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Bioclimatic Design Guidelines for Design Decision Support to Enhance Residential Building Thermal Performance in Tropical Regions

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Abstract: With the rise of building thermal comfort issues, the Bioclimatic Design Guideline for Cambodia (BDGC) has been developed to help architects make informed decisions during their design process to achieve maximum thermal comfort with minimum energy consumption. This paper aims to investigate the reliability of this guideline as decision support to enhance residential building thermal performance by using two research approaches: usability tests and calibrated thermal performance simulations based on real buildings monitoring and simulations using DesignBuilder. Five groups of architects and students in architectural engineering participated in the usability test to redesign two common typologies of single-family homes with weak thermal performance by using bioclimatic design guidelines, such as orientation, improved ventilation, shading, and green rood, to enhance their comfort level. The simulation shows that, by applying bioclimatic design strategies, the indoor temperature in the base case house can be lower from 2 to 4 °C. Various benefits are identified from the integration of the BDGC during the design process for improving residential building design. Moreover, the proposed methodology can be applied to develop and validate bioclimatic guidelines in other regions and various countries worldwide.

Keywords: climate-responsive architecture; design decision support; building thermal performance; bioclimatic solutions; tropical climate

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1. Introduction

Cambodia is a developing country located in southeast Asia with a tropical climate of monsoon weather. Phnom Penh, which is the capital city of Cambodia, accommodates 15% of the overall Cambodian population with an increase of a 3 percent growth rate annually from 1.6 million in 2012 to 2.2 million in 2022 [1]. The rapid migration of populations from provincial areas to urban centers has led to a significant increase in the development of residential buildings in and around city centers. In Phnom Penh, high-rise apartment buildings dominate the city center, while gated communities cover the suburban areas. However, the development of these residential buildings is primarily driven by profit maximization, often at the expense of occupant comfort by favoring the use of air conditioners as a primary solution for achieving thermal comfort in these buildings. Consequently, architects are increasingly compelled to design spaces that rely on air conditioning systems, rather than incorporating natural ventilation as a means of regulating indoor temperature.

Indoor thermal comfort has become a major issue for building design, especially with climate change. Achieving building thermal comfort has been a great challenge for all designers as it depends on various influenced parameters, including physical (air temperature, relative humidity, radiant temperature, and air velocity) and individual factors [2]. To assist thee designers in achieving and ensuring indoor thermal comfort, various international standards, such as ISO 17772-1 [3], ASHRAE 55 [2], and ISO 7730 [4], have been established, focusing on maintaining the indoor environmental quality (IEQ) within buildings. In promoting building sustainability while maintaining the comfort factor, climate-responsive design strategies were introduced into the building sector in 1953 [5]. Bioclimatic design is a branch of climate-responsive design strategies that aims to achieve building comfort with minimum energy consumption considering the surrounding environmental conditions. It is considered to be a design strategy that is eco-friendly, human-friendly, and energy-friendly [6]. Many studies have been conducted to determine bioclimatic design strategies that could improve building thermal performance in various climate conditions [7–10]. Consequently, climate-responsive design strategies have been consolidated into design guidelines to assist architects and designers in achieving optimal comfort and sustainability in building designs. In the semi-arid climate of Pakistan, a prescriptive guide has been developed based on a sensitivity analysis of various passive strategies, including building orientation, opening design, insulation, and building materials [11]. Similarly, in Vietnam, Nguyen [12] proposed a design guideline tailored to three distinct regions of the country, derived from an analysis of passive design principles in vernacular architecture. Another guideline has been formulated for three diverse climatic zones in Nepal, emphasizing site planning, building envelope considerations, building layout, opening design, and placement, among other factors [13]. Most of these guidelines are suitable for residential building design due to their low complexity in function which most accommodates these design strategies. However, bioclimatic design guidelines developed for a specific country are often difficult to apply in other contexts due to variations in practical, cultural, and user knowledge factors. This challenge is particularly pronounced for guidelines that heavily depend on local climate and environmental conditions. Additionally, the practical application and usability of these guidelines have not been extensively explored in professional and educational environments, particularly for decision support during the design process for architects and students.

The literature review above reveals a substantial body of research focused on identifying bioclimatic design strategies for various regions worldwide. However, the application of these strategies within the professional field has been comparatively underexplored. In Cambodia, bioclimatic design strategies remain largely unfamiliar and underutilized by architects and professionals in the building industry, as demonstrated by a survey we conducted in 2021 (the thesis of this finding has yet to be published). Our literature review further reveals that bioclimatic design and sustainable architecture have not been widely studied within the Cambodian context, resulting in limited research on bioclimatic strategies and building thermal comfort. The few available studies provide only a basic overview of sustainable design practices in the construction sector and the attitudes of citizens toward these approaches [14,15]. As previously mentioned, sustainability is often not prioritized in Cambodian building design, due to various constraints, including limited knowledge and insufficient research. Addressing these gaps through focused action is essential to advancing sustainable architecture in the country.

To achieve sustainability and indoor thermal comfort for buildings, what has happened during the architectural design process is very crucial, including the design strategy choices, the decision-making, and the multidisciplinary collaboration of the actors. The architectural design process is complicated and challenging [16]. To ensure a smooth design process, CAD (computer-aided design) has been used for various design activities, adding the goal of thermal comfort and sustainability, and taking the design challenge to another level. Therefore, other technologies of digital tools, such as BES (building energy simulation) and BIM (building information modeling), have been introduced to help with building modeling, analysis, and decision support [17,18].

In our previous study [19], we can see that in developing countries, which are mostly located in tropical regions, the use of tools and technology, such as BIM and BES, are still limited during the architectural design process. More than that, these approaches are not practiced correctly as a decision support tool for architects in the early phase of the design process due to their complexity and lack of expertise. For architects, it is necessary to provide decision support that would not affect their creativity [20]. There are various forms of informed decision support available, including charts, guidelines, standards, decision support systems, simple (steady state) simulations, dynamic (multizonal) simulations, decision support tools, and prescriptive guides. To address the challenge of integrating sustainability and thermal comfort into residential projects, we have developed the Bioclimatic Design Guideline for Cambodia (BDGC). This guideline includes bioclimatic design strategies that architects can incorporate into their projects to enhance thermal performance with the integration of passive design strategies specific to the context. The BDGC serves as a decision support tool aimed at guiding architects throughout the design process to achieve optimal thermal performance in buildings. A detailed overview of this guideline is provided in the following section.

The objective of this study is to investigate the usability of the BDGC to give informed decision support for architects during the design process and how it can help architects design a building with optimal thermal performance. We aim to understand the integration of the BDGC to improve building thermal performance, at which phase of the design process the guideline can be implemented, its impact on building design aspects, and the overall design process. Three research questions were asked upon this objective:

1. How does the BDGC provide decision support for architects and designers to enhance the thermal performance of residential building design in the tropical region of Cambodia?
2. How does the BDGC impact on the overall design process?
3. Is the BDGC suitable to be implemented at the early stages of the design process?

2. Bioclimatic Design Guideline for Cambodia (BDGC)

Cambodia is situated at 13° North latitude and 105° East longitude, with an average altitude of 126 m above sea level. The country experiences a tropical monsoon climate, characterized by two distinct seasons: the dry season and the rainy season. Temperatures remain relatively high throughout the year, ranging from 28 to 35 degrees Celsius, accompanied by consistently high relative humidity. The following climate criteria should be considered when designing buildings in Cambodia:

- High solar elevation throughout the year.
- The Sun moves from east to west through the north axis for 4 months and through the south axis for 8 months.
- Solar elevation is at its highest when moving through the north axis while at its lowest when moving through the south axis.

- The daytime period is similar between the two seasons when the sun normally rises at 6:00 am and sets at 6:30 p.m.
- Dominant winds are between the southwest and northeast, while stronger winds come from the southwest with high humidity and the northeast wind has less humidity.

The BDGC is a bioclimatic design guideline developed in this study specifically for Cambodia, aimed at assisting the designers to create buildings that maximize thermal comfort while minimizing energy consumption. Compared to the international standard devoted to the IEQ, the BDGC shares a similar goal to promote sustainability and comfort in buildings. However, the BDGC is more focused on functioning as a decision-support for architects and students. In Cambodia's hot and humid climate, the aim is to design buildings that limit direct sunlight exposure, enhance natural airflow, reduce humidity levels, and allow openings to remain usable during the rainy season to ensure the continuous circulation of fresh air. Therefore, the BDGC is developed based on the following parameters:

- A thorough analysis of Cambodia's climatic conditions.
- Bioclimatic principles of traditional and current Cambodian houses that have been utilized for decades.
- Passive design strategies that have been studied in similar tropical climates.

Additionally, it takes into account the living conditions of Cambodians, particularly concerning privacy and security. The primary focus of the BDGC is to promote building designs that maximize natural ventilation while protecting buildings from direct solar radiation and rainfall. Figure 1 explains in detail how the BDGC was developed.

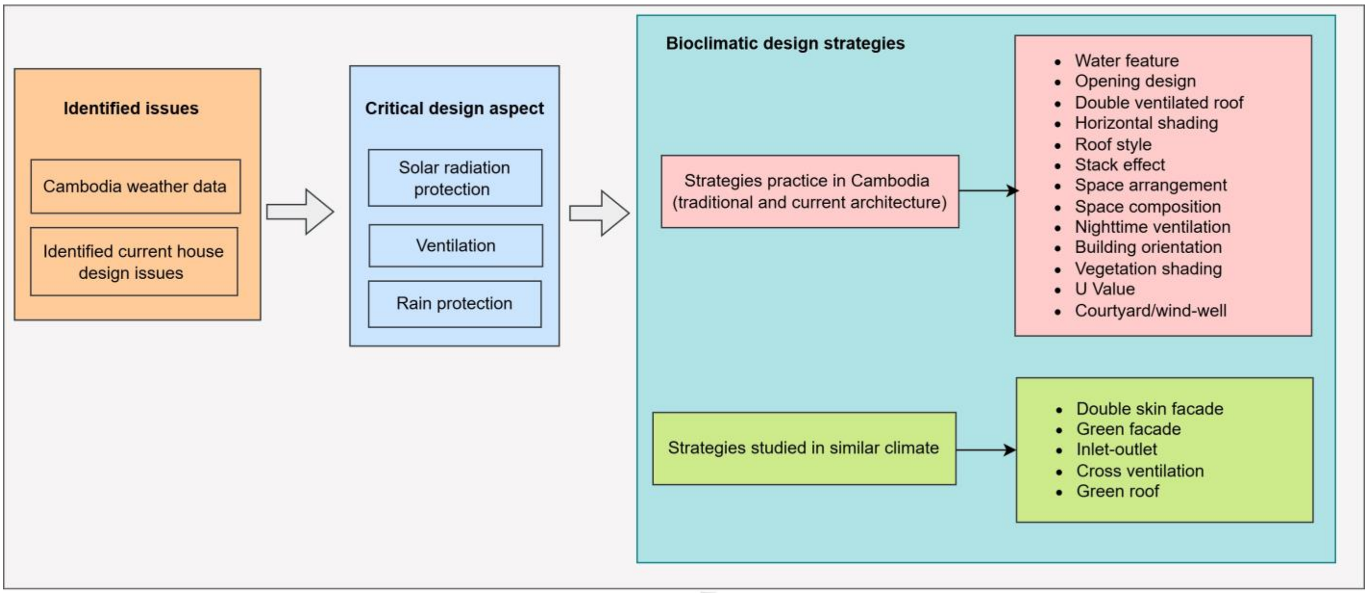

Figure 1. The development of the BDGC.

The BDGC is intended to aid architects and designers in making informed decisions in the early design process when selecting design elements for projects in Cambodia, enabling them to achieve optimal thermal performance for their buildings. It is a simple yet specialized guideline that can be used by students, architects, designers, and individuals with less experience working on Cambodian projects. Due to its simplicity and flexible approach, the BDGC does not require strict adherence to every recommended element but rather serves as a reference for the designers to gain an overall understanding of bioclimatic design strategies and select the most appropriate solutions for their specific projects.

The BDGC consists of 18 design recommendations (see Figure 2) that span the entire design process, from site integration to floor plan development, building envelope design, and recommendations for construction material choices. Each recommended element can be implemented at different stages of the design process. Site integration focuses on building orientation and the creation of a microclimate to enhance the surrounding environment. Floor plan design addresses space arrangement and composition, to establish thermal transition zones. Building envelope design includes the strategic placement and sizing of openings (considering orientation, position, size, and design style) to maximize natural ventilation, as well as the design of walls, roofs, and shading devices to protect against direct solar radiation. Additionally, material selection focused on the U-value is tailored to different orientations to achieve optimal heat insulation.

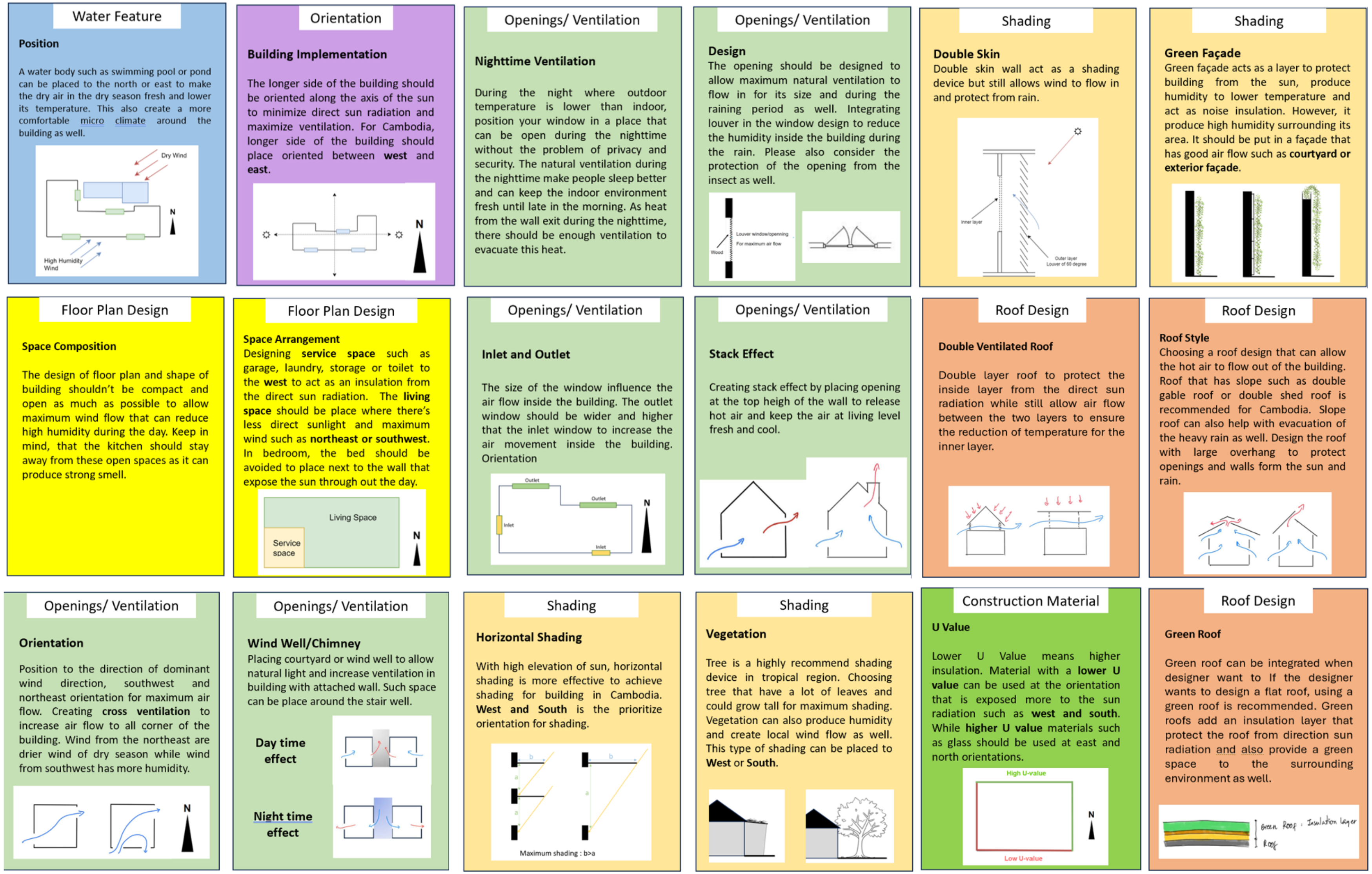

Figure 2. Bioclimatic design guidelines for Cambodia in the form of cards.

3. Methodology

The methodology employed in this study consists of two key phases. The first phase involves conducting a usability test to assess the practicality of the BDGC, its applicability in the design process, and its impact on the designers' decision-making. Following this, the bioclimatic design scenarios generated from the usability test will be used to perform thermal performance simulations, aimed at validating the reliability of the BDGC in enhancing building thermal comfort.

3.1. Usability Test

A usability test is a method employed to assess the usability of a specific object which, in this case, is the BDGC [21]. This type of test typically involves the participants interacting with the object to evaluate its usability and user satisfaction, to improve the object in question. In this study, a test was conducted with five groups and two individual participants. Each group consisted of three members. Three of the groups comprised fourth- and fifth-year architectural engineering students from the Institute of Technology of Cambodia, while the remaining two groups were composed of architects with 2 to 6 years of experience in building design in Cambodia. The two individual participants were architects with over 5 years of professional experience in the field. For the test, the participants were tasked with redesigning a single-family home, either a link house or a detached house. Three groups and one individual worked on the link house, while the remaining participants focused on the detached house. The primary goal of the redesign was to improve the thermal performance of the base case buildings by applying bioclimatic design strategies with the BDGC available as a resource to support decision-making. To facilitate the test, supporting documents were provided, including a base case building plan, and a description of the redesign requirements, which are demonstrated in Table 1, the Phnom Penh climate data, and the BDGC presented in both detailed and card formats.

Each testing procedure starts with answering a pre-test questionnaire, then a briefing of bioclimatic design guidelines and the requirements of the building redesign. The design phase lasts around 2.5 h and the test finishes with a post-test questionnaire. During the design process, we also conducted an observation to identify when and how the BDGC was used to help the designers in decision-making for building thermal comfort (Figure 3 show the design process during the usability test). For individual tests, the think-aloud method was also implemented on the participant for a more in-depth understanding of the participant's approach toward the design process integrating the BDGC. The duration of each test overall is around 4 h.

Table 1. Requirements for redesigning the house.

Both Houses	
- Similar built area and number of floors to the base case - Improving the thermal performance of the building	
Link House	**Detached House**
- House for 3–4 people - Minimum 2 bedrooms (with bathroom-attached) - Living room - Kitchen - Dining area - A space for the house shrine (1 m² on ele--vation)	- House for 5–6 people - Minimum 3 bedrooms (with bathroom attached) - Living room - Kitchen - Dining area - A space for the house shrine (1 m² on elevation)

- Toilet for guests - Garage for 1 car or 2 motorbikes	- Toilet for guests - Storage or laundry - Garage for 1 car and 2 motorbikes

Questionnaire and Design Process Observation

The participants were asked to complete pre-test and post-test questionnaires to assess their satisfaction and confidence in designing a thermally comfortable building using the BDGC. The pre-test questionnaire comprised seven questions focused on the participants' prior experience in designing buildings with the goal of sustainability and comfort, including the methods, design guidelines, and strategies they employed, as well as the tools and methods used for decision-making and evaluating the thermal performance of their designs. The post-test questionnaire sought to see the participants' satisfaction with the BDGC, their confidence in designing a building with optimal comfort from the help of the BDGC, how the BDGC supports decision-making, and their overall perspective on the BDGC.

Figure 3. Process of the usability test.

Throughout the test, we observed the design process to analyze how the BDGC was integrated into the workflow, particularly its influence on design elements and decision-making. Table 2 illustrates an example of an observation sheet completed during the usability test. An innovative aspect of this methodology involved the use of the BDGC cards, allowing architects to approach the design process in a game-like manner. In this method, the participants can choose any cards (a card containing 1 design aspect recommendation from the BDGC) that they would like to cooperate in their project and put those away, which allows observers to see exactly how the BDGC elements were used in the project. Each time a card was selected or drawn out, observers posed questions to better understand the interaction between the BDGC and the architect, and its role as a decision-support tool.

Table 2. Example of observation sheet completed during the usability test.

Time	Action	Problem/Solution/Reason	Design Aspect	Used/Consulted BDGC
0:03	Analyze surrounding environment	Noise from the surrounding building and traffic Shading from the surrounding building		
0:09	Read the BDGC	Understanding guideline recommendation		All
0:17	Analyze design requirement	Identify building function		
0:25	Floor plan diagram	Divided space, pick up a card for function division	Floor plan	Space arrangement

0:30	Master plan design	Adding a pool to northwest, placing building in L shape between north–south	Master plan, building form	Water feature, orientation
0:44	Function diagram in detailed	Placing living space to north, garage to south	Floor plan	Space arrangement and composition

3.2. Simulation of Base Case Building

The two most common house typologies in Cambodia, link and detached house located in Phnom Penh as shown in Figures 4 and 5, were chosen as base case buildings. The base case house is a free-running house with an air-conditioner installed in the bedrooms and having a pedestal fan located in each room of the house. Both of the base case houses are single-family homes with surfaces of 100 m^2 (link house) and 236 m^2 (detached house) and occupied by four people, for a link house, and six people, for a detached house. The houses were built with masonry of burnt clay brick walls, glass windows, and concrete slab roofs which are the common construction materials for residential buildings in Cambodia. The base case buildings are shown to have a weak thermal performance as indicated in our previous study [22].

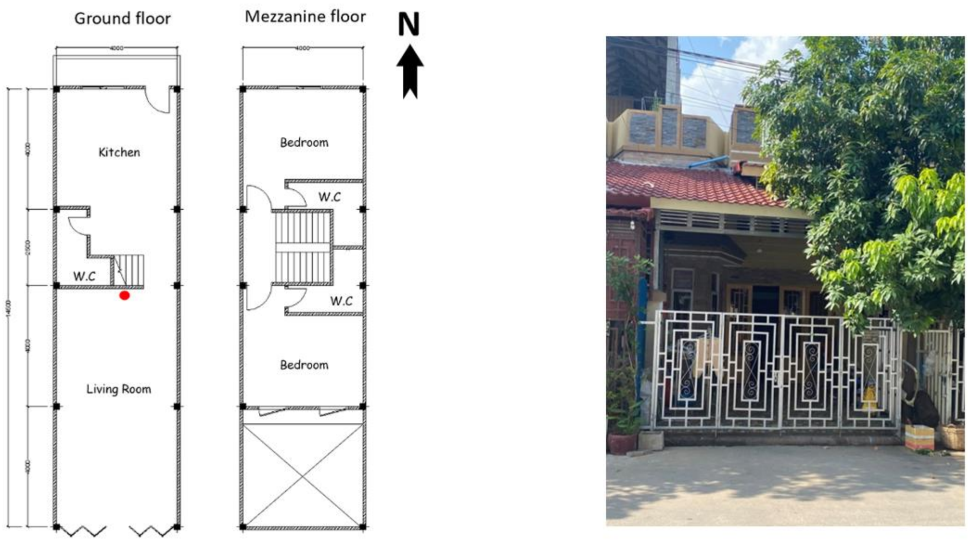

Figure 4. Plan and view the selected base case for the link house.

Figure 5. Plan and view of the selected base case for the detached house.

The base case model was developed using data collected through in situ observations, building monitoring, occupant surveys, and interviews. Indoor air temperature and humidity measurements were taken within the base case house (the sensors were placed in the red dot of the Figure 4 and 5), and these data were used for comparison with simulation results during the calibration process. This approach ensured that the model accurately reflected real-world conditions, providing a reliable foundation for evaluating thermal performance before and after the application of bioclimatic design strategies.

The base case building was modeled in Revit as a BIM model, which included a range of essential data to streamline the thermal simulation process. The BIM model was converted into an analytical model within Revit and exported as a gbXML file. The base case simulation was conducted using DesignBuilder (version 7), a software that employs the EnergyPlus simulation engine, a validated tool for assessing building thermal performance. Multiple calibration runs of the base case simulation were performed using a statistical approach, applying indicators, such as the coefficient of variation of root mean square error (CVRMSE) and the normalized mean bias error (NMBE), adhering to the standards set by ASHRAE [23]. The purpose of this calibration was to ensure that the base case model closely reflected the actual building, allowing for an accurate evaluation of the bioclimatic scenarios. The weather data used for the simulation was the typical meteorological year (TMY) file for Phnom Penh. Table 3 presents the calibrated input parameters for conducting the simulation of the base case model.

Table 3. Calibrated input parameters for base case house simulation.

Link House	Input Model		Link House	Detached House
Construction	External wall	Cement plaster (1 cm)	λ: 0.72 (W/m.K)	λ: 0.72 (W/m.K)
		Brick (20 cm)	λ: 0.72 (W/m.K)	λ: 0.72 (W/m.K)
		Cement plaster (1 cm)	λ: 0.72 (W/m.K)	λ: 0.72 (W/m.K)
	Partition wall	Cement plaster (1 cm)	λ: 0.72 (W/m.K)	λ: 0.72 (W/m.K)
		Brick (20 cm)	λ: 0.72 (W/m.K)	λ: 0.72 (W/m.K)
		Cement plaster (1 cm)	λ: 0.72 (W/m.K)	λ: 0.72 (W/m.K)
	Roof	Reinforced concrete (12 cm)	λ: 1.13 (W/m.K)	λ: 1.13 (W/m.K)
		Cement plaster (1 cm)	λ: 0.72 (W/m.K)	λ: 0.72 (W/m.K)
	Floor	Ceramic clay tile (1 cm)	λ: 0.80 (W/m.K)	λ: 0.80 (W/m.K)
		Reinforced concrete (12 cm)	λ: 1.13 (W/m.K)	λ: 1.13 (W/m.K)
	Airtightness		Model filtration: 0.7 (ac/h)	Model filtration: 0.7 (ac/h)
	Schedule		24/7	24/7
Activities	Household size		4	3
	Building surface		100 m^2	236 m^2
	Density		0.04 person/m^2	0.0012 person/m^2
	Occupancy schedule		24/7	24/7
	Summer clothing		0.5 clo	0.5 clo
	Metabolism level		1 met	1 met
	Equipment		0.05 (W/m^2)	0.004 (W/m^2)
Openings	U value		5.89 (W/m^2.K)	5.77 (W/m^2)
	Total solar transmission		0.72	0.62
	Light transmission		0.68	0.57
Lightning	Normalized power density		5 (W/m^2–100 lux)	5 (W/m^2–100 lux)
	Schedule		8–18 h00 everyday	8–18 h00 everyday
HVAC	Mechanical ventilation		Not applicable	Not applicable
	DHW		Not applicable	Not applicable

Heating	Not applicable	Not applicable
Cooling	Not applicable	Not applicable
Natural ventilation	8–18 h00 everyday	8–18 h00 everyday

3.3. Simulation of Bioclimatic Scenarios

During the usability test, the base case houses were redesigned to incorporate bioclimatic principles from the BDGC, creating bioclimatic houses. These redesigned houses were then subjected to simulation to evaluate their thermal performance in comparison to the base case. The primary thermal comfort parameter used for comparison was air temperature, as it is a highly influential factor in tropical climates. Given the natural adaptation of people in tropical regions to higher temperatures year-round, even a slight reduction in temperature can have a significant impact on comfort levels [24].

The building information generated from the usability test was utilized to modify the base case model in Revit, converting it into a bioclimatic house model. The simulation process for the bioclimatic house followed the same procedure as that used for the base case model, with consistent thermal settings. Since the redesign maintained the same construction materials, the input parameters for the simulation of the bioclimatic scenario remained the same, as detailed in Table 3.

4. Results

The results are divided into three sections. First, the outcomes of the design process during the usability testing are presented, highlighting the BDGC's role in design decision support and its usability from the questionnaire. The second section provides examples of bioclimatic scenarios generated from the test and presents the most used element of the BDGC. Finally, the third section focuses on the simulation of these bioclimatic scenarios, illustrating the improvements in building thermal performance achieved through the application of the BDGC.

4.1. Usability Test

During the usability tests conducted with the seven groups, we identified a design process that integrates the BDGC. Due to the short-term nature of the design task, the architects were unable to explore a wide range of tools to aid in decision-making or engage in extensive research for design inspiration which led all teams to follow a consistent pattern in their design process. They began by analyzing the issues present in the base case design (pre-design phase), followed by a review of the BDGC, selecting design elements from the BDGC that were both interesting and potentially suitable solutions. Subsequently, the teams proceeded with the design process, moving from the floor plan to the façade design to the roof design, then to technical details, and concluded with the documentation. The BDGC cards were consulted and utilized multiple times throughout the design process. The selected elements were re-evaluated when incorporated at various design stages. The BDGC served as a decision-support for the architects at every stage of the design, including floor planning, building envelope development, and technical detailing. As the BDGC was created according to the design phase (site integration to floor plan to building envelope), the BDGC provides architects with a comprehensive understanding of how to approach their building design. Based on the identified issues in the original design and the site's constraints, the participants progressively developed their design, utilizing the BDGC to address and resolve these challenges at each stage of the process.

The pre-test and post-test questionnaires allow for identifying the reliability of the BDGC at the design level as an informed decision method for architects and designers. From the pre-test questionnaire, we can see that 95% of the participants in this test have experienced designing a building to achieve maximum thermal comfort. Their design is normally based on theory from school and the internet and their experience working in the field. Judging from their answers regarding their experience of using design guidelines, there is no existing bioclimatic guideline that they can use that is specific to the context of Cambodia. Normally, they follow passive cooling design strategies in general and focus their design on a single factor, whether on a green façade/roof feature, double skin façade, louver, or shading system. Their decision-making on design choices is generally made through discussion in the team, the client's opinion, or the professor's recommendation for the students. Only 35% of the participants have previously used any tools, such as energy simulation software or design software plugins, to analyze building thermal performance. These tools were typically employed to simulate energy performance and visualize the effects of shading and light. However, detailed simulations of building performance were not conducted by the participants themselves but by other team members in the project. While the participants performed visualization using plugins in the design tool, there is no standardized guideline or tool that they regularly utilize as decision support for achieving building comfort. Without access to a tool that assesses the thermal performance of their final designs or a clear design guideline that they could follow, the participants expressed a lack of confidence in claiming that their buildings would provide adequate comfort. Although the participants claimed to have experience designing buildings for optimum thermal comfort, throughout the design process, they consistently referred back to the BDGC for guidance, particularly when uncertain about specific design parameters (e.g., which orientation has the most benefit for placing a window or shading). When comparing architects and students, it is evident that the BDGC provided greater support to the students, as they possessed less experience and knowledge related to bioclimatic design and design for comfort.

After finishing redesigning the building, the participants were asked to complete the post-test questionnaire. From the answers, we can see that all of the participants used the BDGC to help them in decision-making for redesigning certain aspects of the house, and it allowed them to feel confident in redesigning the building to achieve improved thermal comfort. All of the participants are satisfied with the BDGC and the way that it is categorized according to design phase, which allows it to be easily applied at each design phase. They agree that the BDGC can be utilized from the early design process, particularly after the pre-design phase where site analysis is completed, and design requirements are identified. All of them express their interest in using the BDGC in their future projects.

4.2. Bioclimatic Scenarios

From the usability test, we received seven bioclimatic house scenarios, four scenarios for link houses, and three scenarios for detached houses. We can see some bioclimatic scenarios are similar to each other while some present a very distinct difference in terms of the design aspect. The difference is mostly found in detached houses as the site constraint is not as limited as the link house.

In each bioclimatic scenario, at least eight design elements from the BDGC were regularly integrated into the design aspects, as seen in Figures 6–9. For example, in the case of Link House Scenario 1, the stack effect card is employed to incorporate louvers on the façade, thereby enhancing the stack effect and improving natural ventilation. The frequency used of each design element is as follows:

- Orientation, cross ventilation, stack effect, wind well, horizontal shading, vegetation shading, green façade, double skin façade (all the time)
- Green roof (6 times)
- Space arrangement (4 times)
- Opening design, opening size (2 times)

- Roof style, nighttime ventilation, water feature (1 time)
- Space composition, double ventilation roof, U value (0 times)

The frequency of using different design elements may be influenced by site constraints or the ease of incorporating them into the design. For instance, the integration of the stack effect was observed in all bioclimatic house designs, as it has traditionally been a common design practice in Cambodian residential buildings. This is typically achieved through the use of louvers or breeze blocks positioned at higher wall levels to promote natural ventilation. However, this strategy has recently fallen out of favor due to its incompatibility with air conditioning systems. Interestingly, despite the prevalence of double-ventilation roofs in contemporary Cambodian link houses, none of the participants opted to use this design feature in their redesigns. Instead, the participants opted for green roofs, a more modern roofing style, particularly suited for link houses where ground-level green space is highly limited. The choice of green roofs reflects a growing emphasis on providing accessible green areas within the built environment, offering both aesthetic and environmental benefits in densely populated urban settings where traditional outdoor space is scarce.

The issues identified by the participants from the base case of the link house are generally the lack of ventilation, natural light, and green space; while the problem of the detached house is mostly due to the lack of sun radiation protection (shading). Despite seeing similar issues in the base case design identified by each group, the BDGC elements used for the bioclimatic scenario by each group are different. For the link house, the building layout of the redesign for bioclimatic scenarios is similar to each other and also similar to the base case house due to the constraints of the site and the living conditions of Cambodia. The bioclimatic scenarios are seen integrating a wind well using the staircase, horizontal shading from the balcony, creating a double skin façade with a vertical louver, and adding a green roof. Two distinct differences between the two scenarios are the use of louvers for a stack effect at all floors in scenario 1, while scenario 2 uses the stairwell to create stack ventilation for all spaces. This difference in design will allow us to see its impact on thermal performance in the simulation result.

Figure 6. Link house bioclimatic scenario 1.

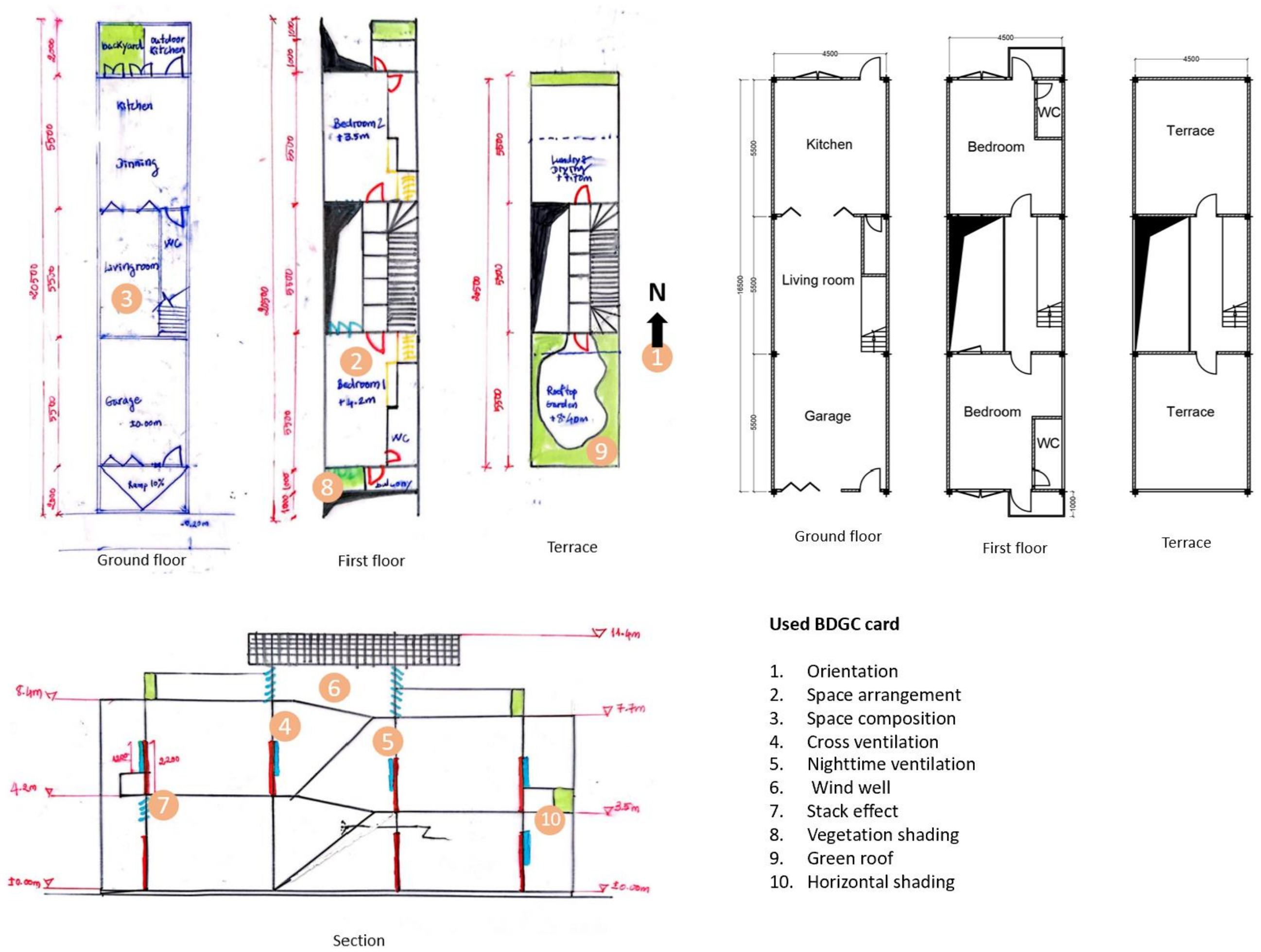

Figure 7. Link house bioclimatic scenario 2.

For the detached house, the design issues identified in the base case building primarily relate to the absence of shading devices and insufficient green space. Given the fewer constraints imposed by the site, the design of the two detached house scenarios exhibits a greater degree of differentiation compared to the link house. The design strategies for both scenarios emphasize the effective utilization of the available land to complement and enhance the overall building design. From the floor plan (see Figures 8 and 9), we can see the two scenarios present a different design of the floor plan layout compared to each other and compared to the base case house, which led the building to have a significantly different form. The two scenarios possess different types of roofs and also a significant difference in terms of the space arrangement of living and sleeping zones. This difference in design would give an interesting insight into the thermal performance that the building will provide. Despite many differences, we can see some similarities in the application of horizontal shading using a balcony, creating a garage space near the living space to provide shade and create a microclimate around that area, the use of vegetation for shading, and the design of opening for the interaction of indoor and outdoor living attracting maximum ventilation.

Figure 8. Detached house bioclimatic scenario 1.

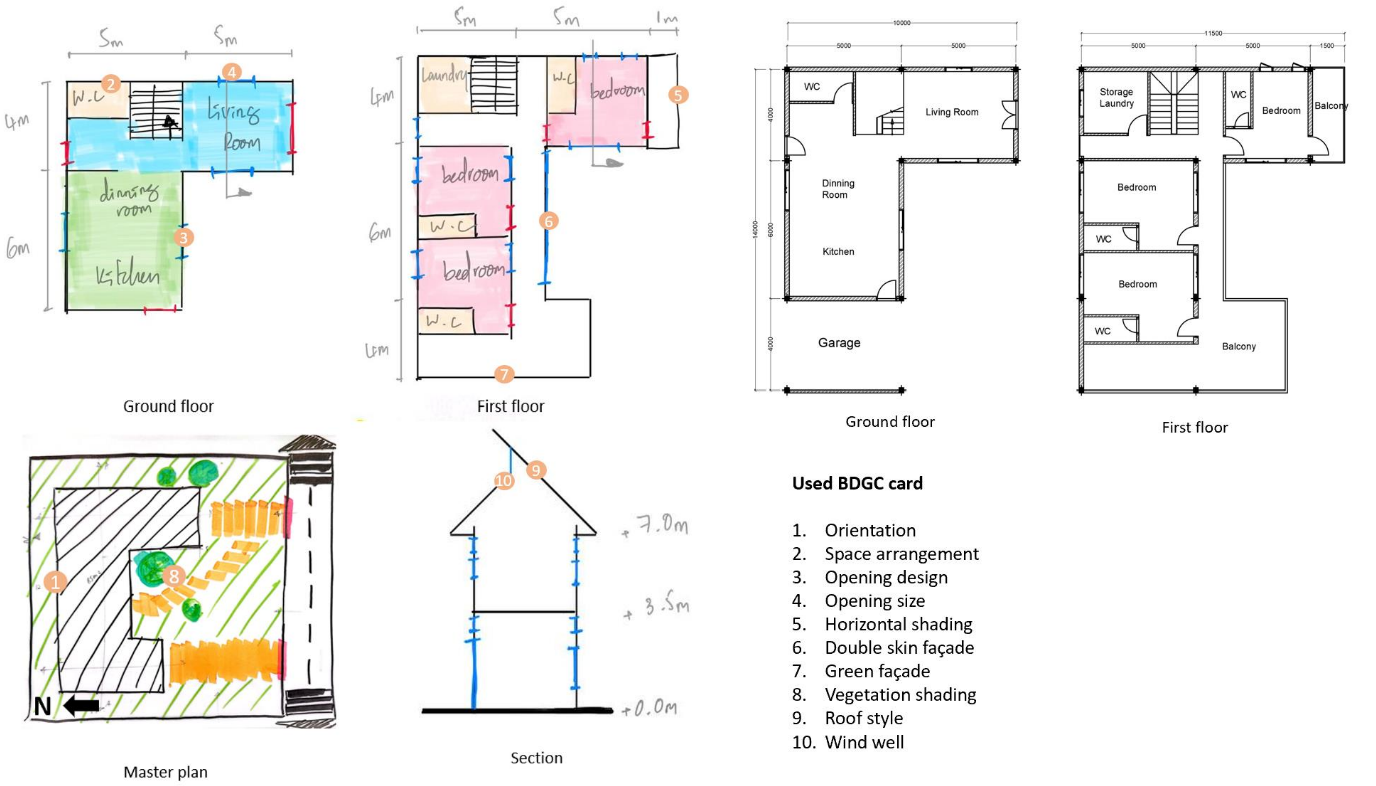

Figure 9. Detached house bioclimatic scenario 2.

Using design guidelines can occasionally constrain the designers to specific practices or restrict the expression of their ideas, as they are required to conform to established criteria. However, an examination of bioclimatic house designs reveals that the BDGC does not inherently limit architectural creativity. The diversity observed in the design aspects of bioclimatic houses demonstrates that the BDGC permits significant variation in architectural expression. Thus, it is reasonable to conclude that these guidelines still give architects considerable freedom to pursue their artistic vision.

From the observation during all seven usability tests, we can see that each test follows a similar design process pattern, as shown in the Figure 10 below. The design process in all tests begins with reviewing the provided documents, then moves through stages of programming, master planning, floor plan design, and envelope design. The integration of the BDGC is present from the first design phase and remains in use throughout each phase. At the initial stage, architects establish specific design goals with the assistance of the BDGC, ensuring alignment with their overarching objectives. They select strategies that seem pertinent to their design aims for integration into the project. The incorporation of each BDGC card typically follows the corresponding design phase. For instance, building orientation is often applied during the master planning phase, space composition during floor plan design, and the stack effect during façade design. As the design progresses and ideas take shape, the participants frequently revisit the BDGC for guidance whenever uncertainties emerge. Some cards chosen at the beginning may be eliminated and rechosen to better fit the evolving design concepts. This identified design process illustrates that the BDGC provides informed decision support to the participants and can be integrated throughout the whole design process.

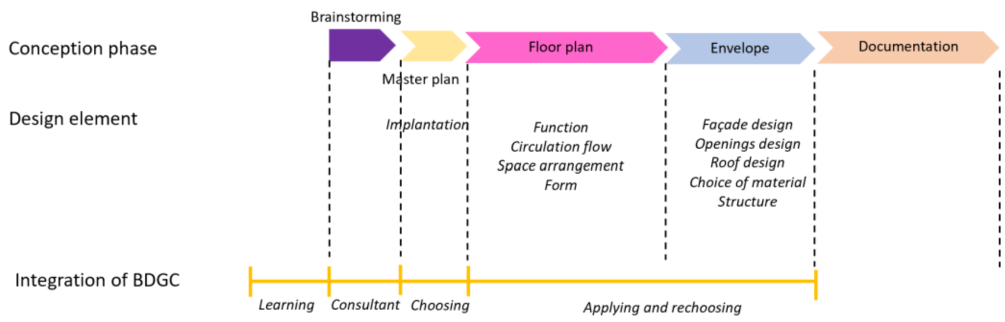

Figure 10. Design process practiced during the usability test.

4.3. Simulation

Cambodia has two distinct seasons: a dry season and a rainy season. However, the country maintains relatively high temperatures throughout the year. The simulation of the four bioclimatic scenarios is carried out for April, which is considered the hottest month in Cambodia. The simulations specifically focused on the living room, as this space is the most frequently occupied area within the house. As the demonstration in Figures 11 and 12 show, the temperature of the bioclimatic scenarios is between 2 to 4 °C lower than the base case house for both house types. This temperature defervescence is notably significant, as it results primarily from the integration of passive design strategies within the building. The temperature variation is more pronounced during the nighttime compared to the daytime. Additionally, the fluctuation in temperature within the bioclimatic scenario buildings is greater than that observed in the base case house. This indicates a substantial difference between daytime and nighttime temperatures. The increased variation is likely due to the nocturnal cooling effect, where design elements, such as wind wells, contribute to a marked decrease in temperature during the night. The overall reduction in indoor temperature can be influenced by several factors, including the following:

- The orientation of the building optimizes natural ventilation and reduces the exposure of wall surfaces to direct solar radiation.
- The strategic arrangement of spaces, positioning living areas away from direct sunlight.
- The placement of windows to create cross ventilation.
- The incorporation of shading elements, such as balconies and double façades, to protect the building from solar heat.
- The stack effect is created by louvers and wind wells, which helps maintain fresh and cool air at the living level and enhances nocturnal cooling efficiency.

In the simulation, certain environmental factors, such as surrounding trees and the green roof, are not modeled. In reality, these elements would contribute to a microclimate and provide additional insulation, likely resulting in even lower indoor temperatures in the bioclimatic house.

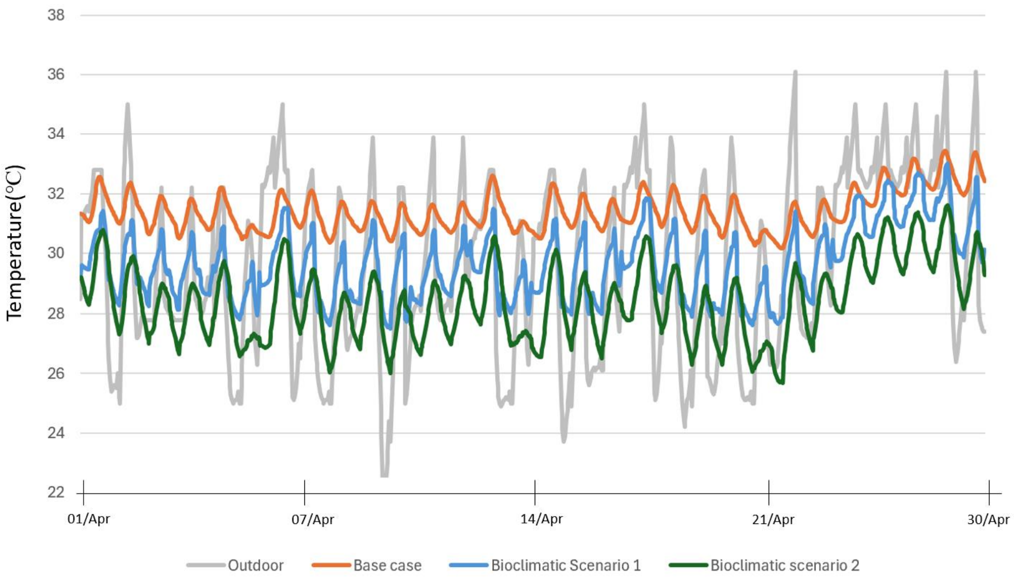

Figure 11. Air temperature of the bioclimatic house compared to the base case for a link house.

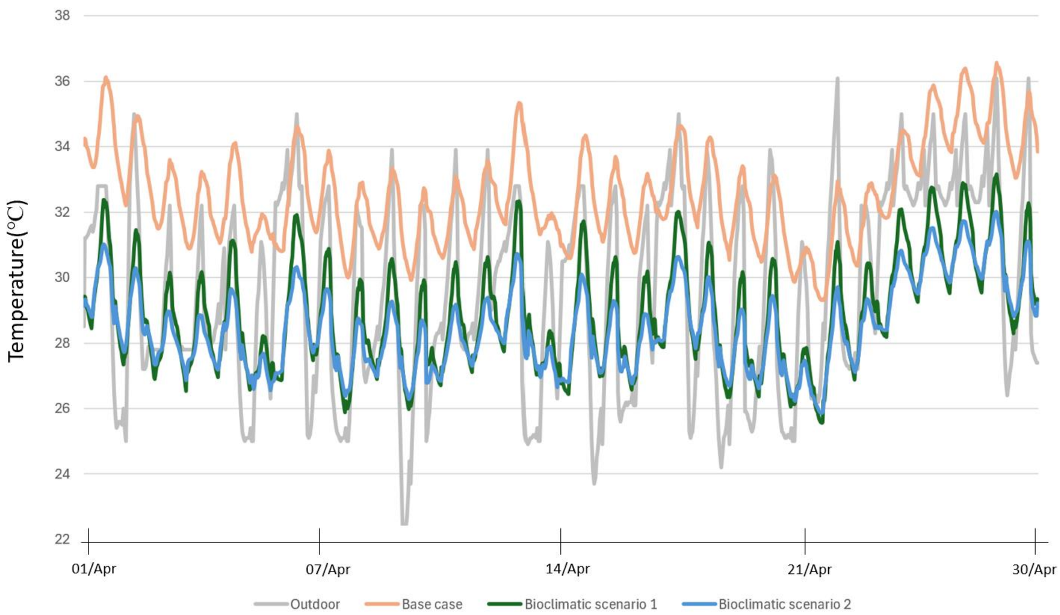

Figure 12. Air temperature of the bioclimatic houses compared to the base case for the detached house.

In the case of the link house, there is a significant difference in thermal performance between Scenario 1 and Scenario 2, despite many similar design features. By contrast, for the detached house, the difference in indoor temperature between the two scenarios is minimal, even though the design aspects differ considerably.

For the link house, Scenario 2 demonstrates better performance than Scenario 1, although the difference in the temperature is not high. The lower temperatures in Scenario 2 are typically observed during the nighttime and early morning, when the living room, positioned directly in the wind well, benefits most from the nocturnal cooling effect. This suggests that the wind well, or stack effect, is a crucial design factor in reducing indoor temperatures and maintaining cooler conditions for longer periods. Consequently, designing openings to facilitate nocturnal cooling is essential. Furthermore, the living room in Scenario 2 is positioned away from exterior walls exposed to the sun, which may also contribute to lower daytime temperatures. Compared to the acceptable thermal comfort range for tropical regions, the average temperature in the bioclimatic scenario remains within acceptable limits. Overall, the building stays within the comfortable temperature range (below 29.5 °C) for 49% of the time.

For the detached house, any design change could affect significantly the indoor temperature as the building is fully exposed to the outdoor environment. It is interesting to see that the temperature in Scenario 1 is lower during the daytime but higher during the nighttime than in Scenario 2. In both scenarios, the living room demonstrates comparable exposure to the outdoor conditions. However, in Scenario 1, the living room is well-protected from solar radiation, with openings oriented towards the north and south, and shading provided by the adjacent parking structure for the south-facing window. By contrast, in Scenario 2, the living room is predominantly oriented toward the south, with no shading for the openings facing west and east. This leads to Scenario 1 maintaining a lower daytime temperature compared to Scenario 2. Nevertheless, during nighttime, Scenario 2 achieves lower temperatures due to the presence of louver systems and the stack effect facilitated by the roof design. If Scenario 2 were to adopt a living room orientation similar to Scenario 1, it could potentially exhibit even better thermal performance. This observation highlights that, despite the assistance of the BDGC, some design elements related to thermal comfort were overlooked by the designers. Notably, the team responsible for Scenario 2 appeared to have consulted the BDGC less frequently during their design process compared to the other group.

The relatively short design duration may have also limited the designers' ability to thoroughly verify bioclimatic strategies, even with the BDGC support. Additionally, although the primary objective is to enhance occupant comfort, the designers are not restricted in terms of functionality and aesthetic considerations, which may sometimes lead to the prioritization of visual appeal and spatial flow over certain aspects of comfort.

5. Discussion

Compared to other design guidelines for similar climates, we observe comparable recommendations emphasizing solar radiation protection and the promotion of airflow. The bioclimatic house in our study, incorporating modifications to building openings and horizontal shading, demonstrated the most significant impact on thermal performance. This aligns with findings from a study in Nigeria [10]; however, it diverges slightly from results in Vietnam, where a greater emphasis was placed on the building envelope (e.g., wall thickness) and roof design to optimize building performance [12]. Although some of these guidelines have not undergone usability testing to evaluate their effectiveness in the design process, similar to our study, a usability assessment conducted on guidelines in Pakistan [11], revealed their potential as reliable tools for informed decision-making and enhancing the participants' confidence in their final building designs.

From the observation of the design process during the usability test, we can see that the BDGC provides decision support and helps architects to enhance the thermal performance of their building design in multiple ways including the following:

- The BDGC helps the participants visualize their design goals, ensuring they do not overlook key design aspects to ensure optimum thermal comfort.
- The comprehensive design elements provided by the BDGC give the participants a holistic understanding of their design which helps them establish design strategies early on that they want to incorporate in their initial design and have a global idea of the building.
- The BDGC helps architects to stay on track with their established goals.
- Design elements within the BDGC can be used from the early design process and support the decision at various stages of the design phase.

With the assistance of the BDGC, the overall design process can proceed smoothly, saving time on research and decision-making. However, the design processes across all groups appear to follow a similar pattern. This could be partly due to the limitations of relying on the BDGC, but it may also be attributed to the limited time available for the design process and the participants' similar educational backgrounds (all participants graduated from the same study program).

Design guidelines in general aim to achieve a good design quality through specification of the preferred outcome and how to achieve it [25], which can lead to a similarity in the outcomes of building designs. However, as evidenced by scenarios from usability tests, the application of the BDGC results in notably diverse building designs. This can be attributed to the fact that the BDGC does not impose rigid constraints on design elements but rather serves as a guiding framework that ensures architects consider key factors essential for optimizing their designs. By using the BDGC, a quick evaluation of the site location and review of the BDGC already provide architects with a global idea of what their initial building design would look like. This is evident during the design process, where architects selectively integrate elements from the BDGC into their initial concepts. Furthermore, the BDGC provides ongoing support, particularly in instances where architects encounter uncertainty at various stages of the design process.

For less experienced architects or students, the BDGC offers a valuable resource, providing rapid insights without necessitating extensive research into design factors that influence a building's thermal performance. For example, the BDGC provides recommendations for optimal window placement for maximizing natural ventilation. Importantly, the BDGC does not require strict adherence; rather, it equips its users with essential information related to improving thermal performance, enabling architects to make informed decisions and tailor design criteria to the specific needs of their projects. Based on the data observed, the BDGC appears to be the most suitable for students or designers with limited experience. The frequency of its use is consistently higher among students and architects with less than five years of experience compared to those with more extensive professional backgrounds. Consequently, this guideline presents a valuable resource for integration into architectural curricula. Furthermore, the incorporation of game-like elements using cards facilitates an improved understanding and application of bioclimatic design principles during the design learning process. Within a pedagogical context, this method effectively enhances the students' comprehension of the rationale behind the implementation of specific design elements as they engage with the card-based system.

The integration of the BDGC is most effective when implemented during the early design phase, as bioclimatic design strategies should be applied as early as possible to prevent potential design conflicts and errors later in the process. Moreover, the use of the BDGC should not be viewed as a one-time application; rather, it should serve as continuous support throughout the entire design process. Its ongoing use proves valuable in decision-making, particularly when alterations or adjustments to the design are required. This continuous support ensures that bioclimatic principles are consistently considered, enhancing the overall design outcome for a building's thermal performance.

Despite the numerous advantages mentioned above, a few challenges were noted with the use of the BDGC:

- The focus on thermal comfort goals may limit architectural comprehensiveness, as the designers may need to balance the BDGC with functional, energy, economic, or aesthetic choices..
- The BDGC does not specify the relative importance of design variables, which may cause architects to attempt to incorporate all elements, potentially prolonging the design process.
- The first-time user of the BDGC has to spend a significant amount of time reviewing the guidelines.

- The BDGC appears more suitable for students or less experienced practitioners. However, some technical terminology in the BDGC is difficult for students to understand.

If we look at the disadvantages of the BDGC application, particularly from the viewpoint of the developer and owner, we can already observe that there are larger surfaces for bioclimatic house in comparison to the base case house, which may be unappealing to developers or owners due to the increased construction costs. However, the size difference is relatively modest, and it is believed that bioclimatic designs can still be achieved with comparable surface areas. Despite the slightly higher initial construction costs, these can be considered a long-term investment in energy savings and occupant well-being. This is where tools for calculating energy consumption become crucial, as they allow owners to evaluate the potential financial savings resulting from their investment in specific bioclimatic design features.

During the design process, the participants emphasized the need for a simple tool that would enable them to easily assess the performance of their designs, such as PHPP [26], thereby facilitating more informed decision-making. Specifically, through the application of the BDGC, they sought to understand how their design choices impact improvements in building comfort. Furthermore, this tool should be adapted to the Cambodian context, where air velocity plays a crucial role in ensuring occupant thermal comfort, thus requiring prioritization in the design evaluation process.

The simulation results of bioclimatic houses demonstrate that integrating the BDGC from the early design phase and consistently applying it throughout the design process enables architects to enhance the building's thermal performance (lower indoor air temperature) through the application of bioclimatic design strategies, ensuring that no critical strategies are overlooked. As highlighted in our literature review, radiant temperature is a significant factor in thermal comfort, particularly in the context of hot climate countries. However, as one of the case study buildings is a link house, its direct exposure to solar radiation, a key driver of the difference between air temperature and radiant temperature, is minimal. Consequently, our discussion on thermal comfort factors focuses exclusively on the air temperature of the building. Additionally, the simulation tool utilized in our study is not well-suited for analyzing radiant temperature, as it has been shown to exhibit inaccuracies, as noted in the study by Alfano et al. [27]. For future research, it would be valuable to explore radiant temperature and operative temperature, particularly in the context of detached houses.

As the simulation of bioclimatic houses incorporating multiple BDGC elements provides valuable insights into how various strategies can synergize to enhance building comfort. This is particularly relevant in the context of Cambodia, where the orientation receiving the highest solar radiation exposure coincides with the prevailing wind direction. The simulation underscores the importance of integrating strategies that address both solar radiation and wind direction to optimize building performance. Notably, the detached house in Scenario 1 demonstrates superior performance compared to Scenario 2, as it effectively prioritizes shading from solar radiation while strategically positioning windows in the second-best orientation for wind flow. This balanced approach highlights the significance of considering multiple environmental factors simultaneously in bioclimatic design. It was observed that buildings with less sun exposure, such as link houses, exhibited lower temperatures compared to detached houses, underscoring the importance of solar shading as a key design element for reducing indoor temperatures. However, as air velocity is considered the most influential factor for thermal comfort in tropical regions [28], designs that prioritize ventilation would be more beneficial in enhancing occupant comfort. Ultimately, only a thermal comfort analysis tool that integrates this hypothesis considering both shading and ventilation would enable architects to make more precise decisions regarding which strategy to prioritize for optimal comfort in tropical regions. For this purpose, the choice of tools for building performance analysis is very important as different tools can exhibit a different data input and result [29]. A design process integrating the application of the BDGC and the simulation tool should be proposed and evaluated to assess its effectiveness in enhancing architectural decision-making and improving building performance. Conducting a sensitivity analysis of all the studied bioclimatic strategies, as was demonstrated by Mahar et al. [6] for cold semi-arid climate, could help to further the prioritization of design elements in the context of Cambodia.

6. Conclusions

The innovative aspect of this study lies in its presentation of the developed BDGC, specifically how it functions as a decision support for architects and how it can be seamlessly integrated into the design process. This study further introduces 18 bioclimatic design elements that can be applied to enhance the thermal performance of buildings. Additionally, several examples of bioclimatic houses are provided, offering practical insights that would be valuable for architects in applying these principles to their designs. Moreover, the use of the BDGC cards during the usability test introduces a creative method in data collection regarding decision-making and would provide a good advantage for students during the learning process in educational settings. By engaging with the cards, the participants can better understand the implications of their design choices, fostering more informed decision-making and deeper comprehension of bioclimatic design principles

This study evaluated the effectiveness of the BDGC as a decision-support during the early design phase and its impact on enhancing the thermal performance of residential buildings in tropical regions. The findings demonstrate that the BDGC is well-suited to facilitating informed decision-making for architects in the early stage of the design process, particularly in establishing the building's initial design concept. Based on thermal performance simulation, integrating the BDGC elements into the design of residential buildings can reduce indoor temperatures by 2 to 4 °C compared to the base case houses, which are typical single-family homes in Cambodia. Eight BDGC elements were consistently integrated into the final designs, with particular emphasis on building orientation, stack effect, and shading provided by balconies and vegetation.

The limitations of this study stem from its focus on residential buildings, specifically single-family homes, which are considered relatively simple in terms of complexity. Applying the BDGC guidelines to more complex building types, such as public or commercial structures, would likely introduce additional challenges. Furthermore, the study did not include a focus group of the participants who did not use the BDGC, limiting the ability to compare how the design process may differ between those who utilize the guidelines and those who do not. Including architects from other institutions could yield additional, potentially valuable perspectives and findings. Conducting a sensitivity analysis of these design elements could offer valuable insights and serve as an important avenue for future research.

Some recommendations are given following the findings from this study:

- The BDGC should be utilized as a decision-support tool from the early stages of design in both professional and educational settings. This would assist architects in achieving greater confidence when designing to achieve thermal comfort.
- There is a clear need for educational initiatives aimed at raising awareness among designers and students regarding thermal comfort, energy efficiency, and bioclimatic design strategies. These can be delivered through workshops, specialized training, and curriculum integration in academic institutions.
- Incorporating the use of the BDGC cards in a game-like manner during the design process in architectural courses could enhance the students' creativity in selecting

and designing buildings with a consciousness of building performance and energy efficiency. This approach is expected to be introduced into undergraduate architectural programs at the Institute of Technology of Cambodia and the University of Liege, Belgium.

- Guidelines, such as the BDGC, should also be adopted as a reference by policymakers to ensure that building designs achieve thermal comfort while minimizing energy consumption.
- A simple tool for analyzing building thermal performance, used in conjunction with the BDGC, would further enhance the architects' ability to make well-informed design decisions.

Finally, the methodology used is reproducible and can be applied in various other countries worldwide to develop and validate context-specific bioclimatic design guidelines.

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