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Thermal Performance Evaluation of Buildings with Coconut Leaf Roofs

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ABSTRACT

Local materials for construction are becoming more popular due to their natural, exotic, and beautiful qualities, which can help the community's economy. Roof materials that mimic organic materials derived from unsustainable synthetic plastics could contribute to environmental pollution. Coconut leaves (Cocos nucifera), found across Indonesia, can be utilised as roofing. This study investigates materials' conductivity, effective thickness, and design and production methods to maximise their economic worth and usefulness. An evaluation was performed to assess the heating capacity of coconut leaf roofing materials relative to unpainted zinc roofs and heat-resistant painted zinc roofs. Evidence indicates that coconut leaf organic roofs effectively lower temperatures on roofs, in attics, and within indoor spaces.
Three models of test houses show that coconut leaf roofs reduce heat on the roof surface by 19.6% and 7.3% and in attics by 5.9% and 2%, respectively, compared to unpainted zinc roofs and heatproof painted zinc roofs. Determining the primary influence on indoor air temperature—whether it is solely the surface temperature of the roof or the temperature within the attic—presents a complex challenge that resists straightforward conclusions. The use of coconut leaves as a roofing material offers a promising sustainable architectural strategy to address problems related to global warming. Further research can be directed to improve the durability of the material.

Keywords *Thermal Performance, Local Materials, Coconut Leaf Roof, Buildings, Sustainability*

1. Introduction

With population expansion and urban development in Indonesia, the construction of low-rise residential and public edifices is accelerating significantly. Roof structure is a considerable and essential component of low-rise buildings. Roof covering materials may include tiles and ceramics, zinc or a combination of metal components, cellulose fibres, thermoplastic polymers, wood sheets, and various local materials. Zinc or aluminium composite serves as the prima ry roofing material in North Sulawesi, Indonesia, comprising around 95% of the existing residential buildings [1]. With the progression of the tourism sector, a variety of establishments such as vacation rental properties, accommodations, eateries, coffee shops, and tourist cottages are being built utilising local and natural resources, as illustrated in figure 1. While organic materials typically exhibit a limited service life, they can endure for 2 to 5 or even 10 years when selected from the finest old branches and maintained with regular care. Moreover, the utilisation of local resources provides a unique aesthetic quality that differentiates them from traditional alternatives, making them especially attractive to international tourists. Sago leaves from sago trees (Metroxylon sago rottb), palm trees (Arenga pinnata), and coconut leaves (Cocos nucifera), prevalent across Indonesia, are frequently utilised as roofing materials in theregion [2, 3, 4]. The utilisation of materials such as sagoleaves, palm sugar leaves, or coconut leaves for roofing represents a longstanding construction practice, largely due to the abundant availability of these resources in the area.

Figure 1. Coconut leaf-roofed cafes and bungalows

The trend of utilising natural materials, which possess a minimal carbon footprint, sharply contrasts with the use ofmodern materials like plastics and other synthetics, whichexhibit a significantly higher carbon footprint. Therecognition of climate change mitigation, prompted by therise in atmospheric greenhouse gases, compelspolicymakers and architects to focus more on the utilisationof alternative materials with reduced carbon emissions. Anextensive examination of sustainable building materialsprovides a comprehensive analysis of the diverse ecofriendly solutions available for construction. Theconstruction sector accounts for approximately 25% ofglobal CO2 emissions [5]. This industry plays a vital role inshaping the modern world, yet it also poses considerablethreats to the environment. The substantial need forbuilding components, along with the resource-heavyprocesses involved, leads to notable carbon emissions,depletion of resources, and environmental harm. Xie et al.[6] examined this environmental issue, emphasising theurgent need to adopt environmentally friendly buildingtechniques that reduce the ecological impact of the sector.An essential approach to achieving this goal is thecomprehensive use of environmentally friendly andenvironmentally conscious building components.

Endo et al. [7] performed a comprehensive examination of sustainable building materials, emphasisingenvironmentally favourable construction alternatives.Their investigation offers an in-depth omany sustainable materials, including their characteristics,ecological advantages, and possible construction applications. Charai et al. [8] also articulated the same message, outlining prospective options for transforming the built environment through an extensive analysis of scientific literature, experimental evaluations, and life cycle assessments. Pearlmutter et al. [9] conducted a omprehensive literature study to ascertain the latest advancements and breakthroughs in sustainable construction materials. The examination encompassed a broad spectrum of sustainable practice options, such as reused materials, biodegradable composites, and carbonneutral alternatives for construction [10, 11].

Ruggerio [12] has revealed a notable variation among countries about this topic. The depletion of natural resources and the effects of greenhouse gases on the ecosystem present significant challenges for low-income countries, largely because their often limited capacity for innovation hinders their ability to effectively tackle environmental issues. It is essential to analyse the possible impacts of innovation and the accessibility of natural assets on this issue. The abundance of natural resources may contribute to mitigating environmental impacts, as indicated by Abera [13].

North Sulawesi ranks second in Indonesia for coconut tree cultivation, including an area of 265,548 hectares and yielding a total production of 265,103.37 metric tonnes in 2021 [1]. Coconut plantations are abundant in this area with dense fruit, as illustrated in figure 2. Despite ongoing efforts to revitalize coconut plants, experts deemed over 3.5 million coconut trees unproductive in 2017 [14].

Figure 2. Coconut trees and their leaves are used for roofing

The utilisation of coconut leaves for roofing construction possesses considerable potential. Currently, there is an insufficient amount of thorough research regarding the thermal performance, physical characteristics, and advancement of coconut leaf roofing materials, in contrast to the extensive studies conducted on roofing materials like concrete, zinc, and cellulose fibre. While rapid weathering and fire risk are significant concerns associated with organic roofs, some studies offer conflicting evidence. Research carried out in Britain indicates that the causes of flames in thatched-roof buildings correspond with the hazards impacting other residential buildings. Out of 3,000 annual fires, only 8-10 take place in thatched-roof structures, highlighting their rarity. The owners of thatched buildings typically demonstrate increased vigilance regarding potential hazards and implement a range of fire control measures [15].

The synthetic roofing material sector, designed to replicate genuine thatch or straw, has progressed and is now being employed in recreational and public structures across Indonesia. Their appearance closely mirrors that of natural materials [16, 17]. The utilisation of these synthetic materials is environmentally detrimental, possesses high embodied energy, and can intensify microplastic contamination, hence contravening the idea of sustainability.

Microplastic pollution can originate from the unregulated application in diverse industrial processes, such as cleaning agents, cosmetic formulations, fertilisers, pharmaceuticals, and the degradation of substantial plastic remnants. Furthermore, microplastics possess the capacity to biomagnify within the food chain via ingesting, inhaling, and translocation, and they can also be transferred into the tissues of humans. Reports indicate that the high adsorption potential of microplastics enables them to retain certain

contaminants on their surfaces. The researchers identified microplastics as a significant environmental concern, attributing this to their pervasive presence, remarkable durability, resistance to degradation, and toxic properties [18]. Experts anticipate that environmental contamination may increase twofold by 2040, resulting in extensive damage [19, 20].
The objective of employing this synthetic roofing material is to establish a natural ambiance and reduce the ambient temperature within the space. Cooling the building's roof cover is crucial for minimising heat transfer via conduction as well as radiation to the attic and the room beneath, as this could jeopardise the thermal comfort of the occupants in the ground floor space. Multiple methods must be implemented, including roof ventilation for cooling [21], radiative insulation [22], spraying water to the roof surface [23], and employing heat exchanger designs to cool the sprayed water [24], as reducing indoor temperatureis crucial for ensuring occupant thermal comfort.

According to the findings of researchers like Rawat and Singh [25], the implementation of different cold roofing materials on cold roofs has the potential to lower room temperature. The implementation of green roofing shows a significant decrease in temperature within corrugated structures. The variation in heat outside the roof space remains minimal in both scenarios; however, the disparity in heat becomes more evident within the inner region. Based on the thermal efficiency of roofs, corrugated zinc
roofing presents a viable alternative sustainable roofing material compared to concrete in buildings [26]. The thermal efficiency of corrugated zinc roofing surpasses that of traditional roofing systems. Factors such as building type, materials, thickness, and the extent of plant coverage influence the thermal characteristics of green roofs. Sheet metal roofs and polymer asphalt coverings exhibit significant temperature variations and heat transfers throughout daily cycles. Gravel roofs provide insulation benefits, specifically during the warmer months. During periods of increasing energy costs or shortages, it is crucial for interested parties to advocate for the adoption of green roofs [27].

This establishes the foundation for determining the ideal roof design for an unconditioned and acclimatised environment [28]. The efficacy and functionality of a green roof are contingent upon the composition and characteristics of the coating. The vegetation and substrate layers, influenced by the prevailing environmental conditions, significantly contribute to the uncertainty in modelling green roof performance [29, 30].

Putting a cold coating on the roof is a common way to stop heat from entering the house. The benefits of these coatings have been shown in many tests. Synnefa et al. [31] examined the effects of cold coats applied to roofs on both cooling and heating burdens, as well as the thermal comfort within dwellings. Their research showed that roofs with more reflectivity cut cooling loads by 18–93% and peak cooling needs in buildings with air conditioning by 11–27%. When Kitsopoulou et al. [32] did a similar study, they showed that using thermochromic dyes in roof coatings can lower the thermal load of residential buildings by 2.19 to 17.13% per year, depending on the weather and the thermal properties of the roof.

Research [33] indicates that extreme heat waves in tropical cities result in notable short-term weather issues, including elevated city temperatures, heightened discomfort among residents, and increased energy consumption. Rahmani et al. [34] indicate that applying a cold layer to the roof can reduce the cooling load of the building and enhance its energy efficiency during the cooling season by reflecting a significant amount of sunlight. Recently, Nie et al. [35] carried out a study focused on coatings. Cold coatings have garnered significant attention f or application in buildings; however, their impact on energy consumption is heavily influenced by weather conditions. The study indicates that buildings located in the hottest regions of the U.S. experience a 30% to 50% increase in comfort on cooler days when cold layers are present, in the absence of space cooling systems. The benefits of using cold coverings on roofs that were just talked about come from studies done in subtropical areas. Also, the above-mentioned study series is more focused on sustainability issues and hasn't looked into how well different roofing materials, like coconut leaf roofing, keep heat in. As it turns out, both using cold coatings on the roof and using organic and local roofing materials, like coconut leaf roofs, can help make buildings more comfortable in humid tropical climates while also making coconut leaf materials more valuable for business. So, this piece will explain how well coconut leaf roofs keep heat in by comparing them to zinc roofs that haven't been painted and those that have been coated with cold coatings.

2. Materials and Methods

2.1. Building a Roof Using Coconut Leaves

The leaves of coconut trees, similar to those of sago and sugar palms, demonstrate considerable potential as a viable roofing material for both dwellings and leisurely architectural applications. The physical attributes and moisture content of the leaves directly influence their pliability. The adoption of organic materials like sago leaves, sugar trees, and coconut leaves for rooftops and tourism facilities has notably increased among the local population. Although this material has a limited service life of 5-10 years, it offers a potential alternative regarding aesthetic quality and the creation of a natural atmosphere. This suggests a growing inclination to recognise and adopt
specialised approaches. The study solely concentrated on the physical characteristics of coconut leaves used as roofs, even though their physical capacity deteriorated over time. Coconut leaves have parallel venation and comprise fronds. The bilateral aspects of the frond exhibit the configuration of coconut leaf strands. Coconut leaves securely affix their fronds to their stems, complicating the removal of even aged leaves. Mature coconut trees can possess fronds of up to 5 meters in length and consist of 65 pairs of leaf blades. The petiole, a broadened structure at the base, functions as an attachment point for the leaf stalk. Coconut trees possess aligned leaves, including pinnate leaf blades, comprising 100-130 individual leaves or 50-65 pairs. The crown and leaf sheath comprise 20 to 30 fronds.

We choose premium leaves of uniform length to manufacture coconut leaf roofing sheets. One frond is bisected along the leaf shaft, enabling one frond to yield two roofs; fronds exhibiting uniform leaf length are retained, while others are destroyed; typically, fronds measuring 1–2 meters in length are preserved, corresponding to the dimensions of the coconut leaf roof sheet. This roof sheet is constructed solely from leaves; in contrast to the sago leaf roof that necessitates bamboo ribs, the coconut leaf roof requires no supplementary materials, making it lighter. Each sheet is positioned beginning at the roof's base and overlaps with a spacing of 10 to 25 cm between each sheet, as seen in figure 3.

Figure 3. Coconut leaf roof sheets and arrangements

2.2. Material and Methods

The research included a comprehensive evaluation of the thermal conductivity and effective dimension of the coconut leaf material used for roofing sheets. Our objective is to thoroughly analyse the thermal performance of coconut leaf roofs. To achieve this objective, we performed a comparative analysis employing a model that incorporated zinc roofing materials without paint alongside zinc roofs treated with cool roof paint. Consequently, we developed three identical models utilising different types of roof coverings.

The uncoated zinc roof model serves as a standard for evaluation, whereas the zinc roof structure featuring a cold roof coating is utilised for comparative analysis with the coconut leaf roof structure. Each model comprises whitepainted multiplex walls lacking windows and plywood ceilings. A thermohygrometer sensor is strategically placed at the base of the roof to accurately measure the temperature of the surface of the roof, the attic, and the occupied area of each model. Six datalogger sensors are employed. The Elitech GSP-6 thermohygrometer sensor quantifies the roof's surface temperature, whereas the RC4HC model assesses the air temperature as well as humidity levels in both the attic and living areas. Each model possesses a maximum capacity of 16,000 points, with a temperature precision approaching 0.5°C and a humidity accuracy of around 3% RH, accompanied by a calibration certificate from the manufacturer. The identical instrument model is utilised to evaluate the same components. All measurements are conducted at 10-minute intervals. The visual representation depicts three test models utilised for comparing the thermal performance of various roofing materials, as demonstrated in figure 4.

Figure 4. Different roof materials on three test models

The measurement data collected over a period of 5 months was distilled into a focused analysis using data from just 1 week (7 consecutive days) for visualisation purposes. The data set comprising solely measurements collected over a week is insufficient for accurately reflecting the seasonal or annual variations in environmental thermal circumstances. The measurement duration of one week in July aligns with the setting of the issue in question and the study's focus. The research site in Manado is situated at the northern extremity of the Sulawesi peninsula, with geographical coordinates of 124°40'-124°50' E and 1°30'-1°40' N. This city experiences a tropical climate, characterised by an average temperature ranging from 24°C to 27°C. The annual average precipitation measures 3,187 mm, with the least amount occurring in August and the highest levels recorded in January. The mean solar irradiation intensity stands at 53%, while the relative humidity fluctuates around ±84%. The core issue in this domain revolves around minimising heat transfer from the external environment into the building.

The measurements collected over a week in July are deemed valid, as they accurately represent the intense weather conditions typical of the yearly period. The thermal conductivity of coconut leaves was measured with the Thermal Conductivity Meter QTM-710 portable, employing the hot wire method and confirming the instrument's accuracy to be within 5% of the reading value.

3. Results and Discussion

3.1. Physical Properties of Coconut Leaves as Roofing Material

Multiple measurements are conducted to ascertain the thermal conductivity of coconut leaves utilising the portable Thermal Conductivity Meter, while ensuring that the surrounding temperature remains constant to uphold reliability and precision. The measurement of leaf thickness is conducted utilising a digital thickness gauge that operates within a range of 0–25 mm, featuring a tolerance of 0.01 mm, which is equivalent to 0.0005 inches. The results of the measurements are presented in Table 1.

Table 1. Coconut leaf thickness and conductivity

	Conductivity (W/mK)	Thickness (mm)
Xmax	0.08736	0.380
Xmin	0.07204	0.250
Median	0.07826	0.295
Average	0.07946	0.298
SD	0.00458	0.038

The conductivity value of coconut leaves was measured at an average of 0.07946 W/mK, accompanied by an average thickness of 0.298 mm. Coconut leaves serve as an effective thermal insulation material, demonstrating significant resistance to heat transfer.

3.2. Thermal Performance of Coconut Leaf Roof

To evaluate the thermal efficiency of coconut leaf roofs, a comparison study was carried out between zinc roofs coated with an anti-heat treatment and unpainted zinc roofs, which were used as a reference model. Measurements were conducted over a span of 7 consecutive days, capturing a diverse array of weather conditions, including notably hot and wet days such as those observed on the fifth day. According to the measurement data, coconut leaf roofs had a significantly lower surface temperature than the other two roofing materials. A heat-resistant painted roof demonstrates a reduced temperature compared to an unpainted zinc roof. During the nighttime, the temperature of coconut leaf roofs exceeds that of alternative materials. The distinct characteristics of the materials account for this phenomenon; metal roofs exhibit a rapid cooling effect when air temperatures decrease, while coconut leaf roofs maintain heat, though at a slower pace, as demonstrated in figure 5a

There is a very consistent pattern in the attic temperature and humidity levels for all three types of roofs. Nonetheless, the disparity in temperature is less pronounced compared to the variation observed in the roof surface temperature, as illustrated in figure 5b. The measurement results of air temperature in the attic for both unpainted and painted zinc roofs showed no significant differences. However, it is worth mentioning that the average attic temperature for the zinc roof painted for heat resistance was marginally lower. This condition demonstrates that the effectiveness of anti heat paint is constrained; while it can reflect a portion of the sun's radiation, its efficacy is contingent upon the application method and environmental factors. Ventilation and insulation in the attic are crucial for regulating the temperature within both the attic and the adjacent living spaces. Applying heat-resistant paint to the zinc

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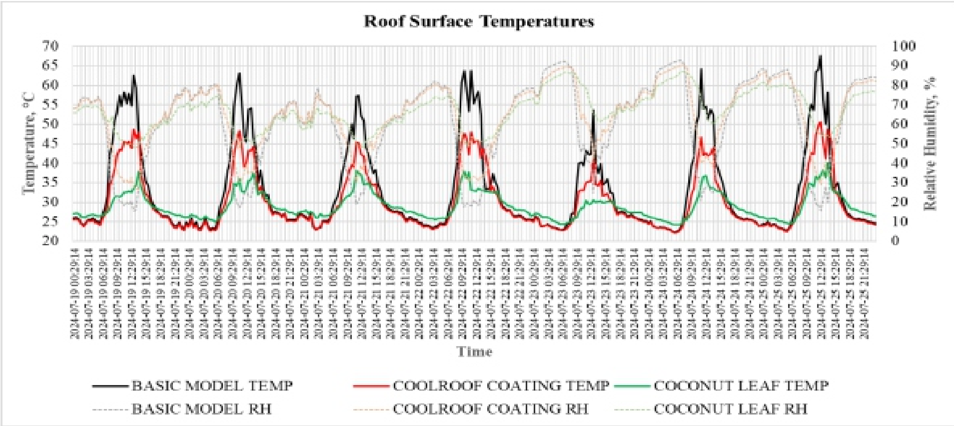
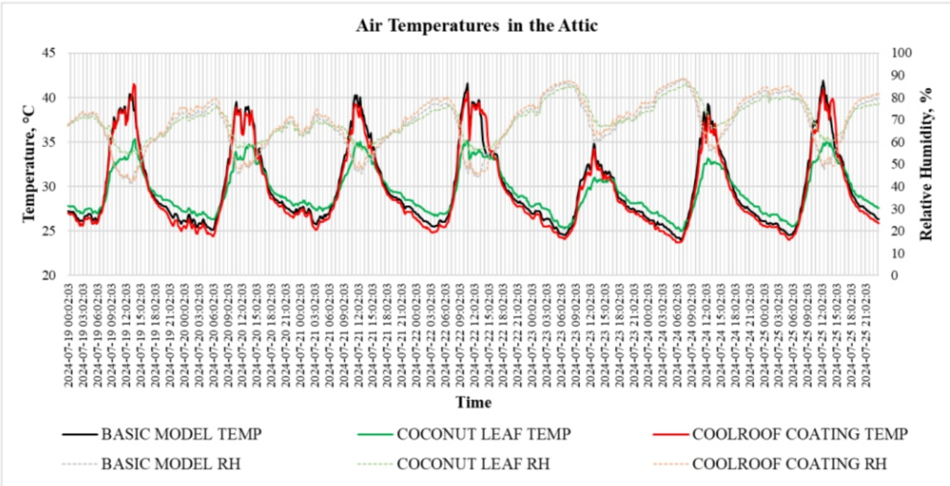
Indoor air temperature conditions are affected by a variety of factors, extending beyond merely the heat emissions from the ceiling or attic. Figure 5c presents a distinct representation of this. Although the coconut leaf roof model's attic air temperature and roof surface temperature are significantly lower than those of the other two roof types, this does not necessarily mean that indoor air temperatures will likewise be lower. According to the measurement data, the internal air temperature of the coconut leaf roof model was somewhat lower than that of the other two models between 6 a.m. and 12 p.m.. After one hour, the air temperature increases, exceeding that of the other two models. Coconut leaves, while being a natural material with commendable insulating properties, are still capable of heat absorption, particularly during the daytime when solar intensity is high. The room subsequently emits the accumulated heat, resulting in an increase in temperature. The absence of ventilation in all three constructed models results in heat being trapped within the room, thereby exacerbating the temperature levels. The capacity of coconut leaves to absorb moisture from the air is another factor affecting this condition. When this absorption occurs alongside elevated humidity levels in the room, it can exacerbate the heat and result in a stifling, warm sensation. In specific circumstances, humidity can enhance the sensation of warmth in a space, despite the actual temperature being relatively low.

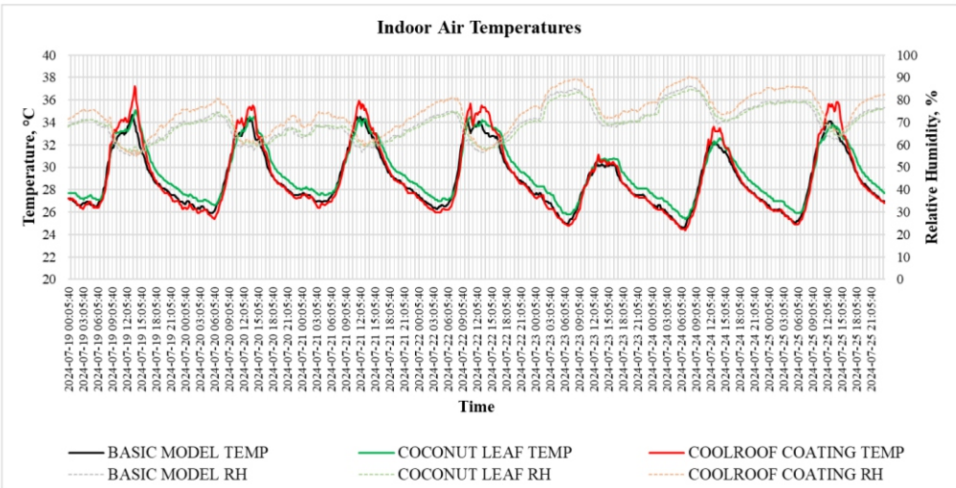
For a thorough analysis, Figure 6.a-c presents the temperature and humidity profiles of the air from 6 a.m. to 6 p.m. on July 21, 2024, across the three models evaluated.



(a)

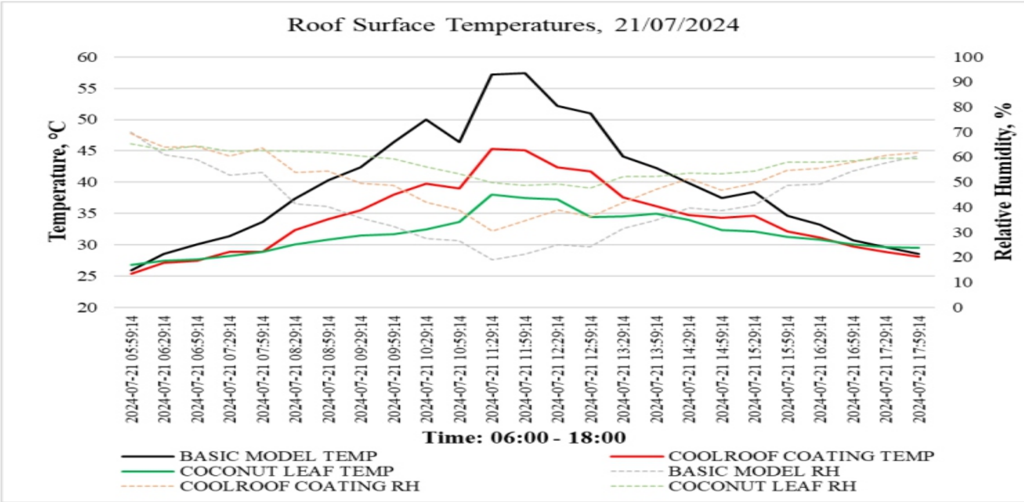


(b)

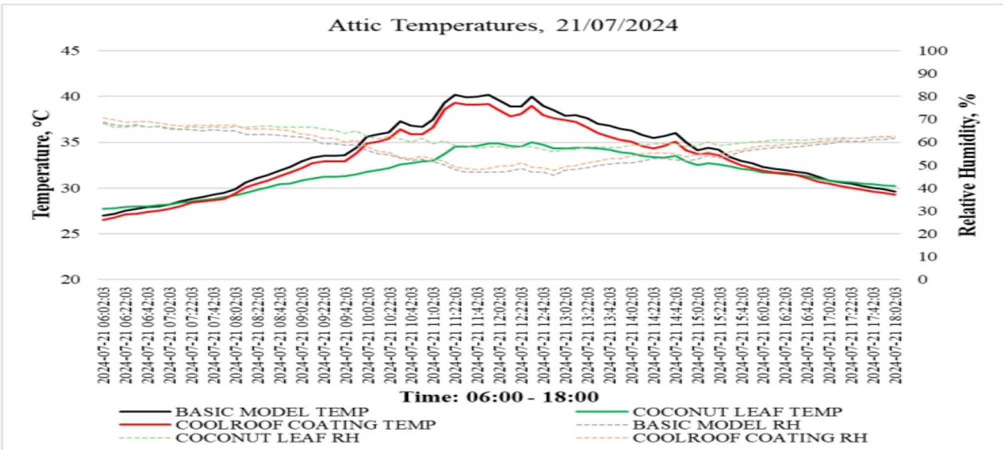


(c)

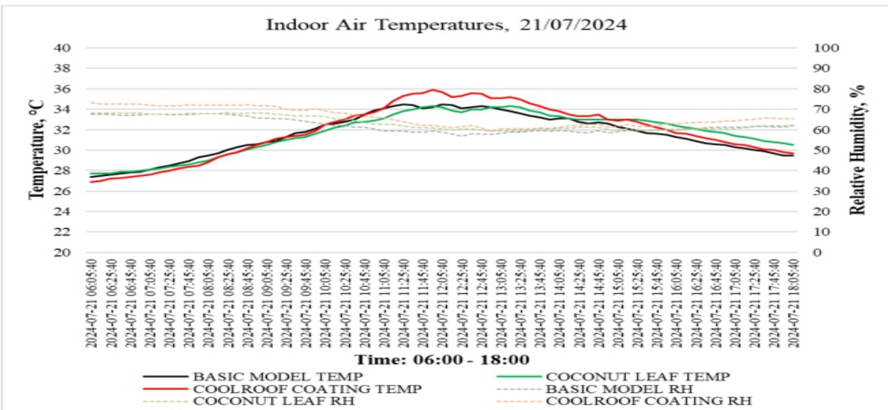
Figure 5. Coconut leaf roof thermal performance vs. others



(a)



(b)



(c)

Figure 6. The comparison of the surface temperature of the roof, the temperature in the attic, and the interior air temperature of the coconut leaf roof model, zinc without paint, and zinc coated with coolroof paint

The maximum observed roof surface temperatures throughout the day were 57°C for unpainted zinc roofs, 45°C for heat-resistant painted zinc roofs, and 38°C for coconut leaf roofs. Figure 6a presents the average temperatures documented throughout this timeframe, specifically 39.6°C, 34.3°C, and 31.8°C, in that order. The measurement results indicate that coconut leaf roofs lower heat on the roof surface by 19.6% and 7.3%, respectively, when compared to the surface temperatures of unpainted zinc roofs and heat-resistant painted zinc roofs. According to the statistics, coconut leaf roofs have better thermal performance than other roofing materials.

A t-test statistical analysis is performed to assess whether a significant difference exists within the measurement data set. The initial test evaluates the data from the roof surface temperature measurements, contrasting the model featuring a coconut leaf roof with the reference model, which is the zinc roof model without paint. The null hypothesis can be rejected and a significant difference is concluded when the result p = 0.00023 is considered statistically significant. The result obtained is p = 0.02823, which suggests a statistically significant difference between the model featuring a coconut leaf roof and the one with a zinc roof that has been treated with antiheat paint.

In the attic, the air temperature recorded for the three types of roofs—unpainted zinc, heat-resistant paint, and coconut leaves—was 40°C, 39°C, and 35°C, respectively, at around 12:30 p.m. Indoor air temperatures peak between 12 p.m. and 1 p.m. The average air temperature in the attic for the reference model, the model featuring a heat-resistant painted roof, and the model utilising a coconut leaf roof is detailed below: The average air temperatures recorded in the attic for the reference model, the model featuring a heatresistant painted roof, and the model utilising a coconut leaf roof are 33.7°C, 33.02°C, and 31.7°C, respectively. The measurement results indicated that coconut leaf roofs reduced the air temperature in the attic by 5.9% and 2% when compared to unpainted zinc roofs and heat-resistant painted zinc roofs, respectively.

This data illustrates the superior thermal performance of the coconut leaf roof. To determine whether the temperature difference was significant, a t-test statistical analysis was conducted. When the reference model and the coconut leaf roof were compared for the attic's air temperature, the p-value was 0.00018, indicating a statistically significant difference. The analysis reveals that the p-value of 0.00954, obtained from comparing the coconut leaf roof and the zinc roof painted with anti-heat, indicates statistical significance. As a result, we are able to dismiss the null hypothesis and assert that a meaningful difference is present.

An unpainted zinc roof measures an indoor air temperature of 34.3°C, while a painted zinc roof with roofcool registers a temperature of 35.6°C. The model featuring a coconut leaf roof exhibited an indoor temperature of 34.5°C, which aligns closely with the temperature recorded for an unpainted zinc roof, as illustrated in figure 6c. It is difficult to determine the degree to which the attic or roof's surface temperature affects the temperature of the air inside when concentrating only on this occurrence. Concerning graph 6c, which displays curves that seem almost compressed and variable, we conducted a t-test statistical analysis to determine if the disparity in indoor air temperature measurements between the unpainted zinc roof model and the heat-reflectivepainted model is statistically significant. The outcome is p = 0.4153, which is greater than 0.05, suggesting that the findings of the statistical test lack statistical significance. This indicates that the variations observed between the two data groups are probably attributable to random chance or sample variability, rather than indicating a genuine difference. Similarly, the analysis of the indoor air temperature measurement results for the coconut leaf roof model compared to the zinc roof without painting, serving as a reference model, yielded a p-value of 0.62858. This signifies that there is no statistically significant disparity between the two models.

The use of coconut leaf roofs clearly demonstrates advantages in lowering air temperatures, particularly in attics. However, its effect on indoor air temperature conditions is highly dependent on the careful selection of materials, methods, and building designs that emphasize passive cooling strategies. This aspect will play a crucial role in initiatives aimed at decreasing carbon emissions. This includes minimising the cooling load associated with air conditioning, employing roofing materials with high energy embodied, such as anti-heat coatings, or utilising synthetic materials like plastic, which are notenvironmentally sustainable.

4. Conclusions

Researchers have examined the thermal performance of coconut tree leaves for use as roofing sheets, proving their low conductivity as an effective heat insulation material. A comparison analysis was performed to assess the efficacy of coconut leaf roofs compared to unpainted zinc roofs and those coated with cool roof paint. The measurement findings illustrate the relative benefits of coconut leaf roofs, especially for the roof's surface temperature and the airtemperature in the attic space. The observed temperature difference between the two roofing materials indicates that coconut leaf roofs exhibit superior thermal performance compared to both unpainted and heat-resistant painted zinc roofs, effectively contributing to a cooler environment. Nonetheless, the analysis of indoor air temperature indicates that while the average performance of coconut leaf roofs is marginally better, the difference is not substantial. This holds true for both models featuring unpainted zinc roofs and those coated with roofcool paint, complicating the process of reaching precise conclusions. This suggests that other factors, in addition to the attic or roof temperature, influence the climatic conditions of the living space under the ceiling. A statistical test validates this, indicating that the differences in measurement data across the three models are minimal. The examination of the roof surface temperature in correlation with the attic air temperature across the three models indicates a significant statistical difference. The evidence indicates that coconut leaf roofs significantly reduce both the roof surface temperature and the air temperature within the attic.

The utilisation of coconut leaf roofs is anticipated to grow and evolve in response to the advancements in the synthetic roofing material sector, particuarly those derived from plastics. This shift is crucial, given the potential rise in carbon emissions and the escalating issue of microplastic pollution, both of which are becoming increasingly detrimental to the environment. A thorough examination of the characteristics and impacts of employing coconut tree leaves as roofing material is necessary for a clear comprehension. Future research should focus on a comparative comparison of the production procedures employed for coconut leaf roofs vs other sustainable roofing materials in the North Sulawesi province of Indonesia. This will assist in evaluating the viability of coconut leaves as a sustainable roofing option, therebysupporting their promotion and integration into the local construction sector.

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An Architectural Study of Tall Buildings in Indonesia in Relation to Past Local Values: A Case Study of the PreColonial and Post-Colonial Era

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ABSTRACT

The tradition of constructing tall buildings in Indonesia has essentially existed since the pre-colonial era. This is evident in the form of Prambanan Temple and other temples from the era of Ancient Mataram. These tall structures were built not only with stone but also with wood. Buildings with layered wooden roofs are known as "Meru," and this type was widely developed during the Majapahitera after Ancient Mataram, with traces still visible today in temples (pura) in Bali. These tower structures are the result of the adaptation of past local elements, crafted with unique creativity, such as corbel tectonics. In pre-Ancient Mataram traditions, these towers can be linked to stonemenhirs in the ancient Austronesian tradition. The phenomenon of constructing towers or tall structures with reference to ancient traditions continued in the post colonial period, reflecting the Meru and temple (pre colonial) concepts. This can be seen during the administrations of Sukarno, Suharto, and even to the present day. This study aims to examine the relationshipbetween tall building architecture in the pre-colonial and post-colonial eras in relation to the development of local identity. The study uses a qualitative, descriptive comparative, and historical approach. The findings show apersistence and distinct creativity in the use of local/past elements in the design of tall buildings, further indicatingthat the tradition of constructing tall structures has indeed been part of Indonesian architectural heritage since the precolonial era.

Keywords *Local Tradition, Tall Buildings, Post - Colonial, Pre-Colonial*

1. Introduction

The tradition of building tall buildings in Indonesia is estimated to have appeared in the pre-colonial era as assuming the form of temple buildings. The architecture of temples in Indonesia shows the existence of a unique construction technology so that in the 9th century it wasable to present tall buildings such as Prambanan temple. The architectural tectonics [1] of this temple shows a distinctive creativity and relies on localisation. This is what distinguishes it from India, considering that the temple was originally a form of ancient Indian culture. In the present era, the construction of high-rise buildings in urban areas is unavoidable in the context of metropolitan life. High-rise buildings have become an important necessity in fulfilling the complexities of urban life, such as high land prices and high density. The architectural styles developed in these high-rise buildings vary greatly, however, in relation to local identity, so it is necessary to develop design ideas that refer to local values. In Indonesia after independence [2], the development of ideas that refer to this locality is shown through several high-rise buildings, although many buildings also favour international styles. In response toglobalisation, studies that refer to localism are needed.

This study seeks to understand the relationship between the ideas of tall buildings in Indonesia in relation to local values, which have been presented in the development of architecture. In the Pre-Colonial/Pre-Modern era, this can be discerned in the temples and meru buildings. In the PostColonial era, modern buildings that also refer to the Pre Colonial era can be recognised. In the Colonial era somemultistorey buildings do show the use of pre-colonial elements, but it is more discernible in the use of ornamentation. This study is more focused on the relationship between pre-colonial and post-colonial highrise buildings that emphasise the role of local elements in them, including the architects (figure 1).

Figure 1. Upper left *Prambanan* Temple 47 m Yogyakarta (Pre-colonial era); Upper Right Autograph tower Jakarta – 100 floors (current era); below: Mandiri Museum, Jakarta – 4 floors (Colonial era) (Research Data and KILTV- Collectie Wereldmuseum (v/h Tropenmuseum)

The attempt to represent local identity through regionalism is one response to the globalisation phenomenon above. Representations that originate from pre-colonial traditions can be one of the references in evoking identity. Postmodernism today provides an opportunity to freely explore sources of design inspiration that present an identity/character, such as the spirit of localism and regionalism. Postmodernism offers challenges (plurality) as well as opportunities to pay attention to the other side of the reality of its society [2].

2. Materials and Methods

In ancient traditions tall upright buildings in the form of towers can be associated with the concept of axis mundi. The latter refers to the universal consciousness thatall that exists. It isthe metaphysical axis of cosmicconnection between heaven and earth and high and low. This concept is also known by other names such as: world tree, world pillar, and cosmic axis. Axis mundi is an ancient concept that describes the "axis of the world" or the centre of the cosmos connecting heaven, earth and the underworld. It is often considered the spiritual centre point of the world, a place where humans can connect with gods or divine forces. In many cultures, this axis mundi is represented by objects or structures that are considered the link betweenthe physical world and the spiritual world, such as cosmic trees, sacred mountains, or buildings such as pyramids and towers [3][4]. A discussion of the roots that refer to tall buildings can start by exploring local values related towering figures.

2.1. Tree of Life

The first towering concept in the local traditions of the archipelago can be recognised through the Tree of Life.This tree is depicted growing on the ground or growing ona vase or pot. This tree in ancient Hindu tradition is known as kalpataru (figure 2). This is an image of a heavenly tree, which is full of flowers, both blooming and budding. On some of the blossoms, in the centre of their open crowns dangle pearls and beads. The flowers and leaves are arranged in a cupped pattern, forming a dense, slightly convex blob, as if emerging from a vase that forms part of the tree trunk. In Hindu mythology, it means a tree that grants wishes. This tree reflects an environmental order that is harmonious and balanced, and is an order that illustrates the harmony of forests, soil, water, air, and living things. Eventually, the relief and name of Kalpataru were used by the government to honour those who contributed to the preservation and sustainability of Indonesia's nature [5]. In the archipelago, the first written source that mentions the term kalpataru is most likely a yupa-shaped inscription left by King Mulawarman of the Kutai Kingdom. Furthermore, the Tantu Panggelaran story mentions a place called Hiranyapura which is filled with kalpataru. Mentions of kalpataru and similar terms are also found in the Udyogaparwa, Brahmandapurana, Ramayana, Arjunawiwaha, and Hariwijaya. The kalpataru symbol refers to the tree relief found in Mendut Temple, and this relief is also found in Pawon Temple, Prambanan Temple, and Borobudur Temple.

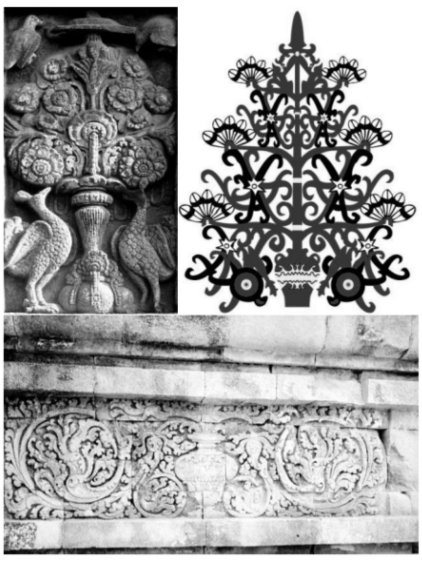


Figure 2. Upper left Relief *Kalpataru;_*, Upper Right *Batang Haring-Dayak*, below: Relief of Purnakalasa (Research Data and KILTV)

Another tree is depicted growing on top of the Vase/Belanga. This tree became known as purnakalasa (figure 2). In India, the purnakalasa motif [6] is a very beautiful decoration, and the various flowers and leaves coming out of the vase have symbolic value as a symbol of fertility and prosperity, related to Kuwera, the god of wealth in Hindu mythology. Purnakalasa is found in each era: Old Classical, Middle Classical, and Late Classical. The placement of purnakalasa ornaments does not bind to the division of the head, body and foot of the temple, but rather indicates a symbol of prosperity and wealth.In the context of Dayak culture, the tree that grows on top of this vase is also known as Batang Garing (figure 2). Batang Garing or Batang Haring means Tree of Life [7]. It is shaped like a spearhead pointing upwards or towards the sky. This is believed to symbolise the kaharingan religious belief (Dayak tribal belief) in Ranying Hatala Langit as the source of all life. Ngaju Dayak communities have a belief that the existence of life began with a tree called batang haring (some write and call it batang garing).This belief is still preserved and is also explained in the book called the Panaturan holy book [8] (Kaharingan Hindu holy book) as a guide or holy book for the Ngaju Dayak community in particular.
Purnakalasa in the temple and the haring trunk in the Dayak tradition are similar in form and meaning, depicting the source of life. In Austronesian culture, the depiction of vegetation on the vase has a strong synergy with the purnakalasa symbol from the Hindu/Buddhist tradition, thus reinforcing the continuous use of these symbols in Nusantara architecture. In the younger Javanese traditionof the Islamic era the Tree of Life can be recognised in the form of gunungan (figure 3). This is a symbol of life, so the elements within it symbolise the entire universe and its contents, from humans to animals to forests and their paraphernalia. Gunungan/kayon gapuran is a macrocosmic symbol depicting the universe or Jagad Raya (big Jagad), while kayon blumbangan is a microcosmic symboldepicting the small world (Jagad kecil/cilik). The pool of water in kayon blumbangan can be interpreted as a sourceof livelihood. There are two giant heads with wings. The wings symbolise sunlight, as a source of energy for life. Trees provide life for humans, as shade, as food producers, and as oxygen producers for breathing [9]. The sacred tree depicted as kalpataru is also called the wishing tree, the tree of life, or the world tree. The image of kalpataru is recognizable on the reliefs of Borobudur, Mendut, Prambanan, Sajiwan and other similar temples. The four branches of the kalpataru tree indicate the cardinal directions, namely West, North, East, and South. The idea of orientation in these four directions is closely related to Mandala in building site planning.

Figure 3. *Gunungan* (Research Data)

2.2. Menhirs and Lingga

Another figure that illustrates the idea of towering is the Menhir monument. Menhirs are pre-Hindu Buddhist cult buildings. Menhirs (figure 4) are also sometimes found at the top of stepped punden buildings. Menhirs in the beliefs of megalithic societies function as a medium of respect,being the throne of the arrival of spirits, as well as symbols of commemorated people [10]. Menhirs are realised from boulders both worked and unworked with the ratio of the shape of the high part more than the width and thickness [11]. This form is the most widely distributed artefact in Indonesia. Thus the Menhir form is a popular form in the megalithic tradition, namely stones in the form of poles or monuments that can be single or in groups. This menhir serves as a means of connecting between humans and those they worship such as ancestral spirits.

Figure 4. Upper – Menhir – Celebes, bwlow *Lingga- Yoni* Ijo Temple (Research Data)

Menhirs can be seen as a physical representation of the aforementioned Axis Mundi as in the context of megalithic beliefs. The upright stone rising into the sky is considered a symbol of the link between the human world (earth) and the divine world (sky).Identical to the Axis Mundi that serves as the centre of the cosmos, the menhir is considered a focal point that connects natural and spiritual forces.

Menhirs are often placed in locations that are considered sacred, such as on hills, valleys, or places that have cosmic significance such as stepped pundens. Menhirs stand as vertical signs, symbolising the vertical connection between earth and sky, the core concept of axis mundi. Menhirs are often believed to be the centre of an area or sacred place,similar to the axis mundi which is considered the centre of the cosmos. In this context, the menhir serves as acentral point where people perform ceremonies or ritualsrelated to natural cycles or belief in the spiritual world.Before the tradition of phallic and yoni worship, the pre Hindu archipelago was already familiar with the tradition of worshipping stone monuments known as menhirs. After the introduction of Hinduism, this monument can then be associated with the phallus. The monument is considered as the axis mundi connecting the world of humans with theworld of gods. The Axis Mundi is placed in the centre of the mandala system. The phallus and menhir have identical upright forms symbolising strength, virility and creative potential. In a spiritual context, both phalluses and menhirs can be seen as symbols of life-giving energy. The phallus is associated with the energy of Siva and creation, while the menhir is more associated with natural and cosmic forces. Both phalluses and menhirs function as symbols of the link between the human world and the divine world or cosmic forces. The phallus is considered a representation of Siva, who creates and destroys the universe, while the menhir is often interpreted as a spiritual centre that connects humans with the forces of nature or worshipped ancestors.Lingga-Yoni (figure 4) is the main element in Shiva Hindu temple buildings. Lingga-Yoni serves as a symbol of fertility: Yoni as the base of the phallus symbolises the womb of the universe, the birthplace of all life. Together, the lingga-yoni symbolises the creative energy and fertility that constantly flow in the cycles of the universe [12][13].Menhirs as Symbols of Cosmic Energy: In the contextof menhirs, the upright stone is often associated with the concept of fertility as well, though not as explicitlygendered as the phallus-yoni. Menhirs, as vertical monuments, are considered representations of cosmicforces that maintain the balance of nature. Upright as Cosmic Representation: Both phalluses and menhirs emphasise vertical symbolism that connects earth and sky.In this sense, they can be seen as symbols of the axis mundi (axis of the world), the link between the physical world and the spiritual world. Rituals and Ceremonies: The phallus-yoni is often the centre of Hindu religious ceremonies involving the offering of water or milk as a symbol of purification and worship of Lord Shiva. Menhirs, while not associated with the worship of a specific deity,are also central to rituals in megalithic cultures, often to honour the forces of nature or ancestors.

2.3. Local Dialogue

The relationship between Lingga and Menhir, as well as the tree of life Batang Haring, Kalpatru, Purnakalasa is nothing but a representation of dialogue with localelements that refer to collective memory. One of the basic ideas that produce various artefacts of human civilisation often arises from the collective unconscious of humans. This collective unconscious [14] then gives rise tomemories that are attached to human thought. These memories can be formed from major events that occurred in human life in the past. According to Assmann, the collective memory of a human civilisation's culture is bornbecause of the relevance of the cultural values to a particular time or period. For a civilisation to have an inherent collective memory, all evidence of that memory must be recorded, or have actuality in relation to the current context. These memories should also at least reflectthe values of life, the existence of certain groups or communities, and the individuals of the civilisation group itself.

Collective memory often emerges from thesubconscious and forms an archetype. An archetype is an unknown and hidden type that contains original, fundamental properties and is even the driving spirit of life. The expression of form in archetypes can be diverse, as the desire to reinforce the reality of an image is the cause of the desire to construct archetypes.

Archetypes give an impression of human inner experience. Archetypes in one place can connect us to similar archetypes in other parts of the world. This is how a specific concept or type can be interpreted similarly across civilisations. Archetypes [15] in typology, according to Mike Brill, are more like 'natural language' and'charge'.

Archetype is a natural agreement on the shape of an object because it has a certain value. Archetypes of sacred places, for example, have specific basic forms that are able to display mystical themes. Archetype is a medium to express the meaning of a place. In history, an archetype can be understood as the origin of a type that is further developed without changing the meaning or value contained in it. Archetypes can explain the relationship

between one architectural form and another in a particular cultural framing. The idea of archetype, collective memory, and primordial image is one of the strong reasons todescribe the dialogue with the past. This can be seen in some examples of classical architecture, such as in Indonesian temple architecture.

2.4. Analytical Approach

This study employs a qualitative and historical approach[16] to examine the architectural representation of tall buildings in the post-colonial era and its relationship with the pre-colonial era. This study seeks to analyse the form of tall buildings that have been built in Indonesia in relation to local values. Assessment and comparison will be conducted on architectural elements such as figure, plan, façade and ornamentation. In general, the research steps taken are:

1. Recognising the relationship of Pre-Colonial and Post-Colonial high-rise architecture with previous architectural values;
2. Interpreting and analysing based on the study to find interconnectedness so that the form of development can be seen. The variables used are architectural elements. These elements are expected to be an important aspect to explain the relationship between the past and the present.

The results of this study are expected to enrich the understanding of architectural studies related toarchitectural transformation from the pre-colonial and post-colonial eras. The use of architectural representations of the past through new designs is part of the process of building identity [17]. This is closely related to the spirit of age or globalisation or the trends of the Zeitgeist, although the local genius factor cannot be ignored and plays a dominant role in it.

2.5. Pre Colonial - Hindu-Buddhist Era

The tradition of building tall buildings in the Nusantara tradition can be shown through Hindu-Buddhist heritage. This is shown through the construction of temple buildings such as the one undertaken during the 9th century with the Prambanan temple. This temple is the first tallest buildingin Southeast Asia. The construction of thistemple is closely related to the Ancient Mataram era which saw many large buildings being erected [18]. The temple buildings in this era were built with a much larger size compared to the temples built in the previous era. This technology was certainly developed from existing traditions such as in theolder Dieng, especially in the stacked stone technique. This Indonesian-style stacked stone technique was thendeveloped into a construction pattern for large temples because it was possible to develop the stacking technique in making the temple bigger, taller and wider. This phenomenon shows that temple construction techniques in the archipelago are indeed unique, such as the steppedcorbel that was inherited until the end of the Hindu-Buddhist era. This stepped corbel was always used in temples in the archipelago both in Java and Sumatra, both Hindu and Buddhist [1]. This stepped corbel technique allows the space inside the temple to be spacious and elevated such as in Bima Temple and its Peak inPrambanan, Kalasan, Sewu. The Kalasan Temple even uses a stepped corbel arrangement transformed into a conical octagon that makes the construction more solid.

In the development of temple architecture, the Bima and Arjuna temples (7-8th century AD) became the basisfor the use of corbel technology. In some previous studies, it was claimed that the two temples were heavily influenced by India, however, when compared to temples in India, architecturally, the anatomical processing, façades, and proportions show significant differences. The fundamental difference is the tectonics, which uses corbel technology (Figure 5), while in Ancient India temple (before 11th century AD) it relies more on post and lintel. The architectural style of temples in Indonesia has its own architectural style since the civilisation in Dieng, although some of the ornaments are still affected by India, they are processed with independent thinking and yield new products.

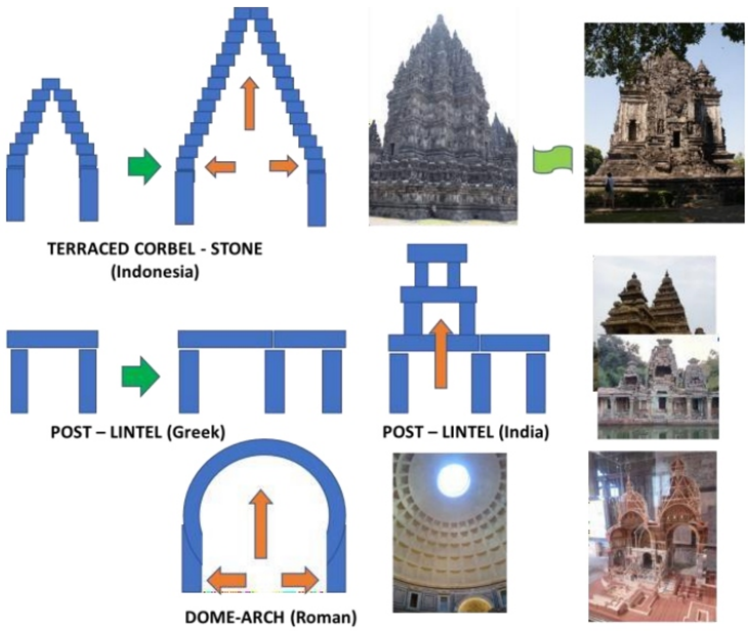


Figure 5. Comparative Studies Tectonic corbel Indonesia (6-9 CE), India (before 11th century AD), Roman Dome (Research Data)

Starting from these old temples, tectonics was subsequently further developed to produce enlarged buildings such as the temples in the Prambanan Era. Prambanan has a more complex architectural stylecompared to Candi Arjuna . The figure of Prambanan (9thcentury AD) shows a unified pattern and a curved pattern compared to the style of temples such as Arjuna, which has
clearer hierarchy between the legs and body, as well asthe body and head. Prambanan Temple has a height dimension up to 47m. None of the temples built contemporaneously with Prambanan in Java happen to be taller than thistemple, nor are those found in India (before 11th century AD).The technology of making tall buildings is assumed to have been developed by architectsin Java in the 9th century. The temples built in this century have large and tall dimensions. The tallest and largest Hindu temple surpassing the Buddhist temples in terms of inner space is Prambanan (Borobudur is the largest Buddhist temple but is not spacious as Prambanan). Buddhist temples that are large and contain inner

space is Prambanan (Borobudur is the largest Buddhist temple but is not spacious as Prambanan). Buddhist temples that are large and contain inner space but rank below the class of Prambanan are the Sewu and Kalasan temples. To build a temple with a height like Prambanan requires not only creativity [19] in architectural form but also reliable engineering aspects. Prambanan can be seen as the first high-rise building in Southeast Asia and South Asia, and it inspired the architecture of later temples that used high-rise building technology, such as the ones encountered in Cambodia, Champa, and India [16].

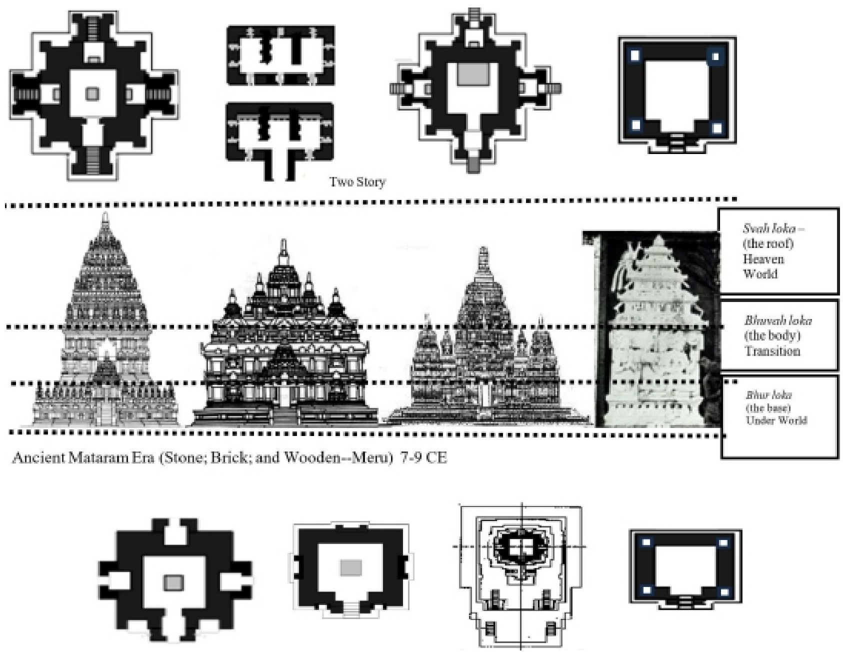
Temple building materials can employ stone and wood. The roof of the temple made of wood isrecognised as Meru. This can be seen in the relief image of the 8th-century Borobudur temple (figure 6). These wooden-roofed temple buildings have basically been recognised as much olderthan Borobudur, namely going back to the 5th century as in Batujaya temple. The roofs of these buildings are thought to be tajug-shaped and stacked, known as ata meru. Sacred buildings generally have stacked roofs to depict sacredness as an expression of heaven or the sky. Based on the comparison of the proportions of the tower-type temples made of stone, it can be assumed that the number of stacked meru roofs of these temples is at least 3, considering thatthe stacked meru roofs have a number of roof stacksranging from 3 to 11. The shape of the roofs of these temples made of tajug wood construction is centralised and can be multi-storeyed at the present time can be found in Bali, or the roofs of barn buildings influenced by ancient Austronesian traditions such as in Karo.

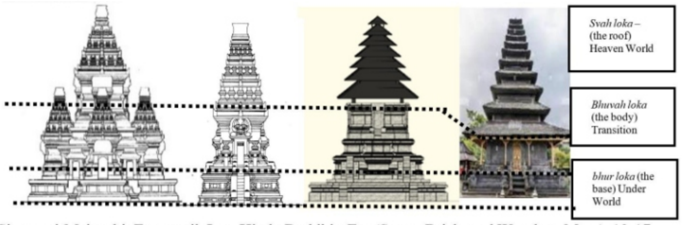
Figure 6. Meru Architecture: Upper Left: Relief Borobudur Temple 8th century AD, Upper Right and Below: Meru In Balinese Temple (13-17th century AD) (Research Data and KILTV)

'Meru' (figure 6) is basically a symbolisation of the axis mundi, a supernatural pole connecting the earthly realmwith the heavenly realm, where 'explicitly' the supernatural pole is depicted as a form of building or architectural work that is sacred. Meru is one type of roof type that isidentified with sacred Hindu buildings in Indonesia andwas widely used in the Majapahit era to Bali. However, meru is a form that can also be associated with Buddhism with its manifestation in the form of pagoda buildings along with chattra elements on the stupa as well as in China, Korea and Japan. However, the oldest Wooden Pagoda building in China dates back to the 10th century while inJava in the 8th century it was already depicted on the reliefs of Borobudur. Another form of the use of the stacked roof/meru type was later seen on the roof of the mosque in the early development of the Islamic era in Indonesia. Meru was born from structures and constructions that are closely related to certain conditions, namely concerning political, economic, social, traditional, cultural, technological issues along with the religious concepts that influence them. It is also closely related to the seismic aspect of the building, as it is considered lighter and more flexible.

This change in dimension can be understood as a transformation in architectural design, including construction technology. This change in the use of dimensions to become larger is basically not only related to technological aspects but also supported by the social, economic and political conditions that took place at that specific time. Building large buildings without being followed by stable security, political, social and economic conditions seems difficult to implement. In this era, at least food was easily available and accessible, so mobilising hundreds or thousands of people for construction work did not pose a big problem. Food is directly related to the well-developed agrarian tradition. It can be described that the conditions at that time were very conducive so that largeprojects could be implemented.

Overall (Figure 7), it can be understood that Hindu Buddhist temple structures symbolize the macrocosm or the universe, which is divided into three parts: the lower realm, where humans are still influenced by desire; the middle realm, where humans have abandoned worldliness and are in a state of purity to meet their God; and the upper realm, the celestial domain where the gods reside. The temple, as a temporary dwelling place for the gods, is designed as a replica of the divine abode located on Mount Mahameru. Therefore, temples are adorned with decorative motifs related to the celestial realm, such as lotus flowers, animals, gods, and celestial maidens. The temple's base symbolizes Bhurloka in Hinduism or Kamaloka in Buddhism, representing the earthly realm. The body of thetemple symbolizes Bhuvarloka, the intermediary realm leading toward perfection. The temple roof always consists of a tiered structure (typically three levels with a crown at the top), gradually narrowing upward and culminating in a crown. The roof represents Swahloka, the abode of the gods. This structure serves as a representation of the process of spiritual attainment, symbolizing the journey of humans from the beginning of life to the ultimate state of moksha, where they unite with the gods in Nirvana.





Singosari-Majapahit Era –until Late Hindu Buddhist Era (Stone; Brick; and Wooden--Meru), 13-17 CE

Figure 7. Several Type of Temple Forms and Layout, Upper: Ancient *Mataram*, Below: *Majapahit-Singosari* and Balinese Temple (Research Data)

Figure 8. Tall Building Pre colonial Era: Upper: Prambanan – Kalasan Temple 8=9 CE, Middle-Below: Majapahit temples brick-stone and meru (14-15 CE). (Research Data, KILTV, Bernet Kempers)

There are several strong architectural aesthetic elements that consistently appear in its design, including: composition, Cartesian-cruciform geometry, volumetric elements, solid-void-cluster, hierarchy, tripartite division, rhythm (repetition and datum), symmetry (focal point and balance), mimetic elements inspired by nature, either in the form of the building or its ornaments, texture, linear elements, chiaroscuro effects (light and shadow), axis/linear/centralized alignments, and proportion-scale. Additionally, some distinctive elements in temple design include: kala ornaments, molding profiles, simbar-antefix ornaments, frame-cartesian geometric ornaments, lines, frames, floral tendrils, medallions, vegetative ornaments, crown treatments, staircase designs, and door-niche designs (both curved and non-curved) [18].Large temples were almost simultaneously erected inthis era such as Borobudur-Mendut-Ngawen in the northand Prambanan, Kalasan, Sewu, Bubrah, SojiwanLumbung, Ijo in the south, among others (figure 8). The management of large projects such as the construction of large temples in this era should have been supported by an adequate project managerial system as well. The construction of the great temples, which almost coincided in time, indicates that they were built by hundreds of human labourers with adequate skills, both in terms of design planning and construction implementation. It is likely that most of the people who lived in this era were dominated by building

experts including reliable carving experts.
People living in this era may have had a main livelihood that was familiar with building expertise and must have been highly skilled builders.

2.6. Post-Colonial Era

During the reign of President Sukarno, monuments were built that used icons in the context of urban landmarks. Iconically, these monuments can be associated withsymbols from the classical era such as temples. These monumentsinclude the National Monument Monas-Jakarta, Tugu Muda Semarang, Tugu Pahlawan Surabaya, and Tugu Alun-Alun Bunder Malang [20]. Sukarno's vision ofnationalism-identity also influenced the form ofmonuments that adapted elements of forms derived from temples (figure 9) such as the National Monument (Monas). As a matter of fact, Monas was the result of a competition initiated by President Sukarno. In the end, the Monas that was built was one that reflected localized values, as developed by Sudarsono based on input from Sukarno. Monas assumes the form of lingga and yoni which are the most sacred elements in Hindu temple buildings and are located in the core space of the temple. This union of lingga and yoni (phallus and womb) is symbolic of the creation of living things (sangkan paraning dumadi) as a manifestation of fertility. On the other hand, the shape profile/mouldingof Monas [2] can be attributed to the development of the profile of Majapahit-era temples. The fundamental valuesin temple architecture, namely fertility, are transformed into the form of Monas.

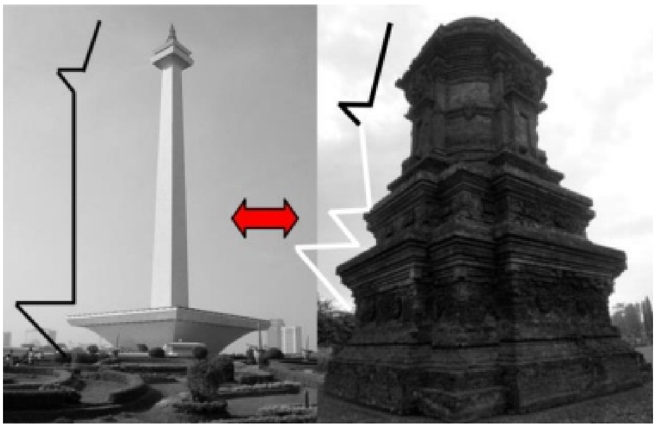


Figure 9. *Monas* (left) and Majapahit Temple (Gunawan Kartapranata and Research Data)

During the Sukarno era, the construction of many high-rise buildings can be recognised as Modern in both pure and added local elements. This can be seen forexample in the Indonesian, Samudra Beach, Bali Beach and Ambarukmo hotels (figure 10) which show strong horizontal lines. The international style and moderncharacteristics are strongly present in these buildings. The roofs were also given floating elements or shield roofs with wide tropical terraces as developed by Silaban, Sudarsono, and others. Thus, during this period, the architectural styles developed were not only referring to local elements such as Monas, and Bank Indonesia but also international styles such as those encountered at these hotels.

Figure 10. *Ambarukmo* Hotel Yogyakarta (Research Data)

In the post-Suharto era, architecture developed more widely, especially with the opening of foreign investment. Many high-rise building designs that adapt local architecture can be seen in some office functions such as Sujudi's work in the building of the Indonesian Embassy in Malaysia [21]. This building adapts elements of meru architecture (figure 11). Meru is a type of roof that is commonly used for building components of a temple complex in the present and temples in the past. The use of Meru elements in the Embassy building shows an effort to raise the value of Indonesia's local architectural identity. Meru, which is found in Bali, is used as a means of presenting the Indonesian character to the international community. The shape of the meru emphasises the strong expression of horizontal lines, which can give rise to an expression of lightness (with wide terraces). Another localised element represented by meru is its tropicality, which is the use of teritis elements.

Figure 11. Indonesia Embassy in Kuala Lumpur and Meru (https://www.kemlu.go.id/id/berita/PublishingImages/201703/4.%20KBRI%20_KL.jpg and Research Data)

The concept of horizontal lines and tropicality can be considered to correspond with Sujudi's modern idealism. Sujudi is one of the architects who developed the elementof contextuality towards the climate but also displayed modernity (visionary). The principle of modernity is shown by the use of concrete material in the form of horizontal lines and terraces. The arrangement of these lines can cause light and shadow effects when exposed to sunlight. Sujudi's work for the Indonesian Embassy in Malaysia is likely to inspire future design works such as the Central Java Governor's Office (figure 12) and may be the Dharmala Building furthermore (according to Paul Rudolph was inspired by the local kampongs roofs).

Figure 12. Governor Office-Semarang and *Dharmala* Office-Jakarta (Research Data)

Another tall building that refers to the elements of past towers can be recognised in AT6's work, the Department of Culture and Tourism building/Sapta-Pesona building [2]. This building is designed with a conceptual approach that resembles a typical Majapahit gate combined with symbols of modern technology in the present. However, the expression that is present hardly resembles a gate, as it is more like a temple building. This is reinforced by the processing of the central façade which depicts the barong/kala element as well asthe decoration in the temples. The temple elements in this building have been transformed into a new form. Elements derived from temples can be seen on the left and right wings which are arranged in steps and kala. The Indonesian Embassy, Sapta-Pesona building still shows the presence of iconic physical elements that indicate a temple building. Buildings that represent temples are also shown in the design of Bank Mandiri Semanggi by the Desa Kota bureau and the Rectorate of Brawijaya University (figure 13). The Bank Mandiri Semanggi building resembles the form of phallus and yoni with volumetric, geometric expressions. Volumetric, geometric and symmetrical attributes in temple architecture can be considered as transferable elements that can be used in the context of modern buildings. The Rectorate of Brawijaya Campus Malang uses a zigzag and symmetrical geometric pattern that is also identical to the division pattern of the temple buildingfigure and this is reinforced by the three-division roof arrangement.

Figure 13. Upper *Saptapesona* Building and *Majapahit* Gate Below *Brawijaya* Rectorate Building and Mandiri Office (Research Data)

After the Suharto era, known as the reformasi era, the use of classical elements of the past in high-rise buildings is shown in the Capital Resident (CR) building by Airmas Asri [22]. The plan of the CR (figure 14) Tower shows the use of cartesian geometric patterns like those used in many temples. The impression of volumetric expression composed by the abstraction of cartesian geometric patterns also corresponds to the massive figure of the temple. The compositional processing of the CR façade that emphasises geometric patterns in the form of lines and frames is also in line with the abstraction of the temple façade, especially the use of lines that also display a textural impression, although not too strong. The vertical composition of the head-body-leg/feet element can also be recognised in this building as well as the tribhuwana division in the temple. The CR crown is impressed by the use of temple roof proportions, although only to the extent of showing a hierarchy. However, in general the composition of the roof shows closeness t

Figure 14. Line 1: Capital Residence and *Prambanan* Temple line 2: Supreme Court Building; line 3: Javanese Temple (Research Data and Lukman Tomayahu)

The idea of using temple representations is also displayed in the Supreme Court Building of the Republic of Indonesia when there is a tower figure by Arkonin in the centre with the function of the office and judicial room moved to the top floor (figure 13). When traced further, the figure of the tower in this building seems to transform the entire form of the building into a harmonious unity and there are several aspects that resemble the architectural design of the temple. The Supreme Court Office Building shows the idea of geometric composition, symmetry, rhythm and repetition, a division of three that refers to the geometry of ancient temples. According to Architect Achmad Noerzaman (Arkonin) [23], temple architecture is one of the most important architectural heritages of the Nusantara after stilt houses. The elements in temple architecture itself are believed to inspire many phenomena in the future in terms of creativity and innovation. In responding to the challenges of the times, all cultural wealth is a strong capital to realise architecture with character in Indonesia, so it becomes a challenge for architects to be able to utilise it and pour it into architectural works.

In addition to Arkonin Bureau, DCM Indonesia Architect Budiman Hendropurnomo features elements inspired by classical architecture such as temples andshrines [24] in several works such as the Binus campus, Apurva Bali Hotel and others. The idea of the tectonic arrangement of the stepped and zigzagged stone blocks of the temple is transformed into the composition of the form of Bina Nusantara Alam Sutera University (figure 15). This idea is also reflected on the Bina Nusantara campus in Malang which uses the Tikus temple composition and the concept of a split gate.

Figure 15. Line 1; *Bina Nusantara* Campus *Alam Sutera*, line 2: *Bina Nusantara* Campus Malang and *Tikus* Temple, line 3 *Apurva* Hotel, Bali, line 4: Ceiling of *Apurva* Lobby and *Tumpang Sari Joglo/* Javanese Temple Ceiling (DCM and Research Data)

The design of the campus building depicts the arrangement of temple stones, but is processed with an asymmetrical stacked pattern, although the figure of the temple building depicts a symmetrical pattern.Thus Budiman (DCM) presents the idea of localisation in it by transforming the architecture of Antiquity into modern buildings through geometry patterns. In addition to Bina Nusantara Alam Sutera University, DCM applies elements of localisation both inspired by temples and others traditional style such as in the Apurva Hotel, MayaSanur and Maya Ubud projects (Balinese (figure 15).

3. Conclusions

Basically, Indonesia has a tradition of building tall buildings since the pre-colonial era (figure 16), as seen in the Hindu-Buddhist temples from the Ancient Mataram to Majapahit era. The temples were built showing a dialogue with the values of the previous tradition. Ideas that originated from old values were subsequently transformed into new forms and processed in accordance with thecontext of the prevailing paradigm. In the post-colonial era, the spirit of building tall buildings by referring to local/past values was also shown by Indonesian moderncontemporary architects. Basically, the architectural potential of the past or pre-colonial era is still relevant to be used today, especially in strengthening local identity in the midst of globalisation. Just like the temple architecture of the past, the architecture of the post-colonial era is expected to demonstrate the excellence of creativity in producing distinctive design products. Indonesia has a wealth of culture, legends, myths that can be used as a source of concepts in design. Thus, the architecture produced can be understood as not only localising the global, but also being able to globalize the local.

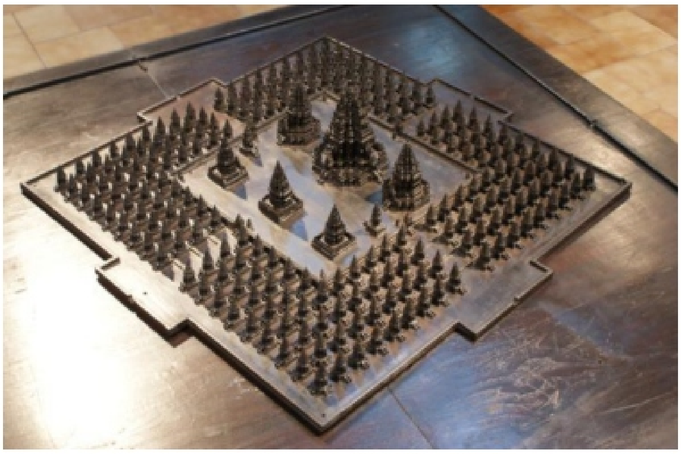


Figure 16. *Prambanan* Temple 9th century AD – The First Highrise/Tall Building in Southeast Asia (Research Data)

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Skin Facade Design for the Thermal Balance in the Mantaro Valley Buildings

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ABSTRACT

Climate change significantly impacts the lifestyle of people living in high Andean areas. For children, heat, combined with other environmental factors like humidity, leads to exhaustion—something experienced daily. Prolonged exposure to heat can cause side effects such as anxiety, and depression, and contribute to mass migrations and regional conflicts, affecting local communities. Given these concerns, this research focuses on the thermal comfort of all types of buildings, whether residential or public. It proposes the importance of controlling internal temperatures, much like green walls or building placement systems that allow air to flow freely, creating cool chambers with stable temperatures for a greater sense of comfort. To achieve this, a system of modular architectural membranes was designed and prototyped. These membranes are tailored to the specific needs of the geographical region where the study was conducted, as each area requires dynamic, flexible geometries capable of forming responsive and intelligent morphologies. The results have effectively met the thermal control needs of buildings in the Mantaro Valley, complying with ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) standards for thermal comfort. Additionally, the system integrates high Andean cultural elements, preserving traditions and art to reinforce identity, as expressed through iconography in the "lliclla," a traditional Andean mantle. Finally, it's important to mention that various tools were used throughout the data collection, implementation, and design modification processes. SketchUp and V-Ray were utilized

1. Introduction

Climate change is a problem that has been worsening since the last century since climatic zones are changing, glaciers are in a constant process of melting, and sea levels are rising [1]. These are effects that were mentioned many years ago, in addition within the contemplations it was that the temperature was going to increase more and more, in the same way, there would be massive decreases in other locations, all of which are due to the effect generated by environmental pollution and the greenhouse effect caused by the increase in temperatures. It also produces effects such as "direct cooling" because it affects not only living conditions, but also agricultural production, and in other cases, livestock activities.

Among the direct consequences that can occur due to the increase in temperature, there are mainly cases in children, which, due to the strong sensation of heat and environmental humidity, causes them to be in a state of fatigue generated by the global temperature increase.

In addition, there are other effects such as the higher incidence of worry, depression, the negative impact on mass migrations and regional conflicts [2], which are considered a strong blow to minimum living conditions because climate change is affecting both the mind and the place in which one lives, causing people to seek a more optimal environment to develop. About the harmful effects on children's health, according to the United Nations Children's Fund (UNICEF), it was found that a total of 377 children in countries between Europe and Central Asia lost their lives due to the effects of extreme heat, 48% of whom were children who were not even in their first year of life.Also in the year 2024 it shows that according to the Disability Adjusted Life Years (DALYs) indicator a total of 32,356 healthy life years were lost [3], furthermore in the fact sheet provided by the non-profit news “Climate Central” entitled: “Climate Change and Children's Health: Extreme Heat” shows that in the United States of America about 9000 adolescent athletes are seen annually for cases and conditions related to high temperatures, also that 12% of children's hospital admissions are directly related to illnesses or conditions caused by heat between the months of May and September, which is summarized in 17000 annual visits to the doctor [4].

So, considering the above, it is known that it is elemental to focus on thermal comfort inside buildings so these extreme temperatures can be counteracted and generate a barrier system that helps control stress levels and related backgrounds; similar to the problem raised by the research, which proposes the implementation of green walls to control the internal temperature [5].

It is considered especially important to generate a system that can be coupled to vertical surfaces, generating the desired thermal control, in addition, related to this, it can be reviewed that there were precedents worldwide about bio-walls, which, more specifically, were considered biostructures for the conservation of internal temperature. Consequently, many of the buildings that are now called traditional buildings were built due to architectural evolutions related to the comfort of the inhabitants, construction strategies, immediate needs, and fundamental cultural influence [6].

A clear example of these is primitive homes, which can be highlighted because they prioritized the capacity to retain internally in the case of those located in areas with temperature drops; in other cases, some considered caves as a place to take refuge from the hardness of the environment; and finally, those who were sheltered in ecosystems in which wetlands or swamps were the ones that prevailed [7].

With human evolution, other needs arose in the search for thermal comfort, and civilizations were born that took advantage of their immediate closest resources to generate optimal thermal comfort for their cities. An example worldwide and about ancient cultures is Machu Picchu, which would be original Solar City of America, because it condensed so many construction techniques with the use of materials that generated comfort within its buildings; one of them would be the city that is oriented towards the east, because it takes advantage of sunlight during the first hours of the day efficiently by being in a location surrounded by high peaks. These worked by controlling the formation of clouds during the summer to regulate the sensation of heat and during the night they provided a distribution of high temperatures as a result of the accumulation of heat during the day. Finally, during winter, it worked so that during the day heat was stored, taking advantage of the low formation of clouds, and when night came, it could retain the internal heat gains in the city walls [8].

Due to the industrial revolutions, there has been an overuse of glass and mechanical devices for temperature control, which has contributed to global warming and the energy crisis. The most prominent consequence of this is the lack of commitment to the environment. This situation is also observed in Bolivia, where the government does not encourage research in the energy and environmental fields, which generates a great need among the inhabitants. This lack drives the search for immediate solutions. In this context, the research entitled “Bioclimatic social housing for Santa Cruz de la Sierra, Bolivia” mentions that bioclimatic housing focuses mainly on energy savings,but lacks an effective internal temperature control system. In the development of this research in Bolivia, data presented such as that one of the most effective ways to moderate the temperature is by adding eaves on the windows or small elements that prevent the entry of solar radiation, either partial or total. In addition, the orientation of the house, the design of its windows and its structure in general have a great impact on temperature regulation. It is crucial to consider the use of materials with a high thermal transfer retarding capacity or with high thermal inertia on external surfaces [9].

Thus, in the near context, the mountain ranges of the Andes, as well as those of the Himalayas, are areas that have the highest altitude cities in the world; in the Andes is La Rinconada, a city at 5000 m a.s.l. with 1000 inhabitants, being the highest city in the world, while the Andes has 109 cities between 3000 and 4000 m a.s.l. Grouped as Meso Andean zones, these are why strategies must be generated to maintain due thermal comfort both internally and externally [10]. Within the basic concepts for the construction of buildings, it is recommended to follow the technical standard of the American Society of Heating, and Air Conditioning Engineers (ASHRAE) of 2005 [11], in addition to being convenient to take advantage of the property of thermal inertia, because it can increase the internal temperature of an environment by up to 11.9% according to studies carried out in Cusco [12].

In Peru, the National Standard for Electrical and Mechanical Installations (EM 110 Thermal and LightComfort with Energy Efficiency) separates the different departments according to their bioclimatic factors, and in the same way, divides each area of each department by the following denominations: marine desert, desert, low inter Andean, meso Andean (Table 1), high Andean, snow capped mountain, mountain eyebrow, humid subtropical and humid tropical [13]. Since the project is located in the Meso-Andean, its zone's special characteristics are highlighted.

Table 1. Bioclimatic characteristics of Junín by bioclimatic zones from National Standard EM 110 Thermal and Light Comfort with Energy Efficiency

CHARACTERISTICS	MESO-ANDEAN ZONE
Average annual temperature	12 ℃
Average Relative Humidity	30 to 50 %
Prevailing wind direction	S - SW
Wind Speed	North 10 m/s, center 7.5 m/s, south 4 m/s, south-east 7 m/s
Solar radiation	2 to 7.5 kWh/m^2
Hours of sunshine	North 6 hours, center 8 to 10 hours, south 7 to 8 hours
Annual Precipitation	150 to 2500 mm
Altitude	3000 to 4000 m a.s.l.
Equivalent in Koppen classification	Dwb

In addition, the International Organization for Standardization (ISO) 7730 standard, mentions that thermal comfort is expressed according to the state of comfort that a person has to ambient humidity, temperature, air speed, and radiation, in addition to the number of individuals that are within the same environment [14]; taking into account the considerations previously mentioned, this article focuses on supplying a control within some of the factors that lead to thermal comfort, heat, humidity and air speed as the main thermal actors, which will be modified through the design and subsequent implementation of architectural skins suitable for the Mantaro Valley and specifically in the city of Huancayo.

To fulfill this intention, it is convenient to design architectural skins, which will be used with the mobile systems generated by the applications and modulations of this type of structure that has a linear, superficial, and spatial grouping [15] , to obtain almost infinite variations in the ability to locate it in any building. This allows older buildings that need to generate comfort to benefit from this design, thus benefiting not only with functionality but also with the ability to renew their appearance and aesthetics; in addition, to have additional functionality for the city of Huancayo, which would be the ability to redirect the water generated by rainfall slightly.The consideration benefits that are obtained in a general way when using these structures are the ease of and construction [16] because the entire system is modular way, to carry out its assembly is similar to the modular toys of the Lego brand, thus having two of the main characteristics that are intended to be fulfilled; firstly, the ability to generate complex facades with only the use of simple parts, i.e. modules; and, secondly, the ability to retain heat without the need for heavy surfaces, avoiding the potential danger of falls, based mainly on the application of biostructures such as green walls and their methodology, which has a lot to do with materials, orientation and location.

2. Materials and Methods

First, the evaluation and study of the "model of the module" that will be used in the architectural skin are carried out based on the environmental conditions of the city of Huancayo. For this, the basis is the studies carried out by Xiao Zhang in 2021 and Hernández in 1984, who, in their studies, have been able to determine the feasibility of each modular form. Depending on the use, they presented a list of possible forms that can be given to them, including the Waterbomb Pattern and Diamond Pattern[17], the most optimal for flat structures; and thus, also, to be able to carry out the second purpose, which is the redirection of rainwater.

To perform the mathematical calculations related to the study, it must be taken into account that comfort within an architectural environment is largely denoted by the materials and each of the characteristics that it brings to the environment since they maintain a balance internally, to have a virtually constant temperature throughout the time [18], but this is variable concerning the context that was studied. In this case, the Mantaro Valley, more specifically the city of Huancayo, has an average annual environmental temperature; according to the website weatherspark.com, which keeps a historical record compiled from January 1, 1980, to December 31, 2016, the average annual temperature of the city of Huancayo ranges between 6 °C and 20 °C (Figure 1).

On the other hand, the National Meteorological and Hydrological Service (Senamhi) indicates that the average annual temperature in the city of Huancayo ranges from 21 °C to 25 °C as the maximum temperature and 7 °C to 11 °C as the minimum temperature, which is a historical average with data taken in a range between 1981 and 2010.Considering that all the data compilations shown above are from periods between 1980 and 2016, we proceeded to obtain an average current temperature, which has a study period between February 15 and March 10, 2024, which resulted in the average maximum temperature in this period being 17.32 °C and a minimum of 8.32 °C (Table 2).

Having the data of the average outdoor temperature, the average indoor temperature, or what is considered a standard temperature for thermal comfort must also be evaluated in these aspects, which can be mentioned that making use of standard 55-2.010 of the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) mentions that the optimal temperature range for internal thermal comfort is included in the range of 20 °C to 24.5 °C (Figure 2).

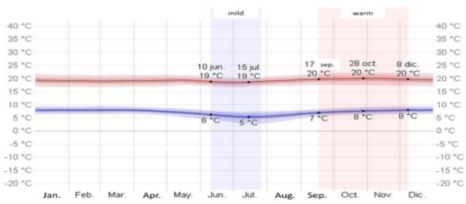


Figure 1. Average temperature in Huancayo January 1980 – December 2016 by © WeatherSpark.com

Table 2. Maximum and minimum temperatures in Huancayo

	Month	Day	Maximum	Minimum
Huancayo Temperature in ℃	February 2024	15	18	9
		16	18	8
		17	19	8
		18	19	9
		19	19	9
		20	19	6
		21	20	6
		22	20	8
		23	18	9
		24	15	8
		25	15	9
		26	16	9
		27	17	9
		28	16	9
		29	17	8
	March 2024	1	15	8
		2	16	8
		3	17	8
		4	17	9
		5	18	9
		6	18	9
		7	15	9
		8	16	8
		9	17	8
		10	18	8
Average			17	8

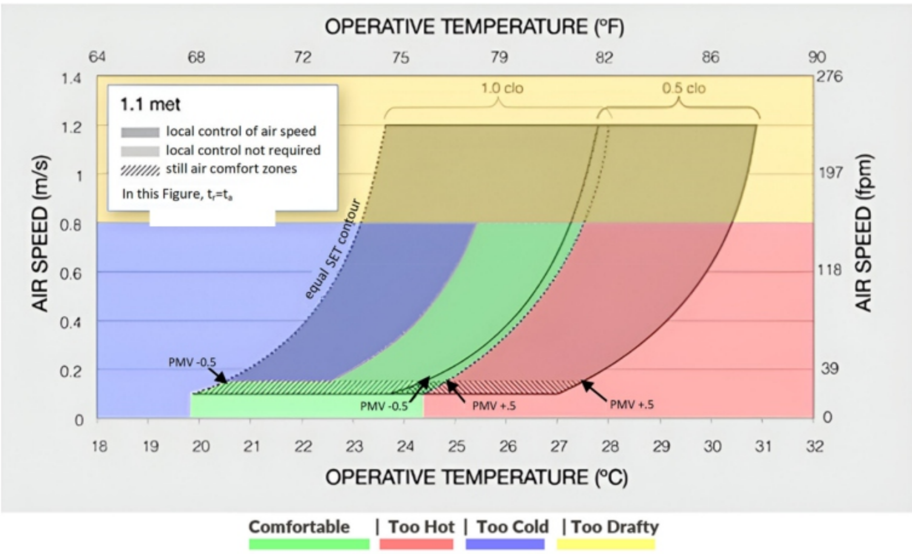


Figure 2. Internal thermal comfort according to ASHRAE 55-2.010

Since already both the external and internal temperatures are obtained with which it will work, the selection of the material is made based on its coefficient or constant of thermal conductivity (λ or k), which is defined as the capacity of energy to be transported in a given time and a solid medium with a cross-sectional area. Also, it has a specific thickness. Among the principal materials that were evaluated for the study, there is the following table specifying these values for subsequent analysis:

Table 3. Thermal conductivity coefficient

Names	Thermal conductivity coefficient (λ) in W/(mK)
Silver	429
Pure aluminium	237
Brass	81-116
Steel	47-58
Stainless steel	12-45

Once we have the materials for the possible selection and also the predetermined needs to generate thermal comfort within the home, we proceed to make the calculations related to the "thermal inertia", which is defined as the heat load capacity of a given built area, about its total mass andits specific heat. The calculations are based on 1 m2 of a wall of noble material with a thickness of 15 cm and 1 m2of glass, with a thickness of 1 cm, this is because they are the most common surfaces that can be observed in the city of Huancayo.

$$Qc = \sum m \ \ . Ce$$

$$Qwwallnoble = mbrick. Cebrick + msand. Cesand + mconcrete. Ceconcrete$$

$$Qwwallnoble = \frac{226.136kgx850J}{kgK} + \frac{70kgx830J}{kgK} + \frac{27.727kgx920J}{kgK}$$

$$Qwwallnoble = \frac{0.1922MJ}{K} + \frac{0.0581MJ}{K} + \frac{0.025508MJ}{K}$$

$$Qwwallnoble = \frac{0.275808MJ}{K}$$

$$QwglassTenvironment = \frac{22kgx780J}{kgK} = \frac{17.16KJ}{K}$$

$$QwglassT > 20°C = \frac{22kgx1100J}{kgK} = \frac{24.2KJ}{K} \quad (1)$$

s part of the calculation, it is also necessary to know the amount of calories generated by the variation in temperature of the selected material, making the calculations based on 1 m2 of surface with 1 mm thickness, the average maximum and minimum temperature in the city of Huancayo, and the calorimetry formula that is expressed by the following equation:

$$Qbrass = mCe\Delta T$$

$$Qbrass = \frac{8730gx0.09calx(17°C - 8°C)}{g°C}$$

$$Qbrass = 7071.3 \ \ Kcal \quad (2)$$

In this result, you can see the amount of calories or energy that a brass plate with the specifications shown above can directly absorb, but this is under the initial idea that it is subjected to a sudden change in temperature.Subsequently, the thermal conductivity formula is applied in a time of 6 hours from noon, to a surface °C, a minimum temperature of 8 °C and the maximum coefficient of thermal conductivity that has the value of 116W/m°C ((the symbol K is replaced by °C because as it rises one degree K also goes up one grade C).degree K also goes up one grade C).

$$\Delta Q = \lambda S \frac{\Delta T° x \Delta t}{\varepsilon}$$

$$\Delta Q = \frac{116W}{m°C} x1m^2 x \frac{(17°C - 8°C)x36000sx6}{0.001m}$$

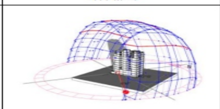
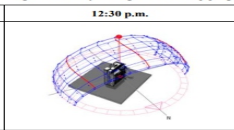
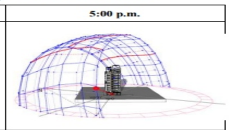
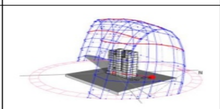
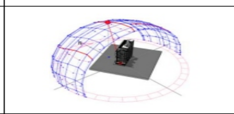
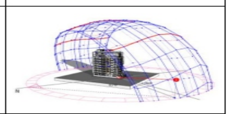
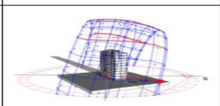
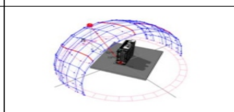
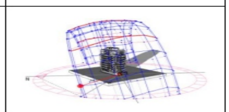
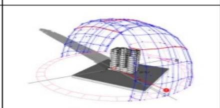
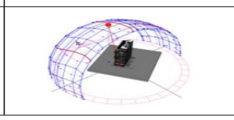
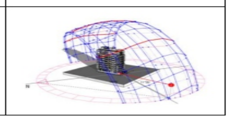
$$\Delta Q = 2.25504x10^{10}J$$

$$\Delta Q = 36000GJ$$

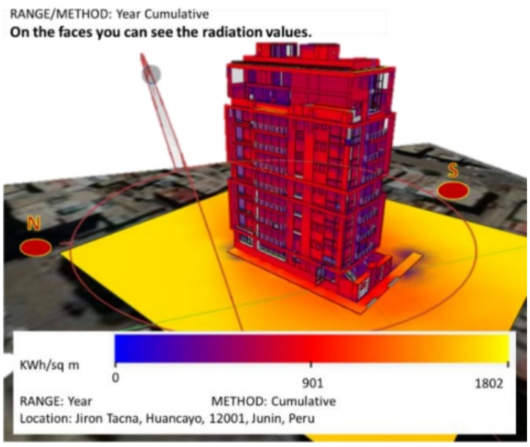
The energy that can be transferred by the brass plate with the specified measurements is a total of 22.5504 GJ over 6 hours.

Next, the analysis was conducted in the SketchUp program, with the CuricSun complement, and the sunlight in a geolocated building in the city of Huancayo was evaluated, taking into consideration the location of the facades in the buildings that respect the rectangular urban grid. It was observed that, during the year, the north facade is the one that receives the most solar lighting; therefore, the east and west facades are at a high level but lower than the north facade, and the south facade, receives little sunlight during the year, as can be seen in the following table:

Table 4. Seasonal solar analysis of buildings in Huancayo using the SketchUp program with the CuricSun add-on

	7:00 a.m.	12:30 p.m.	5:00 p.m.
01 - 01 - 2024			
30 - 03 - 2024			
30 - 06 - 2024			
30 - 09 - 2024			

he above is supported by the solar analysis carried out in the Formit Autodesk programs, because the north, east, and west facades present a medium level of radiation during the year, represented by red; and the south facade, a medium-low level of radiation, represented by a plum color. The entire analysis of the Formit Autodesk program is represented by a color scale, where blue is the area with zero radiation presence, yellow is the yellow area with the highest presence of radiation throughout the year, and red is a transitory value in the aforementioned rating scale (Figure 3-4).



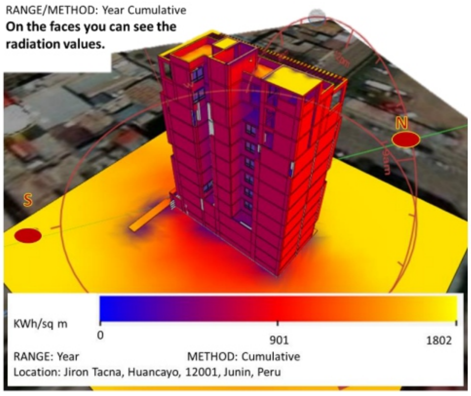


Figure 4. Solar analysis of south facade using the Formit 2024.1. program

3. Results

First, the measurement and comparison of results obtained through digital measurement were carried out, with a digital thermo hygrometer with a probe model HTC 2 of the OEM brand, in which the variation of temperatures can be differentiated, being the trend lines the blue color and its gradient, the maximum and minimum temperatures obtained outdoors during the measurement period; the yellow one, the higher and lower temperatures of the brass surface inside the house in which the measurements were made; all of this in the period from May 2024 in the city of Huancayo, belongs to the department of Junín in Peru (Figure 5).According to the graph, it can be interpreted that the temperature with the use of brass tends to vary according to the external temperature, regulating all the data to a stable temperature, the projection was confirmed by applying Lagrange interpolation, which yielded the graphs that relate the external temperature to the surface without the brass cover and the external temperature to the brass cover, demonstrating that the treated variable varies so that the temperature is in the comfort range, most of the time between 8:00 a.m. and 6:00 p.m. considering temperatures between 5 °C and 45 °C.

All this makes use of the Excel MS programs to generate the data of the matrix calculation and Geogebra to make the final sketch of the algebraic equations that will denote the behavior of the internal temperatures both with and without the use of brass (Figure 6).Finally, after gathering all the data for theoretical calculations, a physical model was developed. This model includes temperature calculations, dimensioning, material selection, and comfort temperature standards according to the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE), as well as electromechanical design considerations. The resulting model is as follows, where pairs of points such as: (A;G), (B;H), (C;I), (D;J), (E;K) and (F;L) share the same value on the axis " x" which represents the external temperature, but on the "y" axis it varies depending on whether the skin facade is used or not, because the latter represents the internal temperature of the building.

The concept of the design was based on the decorative triangular pattern used in the Inca ceramics that came from the Mantaro Valley [19], as can be seen on page 226 of the thesis "Early Peruvian Peasants: The Culture History of a Central Highlands valley" by David Ludwig to obtain the degree of Doctor; finally, the complementary current of influence was the "lliclla" (woven mantle) which are typical cloaks of the high Andean regions of Peru, used both in ancient times and today; in most cases, they are used by women to carry their babies, various objects and food; In addition, they have different geometric shapes that were considered within Inca iconography, as well as motifs of artistic representations in their ornamental objects [20].

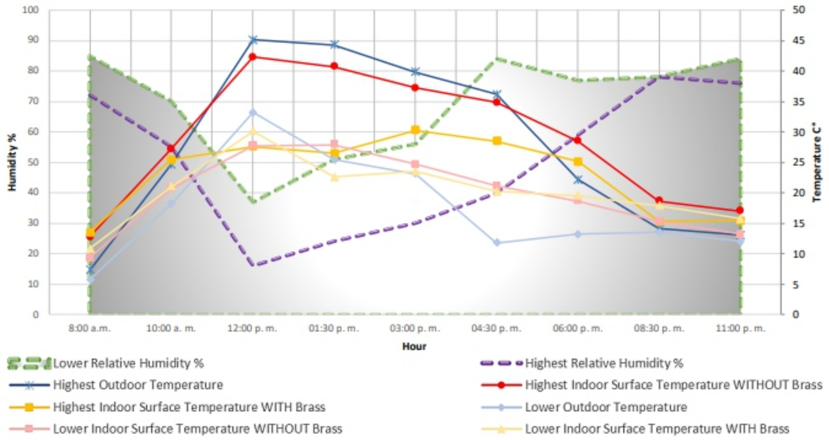


Figure 5. Compilation of temperature and humidity measurement data using or not using the modular membrane, using the Excel MS program

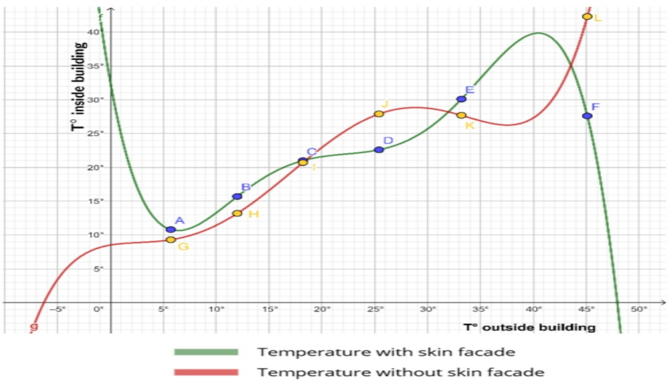


Figure 6. Comparison of predictive algebraic functions, inner T °with membrane vs. outer T °and inner T °without membrane vs. external T °

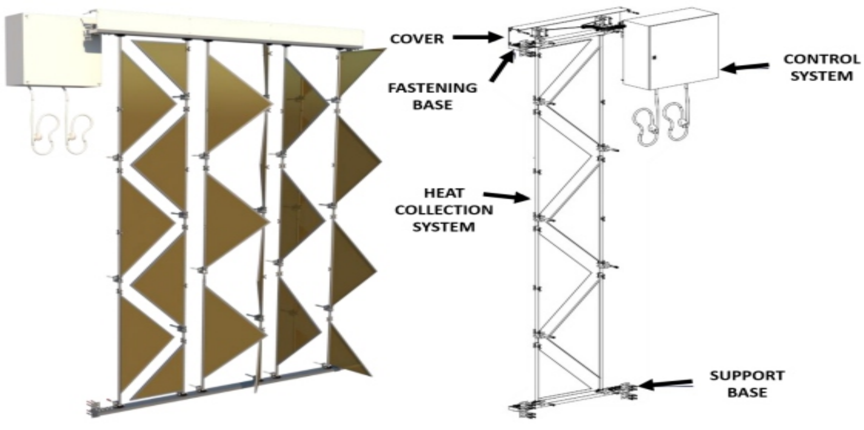


Figure 7. 3D Modeling of the Modular Architectural Membrane

The model consists of a "C" type clamping base, attached and parallel to the support base, attached both at the top and bottom to the heat collection system, all composed of multiple assembly parts, as well as an electric control system and a cover for the protection of the externally located control system (Figure 7). Specifically it is designed to meet the minimal conditions for the fulfillment of SDG 9 (industry, innovation, and infrastructure), which is the development of construction technology that positively influences the current infrastructure [21]. SDG 11 (sustainable cities and communities) specifically complies with subsection 11.4 (redouble efforts to protect and safeguard the world's cultural and natural heritage) due to the shape of the lliclla" and geometric arrangements similar to Inca pottery. Finally, SDG 13 (adopts urgent measures to **c**ombat climate change and its effects) is partially implemented because only subsection 13.2 (incorporates measures related to climate change into national policies, strategies, and plans) is supported.

4 . Discussions

According to Givoni's bioclimatic diagram obtained with Climate Consultant software (Figure 8), design guidelines were provided in accordance with the California energy code so that all hours are comfortable in buildings for users.

According to Givoni's graph, its results reinforce the use of architectural modular membranes during the winter period, given that Huancayo experiences significant climatic variation. During this stationary period, temperature regulation is essential to prevent health issues and create environments that do not hinder productivity.

The system under study shows similarities in insulation between the modular architectural membrane (for the exterior of the building) and the heavy curtains (for the interior). Givoni highlights that heavy curtains are a significant contribution to interior design, helping to prevent heat loss at night and overheating during the day.

The calculated parameters are highly controllable if they remain within the highest and lowest points of the graph corresponding to the Lagrange analysis. Data outside these parameters are considered non controllable or non-measurable, which means the system's behavior in response to such data is unknown.

For buildings with facades that include cantilevers, it is recommended to use a mobile axis system to achieve optimal heat capture, resulting in performance comparable to a smooth facade without overhangs.

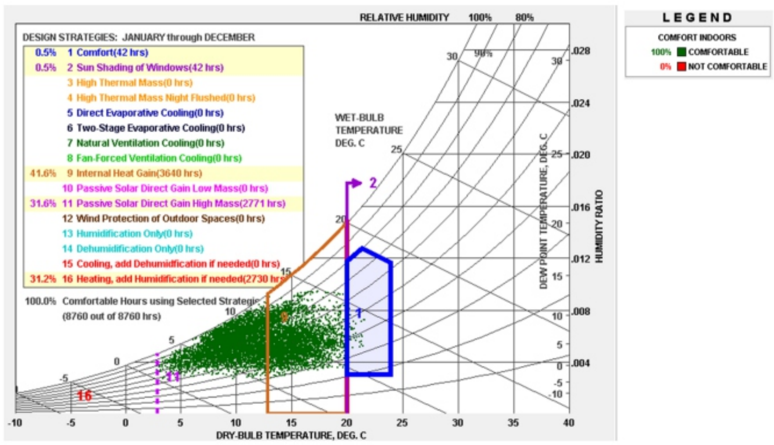


Figure 8. Givoni bioclimatic diagram using the Climate Consultant program

5. Conclusions

As for the materials used, those with high thermal conductivity, such as aluminum and stainless steel, were selected. These materials were carefully chosen not only for their ability to transfer heat efficiently, but also for their ability to reflect and store heat, which facilitates internal temperature control of the buildings without compromising structural integrity. The choice of these materials was key to the success of the project, allowing temperatures to be maintained between 20 and 24 °C consistently. In addition, the resulting structure is durable and energy efficient. The modular façade design, inspired by traditional Andean cultural patterns, adds value to the project by integrating cultural and aesthetic elements. This not only improves the building's energy performance, but also reinforces the cultural identity of the region, harmoniously combining tradition with technological innovation.Specifically, brass plays a key role in this project because of its excellent ability to absorb and retain heat, making it a key material for thermal regulation in buildings. Brass has a moderate thermal conductivity, in the range of 100-150 W/m-K, which allows it to transfer heat efficiently, although not as quickly as copper or aluminium. In addition, its specific heat of approximately 0.380 J/g-°C gives it a remarkable ability to store heat, allowing it to efficiently absorb energy during the hottest hours and releasegradually as the outside temperature drops. This helps stabilize the internal temperature of buildings and optimizes energy use, reducing the need for additional heating or cooling systems. Brass, aluminium and stainless-steel form a strong, lightweight and energyefficient composite.

Choosing these materials was key to the project's success. Each one boosts the modular facade's durability and its ability to regulate internal temperatures. Furthermore, the integration of these materials in a design inspired by traditional Andean cultural patterns not only improves the energy efficiency of the building but also reinforces cultural identity of the region. Brass, in particular, provides a significant advantage in terms of thermal performance, the modular facade design allows for a seamless fusion of tradition and advanced technology.

Finally, physical models and digital simulations have demonstrated the effectiveness of the project. The modular façade system has improved the thermal comfort of the interiors. The optimal temperature values achieved in the project, compared to the extreme values, indicate a significant improvement in thermal regulation, with an average percentage variation of approximately -2.34%, suggesting that the internal temperature values remain more stable and comfortable. This value is beneficial in the internal thermal control of a building, helping to maintain a more balanced temperature and reducing the need for additional heating or cooling systems. This modular approach allows the system to be applied to many building projejects. It benefits both new and existing buildings with thermal and aesthetic improvements. Ultimately, the project ensures thermal functionality and contributes to sustainable development by promoting more efficient infrastructures and more environmentally friendly cities. This meets long-term sustainability goals and improves the quality of life for residents.

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The Impact of Balconies on Daylight Quality in Living Rooms of Jordanian Residential Buildings: A Parametric-based Multi-objective Optimization Approach

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ABSTRACT

Daylighting is a fundamental consideration in the design of buildings and interior spaces. The quality of daylight is significantly influenced by the building envelope, including its openings and shading elements. Balconies, as a type of shading device, can mitigate excessive direct sunlight. This study examines the effect of attached balconies on daylight quality in living rooms. It evaluates three types of balconies -recessed, semi-recessed,
cantilevered- across varying depths, along with the aperture ratios associated with these designs. A parametric multi-objective optimization approach was employed to achieve the study's objectives. The base case model was developed using Grasshopper, a parametric modeling tool integrated with Rhinoceros 3D. Daylight simulations were conducted using the Ladybug and Honeybee plug-ins, focusing on two annual daylight metrics: Daylight Autonomy (DA) and Annual Sunlight Exposure (ASE). Subsequently, a multi-objective optimization process was carried out using Octopus, a Grasshopper plug-in for optimization. This process identified optimal balcony configurations that balance DA and ASE values to enhance daylight quality. The results demonstrate that balconies positively influence daylight quality and effectively reduce visual discomfort in living rooms.
Keywords *Daylight Performance, Balcony, Parametric Model, Optimization*

1. Introduction

This study aimed to investigate the impact of balconies on daylight performance in living rooms of Jordanian residential buildings. Balconies are important architectural elements in residential buildings in Jordan. Considering balconies design in the initial stage of design and understanding their impact on daylighting in interior spaces help in making optimal design decisions, to avoid problems related to visual discomfort, glare, and overheating.Balconies are known as a form of shading devices and they were investigated in research worldwide, as their impact on daylighting in interior spaces and blocking excess sunlight was studied. Despite their important presence in residential units in Jordan to provide semi-private outdoor spaces, there is a shortage of studies that suggest optimal design solutions for balconies to benefit from them in controlling daylighting in indoor spaces.The study adopted a parametric-based multi-objective optimization approach to modeling, simulating and exploring the various options of balconies and apertures design to improve daylight quality and visual comfort interior spaces.

2. Background

Daylight is one of the most important factors responsible for improving the quality of indoor environment, therefore influencing human well-being [1]. The openings of the building control the delivery of daylight to the interior spaces, but openings are also responsible for causing changes in the internal temperature because of heat transfer and the passage of excessive sunlight, thus gaining heat in the summer and losing the required heat in the winter. [2]. Designing buildings in a manner consistent with taking advantage of daylight is not a new topic. The evaluation methods and tools used to achieve this goal are varied over time because of technological development.

Different daylight metrics are used to evaluate daylight performance. These metrics are classified into static and dynamic metrics. The two groups of metrics were categorized based on the sky model and analysis period. The static metrics depend on point-in-time periods with standard sky models while dynamic metrics depend on an annual period with a climate-based sky model [3]. Daylight Factor (DF) is defined as a static daylight performance metric, which is a famous metric developed in 1892 in the United Kingdom by Trotter [4]. Because sky model conditions for measuring DF are standard, the values of DF are not affected by the sun's position, time, climate conditions, and building orientation, which is considered one of the shortcomings of this metric [5, 6]. Dynamic metrics include Daylight Autonomy (DA), Useful Daylight Illuminance (UDI), Spatial Daylight Autonomy (sDA), and Annual Sunlight Exposure (ASE). These metrics predict daylight performance based on building location and orientation, as well as material optical properties and space shape [7].

Building envelope including its shading devices has a direct and crucial role in controlling daylight in interior spaces, as shading devices are very important to improve visual comfort and decrease the undesirable direct daylight [8, 9]. Balconies are defined as overhanging structures surrounded by walls or railings; their main function is to connect interior with exterior spaces, which contribute to decreasing direct sunlight and providing proper levels of daylighting [10, 11]. The effect of balconies on the luminous performance in residential buildings was investigated by other researchers [12, 13]. The results agreed with the literature results of the daylight simulation, as they assured that balconies played a crucial role in increasing visual comfort by reducing direct daylight. In a novel study, Loche, de Souza [1] explored the role of balconies in office buildings to improve daylight quality and decrease solar radiation. The results showed that balconies influenced directly on reducing glare and overheating.

Although there are many studies worldwide that have examined the role of balconies in daylight quality in residential and office buildings, there are no studies in Jordan that have searched this topic, as most published studies focused on the impacts of openings and shading devices on daylight performance in interior spaces [14-18].

The proposed approach in this study deals with balcony parameters (type and depth) and aperture ratio. These parameters are investigated related to their impact on daylight quality by simulating two conflicting daylight performance metrics, then, various options of these parameters are optimized to achieve the required level of daylighting.

3. Methodology

To achieve the research aim, a parametric-based multi-objective optimization approach was adopted. The research methodology comprised three phases: base case modeling, daylight simulation, and multi-objective optimization. Figure 1 illustrates a diagram of the research framework. In the following subsections further details for each phase are provided

ModelingThe base case for this study was a typical residential building located in Amman, Jordan. A parametric model was generated in two parts, by Grasshopper (Algorithmic modelling plugin for Rhino3D) for the first part and by Honeybee (Environmental simulation tool for Grasshopper) for the second one. The second part of this phase was converting the Grasshopper model to a Honeybee model to make it processable by the tools of LB and HB (1.3.0) for daylight calculations, as well as to add a parametric balcony and a parametric aperture overlooking this balcony to the model. The impact of the aperture was investigated regarding its ratio related to the wall (WWR), as it is fixed to the center of the wall. The impact of the aperture position and height was not investigated separately, takinginto consideration the materials of balconies and apertures not considered in this study. Also, the balcony types were limited to different depths of open balconies without glazing, the balcony's handrail was solid, not glazed. The base case was on the ground floor and the impact of other levels was not investigated.

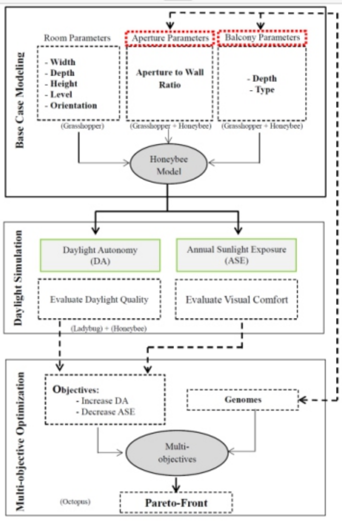


Figure 1. Research Framework

3.2. Daylight Simulation Process

Two conflicting dynamic daylight metrics were used to evaluate daylight performance namely: DA and ASE. The used EnergyPlus weather (EPW) file in this research was provided by the weather station of Queen Alia International Airport in Amman-Jordan. The climate in Jordan combines Mediterranean and desert climates, as it is hot and dry in the summer and cold in the winter. The following simulation in this study could be applied to other countries with different climates by changing the EPW file according to the provided weather data in these countries. Otherwise, the results of this study are valid for countries with similar climates. For calculating DA and ASE metrics for the HB model, a daylight analysis sensors grid was generated. The grid size for this study is 0.5×0.5 m and height is 0.76 m. Also, an annual occupancy schedule was determined from 8 am to 6 pm. The proper percentage of the DA lies between 50-100%, while ASE should not exceed 10%. The adopted metrics in this study indicate the impact of the balcony and aperture on daylight performance without reference to their impact on energy efficiency, which could be investigated in future studies. Moreover, other annual daylight metrics could be examined and assessed in future research to improve daylight quality in indoor spaces, and these metrics include Continuous Daylight Autonomy (cDA), Useful Daylight Illuminance (UDI), Spatial

Daylight Autonomy (sDA), and Daylight Glare Probability (DGP).

3.3. Optimization Process

The plug-in Octopus (0.4) for Grasshopper was used for this phase. Octupus is an evolutionary multi-objectives optimization tool for parametric design and
problem-solving. The purpose of Octopus is to achieve the balance between conflicting objectives by modifying the parameters related to these objectives to generate a range of optimized compromise solutions between the objectives [19]. Octopus plugin requires two main inputs to run, the parameters (Genoms) and the objectives. The parameters of this process were balcony depth, balcony type, and aperture ratio while the objectives were the dynamic daylight metrics DA and ASE, as the goal was to increase DA values and decrease ASE values.

4. Results and Discussion

4.1. Base Case Modelling

This phase involves developing an initial model that represents the standard or existing conditions, serving as a baseline for evaluating improvements. The base case reflects the current design or performance benchmarks and is critical for identifying gaps and opportunities for optimization. This phase resulted in a HB parametric model that can be modified using number sliders for each variable. The main parameters that formed the room were: width, depth, height, and floor level. Table 1 shows the characteristics of the base model in this phase.

Table 1. Base case model characteristics

Parameter	Value\ Description
Room width	*4 m*
Room depth	3 m
Room height	3 m
Floor level	Ground floor
Glazing Transmittance	0.6
Wall Reflectance	0.8

Table 2 shows the variable parameters of the added alcony and aperture to the base case. The balcony arameters were divided into two sections: the balcony epth with the range of: (1.0, 1.1, 1.3, … , 2 meters) and the alcony type with three options: (Recessed Balcony, emi-recessed Balcony, Cantilevered Balcony).

Table 2. Base case variable parameters

Parameter	Value\ Description
Balcony Depth	(1.0, 1.1, 1.3,…. 2) meters
Balcony Type	Recessed Balcony Semi-recessed Balcony Cantilevered Balcony
Aperture Ratio	(30 ,40 ,50 ,60,70 ,80) %

Table 3. Balcony type options

Recessed	Semi-recessed	Recessed
		

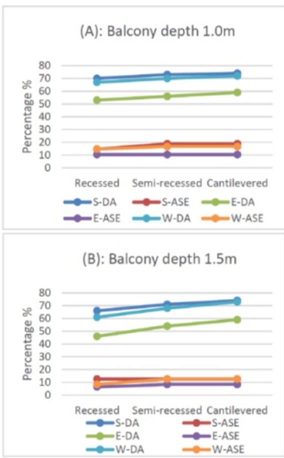
4.2. Daylight Simulation

Two annual daylight metrics DA and ASE were calculated for the HB model. The values of DA and ASE varied depending on changing the parameters. Next, the simulation results were analyzed for each façade (south, east, and west), as each variable (Balcony type, depth, and aperture ratio) was compared individually according to their impact on DA and ASE values.

4.2.1. Balcony Type

4.2.1. Balcony Type

Daylight simulations were conducted for the three types of balconies to measure the effect of each type on the values of DA and ASE. Simulations for these types were carried out on three different balcony depths (1.0, 1.5 and 2.0) m. The aperture ratio was fixed to 30%. Figure 2 shows the daylight simulation results for three models, and each model represents DA and ASE values for balcony types with different depths. The following models (A, B, and C) show the effect of changing the balcony type on DA and ASE values. The values increased significantly when changing the type of balcony from recessed to semi-recessed, and the most effective effect was when changing it to cantilevered on the three facades. However, the increase in DA values was considerable in Model C, where the balcony depth was 2 meters. In contrast, ASE values increased at a lower rate in the south and west facades (Models A and B) and remained constant in the eastern facade at a depth of one meter (Model A). However, the effect was clearer when the depth of the balcony was 2 meters (Model C), as the ASE values increased by greater proportions when changing the balcony type from recessed to cantilevered.Daylight simulations were conducted for the three types of balconies to measure the effect of each type on the values of DA and ASE. Simulations for these types were carried out on three different balcony depths (1.0, 1.5 and 2.0) m. The aperture ratio was fixed to 30%. Figure 2 shows the daylight simulation results for three models, and each model represents DA and ASE values for balcony types with different depths. The following models (A, B, and C) show the effect of changing the balcony type on DA and ASE values. The values increased significantly when changing the type of balcony from recessed to semi-recessed, and the most effective effect was when changing it to cantilevered on the three facades. the increase in DA values was considerable in Model C, where the balcony depth was 2 meters. In contrast, ASE values increased at a lower rate in the south and west facades (Models A and B) and remained constant in the eastern facade at a depth of one meter (Model A). However, the effect was clearer when the depth of the balcony was 2 meters (Model C), as the ASE values increased by greater proportions when changing the balcony type from recessed to cantilevered.



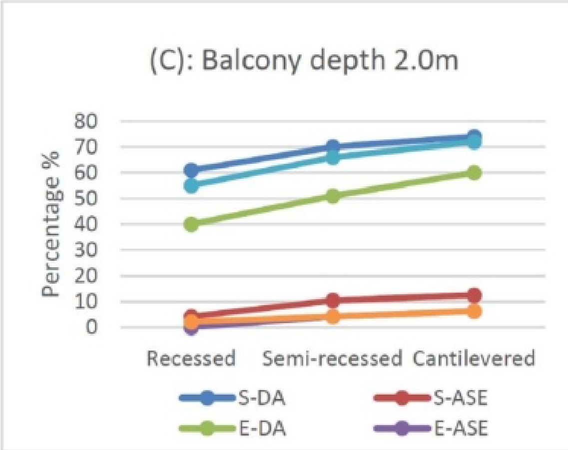


Figure 2. Daylight simulation results for three types of balconies with different balcony depths

4.2.2. Balcony Depth

The impact of balcony depth on DA and ASE values was investigated for the three facades. The results showed that increasing balcony depth significantly decreased ASE values, while this increase had a less effect on the DA values. The results of daylight simulations for three models are presented in Figure 3. The chart for each model represents the impact of balcony depth on DA and ASE values with a different balcony type and the same aperture ratio of 30%. In the recessed and semi-recessed balcony types, there was a decrease in DA values when the depth of the balcony increased from 1 to 2 meters, as in models A and B. In comparison, the values remained equal at all depths when the balcony type was cantilevered (Model C). As for ASE values, there was an obvious decrease in the three models when the depth of the balcony increased, and this decrease was greater when the type of balcony was recessed (Model A).

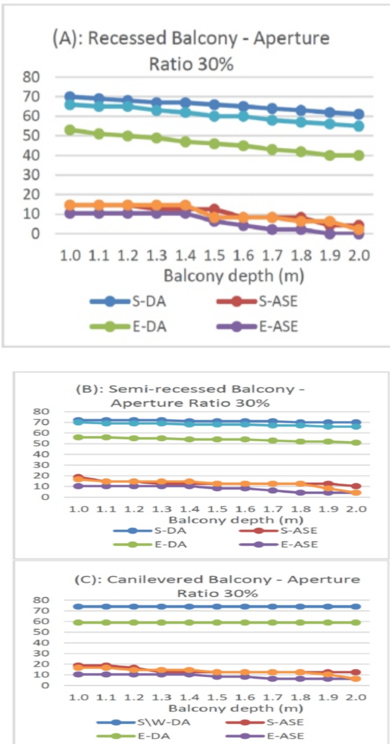


Figure 3. Daylight simulation results for models with different balcony depths

4.2.3. Aperture Ratio

The impact of increasing the aperture ratio on DA and ASE values was examined for the three balcony types (Models A, B, and C) with (1) meter depth as shown in Figure 4. Increasing the aperture ratio led to an increase in DA and ASE values in the three models. Increasing the aperture ratio had the greatest effect on the DA and ASE values compared to the effect of the type and depth of the balcony, as previously reviewed. As shown in Models A, B, and C, these values increased significantly in the three facades, especially the ASE values, which reached extreme levels, exceeding the desired limit of 10%.

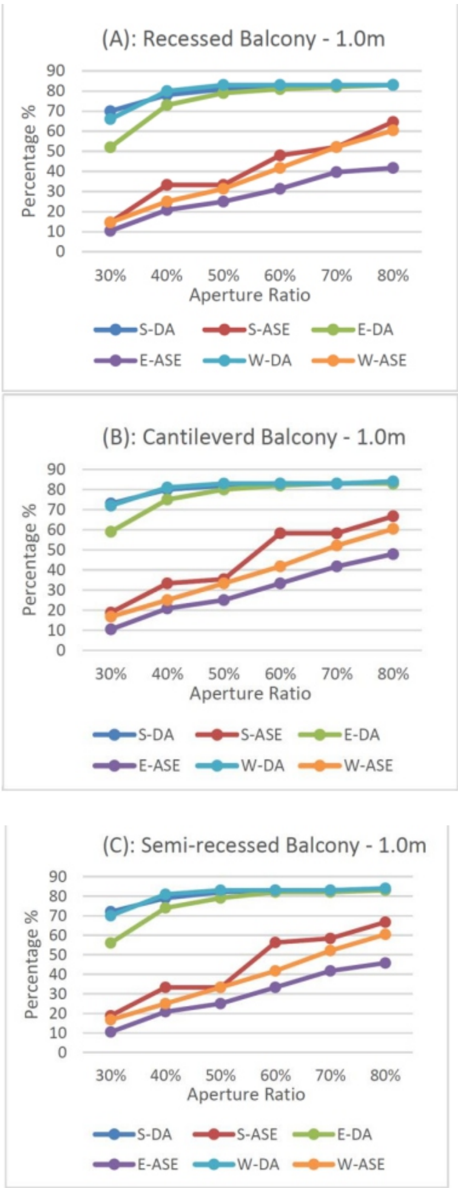


Figure 4. Daylight simulation results for models with different aperture ratios.

4.2.3. Aperture Ratio

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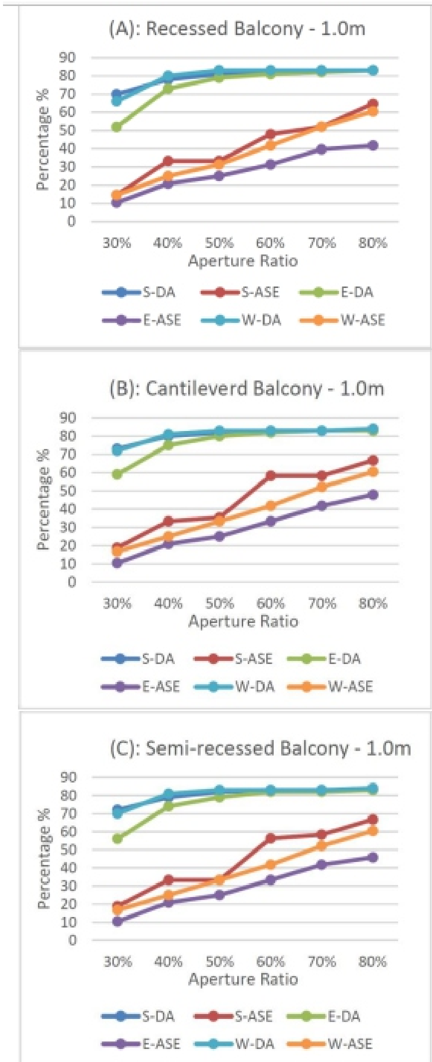

Figure 4. Daylight simulation results for models with different aperture ratios.

4.3. Multi-objective Optimization

4.3.1. South Facade

An optimization process was carried out for the south façade to examine the parameters that achieve the balance between DA and ASE. Table 4 shows the values of the Pareto solutions for the conflicting objectives. The optimal solutions are chosen through a trade-off between the two objectives, as improving one objective depends on reducing the value of the other one [19].

4.3.1.1. Selection of Optimal Models

The optimization process facilitates selecting the optimal models, as it is challenging to simulate each scenario for the base case and compare all variables that achieve the balance between the conflicting objectives: increasing DA value and decreasing ASE value. Semi-recessed balconies with a 30% aperture ratio achieved a proper level of ASE values when the depth of balcony is at least 1.6 m as shown in models (03) and (05). Increasing aperture ratio up to 40% requires changing balcony type to a recessed balcony in order to compensate for the increase in exposure to direct sunlight as in model(10).

For achieving proper levels of DA and ASE values with a cantilevered balcony, it requires to increase balcony depth up to 2.0 m with a 30% aperture ratio as in (07). Model (2) with a recessed balcony, 1.7 m depth, and a 30% aperture ratio achieves the lowest value of ASE compared to other models.

Table 4. Pareto solutions for the south façade

Model #	Parameters			Objectives	
	Balcony Depth (m)	Balcony Type	Aperture Ratio	DA (%)	ASE (%)
01	1.9	Recessed	30%	62	4.2
02	1.7	Recessed	30%	64	8.3
03	2.0	Semi-recessed	30%	70	10.4
04	1.8	Semi-recessed	30%	70	12.5
05	1.6	Semi-recessed	30%	71	12.5
06	1.1	Semi-recessed	30%	72	14.6
07	2.0	Cantilevered	30%	74	12.5
08	2.0	Recessed	40%	75	12.5
09	1.2	Cantilevered	30%	74	16.7
10	1.8	Recessed	40%	76	12.5
11	1.9	Semi-recessed	40%	78	16.7
12	2.0	Recessed	50%	79	14.6
13	1.7	Cantilevered	40%	80	16.7
14	2.0	Semi-recessed	50%	81	16.7
15	2.0	Recessed	60%	81	20.8
16	1.9	Cantilevered	50%	82	20.8
17	1.9	Semi-recessed	70%	83	25.0
18	2.0	Cantilevered	70%	83	27.1

The extreme value for each objective
The selected optimal models

4.3.2. East Façade

The values of the Pareto solutions for the east facade are shown in Table 5 which illustrates the extreme value for each objective and the in-between values that approach the desired levels of DA and ASE. In this façade, increasing the aperture ratio is possible, while keeping ASE values within a proper range.

4.3.2.1. Selection of Optimal Models

Six optimal models were selected from Table 5, as these models achieved the desired levels of DA and ASE values for the east facade. In this facade, the required values of DA and ASE are achieved in models with an aperture ratio exceeding 40% and may reach up to 80%, as in models (13), and (17). But the balcony type in these models must be recessed with at least 2.0 m depth. In models with aperture ratio of 40%, there was a possibility to reduce balcony depth up to 1.7 m with semi-recessed balcony type as in model (09), or recessed balcony with 2.0 m balcony depth to achieve lower ASE values in model (07). Models with cantilevered balcony achieved suitable values for DA and ASE at a depth of 2.0 meters with an aperture ratio of 30%, as in model (05).

4.3.3. West Façade

The various scenarios and parameters for the west facade were investigated by carrying out the optimization process in Octopus plugin. Table 6 shows the Pareto optimal solutions for the west facade. The values represent the extreme value for each objective and the in-between values that approach the proper levels of DA and ASE.

4.3.3.1. Selection of Optimal Models

All the selected models that achieved the optimal DA and ASE values in the west façade had an aperture with a ratio of 30%. The lowest ASE value was achieved in model (04) with a semi-recessed balcony of 2.0 m depth.

Table 5. Pareto solutions for the east façade

Model #	Parameters			Objectives	
	Balcony Depth (m)	Balcony Type	Aperture Ratio	DA (%)	ASE (%)
01	1.9	Recessed	30%	41	0.0
02	1.7	Recessed	30%	44	2.1
03	1.8	Semi-recessed	30%	53	4.2
04	1.0	Recessed	30%	53	10.4
05	2.0	Cantilevered	30%	59	6.3
06	1.0	Cantilevered	30%	59	10.4
07	2.0	Recessed	40%	65	6.3
08	1.9	Recessed	40%	66	8.3
09	1.7	Semi-recessed	40%	72	10.4
10	2.0	Cantilevered	40%	75	10.4
11	1.5	Cantilevered	40%	75	14.6
12	1.8	Recessed	60%	75	14.6
13	2.0	Recessed	60%	79	10.4
14	2.0	Recessed	70%	81	10.4
15	1.0	Recessed	40%	73	20.8
16	1.0	Cantilevered	40%	75	20.8
17	2.0	Recessed	80%	82	12.5
18	1.9	Recessed	80%	82	14.6
19	1.8	Recessed	80%	82	16.7
20	1.8	Semi-recessed	80%	82	22.9

The extreme value for each objective

The selected optimal models

Table 6. Pareto solutions for the west façade

Model #	Parameters			Objectives	
	Balcony Depth (m)	Balcony Type	Aperture Ratio	DA (%)	ASE (%)
01	2.0	Recessed	30%	54	2.1
02	1.9	Recessed	30%	56	6.3
03	1.7	Recessed	30%	58	8.3
04	2.0	Semi-recessed	30%	66	4.2
05	1.9	Semi-recessed	30%	66	8.3
06	1.0	Recessed	30%	66	14.6
07	2.0	Cantilevered	30%	73	6.3
08	1.9	Cantilevered	30%	73	10.4
09	1.6	Cantilevered	30%	73	12.5
10	1.3	Cantilevered	30%	72	14.6
11	2.0	Recessed	40%	76	14.6
12	1.7	Recessed	40%	77	18.8
13	2.0	Semi-recessed	40%	80	16.7
14	2.0	Cantilevered	40%	81	16.7
15	1.1	Recessed	40%	80	20.8
16	1.2	Cantilevered	40%	81	20.8
17	2.0	Cantilevered	50%	83	18.8
18	1.0	Recessed	40%	80	25
19	1.9	Cantilevered	50%	83	20.8
20	2.0	Semi-recessed	80%	83	31.1

The extreme value for each objective

The selected optimal models

As for recessed balcony type, it achieved the optimal DA and ASE values at 1.7 m depth, as in model (03). Cantilevered balconies achieved balance between the conflicting objectives in two models (07) and (09) at 2.0 and 1.7 m depth.

5. Conclusions

This study highlights the significant role of balconies in enhancing daylight quality and mitigating visual discomfort in living rooms of residential buildings in Jordan. By employing a parametric-based multi-objective optimization approach, the research examined three balcony types—recessed, semi-recessed, and cantilevered—across varying depths, in addition to aperture-to-wall ratios. The findings demonstrated that balconies contribute positively to controlling excessive direct sunlight and improving indoor visual comfort by balancing Daylight Autonomy (DA) and Annual Sunlight Exposure (ASE) metrics.The study's recommendations include increasing aperture ratios up to 40% on the south façade and up to 80% on the east façade, with balconies effectively managing sunlight exposure to enhance daylight quality. However, for the west façade, the aperture ratio should not exceed 30% due to the high potential for glare and visual discomfort. These recommendations contrast with the ASHRAE-prescribed maximum Window-to-Wall Ratio (WWR) of 40%, suggesting the need for localized adaptation of standards to account for specific climatic and contextual factors.

Furthermore, the research confirmed the effectiveness of balconies in reducing visual discomfort and glare, aligning with previous studies that have recognized the role of balconies in achieving optimal daylighting and enhancing visual comfort. By blocking undesirable sunlight through overhangs and strategically managing daylight penetration, balconies support both functional and aesthetic objectives in residential design.These findings underscore the importance of integrating balcony design as a key component in residential architecture, particularly in regions with similar climatic conditions to Jordan. Future studies could expand this work by exploring the interplay between balcony design and other environmental factors, such as thermal comfort and energy efficiency, to provide a more comprehensive understanding of their role in sustainable building design.The following are detailed recommendations for designers to consider when designing balconies improve daylight quality in interior spaces:

(a) For the south façade:

1. Living rooms with recessed balconies, 1.7 m depth, and a 30% aperture ratio are optimal for achieving the lowest ASE values and adequate DA.
2. Semi-recessed balconies with a 30% aperture ratio achieve appropriate DA and ASE values when the balcony depth is at least 1.6 m.
3. Recessed balconies with a 40% aperture ratio achieve adequate DA and ASE values when the depth is 1.8 m.4. Cantilevered balconies require a depth of 2.0 m with a 30% aperture ratio to achieve proper DA and ASE levels.

(b) For the east façade:

1. Living rooms with aperture ratios exceeding 40% up to 80% and recessed balconies of 2.0 m depth achieve a balance between DA and ASE values.
2. Semi-recessed balconies with a depth of 1.7 m reach proper DA and ASE levels when the aperture ratio is fixed at 40%.
3. Recessed balconies with a 2.0 m depth and a 40% aperture ratio achieve the lowest ASE values and adequate DA.
4. Cantilevered balconies with a 2.0 m depth achieve the lowest ASE values when the ratio is reduced to 30%.

(c) For the west

1.Living rooms with a 30% aperture ratio and any balcony type (recessed, semi-recessed, or cantilevered) achieve the required DA and ASE values.
2. Semi-recessed balconies of 2.0 m depth achieve the lowest ASE values.
3. Recessed balconies with a 1.7 m depth meet the required DA and ASE levels.
4. Cantilevered balconies with depths of 1.7 m and 2.0 m achieve appropriate DA and ASE values.

These findings confirm the effectiveness of balconies in visual discomfort and glare while enhancing daylight quality. By blocking undesirable sunlight through overhangs and strategically managing daylight penetration, balconies support both functional and aesthetic objectives in residential design.Future studies could expand this work by exploring the interaction between balcony design and other environmental factors, such as thermal comfort and energy efficiency, to provide a more comprehensive understanding of their role in sustainable building design.

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