Tower, b) ECB, and c) HWUM.*