LIÈGE université
Sciences Appliquées

INSTITUT DE TECHNOLOGIE DU CAMBODGE

ARES
ACADÉMIE
DE RECHERCHE ET
D'ENSEIGNEMENT
SUPÉRIEUR

ARCHITECTURAL DESIGN PROCESS
FOR A BIOCLIMATIC BUILDING
Methods and design strategies for building comfort in the tropical climate

A thesis submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy (Phd) in Engineering Science

by

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DOCTORAL COLLEGE IN ARCHITECTURE, ENGINEERING AND GEOLOGY

DECEMBER 2024

This document present the thesis research entitled

ARCHITECTURAL DESIGN PROCESS OF A BIOCLIMATIC BUILDING: Study of methods and design strategies for building comfort in the tropical climate

Presented to obtaining the degree of Doctor of Engineering Sciences by:

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A thesis co-supervised and submitted by a joint supervision agreement between the University of Liège and Institute of Technology of Cambodia

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This research is funded by:
ARES – Académie de recherche et d’enseignement supérieur

Citation:
Taing. K, (2024). *Architectural design process for a bioclimatic building: Study of methods and design strategies for building comfort in the tropical climate.* Doctoral thesis. University of Liege and Institute of Technology of Cambodia, pp. XX

ABSTRACT

Buildings are one of the main problems causing global warming for our planet. From construction to operation to demolition, the whole life cycle of the building would leave some issues that add to the environmental problems. Cambodia is currently facing with construction boom in almost all urban areas especially the capital city Phnom Penh. The rapid construction of residential space doesn't take into account the importance of building thermal comfort and sustainability. We see that what happens during the architectural design process could contribute to solving these issues.

The objective of this thesis is to analyze bioclimatic design strategies and thermal performance analysis methods as decision support for designers in the early design process to achieve optimal thermal comfort for buildings in the context of Cambodia.

Qualitative, quantitative, and modeling which are divided into 5 phase methodologies were used for data collection and analysis. First, a literature review and diagnostic survey were conducted to understand current issues concerning residential building thermal performance, the practice of BIM, and bioclimatic design in the construction sector in Cambodia. The monitoring of building thermal performance is then put into place alongside occupant surveys and interviews to investigate the thermal performance of current residential buildings in Phnom Penh. Next, we conducted a building thermal performance simulation with the Building Information Modeling (BIM) model and Design Builder to test their effectiveness as a support decision system for architects during the design process. This first insight about the BIM model and Building Performance Simulation (BPS), led to another investigation of identifying the current architectural design process practiced in Cambodia with the integration of these two methods. A simplified method in the form of a spreadsheet called Esad has been developed to help architects in the decision-making of design strategies since the early design process. The final part of the thesis is creating the bioclimatic design guidelines for Cambodia that consist of design elements from analyzing the Cambodian weather and living conditions, the existing passive design for tropical regions, and Cambodian traditional houses. The bioclimatic design guideline is validated through a usability test with students and architects in Cambodia and simulations of the bioclimatic building scenarios produced from this test.

Both Esad and bioclimatic design guidelines are proposed as decision support for architects and students in both professional and educational environments to ensure optimum building thermal comfort.

Keywords: Thermal comfort, Bioclimatic design, BIM model, BPS, Architectural design process, Cambodia

RESUME

Le bâtiment est l'un des principaux problèmes à l'origine du réchauffement climatique de notre planète. De la construction à l'exploitation en passant par la démolition, tout le cycle de vie du bâtiment laisse des problèmes qui s'ajoutent aux problèmes environnementaux. Le Cambodge est actuellement confronté à un boom de la construction dans presque toutes les zones urbaines, en particulier dans la capitale Phnom Penh. La construction rapide des bâtiments résidentiels ne prend pas en compte l'importance du confort thermique et de la durabilité des bâtiments. Nous voyons que ce qui se passe pendant le processus de conception architecturale pourrait contribuer à résoudre ces problèmes.

L'objectif de cette thèse est d'analyser les stratégies de conception bioclimatique et la méthode d'analyse des performances thermiques comme système d'aide à la décision pour les concepteurs dans le processus de conception précoce afin d'obtenir un confort thermique optimal des bâtiments dans le contexte du Cambodge.

Des méthodologies qualitatives, quantitatives et de modélisation divisée en 5 phases ont été utilisées pour la collecte et l'analyse des données. Tout d'abord, une revue de la littérature et une enquête diagnostique ont été menées pour comprendre les problèmes actuels concernant la performance thermique des bâtiments résidentiels, la pratique du BIM et la conception bioclimatique dans le secteur de la construction au Cambodge. Le suivi des performances thermiques des bâtiments est ensuite mis en place parallèlement à une enquête et à des entretiens auprès des occupants pour étudier les performances thermiques des bâtiments résidentiels actuels à Phnom Penh. Ensuite, nous avons réalisé une simulation de performance thermique du bâtiment avec le modèle Building Information Modeling (BIM) et Design Builder pour tester leur efficacité en tant que système d'aide à la décision pour l'architecte pendant le processus de conception. Ce premier aperçu sur le BIM et la simulation des performances du bâtiment (BPS) a conduit à une autre enquête visant à identifier le processus de conception architecturale actuel pratiqué au Cambodge avec l'intégration de ces deux méthodes. Une méthode simplifiée sous forme de feuille de calcul appelée Esad est développée pour aider l'architecte à prendre des décisions sur les stratégies de conception depuis le début du processus de conception. La dernière partie de la thèse consiste à créer un guide de conception bioclimatique pour le Cambodge qui se compose d'éléments de conception issus de l'analyse des conditions météorologiques et de vie au Cambodge, de la conception passive existante pour la région tropicale et de la maison traditionnelle cambodgienne. Le guide de conception bioclimatique est validé par un test d'utilisabilité avec un étudiant et un architecte au Cambodge et une simulation des scénarios de construction bioclimatiques produits à partir de ce test.

Esad et le guide de conception bioclimatique sont tous deux proposés comme système d'aide à la décision pour l'architecte et l'étudiant dans les environnements professionnels et éducatifs afin de garantir un confort thermique optimal du bâtiment.

សេចក្តីសង្ខេប

អគារគឺជាបញ្ហាចម្បងមួយដែលបណ្តាលឱ្យមានការឡើងកំដៅផែនដីសម្រាប់ភពផែនដីរបស់យើង។ ចាប់ពីការសាងសង់រហូតដល់ការកំទេចចោល វដ្តជីវិតទាំងមូលនៃអគារបន្សល់ទុកនូវបញ្ហាជាច្រើនទៅដល់បរិស្ថាន។ ជាក់ស្តែងប្រទេសកម្ពុជានាពេលបច្ចុប្បន្នកំពុងប្រឈមមុខនឹងការរីកចម្រើនផ្នែកសំណង់ជាទម្ងន់នៅគ្រប់តំបន់ទីប្រជុំជន ជាពិសេសរាជធានីភ្នំពេញ។ ការសាងសង់លំនៅឋានយ៉ាងឆាប់រហ័សទាំងនេះមិនបានគិតអំពីសារៈសំខាន់នៃការសាងសង់អគារដែលផ្តល់ផាសុកភាពគ្រប់គ្រាន់ និងត្រូវការប្រើប្រាស់ថាមពលអគ្គិសនីដោយសន្សំសំចៃ។ យើងឃើញថាសកម្មភាពនៅក្នុងដំណាក់កាលនៃការរចនាអគារ អាចចូលរួមចំណែកក្នុងការដោះស្រាយបញ្ហាទាំងនេះ។

គោលបំណងនៃនិក្ខេបបទនេះគឺការសិក្សាទៅលើការរចនានៃជីវអាកាសធាតុ (Bioclimatic Design) និងវិធីសាស្ត្រប្រើប្រាស់ក្នុងការវាយតម្លៃផាសុកភាពរបស់អគារនានា ដែលអាចដើរតួជាជំនួយដល់ការសម្រេចចិត្តរបស់ស្ថាបត្យករតាំងពីដំណាក់កាលដំបូងនៃការរចនាអគារ ដែលធ្វើយ៉ាងណាអោយអគារផ្តល់បាននូវផាសុកភាពខ្ពស់បំផុតនៅក្នុងបរិបទប្រទេសកម្ពុជា។

ការស្រាវជ្រាវនេះត្រូវបានបែងចែកជា 6 ដំណាក់កាល។ ជាដំបូងយើងធ្វើការសិក្សាទៅលើការស្រាវជ្រាវដែលបានធ្វើរួចក្នុងប្រធានបទស្រដៀងគ្នា និងការធ្វើសម្រង់មតិដើម្បីយល់ដឹងអំពីបញ្ហាដែលកំពុងតែប្រឈមនាពេលបច្ចុប្បន្នទាក់ទងនឹងផាសុកភាពនៃលំនៅឋាន ការប្រើប្រាស់ BIM និង ការរចនានៃជីវអាកាសធាតុ (Bioclimatic Design) នៅក្នុងវិស័យសំណង់នៅប្រទេសកម្ពុជា។ ដំណាក់កាលទី 2 ផ្តោតសំខាន់ទៅលើការវាស់វែងកត្តាដែលជះឥទ្ធិពលដល់ផាសុកភាពអគារ និងការសម្ភាសន៍ជាមួយអ្នកដែលរស់នៅក្នុងអគារ ដើម្បីស៊ើបអង្កេតទៅលើផាសុកភាពលំនៅឋាននាពេលបច្ចុប្បន្ននៅទីក្រុងភ្នំពេញ។ បន្ទាប់មកយើងធ្វើការវាយតម្លៃទៅលើ BIM Model និងកម្មវិធី Design Builder ក្នុងការដើរតួជាជំនួយដល់ការសម្រេចចិត្តរបស់ស្ថាបត្យករក្នុងដំណាក់កាលនៃការរចនាអគារតាមរយៈ Simulation។ លទ្ធផលនៃដំណាក់កាលទី2 ជំរុញដល់ការស៊ើបអង្កេតមួយទៀតដើម្បីកំណត់អត្តសញ្ញាណដំណើរការរចនាស្ថាបត្យកម្មដែលរួមបញ្ចូលនូវការប្រើប្រាស់ BIM និង BPS ដែលកំពុងតែអនុវត្តនៅប្រទេសកម្ពុជា។ វិធីសាស្ត្រសាមញ្ញមួយក្នុងទម្រង់ Spreadsheet ដែលមានឈ្មោះថា Esad ត្រូវបានបង្កើតឡើងដើម្បីជួយដល់ការសម្រេចចិត្តរបស់ស្ថាបត្យករក្នុងការជ្រើសរើសយុទ្ធសាស្ត្ររចនា (Design Strategies) ដែលសមស្របបំផុតសម្រាប់ផាសុកភាពនិងចីរភាពនៃអគារ។ ដំណាក់កាលចុងក្រោយនៃការស្រាវជ្រាវនេះផ្តោតទៅលើការបង្កើតគោលការណ៍ណែនាំរចនានៃជីវអាកាសធាតុe សម្រាប់ប្រទេសកម្ពុជា តាមរយៈការវិភាគទៅលើអាកាសធាតុនិងស្ថានភាពរស់នៅ នៅក្នុងប្រទេសកម្ពុជា គោលការណ៍រចនា Passive Design ដែលមានស្រាប់នៅក្នុងតំបន់ត្រូពិចនិងផ្ទះខ្មែរ។ គោលការណ៍ណែនាំរចនានៃជីវអាកាសធាតុ

(Bioclimatic Design Guideline) នេះត្រូវបានវាយតម្លៃសក្តានុពលនៃការប្រើប្រាស់តាមរយៈការធ្វើតេស្តប្រើប្រាស់ជាមួយនិស្សិតស្ថាបត្យកម្ម និងស្ថាបត្យករកម្ពុជា បូករួមជាមួយការធ្វើ Simulation នៃសេណារីយ៉ូអគារបែបជីវអាកាសធាតុ ដែលផលិតចេញពីការធ្វើតេស្តនេះ។

ទាំង Esad និងគោលការណ៍ណែនាំរចនានៃជីវអាកាសធាតុ (Bioclimatic Design Guideline) ត្រូវបានស្នើឡើងជាប្រព័ន្ធគាំទ្រការសម្រេចចិត្តសម្រាប់ស្ថាបត្យករ និងនិស្សិតទាំងក្នុងបរិបទវិជ្ជាជីវៈ និងការអប់រំ ដើម្បីធានាបាននូវផាសុកភាពក្នុងអគារល្អបំផុត។

ACKNOWLEDGEMENT

My biggest gratitude toward my **advisor** Prof. **Pierre LECLERCQ** for believing in me to achieve this thesis, for many advice for both my research work and personal life, and for all the encouragement along the way during my time in Belgium and never once lost hope in me. It has been my great pleasure to be your student and have worked alongside you for the past 4 years. I could never ask for a better advisor.

Thank you to my **co-advisor** Prof. **Virak HAN** for his guidance in my research and my academic career at ITC despite the 10000km distance. Thank you to my **thesis committee** Prof. **Sigrid REITER** and Prof. **Phillipe ANDRE** for being the guiding team since my master's day, and for their valuable time and much relevant advice for the project. This project and manuscript will never be completed without any of you.

Thank you to all the members of the jury, Prof. **Samia Ben RAJEB**, Dr. **Sarin CHAN,** and Dr. **Fabien THIBAULT** for agreeing to review and evaluate this manuscript.

To my dearest friends **Kannary KETH** and **Makara LONG**, I'm so glad to have shared this PhD journey with you. Thank you for your motivation through difficult times, and many exchanges about research and life. To all my colleagues at **LUCID** thank you for many happy lunch breaks, for creating a pleasant work environment, and for being there through all my tough times. Special thanks to **Marine MARECHAL**, **Xaviera CALIXTE** for participating in the writing of project CAMBOdIA which allow me the opportunity to do this PhD, and for your unconditional support since day one of my thesis. And to **Aurélie JEUNEJEAN**, thank you for your time, and effort sacrifice to help me achieve the final part of this work. You have all become my close friends for life.

MOM and **DAD** thank you for your unconditional love, for simply being the best parents ever, and for convincing me that PhD is a good idea when I have doubts. My **sister Singing and grandma,** thank you for being my biggest supporter of everything I do.

And finally, my beloved **husband Lypheng,** the love of my life, the man with that I share all my happiness and my sorrows. Thank you for always there ready to lend me your strength. You have been my biggest motivation throughout this PhD journey and the strongest pillar for me to rely on. I couldn't have made it here today without you.

Finance and research material support: thank you to **ARES** and project **CAMBOdIA** for financial support for all 4 years of my PhD journey. Special thanks to **the Thermal lab** at ITC and **BEM lab** at ULiege for their support of research equipment. And to the owners of the case study buildings, and all the participants in surveys, interviews, and usability tests, thank you for providing data to make my research possible.

TABLE OF CONTENTS

INTRODUCTION

Welcome to the first chapter of this thesis where the background and context of the research subject are presented. The aim and motivation of the study are addressed regarding the general issues related to the topic. The structure of this manuscript will be presented at the end of the chapter to guide you through a smooth reading of the whole manuscript.

0.1 Thermal Comfort and Sustainability

"*Given the tremendous size and heat capacity of the global oceans, it takes a massive amount of added heat energy to raise Earth's average yearly surface temperature even a small amount. The roughly 2-degree Fahrenheit (1 degrees Celsius) increase in global average surface temperature that has occurred since the pre-industrial era (1850-1900 in NOAA's record) might seem small, but it means a significant increase in accumulated heat*"(Lindsey & Dahlman, 2024).

It is evidence that all industries contribute to the environmental problem which results in climate change. The construction sector has been known to play a major role in polluting the environment among other industries. A building impacts the environment throughout its entire life cycle. From the construction phase to the operational phase and ultimately to the demolition phase, buildings generate a carbon footprint at each stage. The operation phase is known to be the most challenging phase of all, especially for buildings with poor design on building comfort where energy demand for lighting, cooling, and heating keeps increasing.

Thermal comfort has emerged as the most critical factor among the three principal aspects of comfort that a building must provide. As climate patterns shift and socio-cultural dynamics evolve, the importance of designing buildings with high thermal performance has become more and more crucial to achieve as it relies on both physical and human factors (Alghamdi et al., 2022). In hot climate regions such as the tropics, air conditioning has become the predominant method of ensuring thermal comfort, particularly in densely populated urban areas. However, air conditioning is not a sustainable solution for thermal comfort. Its widespread use exacerbates climate change, leading to increased energy demands for cooling, which perpetuates a continuous cycle of environmental degradation.

With all these environmental problems, sustainability has become the topic of discussion in all aspects. The term sustainability appeared for the first time in 1987 in the Brutland Report produced by the United Nations. In this report, sustainability was defined as "*meeting the needs of the present without compromising the ability of future generations to meet their own needs*" (Keeble, 1987). This term has then been practiced in various aspects of society, economics, and the environment to ensure a better future for all. Sustainable Development Goals (SDGs) that were set out by the United Nations in 2015, have then become the development goal of all countries with the intended to be achieved by 2030.

In the construction sector, sustainability encompasses several practices aimed at reducing environmental impact. This includes utilizing local materials to minimize carbon emissions associated with transportation, designing buildings to achieve maximum comfort with minimal energy consumption, and employing renewable and recycled materials to reduce construction waste. Additionally, sustainability in construction involves various other strategies to mitigate environmental impact throughout the building's life cycle.

Architects are the key actors in helping promote sustainability in the construction sector to reduce environmental issues caused by buildings. Since 1993, the Union of International Architects (UIA) has officially placed sustainable architecture on its agenda (UIA, 1993). To respond to the SDGs goal, the UIA formed a Sustainable Development Goal Commission in 2018 and produced an architecture guide for building sustainability (UIA, 2018). According to this guide, architects can design a building that provides a well-built environment, quality of indoor living, achieves comfort to lower energy consumption in the building, uses sustainable material to reduce energy production and waste in the demolition, uses renewable or alternative energy resources, creating a building that adapts to the changing climate and can be access to all. Architects have started practicing sustainable development more and more in their projects. The building focuses more on being eco-friendly, energy friendly and human-friendly. With the SDGs goal, sustainability in architecture isn’t a trend anymore. It has the movement and passion of all designers.

The SDGs goal has been applied to all countries around the world. For developing countries such as Cambodia, thanks to this goal, we start to see movement of sustainability in the construction sector. The Phnom Penh sustainable city plan that was introduced in 2018 follows the SDGs goals of the United Nations with an aim to promote sustainable development involved with construction in the urban areas as well (NCSD-MOE et al., 2018). Later, the Ministry of Environment of Cambodia has started developing Cambodia’s guidelines and certification for green building such as CamGCGB (NCSD, 2021). This guideline aims to promote sustainable architecture in Cambodia. CamGCGB will become a policy that all people involved in the construction sector need to follow and apply sustainable development in their projects. This guideline is still in the process of being finalized due to insufficient scientific data for its validation. We can see the initiative in the application of sustainability in the construction sector in Cambodia. However, existing approaches largely focus on social and political dimensions rather than technical or environmental aspects.

As air conditioner isn’t a sustainable solution to improve building thermal performance, researchers have conducted numerous studies to find an alternative solution that is more environmentally cautious (Alghamdi et al., 2022; Memon et al., 2008; Peci-Lopez & De Adana, 2015). Sustainable design principles such as climate-responsive strategies have become one of the study trends that has gained more and more attention in the research domain as well as the professional field. It is a design principle that focuses on passive or bioclimatic design with response to climate conditions and the aim to achieve maximum thermal comfort with minimum energy consumption. Many guidelines and methods have been developed for various countries to help architects achieve designing bioclimatic buildings. However, as studies about thermal comfort show that a thermal comfort standard in one country can be different to another as it depends on the adaptation of each person (Van Hoof, 2008) and the variation of different climate conditions in parts of the world, some of these findings unfortunately can’t be applied to all regions. Therefore, similar studies need to be conducted for different types of climate and people's resilience.

0.2 Architectural Design Assistant

As architects and engineers, we agree that designing a building is a challenging task. The architectural design process is considered one of the complex and challenging process of the building life cycle (Barelkowski, 2018). Design assistants were then developed to help architects, engineers, and designers to expedite their design process. CAD (Computer-aid design) was the first computer-aid tool for drawing and modeling buildings and other design (Tornincasa & Torino, 2010). Since 1957, CAD has been active strongly in the design sector, even though pencil and paper remain the primary way for draftsmanship. However, designing a building with maximum comfort, on a fixed budget and timeline, to fit a certain aesthetic while integrating sustainable principles takes the challenge to another level. Therefore, CAD has become more revolutionized. The problem of thermal comfort resulted in the development of simulation tools to evaluate building thermal performance or energy demand since the 80s (Hensen & Lamberts, 2019). In the research community, BPS (Building performance simulation) or BES (Building energy simulation) has been used to test design, construction material, active system control, and building operation to improve building thermal performance and lower energy consumption (de Wilde, 2019). In the professional field, this tool has slowly cooperated into the design process as a decision support tool for architects and designers in their choices of building design to maintain the comfort and sustainability of the building.

BIM (Building information modeling) is another approach that has been integrated into the construction sector as well (Aryani et al., 2014). According to Hoscheid and Halin (2018), “*BIM is a process that improves each facility’s lifecycle phase, design and construction included, using standardized human and machine-readable information. It is often described as an emerging technological and procedural shift within the Architecture, Engineering, and Construction (AEC) industry*”(E. Hochscheid & Halin, 2018). The BIM model is used to share building information between stakeholders to enhance collaboration and coordination of the project. The innovation of BIM makes it applicable from the design phase to construction until the operation phase. In the early days of BIM application, it is mostly applied in the construction phase. However, it has slowly integrated into the design phase as a model for facilitating project collaboration and coordination between stakeholders. BIM software can slowly be seen replacing traditional CAD software such as Autocad and SketchUp (Ibrahim, 2006). A BIM model contains a lot of building information that can be accessed to do various simulations. Software such as Revit has a directly connected platform such as Insight that can perform and calculate energy demand for the building directly from the BIM model that has been transformed into the BES model in Revit itself. As a result, it has been claimed that BIM promotes building sustainability since it started to integrate with BES, assess the green building certificate and its benefit during the construction phase (Alwan et al., 2015; Ayman et al., 2020; Lu et al., 2017). BIM model has been used to create BES model and conduct simulation for building thermal performance which could save time needed for modeling BES model in energy software. The application of BIM and BES is widely used in Western and developing countries where a lot of resources are available (Bui et al., 2016). However, for developing countries, the application of these approaches remains a challenging task.

0.3 Aims and Motivation

The motivation for this PhD research comes from the rising concern of the building environment in terms of thermal comfort for residential buildings in the urban area in Cambodia. As urban populations continue to rise, the demand for energy-efficient and comfortable residential buildings has become increasingly critical. In many developing countries, such as Cambodia, the rapid pace of urbanization has often outstripped the implementation of sustainable building practices, leading to widespread issues of thermal discomfort and high energy consumption in urban houses.

Addressing these challenges, the global aim of this thesis is to identify the current house design malfunction and seek methods that can help architects to improve its thermal performance. The study looks into the development of a decision support system to assist architects and designers during their design process related to bioclimatic design strategies and non-expert requirement tool for building thermal performance analysis. This research not only seeks to improve the thermal comfort and energy efficiency of residential buildings in Cambodia but also aspires to raise awareness about the practice of sustainable design strategies and the application of different methods to help architects and designers to achieve designing a comfortable building. The findings from this study could inform policymakers, architects, and urban planners, fostering a more sustainable approach to residential building design that balances human comfort with environmental responsibility.

0.4 Research Boundaries

Before diving deep into the manuscript, we would like to address the boundary that this research is limited to as below:

- Indoor Thermal Comfort: This research centers on indoor thermal comfort and does not address other comfort factors such as indoor air quality, acoustic comfort, or visual comfort.
- BIM Model Focus: The study specifically examines the use of BIM models as a tool, excluding other aspects of BIM application such as methodology, process, and management.
- Architectural Design Process: The scope of this study is confined to the architectural design process, excluding the construction phase and other design processes.
- Design Strategies: The study is limited to analyzing bioclimatic and passive design strategies. Mechanical ventilation systems, including air conditioners and other HVAC systems, are outside the scope of this research.
- Building Types: The focus is on contemporary residential buildings, specifically single-family houses and low-rise apartments. Traditional houses and other building types, such as educational, industrial, commercial, and office buildings, are not included.
- Geographic Focus: Cambodia is selected as the primary climate and context for this study.

0.5 Structure of Manuscripts

Figure 0-1 present the structure and chapter of this manuscript and describe the workflow put into place. The manuscript of this thesis consists of 10 chapters. This **introduction** expresses the background and the motivation of this thesis. The manuscript then followed by other 9 chapters that explain:

- **Chapter 1**: The literature review of existing studies related to thermal performance, climate responsive strategies, application of BPS and BIM to assess building thermal performance, and the architectural design process integrating these two approaches.
- **Chapter 2**: Discusses the problem statement of the research derived from the literature review and in-situ observation. Research questions and the objectives of the thesis will be established in this chapter.
- **Chapter 3**: Describes the methodology and step of its application to answer the research questions and to achieve the objectives of the study.
- **Chapter 4**: Analyze the first data collection and the result of the study where the thermal performance of the current residential building in Phnom Penh, an adaptive comfort model is proposed for Cambodia and the current house design issues are identified.

- **Chapter 5**: Conducts the simulation of case study building to analyze the application of BIM and BES in analyzing thermal performance and discusses the efficiency of these tools as a design assistant during the design process.
- **Chapter 6**: Analyze the integration of BIM and BES in the architectural design process for the context of Cambodia is analyzed including its ability to apply in the early design process as a decision support system and identify a current architectural design process including tool, design strategies, and collective design collaboration. A non-expert requirement tool in a form spreadsheet is proposed for building thermal performance analysis.
- **Chapter 7**: Proposes a bioclimatic design guideline for Cambodia. The validation of this guideline is done through a usability test and BPS of the bioclimatic building scenarios received from the test. The architectural design process integrating decision support systems since the early design phase is discussed.
- **Chapter 8**: Presents the answer to all the research questions and general discussion of the methodologies applied and the findings of this thesis.
- **Conclusion**: The last chapter summarizes all the findings and original contributions of this thesis. The research limitations, perspectives, and recommendations from the author are addressed.

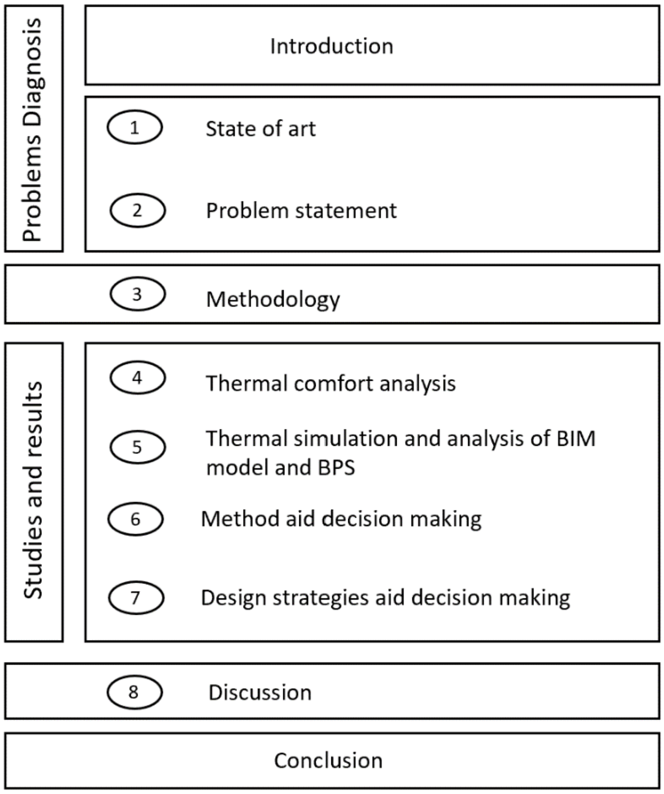


Figure 0-1: Structure of the manuscript

To facilitate the reading of this manuscript, at the beginning of every chapter, there is a summary of the objectives and the structure of the chapter. Additionally, the end of those chapters presents a summary of the findings addressing that chapter’s objectives and the link to the next chapter of the manuscript.

CHAPTER 1

LITERATURE REVIEW

This chapter aims to review the existing research relevant to the key themes of this study. We will commence with an examination of research studies related to thermal comfort, including method analyses, adaptive comfort models, and findings specific to tropical regions. Following this, we will explore the application of BPS and BIM in the context of building thermal performance analysis and sustainability promotion. The chapter will then address studies on climate-responsive design strategies, focusing on their impact on building thermal performance and research in Cambodia. Finally, we will present findings related to the architectural design process.

1.1 Thermal Comfort

There are 3 comforts in building that most architects aim to achieve during their design process such as thermal comfort, visual comfort, and acoustic comfort. Thermal comfort is one the most challenging factors to obtain in building design as it revolves around physical parameters and human abilities in adaptation to their surroundings environment. According to ASHRAE, thermal comfort is defined as "*the condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation*'' (ASHRAE, 2017). Hence, thermal comfort is influenced by both physical and physiological parameters. It depends on factors such as air temperature, relative humidity, radiant temperature, metabolic rate, and clothing insulation. However, other factors such as age, gender, emotion, and people's adaptation also influence one's comfort level which leads thermal comfort to vary from one person to another even if they are sitting in the same room, wearing the same clothes, and doing the same activities. A study in Nanjing, China shows that the psychological adaptation of occupant has a high impact on their comfort level (Zhuang et al., 2022). According to this study, "*the thermal sensitivity to skin/operative temperature change is influenced by psychological adaptation, and the higher the psychological adaptation, the lower the sensitivity to skin/operative temperature change*" (Zhuang et al., 2022). The adaptation of people to a certain climate or environment is what intrigue one of our research objectives.

Thermal comfort significantly influences occupant satisfaction with their surroundings environment and productivity. Although it started out as a topic related to human physiology, it has then become an interesting topic for building scientists. Thermal comfort standards can help architects and engineers design buildings that could provide thermal comfort for their occupants in both natural and controlled ventilation. Therefore, the question of building quality and human well-being caused by thermal comfort has become an interesting research topic.

The study about thermal comfort started hundreds of years ago. The first study related to this topic was probably the one conducted by Haldane in 1905 which investigated the limit of how humans can exist and work normally when the temperature is abnormally high (Haldane, 1905). Later, research on this topic started focusing on defining comfort models, acceptable influenced parameter value for comfort, methods analysis of thermal comfort, BPS, and assessment of various types of buildings thermal performance in different climates, etc...

Recently, research studies in the construction sector related to this topic are more focused on the impact of building design or construction material in improving building thermal performance, adaptative comfort model, and control of energy-neutral buildings. However, the study on how to improve thermal comfort for occupants is still an issue that hasn't been solved in many parts of the world, especially in developing countries such as Cambodia. Designing a comfortable building is therefore still a challenge for architects and designers in such countries. With global climate change and the variation of people’s thermal comfort adaptation in different climates and regions, research around this topic is expected to be an ongoing trend for the foreseeable future.

1.1.1 Methods for Thermal Comfort Analysis

In 1970, a study by Fanger proposed the first comfort model based on the steady-state thermal comfort theory in a climate chamber by exploiting the heat balance principle. It has then become the foundation of international comfort standards for building thermal performance evaluation which later was adopted into ISO 7733 (Fanger, 1970; ISO-7730, 2005). The globally accepted Predicted Mean Vote (PMV) and Percentage of Dissatisfaction (PDD) by Fanger range on a 7-point thermal sensation scale from -3 (very cold) to +3 (very hot). The relationship between PMV and PDD is shown in Figure 1-1 and can be calculated using thermal comfort-influenced parameters with equations written as:

$$PMV = (0.303\,exp(-0.036M) + 0.028)[M - 3.0510^{-3}(5733 - 6.99M - p_a) - 0.42(M - 58.15) - 1.710^{-5}M(5867 - p_a) - 0.0014M(34 - t_a) - 3.9610^{-8}f_{cl}((t_{cl} + 273)^4 - (t_r + 273)^4) - f_{cl}h_c(t_{cl} - t_a)] \tag{Eq. 1-1}$$

$$t_{cl} = 35.7 - 0.028M - 0.155I_{cl}[3.96 \times 10^{-8}f_{cl}((t_{cl} + 273)^4 - (t_r + 273)^4) + f_{cl}h_c(t_{cl} - t_a)] \tag{Eq. 1-2}$$

$$h_c = \begin{cases} 12.1\sqrt{v} \;\; if\; 2.38(t_{cl} - t_a)^{0.25} \leq 12.1\sqrt{v} \\ 2.38(t_{cl} - t_a)^{0.25} \; if \;\; 2.38(t_{cl} - t_a)^{0.25} > 12.1\sqrt{v} \end{cases} \tag{Eq. 1-3}$$

$$f_{cl} = \begin{cases} 1.00 + 0.2I_{cl}\; if\; I_{cl} \leq 0.5\; clo \\ 1.05 + 0.2I_{cl}\; if\; I_{cl} > 0.5\; clo \end{cases} \tag{Eq. 1-4}$$

$$PDD = 100 - 95e^{-(0.03353PMV^4 + 0.2179PMV^2)} \tag{Eq. 1-5}$$

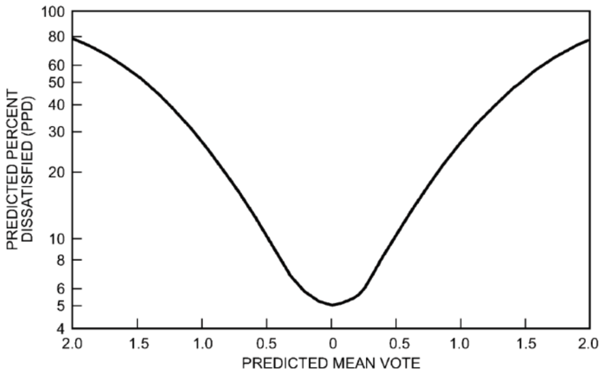
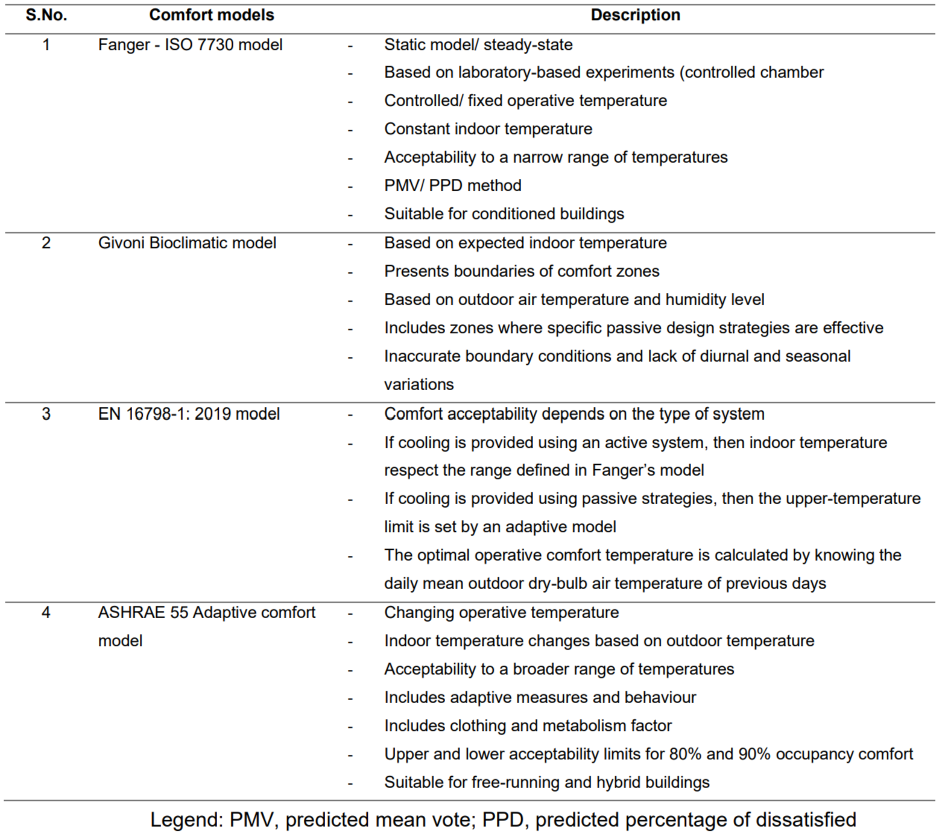


Figure 1-1: PDD as a function of PMV.

Thermal comfort is usually analyzed based on comfort models. Four models are frequently used such as Fanger's model which later adopted into ISO 7730 standard (Fanger, 1970; ISO7730, 2005), Givoni bioclimatic chart (Givoni, 1969), EN 16798-1 European comfort model (EN 19768-1, 2019), and American adaptive comfort model ASHRAE 55 (ASHRAE, 2017). The comparison between the 4 comfort models is identified in the table below.



S.No.	Comfort models	Description
1	Fanger - ISO 7730 model	- Static model/ steady-state - Based on laboratory-based experiments (controlled chamber - Controlled/ fixed operative temperature - Constant indoor temperature - Acceptability to a narrow range of temperatures - PMV/ PPD method - Suitable for conditioned buildings
2	Givoni Bioclimatic model	- Based on expected indoor temperature - Presents boundaries of comfort zones - Based on outdoor air temperature and humidity level - Includes zones where specific passive design strategies are effective - Inaccurate boundary conditions and lack of diurnal and seasonal variations
3	EN 16798-1: 2019 model	- Comfort acceptability depends on the type of system - If cooling is provided using an active system, then indoor temperature respect the range defined in Fanger's model - If cooling is provided using passive strategies, then the upper-temperature limit is set by an adaptive model - The optimal operative comfort temperature is calculated by knowing the daily mean outdoor dry-bulb air temperature of previous days
4	ASHRAE 55 Adaptive comfort model	- Changing operative temperature - Indoor temperature changes based on outdoor temperature - Acceptability to a broader range of temperatures - Includes adaptive measures and behaviour - Includes clothing and metabolism factor - Upper and lower acceptability limits for 80% and 90% occupancy comfort - Suitable for free-running and hybrid buildings

Legend: PMV, predicted mean vote; PPD, predicted percentage of dissatisfied

Figure 1-2: Comparison of the 4 comfort model (Mahar, 2021).

Data collection for building thermal evaluation in existing buildings can be done through building monitoring (measurement of influential parameters) or surveys and interviews with the occupant. In this case, the survey and interview can be conducted using the comfort prediction model. It is based on the thermal comfort scale by Bedford or the sensation scale by ASHRAE where occupants can vote on their thermal satisfaction and sensation from a 7-range scale as shown in Table 1-1. The ASHRAE scale is frequently used compared to Bedford. In this case, it can be assumed that the sensation level defines the comfort level which means voting for neutral means comfortable. However, in practice, this assumption does not consistently hold true (N. H. Wong et al., 2002).

Table 1-1: Thermal sensation scale by Bedford and ASHRAE.

Bedford scale	ASHRAE scale
7 too much warm	+3 hot
6 too warm	+2 warm
5 comfortably warm	+1 slightly warm
4 comfortable	0 neutral
3 comfortably cool	-1 slightly cool
2 too cool	-2 cool
1 too much cool	-3 cold

1.1.2 Thermal Comfort in Tropical Region

Research on thermal comfort in temperate climates and controlled ventilation has been widely conducted. As a result, ASHRAE (ASHRAE, 2017) and ISO (ISO7730, 2005) have become an international standard for thermal comfort study and evaluation. The first investigation related to thermal comfort in tropical climate was by Webb in 1949-1950 where 20 people who were long resident in Singapore were observed. Based on climatic index of air temperature, relative humidity, and air velocity, if it is assumed that the ideal air velocity indoors is 0.2 m/s and the ideal relative humidity 70% then the air temperature at which discomfort would be a minimum of 28.86 ℃ (WEBB, 1959). Later on, another study was conducted by Ellis in 1953 where 34 Europeans and 99 Asians who lived in Singapore were asked to vote on their thermal comfort level according to the Bedford scale (see Table 1-1). It is concluded that the majority of inactive, lightly dressed, and adjusted to the environment European men and women in Singapore are reasonably comfortable with their indoor thermal environment provided the effective temperature does not exceed 25.53℃ or fall below 22.76℃ (Ellis, 1953). After that, another study in Singapore was conducted by De Dear in 1990 based on 583 respondents in naturally ventilated conditions and 235 in air-conditioned conditions ventilation along with indoor climatic measurements. It was found that in the naturally ventilated apartment, the occupant felt halfway between neutral or slightly warm with the operative temperature of 29.6 ℃, relative humidity of 74%, and air velocity of 0.22m/s when their clothing insulation is 0.26 clo and metabolic rate is 70w/m^2 (de Dear et al., 1991). From this period until recently many studies have been conducted in Thailand (Busch, 1992), Pakistan (Nicol & Roaf, 1996), Bangladesh (Mallick, 1996), Indonesia (Feriadi & Wong, 2004), and Mexico (López-Pérez et al., 2019) to determine an acceptable range for their respective case study regions. Table 1-2 summarizes the acceptable value of parameters found in these studies.

Table 1-2: Influenced parameter acceptable range for comfort in natural ventilation conditions in tropical region.

Country	Study	Temperature (℃)	Relative humidity (%)	Air velocity (m/s)
Singapore	(WEBB, 1959)	28.86	70	0.2
Thailand	(Busch, 1992) (Taweekun & Tantiwichien, 2013) (Rangsiraksa, 2006)	28.5 24 -27 25.5-30.5	- 50-70	- 0.2
Bangladesh	(Mallick, 1996)	24 - 32	54 - 90	0 - 0.15
Pakistan	(Nicol & Roaf, 1996)	30	-	-
Indonesia	(Feriadi & Wong, 2004) (Santosa, 1988)	29.2 27.4	-	-
Mexico	(López-Pérez et al., 2019)	26,9 ±1,6	52,1 ± 5,2	0,14 ± 0,03

According to ASHRAE with air velocity of 0.1m/s, clothing insulation of 0.5 clo, and metabolic rate of 1 to 1.3 met, an acceptable value for temperature is between 25 to 28 ℃ (ASHRAE, 2017). We can see that the overall acceptable temperature for people living in tropical climates is above the acceptable temperature indicated by ASHRAE. This shows that people's adaptation to certain climate conditions can alter their comfort level. People who live in tropical regions with hot climate conditions can tolerate a higher temperature than those who used to live in temperate climate conditions. Given that temperature and relative humidity are factors that cannot be easily modified through naturally ventilated building design within tropical climates, air velocity emerges as the most influential factor for occupant thermal comfort (Feriadi & Wong, 2004; Nor Azli et al., 2023; Taing et al., 2023). This reliance on air movement is reflected in the widespread use of pedestal and ceiling fans in households across the region, as they help to enhance airflow and improve comfort in otherwise challenging environmental conditions.

As the acceptable range of influenced parameters can vary according to climate conditions and the adaptation of people, many studies have been conducted to identify an adaptive comfort model that is suitable for different climate conditions. Most of these studies are based on evaluating the Fanger model and adding correction coefficients.

1.1.3 Adaptive Comfort Model

Even though the PMV-PDD model has been used and accepted globally, many field studies have shown that the model fails to predict the thermal comfort of space in naturally ventilated conditions and isn't adaptable for all parts of the world even in a controlled ventilation room. This is because this model doesn't take into account the human interaction and adaptation behavior with their surrounding environment. In the 1980s, the discussion about adaptive principles related to this comfort model began which was initiated by Michael A. Humphreys (Centnerova, 2018). In 1997, Brager and de Dear did a literature study on thermal adaptation in the built environment (Brager & De Dear, 1998) and later developed an adaptive thermal comfort model which was included in the ASHRAE 55 (ASHRAE, 2017; de Dear & Brager, 1998).

So far, many adaptive models have been developed for countries in different climates, especially in tropical hot and humid regions as Fanger models were developed in the temperate climate. A study in Malaysia shows that the Fanger model uses heat balance, presents challenges in identifying the most influential parameters. Due to the sociocultural context of Malaysia, clothing insulation and metabolism rate are two influential parameters that they investigated. It turns out that Malaysians accustomed to wearing high clothing insulation even in hot weather define a new adaptive model that offers a PMV limitation of ±1.3 for 80% occupant satisfaction, with an increment of ±0.3 compared to the initial PMV limitation according to the ASHRAE standard (Pao & Kee, 2013). A similar study was also conducted in the coastal town of Benin by Olissan where he found out that relative humidity is the most influential parameter, and people can tolerate higher temperatures. More than that, air conditioners can quickly change people's sensation vote to negative. He proposed an adaptive model for PMV new as PMV – $0.15t_a$ + 0.046RH (Olissan et al., 2016). The adaptive comfort model was identified in similar studies for other countries with variations in climate and sociocultural such as China (Li et al., 2009) and Vietnam (Nguyen et al., 2012). With the adaptive comfort model shown to be related to both climate and cultural aspects, an adaptive model from one country might not be suitable for the countries even with the similarity of climate conditions due to lifestyle differences. Although numerous studies on this topic have been conducted in tropical regions, less scientifically resourced countries like Cambodia have yet to develop their adaptive models.

1.2 Building Performance Simulation

The question around thermal comfort has led to the development of simulation engines to analyze building performance to facilitate the design of buildings and avoid numerous in-situ measurements of influential parameters. Building performance simulation (BPS) is a methodology that 'employs a large number of mathematical models to simulate a building's performance under a given set of boundary conditions' (Beausoleil-Morrison, 2021). To put it simply, it is a computer-based replication of a building using a mathematical model created on the fundamentals of physics principles to analyze certain aspects of the building. In scientific literature, BPS is adopted for various types of performance for buildings. However, since the 1980s, it is well known that BPS is normally linked with Building Energy Simulation (BES) (Hensen & Lamberts, 2019). The increasing focus on thermal comfort and energy consumption keeps BES as a central concept for BPS. Since then, many BPS tools have been developed to analyze building thermal and energy performance and act as a decision support tool for architects and designers during the building design process.

1.2.1 Building Thermal Performance Analysis Using BPS

Building performance analysis is conducted to assess the 3 comforts of the building in terms of thermal, light, and acoustic with association to the energy consumption. In order to achieve sustainable design in buildings, architects and designers have been using BPS as a tool for decision-making in analyzing the building performance and testing different design aspects of the building to achieve minimum energy consumption. An editorial by Spitler (2006) mentioned that "*building thermal performance using digital computers has been an active area of investigation since the 1960s, with much of the early work focusing on load calculations and energy analysis. Over time, the simulation domain has grown richer and more integrated, with available tools integrating simulation of heat and mass transfer in the building fabric, airflow in and through the building, daylighting, and a vast array of system types and components*" (Spitler, 2006). For many years, BPS has been a reliable tool for architects and designers during the building design process for thermal performance.

To analyze the thermal comfort of an existing building, in-situ measurements of influential parameters or surveys and interviews with occupants using PMV can be done. For new-built buildings, to help designers estimate in advance the thermal or energy performance of the building, thermal or energy simulation has become the main used method. BES software such as DOE-2, EnergyPlus, TRNSYS, eQuest, and Design Builder are widely used and known to be among the best BPS tools (Roman et al., 2020). These tools can work alone by itself to perform the simulation or use pre-modeling of 3D models or BIM models from the CAD and BIM software. Each software has its own specificity of input data (file) and output data.

In scientific research, BES software has been extensively utilized to predict building thermal comfort and evaluate various construction materials and design parameters to enhance thermal performance. While BPS has demonstrated its utility as a valuable tool, numerous challenges have been identified in its application across different contexts. A study has shown that BPS wasn't well practiced in the day-to-day work of architects in both developed and developing countries (Soebarto et al., 2015). Conducting a BPS using BES software is complex and detailed, often demanding significant time and effort. Conducting a BPS to analyze or evaluate the thermal performance of a building requires a lot of time and data input to get an accurate and reliable result. Most of the BPS software was developed in Western countries within temperate climates and normally follows the standard applied in their respective country. More than that, as building thermal performance is influenced by many factors, it is hard to predict thermal performance through simulation compared to building in-situ monitoring. BPS developed in temperate climate countries focus on keeping the heat inside the building whereas buildings in hot countries want to release heat from the building. Therefore, some software functions aren't useful, and the necessary functions can't be found. As a result, questions about the efficiency of the application of these software for a case study in countries with a hot climate arise. A study in Egypt by Attia (2011) showed that BPS wasn't practiced strongly in the design community and haven't much cooperated during the design process due to the barrier of lacking informative support for decision-making and the interoperability between the geometry of CAD and BPS tool (Attia et al., 2011).

As mentioned earlier there are many BPS tools available. However, these tools are very detailed simulations that would be more adaptable at the later stage of the design process (Ritter et al., 2015). The use of the BPS tool in the early design process has been little discussed. Studies have shown that sustainable design strategies have always been implemented since the early design phase. Therefore, decision support tools should be applied in a similar way. During the design process, two types of tools are normally used, design tools such as CAD or Revit and decision support tools such as BPS. A study shows that simulation tools can be divided into 3 categories (Han et al., 2018):

- The simulation plugin for the design tool
- The geometry user interface for a simulation engine
- The self-governed simulation tool

The plug-in of simulation in the design tool where the designer doesn't require a lot of time and input data is recommended to integrate in the early design process (Han et al., 2018).

It is evident that the result from the simulation isn't always accurate as the actual building can receive impact from microclimate, occupant behavior, and the control of HVAC system on building thermal performance. For existing buildings, to validate the result from the simulation, calibration is one of the widely used methods. The calibration process usually consists of the comparison between in-situ measurement parameters and results from the simulation. Many trials and errors can be performed to receive the most accurate result from the simulation. According to ASHRAE, the numerical model can be considered calibrated, or the simulation result is acceptable based on two statistical indices Normalized Mean Bias Error (NMBE) and Coefficient of Variation of Root Square Mean Error CV(RMSE). Per ASHRAE standard, the acceptability of these two indicators for a calibrated model is shown in Table 1-3(ASHRAE, 2014).

Table 1-3: Acceptable indices value by ASHRAE standard

Statistical indices	Monthly simulation	Hourly simulation
NMBE	< 5%	< 10%
CV(RMSE)	< 15%	< 30%

1.3 BIM

1.3.1 Terms and Definitions

The advancement of technologies happens in all industries including the construction sector. As discussed in the introduction of this manuscript, the design domain has already witnessed a significant evolution, transitioning from traditional paper-based methods to CAD systems. In recent years, BIM has emerged as a prominent research trend within the construction scientific community. Today, architecture extends beyond drawing and design, it increasingly encompasses the sharing and communication of information and data among stakeholders.

The definition of BIM is often misunderstood by many people. Some thought of it as a modeling tool and some even think that it is just Revit. According to Bazjanac, BIM is "*an instance of a populated data model of buildings that contains multi-disciplinary data specific to a particular building, which they describe unambiguously. It contains all data that define the building and are pertinent from the point of view of more than one discipline*"(Bazjanac, 2004). For Hochscheid (2018), she specifies that the acronym BIM can stand for Building Information Modeling/Model/Management. BIM (Building Information Modeling) is an approach that brings together a set of methods, processes, and tools that exploit all the information of the building structure. Building information is connected to a digital model (Building Information Model) which is a digital presentation of geometric and functional characteristics of the building structure and design. Building information needs to be managed (Building Information Management) in order to be used and shared between actors and phases of the project (É. Hochscheid & Halin, 2018). In this manuscript, BIM focuses on the Building Information Model, where the building model contains all building data and information that facilitate building analysis, project coordination, planning, and collaboration between stakeholders. The BIM model is usually the first step of BIM to be practiced in the professional or educational environment of architecture.

1.3.2 Advantage and Limitation/Barrier of BIM

BIM has started integrating into the construction and architecture domain to counter the social and economic challenges of building in both the design and construction phases. Many advantages can be derived from the practice of BIM in a project which is why it has been more and more used in the ACE (Architecture, Construction and Engineering) sector. As mentioned previously, BIM makes all building information available to all stakeholders (A. K. D. Wong et al., 2010) and support decision-making in the design and construction phases through better management, coordination, collaboration, and use of information (Fischer & Kunz, 2004). It is described that BIM helps to increase productivity and production efficiency due to its ability that allow stakeholders to control crucial factors such as cost, time, and quality in a more efficient way (Azhar et al., 2008; Love et al., 2011). In many studies, BIM shown to provide benefits throughout the whole building life cycle (Bryde et al., 2013; Toan et al., 2022).

In the pre-construction or design phase, BIM also works as a decision support tool. According to Cullen (2016), BIM helps minimize the surprise of clients by performing value engineering with cost estimation of building construction and operation (i.eg. energy consumption) for them to have a conscious decision-making with factors that crucial for them (Cullen, 2016). The initial building design can significantly impact the subsequent stages of the design process. Therefore, conducting building energy analysis during the early design phase by linking BIM with BES tools is crucial for estimating energy demand for heating and cooling (Eastman, 2008). This approach facilitates decision-making for both the architect and client, helping them prioritize building comfort and quality while avoiding delays in the design process (Stumpf & Kim, 2011).

Despite its many advantages throughout the building life cycle, implementation of BIM in real projects isn’t easy and has been a question asked by researchers and stakeholders. Some limitations and barriers can be found with the application of BIM in the design and construction phases especially in developing countries (N. A. A. Ismail et al., 2017). In general, technology BIM favors the collaboration and coordination of projects that provide more benefits in the construction phase. It was pointed out that this approach is designed to economically and ecologically optimize the construction of a building and not for its design (Levan, 2016). Integrating BIM in the design phase can therefore add tasks and require more workload from the architect where the benefit can be recovered only in the construction phase (Sergeevich et al., 2019). However, a study in Malaysia found that based on the Level of Development (LOD) of the project, BIM provides more benefits during the design phase rather than in the construction, facilities, operation, and maintenance phase (H. S. Ibrahim et al., 2019). Nevertheless, a study in the Middle East and North African developing countries indicate that there are numerous barriers to the implementation of BIM in the design phase. These barriers include a general lack of knowledge and awareness of BIM, commercial issues and investment costs, a shortage of BIM expertise, challenges related to the interoperability of BIM models, and client demands. (El Hajj et al., 2021).

1.3.3 BIM Integration in BPS and Sustainability

It is claimed that BIM helps promote sustainability in the construction sector. In developed countries, BIM has been more and more integrated into the building sector from the building design stage to construction to the operation stage. There are many studies conducted to identify its advantages, efficiency, and barriers of integrated BIM to promote building sustainability. A review study shows that in terms of environmental challenges, BIM provides benefits in "*Promoting carbon emission reduction*" and "*Enhancing material wastage reduction*" (Datta et al., 2023). BIM is used in a study to analyze the relationship between cost and energy saving in the architectural design process (Wei & Chen, 2020). A study on using BIM for building evaluation and energy analysis shows that using BIM can help quickly and efficiently perform green building certificate evaluation such as LEED (Alwan et al., 2015). BIM was also applied to analyze a whole building life cycle assessment to reduce the carbon footprint caused by building as well (Panteli et al., 2018). The active use of BIM in helping to achieve sustainable building introduces the term '*Green BIM*' which includes BEM (Building Energy Modeling) to analyze the building energy performance or thermal performance to minimize energy consumption (Maltese et al., 2017). From our findings which will be explained in more detail in Chapter 6, in Cambodia, the integration of BIM and BES is still limited and lacks of efficient method for its application into the architectural design process (Taing et al., 2024).

The capacity of importing BIM data facilitates BPS by reducing the time and effort required for building modeling and certain data input in BEM. The green building XML file (gbXML) is a schema developed for sharing building information from the BIM model to BEM. There are many BPS tools that has the ability to adopt this into their software for conducting building simulations. Table 1-4 shows the interoperability of commonly used BPS tools with BIM software studies by Bahar et al., in 2013. However, the BIM-BEM data interoperability issues were reported in various research (Cemesova et al., 2015; Steel et al., 2012).

Table 1-4: Interoperability of BPS tool with BIM (Bahar et al., 2013).

Tool	Application	Input data	Output data	BIM-based geometry import
EnergyPlus	Energy Simulation, thermal design and analysis, Heating and cooling loads, Validation; Solar control, Overshadowing, Natural and artificial lighting, Life cycle assessment, Life cycle costing, Scheduling	ifc, gbXML, text	ASCII	.ifc compatible. (BIM Application)
TRNSYS	Environmental design, 3D Model (3D Design), thermal design and analysis, heating and cooling loads, Solar control, overshadowing, prevailing winds & air Flow, electrical, photovoltaic, hydrogen systems, Life cycle costing.	.skp, ASCII, .xml	ASCII (Simulation Studio Tool : HTML, C++)	no
eQuest	Energy performance, simulation, energy use analysis, conceptual design performance analysis, 3D Model (3D Design), thermal design and analysis, heating and cooling loads, Solar control, overshadowing, Lighting system, life cycle assessment, life cycle costing, Scheduling	gbXML, .dwg, dxf	dxf, gbXML, .xls	Support gbXML format
Design Builder	Environmental design, 3D Model (3D Design), thermal design and analysis, heating and cooling loads, natural and artificial lighting, Internal air, mean radiant and operative temperatures, humidity, CO2 emissions, solar shading, heat transmission, solar shading, scheduling.	gbXML, .dxf, .pdf, .bmp, .jpg	CAD: AutoCAD, Microstation, SketchUp using 3-D dxf, .epw, .csv, .tmy, .tmy2	Provides interoperability with BIM models through its .gbXML import capability

Generally, a workflow of BIM to BEM can be described as in Figure 1-3. It normally starts with modeling the actual building in Revit or Archicad or other BIM software. The model has then added some energy-related parameters that can be converted into a gbXML file and then imported into BPS software. However, as energy models have little control over this function, some data can't be fully transferred into BEM. Therefore, modelers have to spend time to re-prepare the imported energy model for the accuracy of the result for the simulation. A study was conducted to introduce a platform called gbEplus which is a gxBML Energy Plus translator that converts gbXML into a ready-to-simulate Energy Plus model to facilitate this obstacle (Xu et al., 2019). However, the use of this translator hasn't been found in other studies and the translator file can't be found on the internet (searching in June 2024) despite claiming it to be open access. As building design can be continuously changed throughout the design process and due to the complexity of BPS, it is sometimes integrated at the end of the design process.

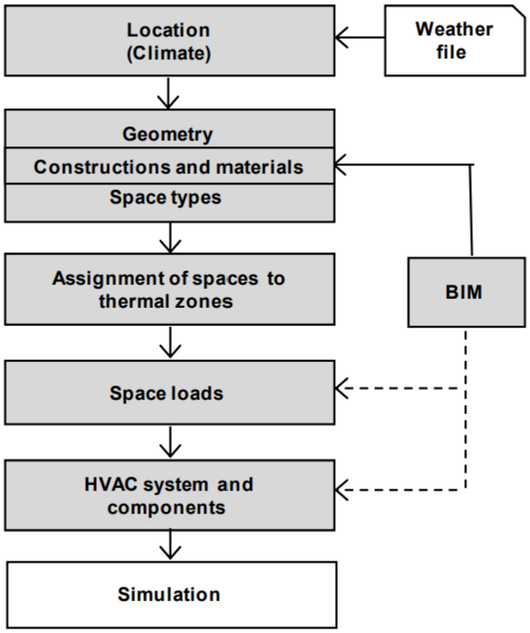


Figure 1-3: An ideal workflow for energy performance in a BPS tool with BIM (Maile et al., 2007).

1.4 Bioclimatic Design

The growing challenges related to thermal comfort have prompted extensive research aimed at identifying effective solutions. These solutions have emerged from studies focused on testing various building design strategies, construction materials, and active systems. Given the critical role of sustainable design in mitigating building-environment related issues, design strategies are consistently developed with sustainability as a guiding principle. Consequently, climate-responsive design strategies have become a central approach in building design, aiming to achieve optimal thermal comfort while minimizing energy consumption. This term is closely associated with concepts such as bioclimatic design and passive design strategies

The term bioclimatic approach was first mentioned in 1963 by researcher Victor Olgyay. He gives its definition as ‘a regionalist approach to architectural design based on the use of quantitative data related such as climatic data and human comfort requirements’ (Olgyay, 1963). To simplify, bioclimatic design is a design strategy that is based on the condition of climate and environment surrounding that building to provide comfort for occupants in that building. The goal of bioclimatic design is to design a building that takes into account the impact of the surrounding environment on the building to obtain a high-performance building that ensures occupant well-being with low energy consumption. Therefore, bioclimatic design has become a design strategy that is human-friendly, eco-friendly, and energy-friendly which would be the most sustainable approach to design a building (Zr & Mochtar, 2013). The practice of bioclimatic strategies can be found in vernacular and traditional buildings around the world. The vernacular and traditional architecture reflects on a climate, culture, history, lifestyle, technology, and availability of resources from the specific location in which it was built. It could be said that these types of architecture are the origin of the application of bioclimatic design.

The first academic publication about climate-responsive design was probably by Aronin in 1953 (Aronin, 1953). However, the study of Olgyay in 1963 gained more attention in the scientific circle (Olgyay, 1963). In his study, Olgyay invented a bioclimatic chart for the United States which established the foundation of the bioclimatic approach. The bioclimatic chart was used to analyze various climates in the United States and findings were turned into architectural design strategies. His greatest contribution was the systematic integration of human thermal comfort for building design and climate analysis.

The next well-known person who took his path on this topic was Givoni in 1969. Contrary to the study of Olgyay, he developed a bioclimatic chart on a psychometric chart which is used widely in building and thermal comfort research (Givoni, 1969). As mentioned in the earlier section of this chapter, the Givoni comfort model is among the models commonly used for thermal comfort analysis. His work inspired researchers to develop a bioclimatic design guideline for different climates and cultures in multiple regions around the world (Cofaigh et al., 1996; Givoni, 1998; Ranck, 2009; Koenigsberger et al., 2013; Nguyen, 2013; ONU-HABITAT, 2015; Mahar, 2021).

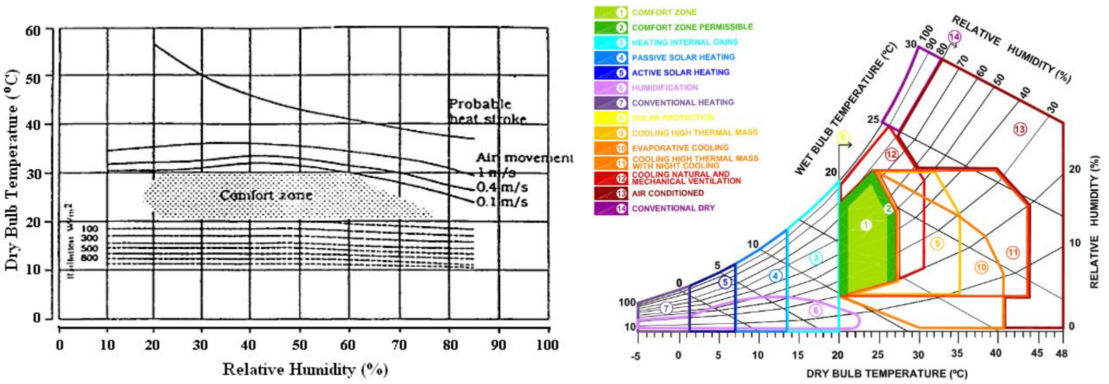


Figure 1-4: Bioclimatic chart by Olgyay (a) and Givoni (b)

However, as culture plays an important role in building design, some guides that could be implemented into similar climate regions still need some alteration. It can be seen that the study of climate-responsive or bioclimatic design hasn’t been conducted for various climates and cultures, especially the third-world countries where scientific research is still limited. A study about local techniques and available resources to fit with climate, culture, and living conditions for optimum comfort and minimum energy consumption is therefore needed in these countries.

1.4.1 Bioclimatic Strategies to Achieve Thermal Comfort

The application of bioclimatic strategies has been undergoing numerous studies of its efficiency in improving indoor thermal performance. As a climate-responsive design method, the bioclimatic design strategies naturally vary according to specific climate conditions. This approach is primarily achieved through passive cooling and heating strategies. In hot climates, bioclimatic design emphasizes passive cooling, whereas in cooler regions, the focus shifts to passive heating strategies. From vernacular architecture and traditional strategies to new technology applications, many studies have been trying the find the best bioclimatic strategies for each climate (Antarikananda et al., 2006; Mantziou, 2009).

To evaluate thermal performance through the integration of a bioclimatic approach, building monitoring and BPS are often used as the research method. A review study published bioclimatic strategies through several passive cooling methods such as solar protection, evaporative cooling, cooling through high thermal mass, nocturnal renovation, conventional dehumidification, and additional mechanical ventilation (Manzano-Agugliaro et al., 2015). A study in Poland shows that using the passive cooling solution with shading and building airing naturally can increase thermal comfort to 15% and reduce discomfort hours by 90% respectively (Ferdyn-Grygierek et al., 2021). Another study in a different climate of hot and dry Egypt analyze different design scenarios including the roof type, effect of the pergola, and veranda using the BPS tool. The results show that the most influential building features on the thermal comfort of the building were the low-pitched roofs and top chimney elements, which achieved 12.6% and 5% improvement in the summer and 13% and 6.8% in winter (Hany & Alaa, 2021). The bioclimatic design elements that are mostly tested for their efficiency in improving building thermal performance can be seen to be the building orientation, opening design, façade/roof design, and shading device (Ariff et al., 2019; Mahar et al., 2019; Panteli et al., 2018; Wang et al., 2007).

The strategies are put together to create a certain design guideline as decision support material for architects during the design process to help them achieve building optimum performance (MAHAR, 2017; Nguyen, 2013). These guidelines can be seen validated for their application for informed decision-making through usability test (MAHAR, 2017).

1.4.2 Bioclimatic Approach in Cambodia

Cambodian traditional house can be represented as a bioclimatic building. It considers the environmental and climate factors in housing design and also the lifestyle and tradition of Cambodian. As with many aspects of life, living practices have evolved over the decades in response to new knowledge and technological advancements. Consequently, the traditional Cambodian house, much like vernacular architecture in other parts of the world, has seen a decline in appearance. While these traditional structures still exist in rural areas, their construction has become increasingly rare in urban and city environments.

Vann Molyvan was a Cambodian architect famous for designing a project that considered the climate, the culture, and the living context of Cambodians. His 100-villa project that was built during the 1960s is a perfect example of Cambodian bioclimatic building. A part of the project still exists today but due to climate change and the evolving lifestyle of Cambodian people, these houses have been transforming to something completely different from their original design, i.e., closing off the louver to favor the use of AC. Therefore, even though bioclimatic buildings already existed in Cambodia, it hasn’t been used in the way that it was intended. However, the architecture of Vann Molyvan remains as a reminder to design responsively to climate and living context.

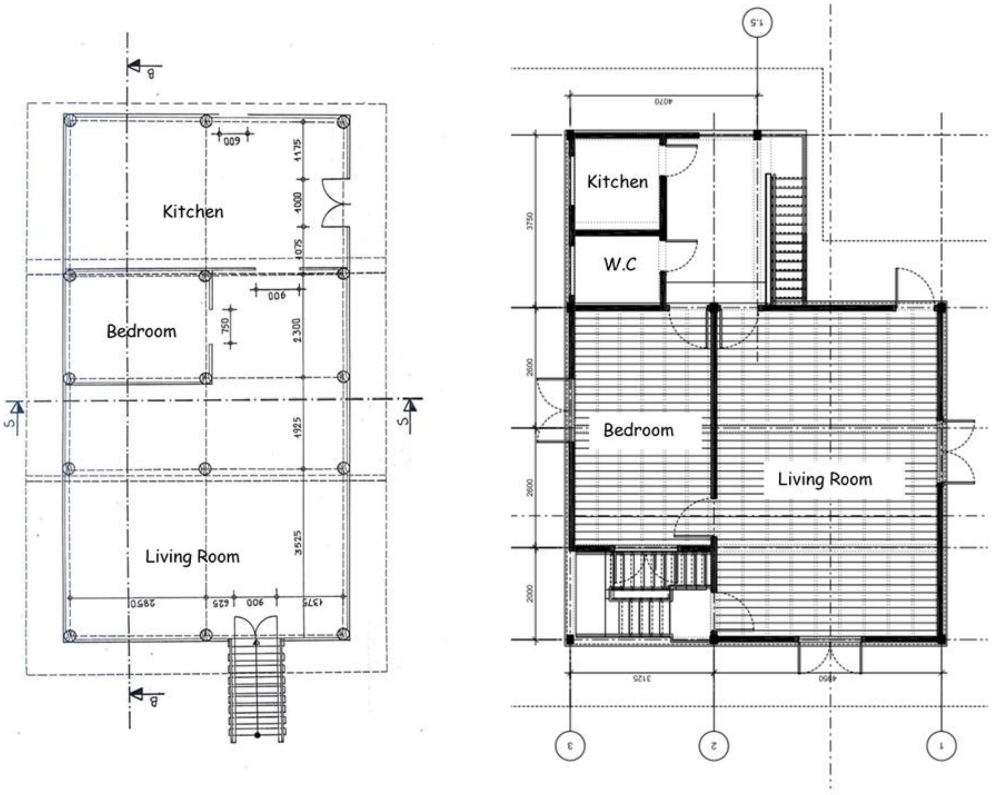
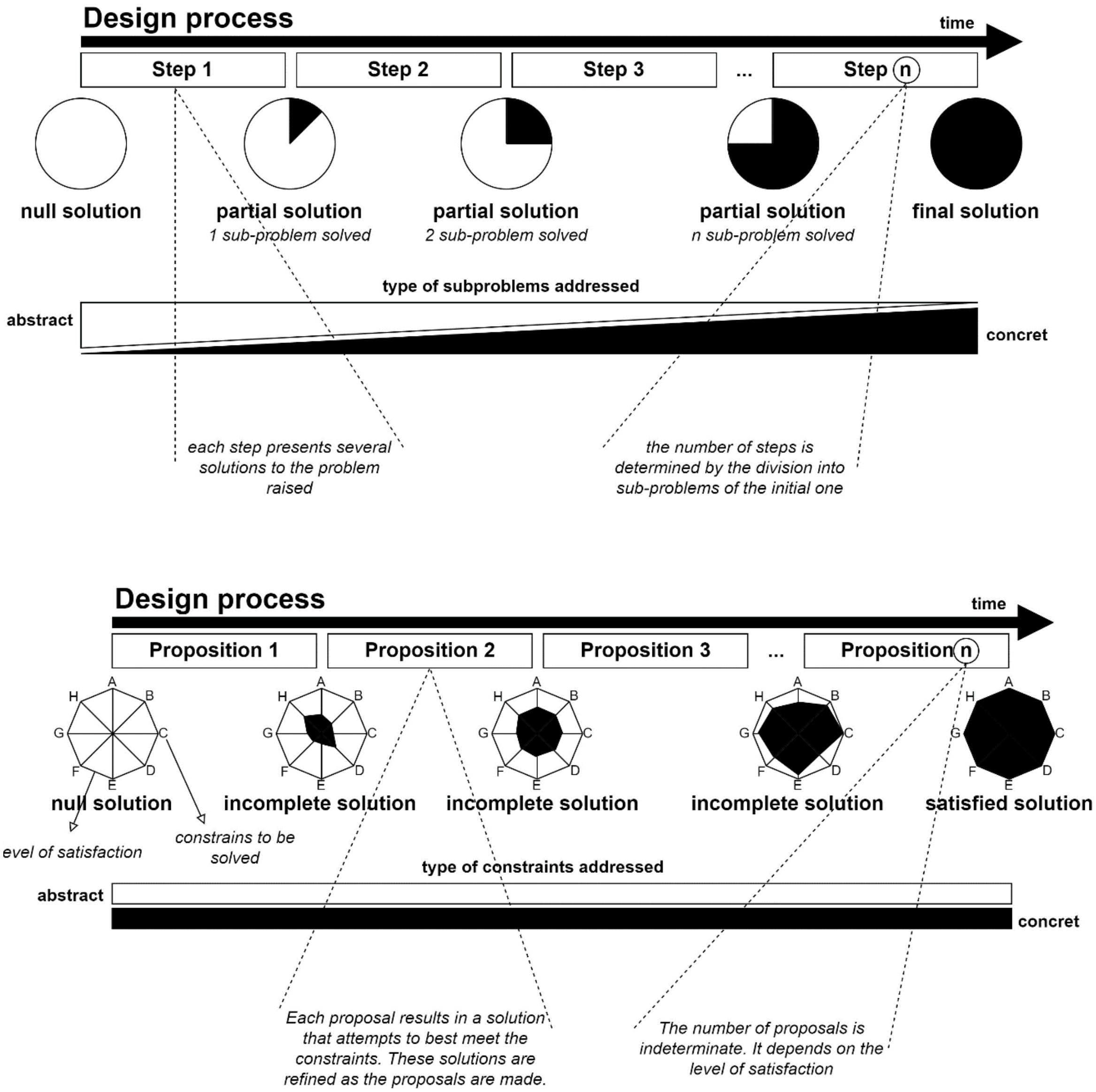


Figure 1-5: Cambodian traditional house plan (left), Vann Molyvan bioclimatic house (right).

Just like in other countries, we can see the evidence of the bioclimatic approach application in Cambodian architecture. Contrary, academic research that relates to this topic is almost nonexistent. Architectural books published in Cambodia focus more on the history of traditional architecture, construction technique, and architectural style, e.g., the Cambodian Wooden House book by Darryl and Hok (2022). There are several studies that talk about the importance of the application of the bioclimatic approach or sustainable design in the construction sector (Karagianni et al., 2022; Waibel, 2017). However, comprehensive research on the application of bioclimatic principles, specifically in terms of contemporary bioclimatic design strategies and their integration into the design process, is currently lacking. Therefore, a study on how a bioclimatic approach can be effectively integrated within the current context of Cambodia and how it impacts on the architectural design process for building comfort is necessary.

1.5 Architectural Design Process

The architectural design process plays a pivotal role in determining the sustainability and thermal performance of buildings. Each stage of the design process requires different tools to transform ideas into plans and models and for decision-making support. Collaboration between architects in the team and with other stakeholders during this phase also helps to minimize possible errors in the post-design and construction phases. Globally, in theory, there are two approaches toward the design process. A linear design timeline where the design phase is validated step by step is called an "*engineering design*" approach and a "*cognitive*" approach where considering design process is considered as a loop with formulation of problems and finding solutions to these constraints. In the thesis of Calixte, these two approaches are explained in detail and can be described in the figure below (X. Calixte, 2021).



each step presents several solutions to the problem raised

the number of steps is determined by the division into sub-problems of the initial one

Each proposal results in a solution that attempts to best meet the constraints. These solutions are refined as the proposals are made.

The number of proposals is indeterminate. It depends on the level of satisfaction

Figure 1-6: The two approaches of design process theory. Approach engineering design (top), cognitive approach (bottom) translate from the original figure (French to English) by the author (X. Calixte, 2021).

In professional work, an architectural design process would be seen combining the two approaches. It usually consists of 6 or 7 phases until the construction phase starts. Figure 1-7 explains the whole design process with the evolution, the task, and the actor that normally required in each phase. However, the main design work normally ends within 4 phases from pre-design to documentation which according to Figure 1-7 is between the design development and building permitting.

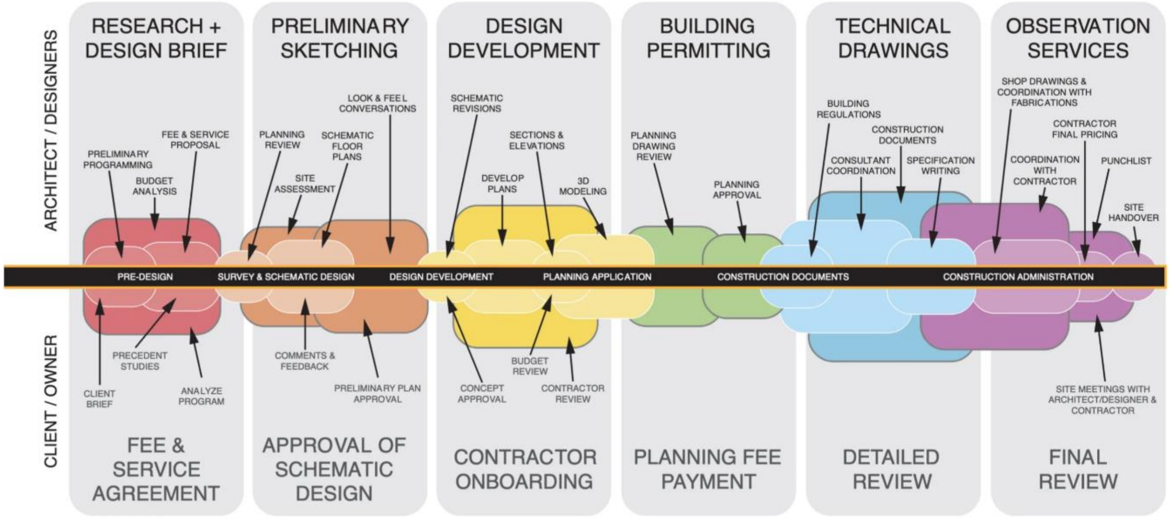


Figure 1-7: Architectural design process in professional work ((Seificar, 2023).

In the main 4 design phase, each phase focuses on:

- Pre-design: the start of the design process where the architect analyzes the location to come up with possible solutions that suit with requirements of the client. Building program is normally determined in this stage.
- Preliminary/ Schematic design: the first draft of the building concept where the design of building function, form, and envelope occurs.
- Design development: the conception made in the previous phase begins to get into more detail in terms of size, design, and materials.
- Documentation: finalization of the design and prepare necessary documents for the construction phase.

To accommodate the new design strategies, tools, and technologies, some design processes are proposed by various studies. An Integrated Design Process (IDP) was proposed by a study to enhance collaboration between actors and architects to achieve building design with aesthetic, functional, and technical requirements. IDP consists of 5 design phases including problem or idea, analysis, sketching, synthesis, and presentation (Thuesen et al., 2019). Another study proposes a 6 design phase to enhance the cooperation of sustainability of the design process called DESPROSU (Farias Stipo, 2015) as shown in Figure 1-8. To integrate BIM and BES more effectively in attaining sustainable building, our study proposes a 5 phase design process where integration of BIM since the early design phase is underlined (Taing et al., 2024).

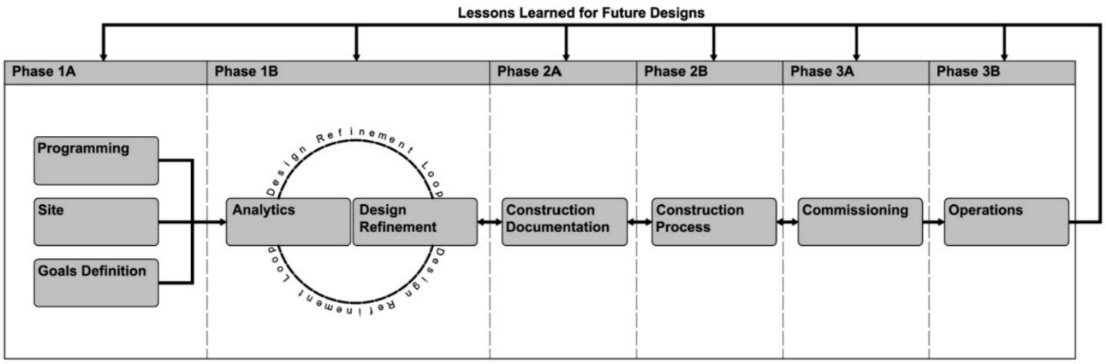
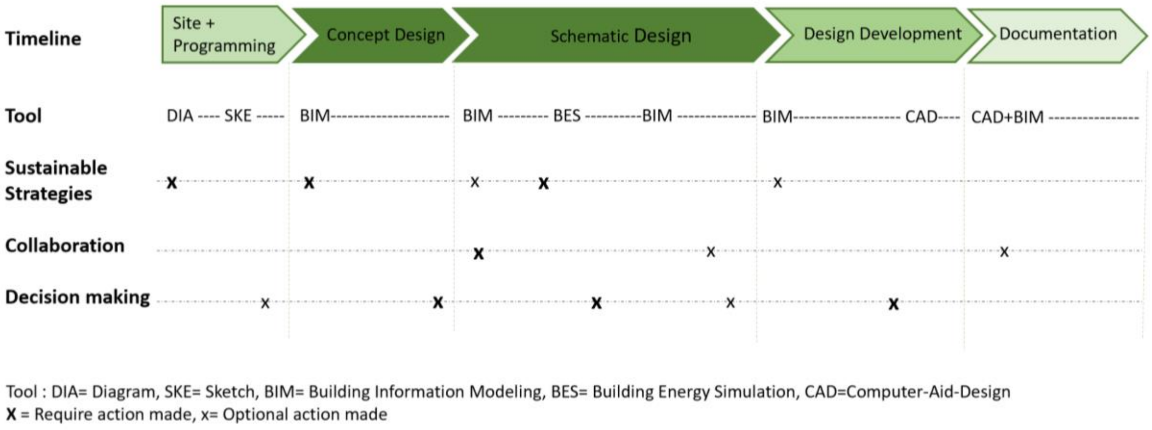


Figure 1-8: Design process DEPROSU (Farias Stipo, 2015).



Tool : DIA= Diagram, SKE= Sketch, BIM= Building Information Modeling, BES= Building Energy Simulation, CAD=Computer-Aid-Design
X = Require action made, x= Optional action made

Figure 1-9: Architectural design process with integration of BIM and BES for sustainability (Taing et al., 2024).

In this thesis, we are interested in the early design process between pre-design to schematic design with an emphasis on the evolution of design concepts, the tools employed, and decision support mechanisms. By integrating the objectives of sustainability and comfort for building design, it is curious to see how these two phases can be transformed and their impact on the rest of the design process.

1.5.1 Design and Decision Support Tool

In the entire design process, many design tools are used. To turn a design idea or in this case, a design conception into a plan and model requires different tools at different design phases. In the earlier section, we have already discussed a few tools that are used for drawing and modeling such as CAD and BIM, and the tools used for building analysis such as BPS. Some of these tools can be classified according to their usage throughout the design process. According to the study in Belgium, design support tools used during the design process are classified into 6 categories such as knowledge-based tools, communication tools, modeling tools, presentation tools, structuring tools, and evaluation and analysis tools (Weytjens et al., 2009). Some tools can belong to more than one category, serving not only as design support instruments but also as aids in decision-making through the evaluation and analysis of building designs.

In the decision-making process at any stage of the design phase, designer interact with the representation of the conception idea and apply their knowledge to improve the design quality (Oxman, 1997). Performance is known to be an influential tool in supporting decision-making. By employing performance simulation software, the designer leverages their visual intelligence to connect implicit knowledge with the performance data presented in the simulation, enabling them to make informed decisions (Oxman, 2007). The visualization of the simulation result helps designers to identify the impact of the design characteristic that they want to evaluate and allows them to reshape the design idea and improve building performance (Crawley et al., 2008). In the early design phase, designers explore various design ideas which make the initial design concept more intensely impact the building performance than the later phase. Hence, the decision-making in this phase is crucial and needs the right decision support tool.

1.5.2 Collective Design Work

In an architectural project, many tasks are required including drawing, modeling, building analysis, cost estimation, and planning. The architectural design process is therefore usually realized through teamwork within the same discipline or integration of multidisciplinary experts for structural and MEP (Mechanical, Electrical, and Plumbing). With technology and sustainability added into the constraint of the design timeline, collective activities are essential for parallel design sessions (e.g., modeling and simulation). In the research domain, this type of design work is called collective design (Visser, 2001). Indeed, to be able to carry out the collective design, we need to understand how each actor works together as a group to achieve each task. Two methods can be observed of how actors perform together which are given definition by authors such as Visser (2001), Caroly and Weill-Fassina (2007), and Safin (2011) :

- Collaborative work or co-design: where multiple actors have the same objective and collaborate for the realization of the same task. The decision-making process and agreement on task evolution are made by all actors involved.
- Cooperative work or distribution-design: where the task is divided among various actors. Each actor independently works to realize their objectives and parallel with each other. This type of collective design needs to be regularly brought together to ensure the coherence of the project.

Throughout the design process, despite working in a team or a collective design space there are moments when architects reflect and work separately. The term for different of this working space was identified by a study by Ben Rajeb and Leclercq (2015): working individually (I-space), where certain architects work between them (space-between), and when all the architects in the team work together (we-space) (Ben Rajeb & Leclercq, 2015). This working space can help to identify during each design phase the collaboration of actors throughout their design process.

1.5.3 Integration of Bioclimatic Design and BPS in the Design Process

In the previous section, we can see that adding certain design strategies, guidelines, and tools can alter the design process from traditional practice. Many designs process was proposed to accommodate this alteration. In this section, we would like to explore how bioclimatic design and BPS can be integrated into architectural design processes including advantages and limitations.

In terms of BPS, it was found that this approach wasn’t well used during the design process in both professional and educational settings. Despite providing many advantages for building analysis and the ability to be a decision support tool, the practice of BPS was considered by users as the ‘design tool’ (Soebarto et al., 2015). The limited adoption of BPS during the design process can be attributed primarily to the fact that building performance analysis is often not prioritized by architects. Even when such analyses are undertaken, they are not necessarily conducted using BPS methodologies. Furthermore, when BPS is integrated into the design process, it is typically carried out by a combination of in-house experts and external consultants, rather than by the project architect (Soebarto et al., 2015). A study by Negendahl (2015) on how BPS can be integrated into the early design process show that an integrated dynamic model combines a design tool, a visual programming language, and a BPS would provide better support for the designer during the early stages of design compared to alternatives such as the current implementation of IFC or gbXML, or the use of standalone simulation packages. Our study also recommends BPS to be integrated at the middle phase of the design process along with BIM application to achieve sustainability in building design (Taing et al., 2024).

Similarly to BPS, bioclimatic design in the form of guidelines or standards can also provide informed decision-making for architects. However, in contrast to BPS, bioclimatic design proposes numerous strategies that can establish the objectives for building design, which architects must consider to achieve optimal building performance. Consequently, bioclimatic design typically begins its integration at the pre-design phase or early design phase. However, there is no definitive approach to integrating bioclimatic design into the design process, as it depends on the specific context, design timeline, and the preferences of the architect. The main barriers that limit the integration of bioclimatic design during the design process are its limit on creativity, lack of knowledge, lack of confidence, cultural and social impact, building regulation... Maciel (2007) explain in more detail about this point in her thesis. In her study, she also proposes several actions to enhance the successful implementation of bioclimatic design during the design process. These actions include the enforcement of policy and building regulations, encouraging architects' commitment, showcasing examples of passive design, and advancing technical knowledge through formal architectural education. Numerous researchers have investigated the application of bioclimatic principles to address various issues related to building comfort and sustainability (Larasati Zr & Mochtar, 2013; Mohammed et al., 2018). However, there is a significant lack of research focusing on how these principles are integrated into the design process, particularly within professional practice.

1.6 Chapter Conclusion

The literature review was done for 5 keywords (Thermal comfort, Bioclimatic design, BPS, BIM, and Architectural design process) that related to the general issues declared in the previous chapter.

Through this literature review, it is revealed that while research on thermal comfort is extensive globally, it remains underexplored in Cambodia. There is a notable absence of studies addressing the thermal performance of various building types in Cambodia, as well as the establishment of comfort standards or adaptive comfort models specific to the region. Research on climate-responsive strategies and overall sustainability in architecture is similarly scarce in Cambodia. Although BIM and BPS are emerging research trends in architectural technology, they have predominantly been studied within the context of developed countries. We identify a gap in the analysis of these approaches as decision support systems during the early design process, particularly in resource-constrained settings. It is therefore of significant interest to investigate how BIM and BPS could serve as decision support tools since the early design process to enhance comfort and sustainability in Cambodia or whether another tool/method should be implemented.

CHAPTER 2

PROBLEM STATEMENT

We *took the liberty of this chapter to present the problem statement and explain in detail the issues around the topic that this work aims to resolve. The research objectives are derived from the discussion and the research questions are developed to answer each objective of the issues.*

2.1 Housing Comfort Issues in Cambodia

Cambodia is a country located at 13° North latitude and 105° East longitude in the Southeast Asia. It expands on an area of 181,035km^2, bordered by Thailand, Laos, Vietnam, and the Gulf of Thailand. The landscape of Cambodia is characterized by a low-lying central plain that is surrounded by upland and low mountain ranges including 2 rivers, Tonle Sap and the upper reaches of the Mekong River. Thanks to its landscape, Cambodia is full of natural resources and rarely experiences any natural disaster except for the seasonal flood of the region near the Tonle Sap River. Cambodia is comprised of 25 provinces with Phnom Penh as the capital. Phnom Penh is the largest city located in the south-central region of the country with the junction of the Mekong and Tonle Sap Rivers at 12m elevation above sea level. Being the capital city, it plays the role of the center of economic, political, industrial, educational, and cultural activities. It is the most populated city in Cambodia with 2.283 million people under the area of 679 km^2. With a population density of 3362 people/km^2, Phnom Penh is the fifth densest city in Southeast Asia.

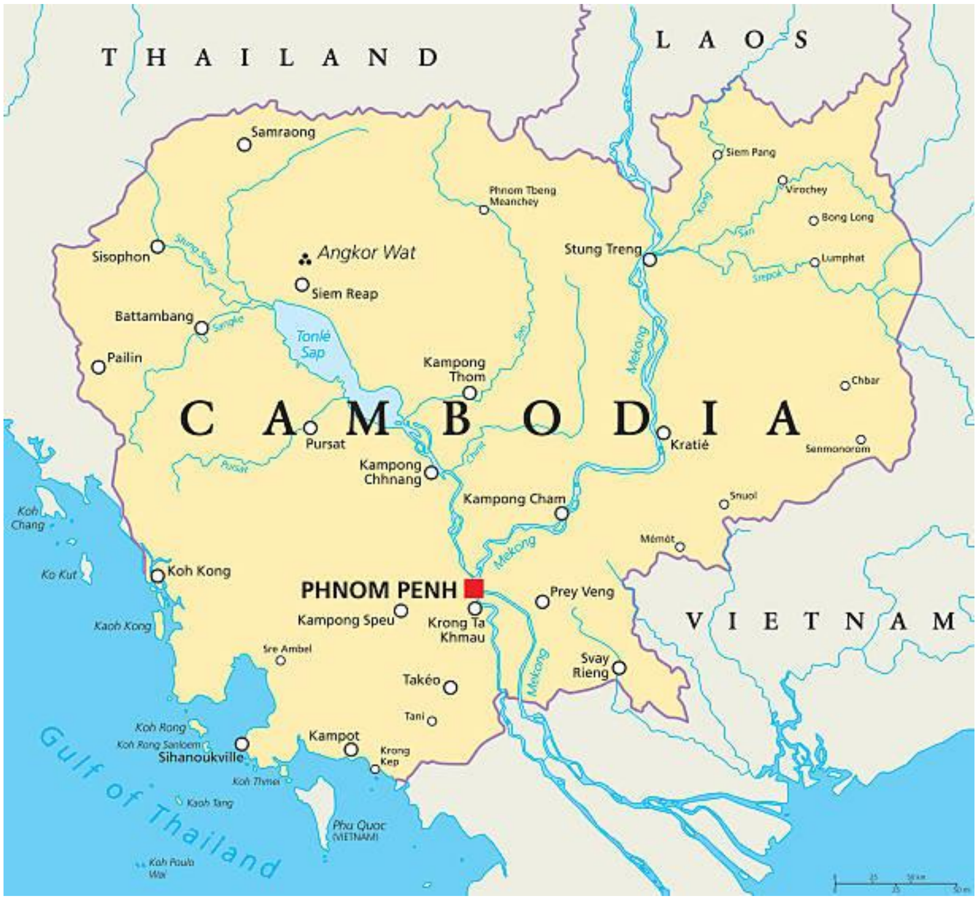


Figure 2-1: Location of Phnom Penh.

According to Series Thematic Report on Population Projection, the population in Cambodia was 15.6 million in 2019 with an estimation of 17.5 million in 2025 (NISMP, 2021). Remaining as a rural country, the population in the rural area was estimated at 74% in 2022. However, the population in Phnom Penh has been increasing at a 3 percent growth rate annually from 1.6 million in 2012 to 2.2 million in 2022. Over the last decade, Phnom Penh has been experiencing significant urbanization growth and this trend will continue until 2035 and beyond. Initially, due to obstacles of the Mekong River, the urban expansion in Phnom Penh first started toward the westward direction. Subsequently, with the construction of new bridges, this urban sprawl shifted eastward, traversing the Mekong River. In 2010, 20 communes in the neighboring province were transferred into Phnom Penh municipality to accommodate the huge migration of people from the countryside. The west part of the city has been transformed into an industrial section.

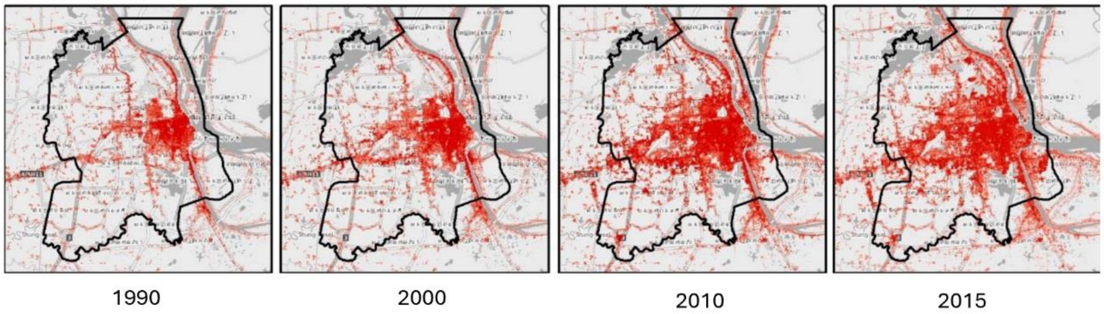


Figure 2-2: Urban sprawl of Phnom Penh from 1990 to 2015 (Project, 2020).

The construction boom in Cambodia started in the 2010s (Roughneen, 2016). With significant migration from the countryside to the city and the arrival of foreigners, Phnom Penh experiences the most construction boom in all the country. Residential buildings have become the focus of developers and investors. Many high-rise condos and apartment buildings and Borey (a gated community) have dramatically appeared replacing low-rise buildings, and historical villas with private gardens in the early 1990s (Mund et al., 2020). The number of gated communities in the city increased from 77 in 2011 to 128 in 2014 (Meng, 2014), and further grew to 140 by 2021(Smith, 2021). With this trend expected to continue to happen until 2035, many Borey are already planned to be built.

The rapid growth of buildings and infrastructure hasn’t been taking into account the sustainable aspect when designing. Gradually the designing of buildings in Cambodia focuses more on the form and aesthetics of the building rather than functionality and comfort. The traditional design that adapts to the hot humid climate of the country has been slowly disappearing and replaced by buildings with a neoclassical style that is influenced by the Western country. While there are architects who try to promote sustainable design in their projects, the number remains low, and indoor comfort has been overlooked by architects, occupants, and investors.

Usually, small residential buildings in Cambodia are built with minimal financial investment and lack of consultation with architects. Small houses such as townhouses (link houses or detached row houses) are normally built without specific floor plans by copying from their neighbor or following the trend they saw on the internet. Larger scale housing projects were not fully analyzed during the design process to benefit maximum profit for investors. Consequently, the current architectural designs do not guarantee indoor comfort for occupants. As a country with relatively hot temperatures throughout the whole year, people resorted to using electric fans or air conditioners to improve indoor thermal comfort. By 2020, an estimated 1 million air conditioners were in use in Cambodia, with the majority of these units found in urban households, which account for only 25.1 percent of the country's population (NCSD, 2022). The prominent usage of air conditioners for thermal comfort has led the design of buildings to focus on having a compact space with fewer openings for natural ventilation to optimize the usage of air conditioners.

The apartments that have been built for the solution of housing demand in the city center of Phnom Penh haven’t been the popular option for Cambodians as occupation rates remain low in these high-rise buildings (Nam, 2017). In this economy, link houses have become the mass construction of residential buildings, particularly within Borey developments, as evidenced by the increasing number of such projects discussed above. Link houses in Borey have become the popular option for families due to their accessibility and the preference of Cambodians for homeownership that includes ownership of the underlying land. For investors and developers, with the land in the city being expensive, they want to build the house as much as they can. As a result, the house isn’t provided with enough green space or openings to access natural ventilation. With the houses built so close to one another, due to privacy concerns, windows can’t be opened for their purpose of accessing natural ventilation into the house. Electric fans and air conditioners have then become the primary solution to comfort living in the city.

In the countryside or vulnerable communities in suburban areas where people can’t afford air conditioners or the electricity can’t support the use of air conditioners, electric fan is the main solution to occupant thermal comfort as seen in Figure 2-3. The design of houses in the countryside still follows some of the traditional designs that favor ventilation and every house has enough green space and is mostly built as a detached house. Hence, electric fans can still be used during the highest temperature season from March to June. However, the design of some houses starts to follow the housing trend in the city with the use of a lot of glass as they think the use of glass in their house represents their wealth. Windows are normally designed as sliding windows from glass with no sun radiation protection which doesn’t maximize the capacity of airflow into the building. Trees and green grass are starting to get replaced by concrete slabs for the outdoor area surrounding the house.

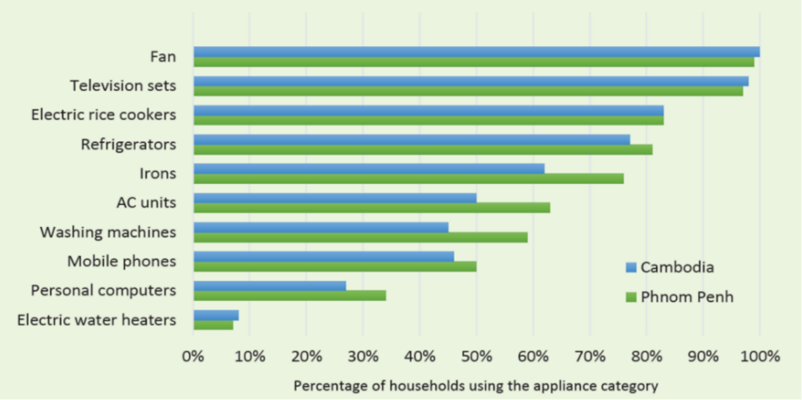


Figure 2-3: Appliance ownership in Cambodia, by type, 2018, source: Building Energy Structure and Lifestyle Database of Asia 2018.

For architects that try to integrate sustainable strategies for comfort in their building design, they have to follow design principles and methods developed by other countries in similar climates as such design principles or guidelines for Cambodia are almost non-existent. Knowledge about sustainable design and comfort is still in question for both building designers and occupants. It is therefore crucial to raise awareness on this issue and provide architects with the necessary resources and support to design buildings that achieve thermal comfort while ensuring sustainability. Design strategies and technology applications during the design process are the important factors that should be discussed to achieve this goal.

2.2 Technology for Building Comfort and Sustainability in Cambodia

As mentioned above the main issue for houses in Cambodia is its thermal performance. This can result from limited awareness about the topic in general and limited construction budget which refers to no participation from architects during the design process, etc. The awareness of sustainability can be seen as very limited for Cambodia citizens, architects, and designers and the adoption of sustainable construction is still poor in Cambodia (Durdyev et al., 2018). As difficult as it is to design a building that could fit with the taste and living lifestyle of the owner and respect the budget, adding sustainable strategies to achieve optimal thermal comfort in this climate transition can be even more challenging. Methods and tools have been therefore developed to add architect and designer during the design process to achieve this goal.

In the construction field, new technology has been invented to help promote sustainability. Many energy and environmental software have been developed to analyze energy performance, building life cycle assessment, building impact on the environment, etc. In developing countries like Cambodia, however, limitations in the research domain often result in the adoption of technologies and design methods that are based on practices, techniques, or standards established by developed nations. As discussed in the previous chapter, tools and standards such as thermal performance software cannot be applied directly within the Cambodian context due to differences in climate conditions, construction materials, HVAC systems, and occupant behavior. Therefore, these tools and standards require calibration or the modification of specific parameters to ensure their accuracy and relevance in Cambodia. (Taing & Leclercq, 2022).

In the Western and more developed countries, as their research field is more advanced, they can create certain analysis tools specific use for their own country. For example, Belgium used Totem to analyze the impact of buildings on the environment or PEB to analyze the energy performance of buildings. Germany developed PHPP, a tool to analyze the energy performance of buildings in the form of a spreadsheet. The United Kingdom created DesignBuilder which can be used to analyze both the energy and thermal performance of buildings using building 3D or IFC files. In Cambodia, tools such as those mentioned above haven’t been developed yet. More than that, necessary data for analyzing building energy or thermal performance such as climate or construction material properties is still limited which complicates the effective application of these tools within the Cambodian context.

Methods such as BIM and BPS have been put into practice during the design and construction process to help architects and engineers achieve sustainable building. BIM model and BPS have been used to facilitate building energy and thermal performance simulation to evaluate design concepts that optimize building thermal performance and minimize the consumption of heating and cooling. We see the importance and benefit of these two approaches in the previous chapter but also the barrier in terms of implementation in the professional field. Nevertheless, numerous studies have been conducted trying to help its application more smoothly. Hence, in Western countries, these methods have been used widely by architects, engineers, and consultants since the last decade. However, in Cambodia, where knowledge and practice of these two methods are still limited (Taing et al., 2024) and where resources for scientific studies related to these issues are scarce, can these approaches be effectively integrated to assist architects and designers in promoting comfort and sustainability in their buildings? To design a truly sustainable building, bioclimatic design must be integrated from the early stages of the design process, making decision-making at this phase crucial. Given the extensive data requirements of BIM and the complexity of BES, is it feasible to access and utilize these tools effectively at this stage?

2.3 Objective of the PhD Thesis

The primary focus of this thesis is to address the issue of comfort in residential buildings in the urban area in Cambodia. The overall goal of this PhD research is to develop decision support materials that aid architects and designers in creating comfortable living spaces. These materials are designed to be user-friendly and to assist architects from the early design phases in ensuring that houses provide optimal comfort and align with bioclimatic principles.

To address the global aims of the thesis, the research aims to achieve two main objectives:

- To propose bioclimatic design guidelines that help achieve optimal thermal comfort tailored to the climatic conditions and living contexts of Cambodia.
- To identify methods that facilitate architects and designers in analyzing building thermal performance from the early stages of the design process, enabling informed decision-making when selecting design strategies

Figure 2-4 explains how our objectives respond to the problem statement outlined above, highlighting its position within the framework of the issues.

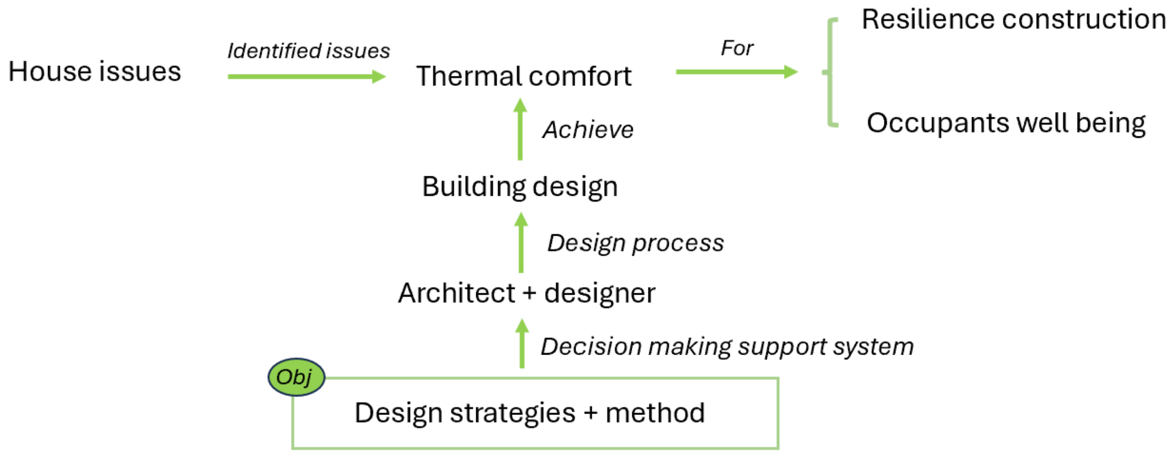


Figure 2-4: Diagram showing objectives of this PhD thesis answering to the problem statement.

2.4 Research Questions

Concerning the comfort issues in current houses, we exploited two research questions concerning the thermal performance of current houses in the city that follow the current and foreseeable future design trend and propose sustainable design strategies to help designers since the early design phase to achieve designing a building with optimal thermal performance.

- **Q1**: What is the thermal performance of current residential buildings in Cambodia? (Chapter 4)

- **Q2**: What are the effective bioclimatic design strategies to achieve thermal comfort in buildings in Cambodia to fit with climate transition and the change of socio-cultural? (Chapter 7)

Two other research questions are proposed to identify methods to facilitate architects in analyzing their building design for thermal comfort. These two research questions aim to analyze the application of BIM and BPS and propose tools, methods, or strategies to help architects and designers have informed decision-making in their building design choices since the early design phase.

- **Q3**: Can BIM and BPS assist designers in achieving maximum thermal comfort in the building during the design process in the context of Cambodia? (Chapter 5)

- **Q4**: What methods can be implemented to facilitate analysis of thermal comfort to achieve bioclimatic buildings in the early design phase? (Chapter 6)

Overall, the research questions of this PhD thesis aim to answer the current issues in Cambodia in terms of housing issues and sustainability by focusing on bioclimatic design strategies to provide maximum thermal comfort for houses in hot-humid climates and how architects can integrate tools such as BIM and BPS during the design process to achieve designing a comfortable and sustainable building.

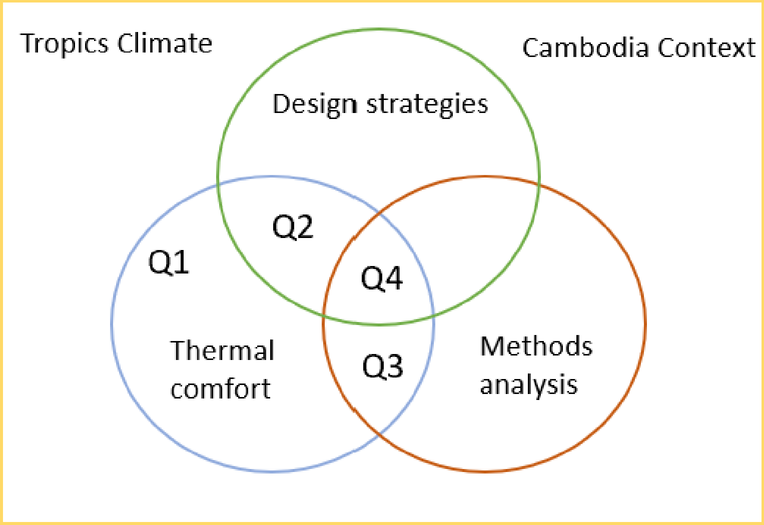


Figure 2-5: Diagram of research questions aims to answer each problem statement.

2.5 Chapter Conclusion

The primary objective of this thesis is to address the issue of thermal comfort in current Cambodian houses. Consequently, this research seeks to determine how to enhance thermal comfort in future Cambodian residences while minimizing energy consumption by providing architects with decision support materials during the architectural design process. To explore this goal, four specific research questions have been developed:

- What is the thermal performance of current houses in Cambodia?
- What are the effective design strategies that could improve building thermal performance in Cambodia?
- How can BIM and BPS assist designers in achieving optimal building thermal comfort during the design process in the context of Cambodia?
- What methods can be implemented to facilitate the analysis of thermal comfort to achieve bioclimatic buildings from the early stages of the design process?

CHAPTER 3

METHODOLOGY

This chapter provides a comprehensive overview of the research methodology employed throughout the study. It outlines the specific steps undertaken at each phase of the research process to achieve the stated objectives and addresses the research questions announced in the preceding chapter. The selection of methods is critically examined, with a rationale provided for their appropriateness in the context of this research.

3.1 General Methods Used for this Research

To successfully conduct a research study, various methodologies can be employed for data collection and analysis to achieve the study's objectives. Three principal research methodologies are commonly practiced: qualitative, quantitative, and mixed methods. To address the four research questions outlined in the previous chapter, a five-step methodology was implemented for this study. The mixed-method approach, incorporating quantitative, qualitative, and modeling techniques, was utilized for this PhD thesis. Employing mixed methods is crucial for this study to ensure appropriate data collection, analysis, and validation, as it centers on human interactions (architect and occupant) and the built environment. Within these three main methodologies, numerous specific methods are employed to conduct this research. Table 3-1 provides a detailed description of each method used within the different methodologies.

Table 3-1: Methods used to conduct the PhD research

Methodology used	Methods used
Quantitative	Thermal comfort survey (207 respondents) BIM and Bioclimatic survey (106 respondents) Building comfort measurement (5 houses) Usability test (7 groups = 17 participants)
Qualitative	Interview BIM and BPS (10 companies = 13 architects) Interview building comfort (4 houses = 15 occupants) Observation design process (4 groups = 20 students) Usability test (7 groups = 17 participants)
Modeling	BIM modelling (7 models) Simulation (7 cases) Calibration (3 models, ≈50 trials and errors)

Figure 3-1 describes in detail the phases of this research. The research starts with quantitative research to identify the initial problems currently faced in terms of building thermal comfort, awareness of bioclimatic design, and BIM in the building sector which we questioned during the literature review. The online survey allows us to understand the perception of occupants toward their houses, the characteristic of houses such as the material used, their adaption to the comfort of the building, their behavior toward energy consumption, and their preparation before the construction of their houses. Other quantitative research includes the measurement of thermal comfort influenced parameters and occupants survey to have an in-depth analysis of the current thermal performance of houses in urban areas in Cambodia.

Qualitative research was also conducted alongside building monitoring through structured interviews with the occupants residing in the case study building. Additionally, semi-structured interviews with architects were undertaken to investigate the practices of BIM and BPS in sustainable building design in Cambodia. To complement the architect interviews, observations of architectural students were carried out to understand the long-term design processes aimed at achieving optimal thermal comfort in their buildings.

A mixed-method approach was also used to perform a usability test to analyze and validate the bioclimatic design guidelines that we developed to aid architects in designing a bioclimatic building since the early design phase. This also includes questionnaires and observation of the user experience and interaction with the guideline.

This study also incorporates a numerical modeling approach, utilizing simulations with the BIM model and BPS to investigate their reliability and integration in performing thermal comfort analysis. Calibration methods were employed to validate the accuracy of the models and to create a baseline model, which was subsequently used to identify the influence of the bioclimatic approach on residential building design in the context of Cambodia.

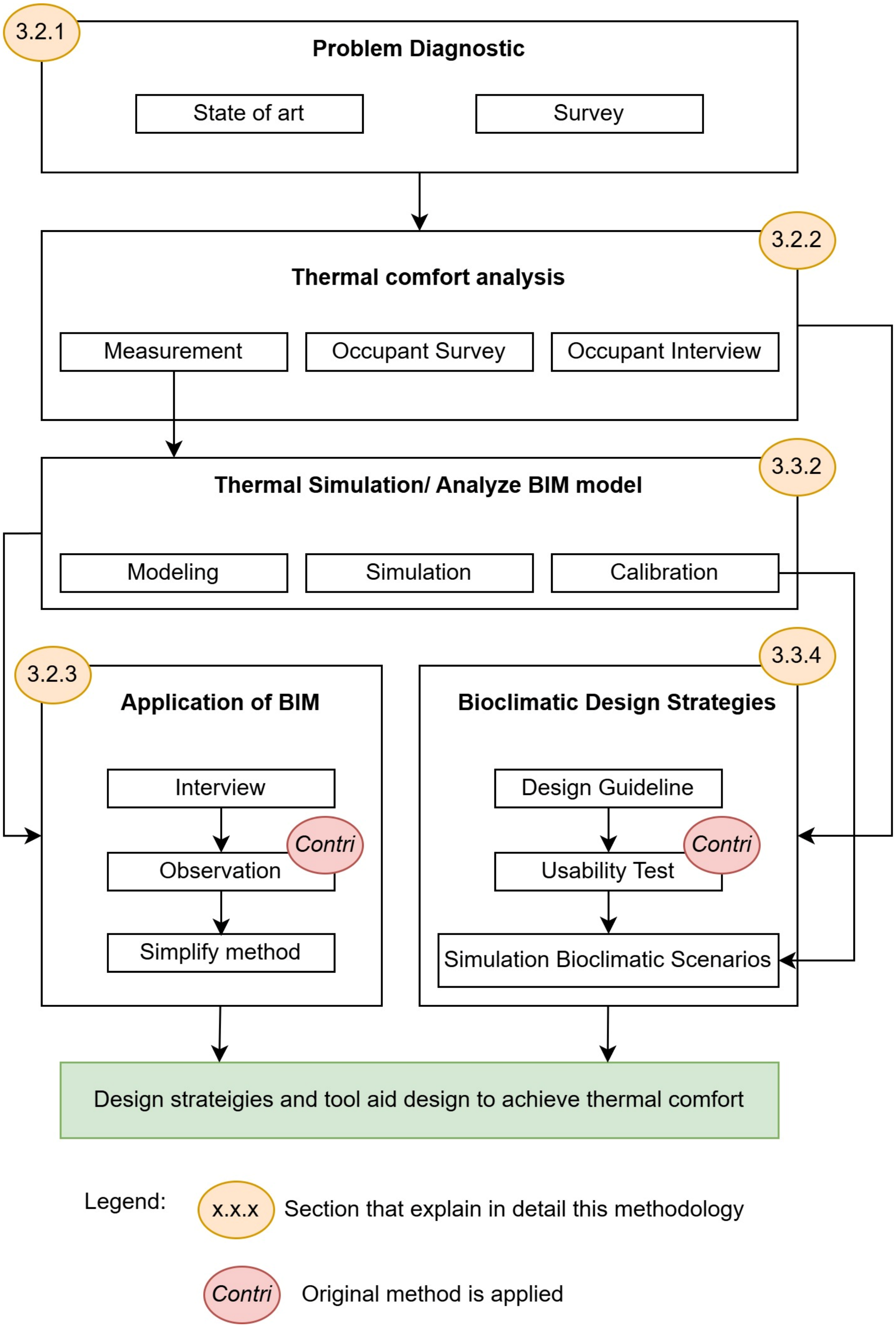


Figure 3-1: Methodology implemented for this research.

3.2 Data Collection

3.2.1 Problem Diagnosis

The objective of this study focuses on the thermal comfort of buildings, the application of bioclimatic design, and BIM in the context of Cambodia. The first method put in place is to identify and have a first insight into that problem based on our hypothesis derived from the state of the art and the problem statement. For this purpose, two online surveys were put into place. The thermal comfort survey aims to investigate the thermal performance of current residential buildings in Cambodia. The questionnaire for this survey was designed based on the ASHRAE thermal performance questionnaire (ASHRAE, 2017). As it is a global survey without a specific layout of the building in mind, a few more questions related to the condition of the house and occupant behavior toward using air conditioners were added. The second survey aims to identify the awareness of bioclimatic design and BIM in the ACE sector in Cambodia. This survey also allows us to have an initial insight into the application of BIM and bioclimatic design in the construction sector in general. Method Design UX was used to form the questionnaire for this survey and classify the focus group (Lallemand & Gronier, 2018).

3.2.2 Current Residential Buildings Thermal Performance

- **Building monitoring**

The collection of data necessary for thermal comfort analysis of residential buildings in Cambodia includes the choosing of case study buildings, site visits to survey the building, and measurement of thermal comfort influenced parameters. The measurement parameters are air temperature, relative humidity, and air velocity. Air temperature and relative humidity were measured for 2 months: 1 month (01 April – 01 May 2021) in dry season and 1 month (25 June – 05 August 2021) in rainy season. The measurement of air velocity was done during the period of the measurement of the other two parameters in the rainy season. Easylog data loggers were used for the measurement of air temperature and relative humidity. Alnor velometer (hot wire anemometer) was used for the measurement of air velocity. More details concerning the measurement of the influence parameters can be found in the next chapter.

- **Occupant survey and interview**

In addition to the building monitoring, occupant surveys and interviews were carried out to further analyze the building thermal performance of each case study building. The survey was sent out to all occupants in the case study buildings to answer by voting on their sensation using the PMV method. The purpose of the survey is to compare the occupant sensation to the measurement data to identify a comfortable and uncomfortable value of air temperature, air velocity, and relative humidity. The structured interview with occupants was also done during the site visit (the period of measurement) to understand their overall sensation, satisfaction with the thermal performance of their house throughout the year (different outdoor climate conditions), and occupant behavior toward improving their thermal comfort. The questionnaire used for both the survey and interview is based on the ASHRAE guide (ASHRAE, 2017).

3.2.3 Investigation of BIM and BES in the Design Process to Achieve Sustainable Buildings

- **Architect interview**

To understand about application of BIM and BPS in the design process, we conducted a semi-structured interview with architects in Cambodia. This interview aims to identify a current design process integrating BIM and BPS to achieve a sustainable building in the context of Cambodia. 10 architectural firms located in Phnom Penh and Siem Reap that fit our criteria were chosen for this interview.

- **Student observation**

This observation is the in-depth analysis of the design process for a sustainable building to identify a design timeline with details of the design phase, tools, integration of bioclimatic design target, collective design, and decision making. The observation was conducted with 4th year architectural engineering student at the Institute of Technology of Cambodia (ITC) during their Architectural Studio class. In this observation, we collected information such as tools used during the design process, design principles to achieve a sustainable and comfortable building, decision-making in each design phase, and team collaboration. We try to identify where BIM and BPS can be integrated for such a design process to achieve bioclimatic building. This observation is to obtain complementary data for the interview. More details about data collection in this research phase are presented in Chapter 6.

3.3 Data Analysis

3.3.1 Thermal Comfort Analysis

The data received for thermal comfort analysis are both quantitative and qualitative data. The analysis of data from the monitoring and occupant survey is based on statistical approach and qualitative analysis from the occupant interview. The PMV method is also used to evaluate occupant comfort level. The linear regression model is used to create the adaptive comfort model (adaptive PMV) for Cambodia.

3.3.2 BIM and BPS Reliability for Thermal Performance Analysis

This step of methodology is to answer the second research question. In this step, we focus on analyzing the impact of using the BIM model to analyze building thermal performance. The plugin for thermal simulation that works with the BIM model as mentioned in the literature review was tested before choosing the most suitable one. The tested software includes Revit Energy Analysis-Insight, Green Building Studio, and DesignBuilder. DesignBuilder turns out to be the most suitable software and is chosen as the simulation engine for this study. The details on how these software were performed are described in Chapter 5.

- **BIM modeling**

The process of this research phase starts with the modeling of the BIM model for case study buildings using the software Revit. The BIM models created in the software Revit are based on actual data, including all information of building needed for a building thermal simulation such as the geometry of the building, the construction materials, building types, building occupancy… BIM models from Revit were exported as gXbML files and imported into Design Builder to transform into BES models.

- **Simulation and calibration**

In DesignBuilder, Energyplus is the simulation engine used for conducting thermal performance simulation which is a validated tool used by many study (Ferdyn-Grygierek et al., 2021; A. Ismail et al., 2015; Mahar, 2021). Calibration of all case study buildings was done to ensure the accuracy of the model used for the simulation of bioclimatic design strategies. During calibration, many trials and errors were performed. Different parameters were adjusted in each trial to find the suitable value to put in each parameter to receive optimal accurate simulation results. Three methods are used to evaluate the calibration results including Normalised Mean Bias Error (NMBE), Coefficient of Variation of Root Square Mean Error (CV(RMSE) (ASHRAE, 2014), and linear regression analysis model of measured and simulation data (ASHRAE, 2009). The calibrated model will be used for other thermal simulations such as bioclimatic building scenarios.

3.3.3 Sustainable Design Process Integrated BIM and BPS in the Context of Cambodia

Data received from the interview and observation are analyzed based on mixed methods. Vireli which is a platform developed by LUCID specifically for this PhD research is used to visualize the enormous amount of data collected from the observation to facilitate its analysis. More description of the creation and utilization of VIRELI can be found in Chapter 6.

3.3.4 Bioclimatic Design Guidelines

- **Usability test of the design guidelines**

A bioclimatic design guideline for Cambodia (BDGC) is developed to aid designers in making an informed decision to design buildings with maximum thermal comfort. This guideline is created based on an analysis of Cambodian weather data, passive cooling strategies for tropical regions, Cambodian traditional house design, and data from the architect interview and student observation. It contains 18 design elements aim at creating a surrounding microclimate, building sun and rain protection, and maximum natural ventilation. The scoping of BDGC is presented in Chapter 7.

The usability test is conducted with architects and students of architecture from ITC. The test was divided into 5 groups of 3 members and 2 individual tests. The participants were asked to redesign the case study buildings using BDGC to help achieve building thermal comfort since the early design phase. This test allows us to evaluate the practicality of BDGC during the design process and how it helps the designer to achieve and gives them confidence in designing a building that provides maximum thermal comfort. Design process observation, pre-test, and post-test questionnaires are the methods used to collect data during this test. The analysis of these data is based on both quantitative and qualitative methods.

- **Validation of design guidelines through simulation**

From the usability test, 7 design scenarios of case study building redesign using BDGC are produced. The calibrated model created in Chapter 5 was used to simulate these building scenarios to compare their thermal performance before and after the application of bioclimatic strategies. The results will allow us to be able to assess the effectiveness of the design guidelines in terms of application for building thermal comfort improvement.

3.4 Chapter Conclusion

In this PhD research, both qualitative and quantitative methods are used for data collection, analysis, and result validation. The use of mixed methods is particularly well-suited for this study, as it involves the assessment of building performance, which requires a statistical approach, as well as the evaluation of human behavior specifically, that of designers and occupants which necessitates a qualitative approach. The methods utilized for data collection and analysis have been extensively practiced and validated by other researchers in the field.

The modeling approach revolves around simulation, calibration, and numerical models are also used in this study to better analyze building thermal performance with the application of BDGC and design/decision support tool integrated during the design process.

CHAPTER 4

HOUSING THERMAL PERFORMANCE AND DESIGN ISSUES IN CAMBODIA

In this chapter, we discuss the thermal performance and design issues of contemporary residential buildings in Cambodia. To gain an initial understanding of the comfort levels in Phnom Penh's housing, an online global survey was distributed prior to conducting detailed measurements of influencing parameters. Following this, five houses representing the three most common residential building typologies in Phnom Penh are selected as case study buildings. In addition to measuring the relevant parameters, interviews and surveys are conducted with the occupants of these case study buildings to gather qualitative insights into their living conditions. An acceptable value of influenced parameters and an adoptive comfort model are identified in this study.

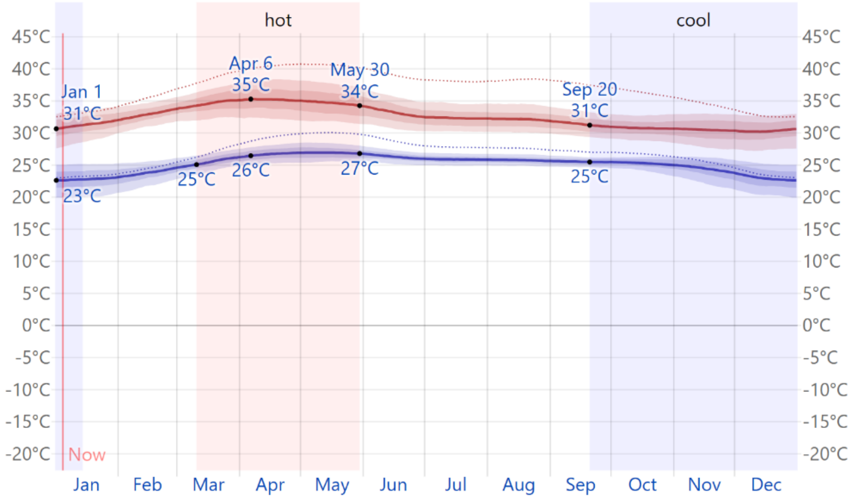
Part of this chapter was presented at the AICEE conference in Phnom Penh Cambodia and was published in the IOP Conference Series: Earth and Environmental Science (Taing et al., 2023).

Taing, K., Andre, P., & Leclercq, P. (2023). Analysis of Thermal Performance of Naturally Ventilated Residential Building in Tropical Climate: Case Study of Phnom Penh, Cambodia. IOP Conference Series: Earth and Environmental Science, 1199(1), 012038. https://doi.org/10.1088/1755-1315/1199/1/012038

4.1 The Study Area

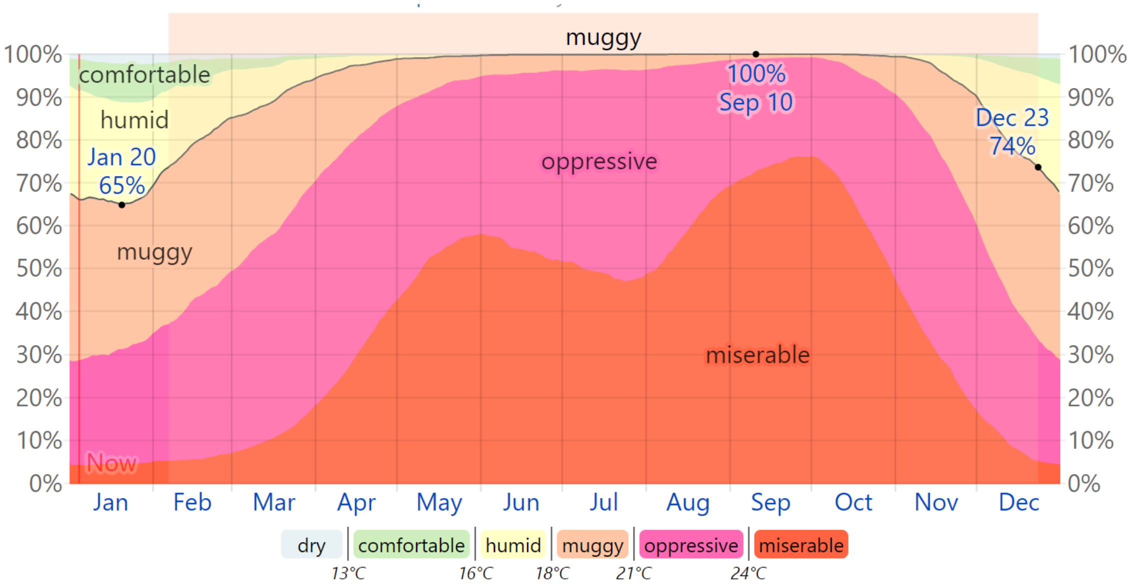
4.1.1 Weather and Climate Data of Phnom Penh

Cambodia, like other countries in Southeast Asia, is dominated by monsoon which results in having 2 specific seasons, the dry season starts from November to April and the rainy season from May to October. The weather conditions throughout the country are similar to each other from one region to another. Phnom Penh, being the capital city with the most population and the most polluted, has a relatively higher temperature than the other parts of the country. The relative humidity of the country is always high within the range of 60% to 85% and the average temperature is around 33℃ in the dry season to 30℃ in the rainy season. The hottest months are March to May when the temperature can rise to 38℃ and the coldest month is December when temperatures can go down to 28℃. In recent years due to climate change, the low temperature month can last only a few weeks or a few days. The wind flows from the northeast in the dry season with less humidity and flows from the southwest in the rainy season with a lot of humidity. The rain in Cambodia is normally strong and can last up to 2 hours. As a country where it can be windy, the rain normally comes down at an angle. As a tropical country, when designing a building weather factors such as temperature, solar radiation, wind speed, and direction, humidity, and rain are crucial to be well considered. Figure 4-1 to Figure 4-8 provide more information about the climate data of Phnom Penh, the results are based on TMY recorded for each hour between 8:00 AM to 9:00 PM each day for an analyzing period from 1980 to 2016.



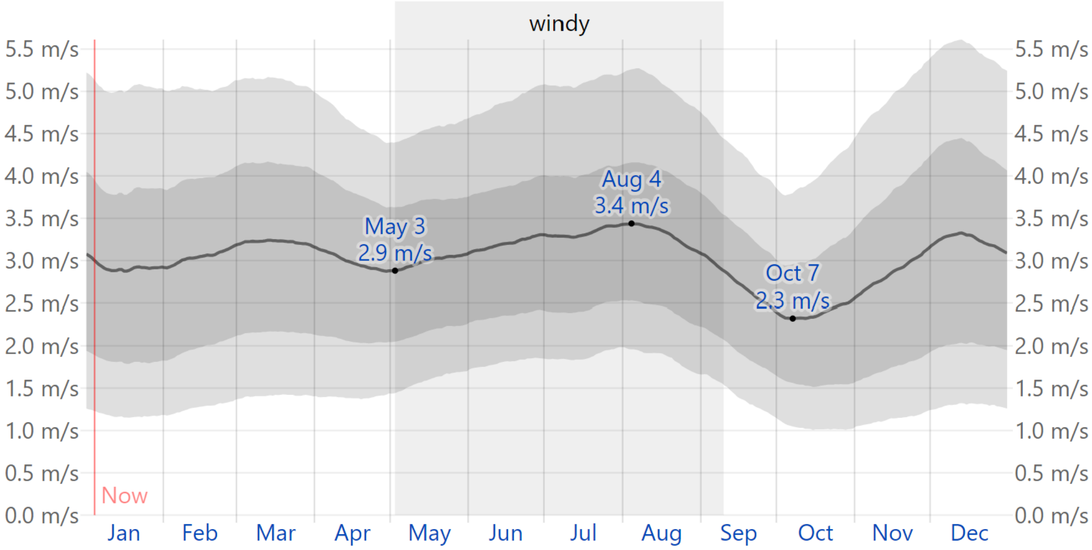
The daily average high (red line) and low (blue line) temperature, with 25th to 75th and 10th to 90th percentile bands. The thin dotted lines are the corresponding average perceived temperatures.

Figure 4-1: Average high and low temperature in Phnom Penh, source: Weather Spark.



The percentage of time spent at various humidity comfort levels, categorized by dew point.

Figure 4-2: Humidity comfort level in Phnom Penh, source: Weather Spark.



The average of mean hourly wind speeds (dark gray line), with 25th to 75th and 10th to 90th percentile bands.

Figure 4-3: Average wind speed in Phnom Penh, source: Weather Spark.

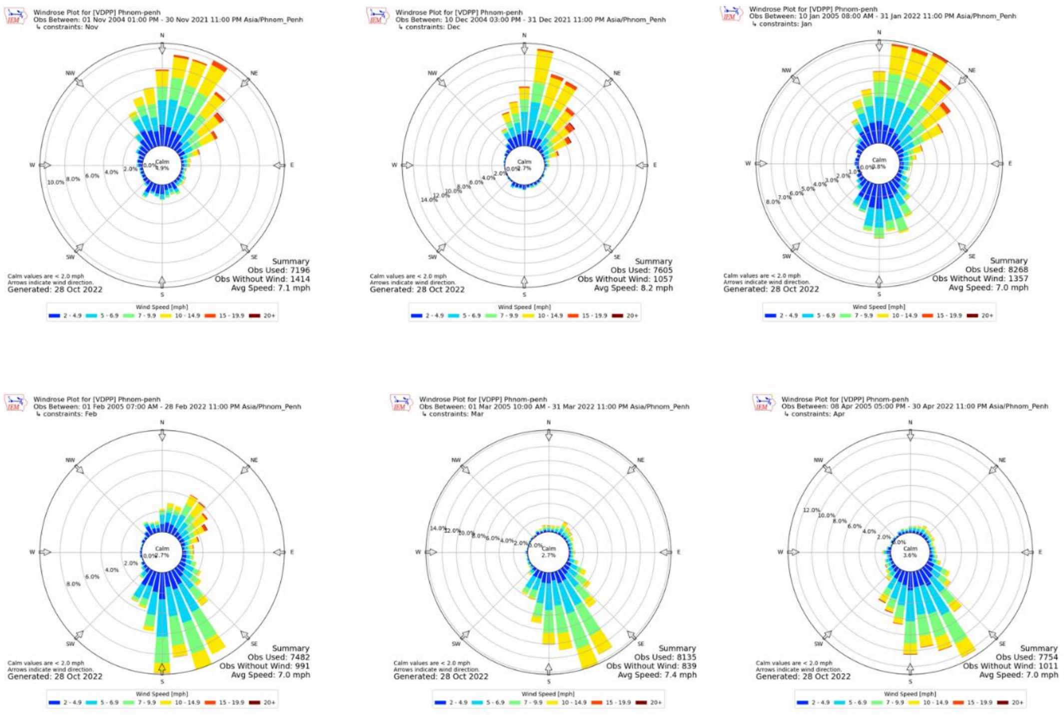


Figure 4-4: Wind rose of Phnom Penh in the dry season, source: Weather Spark.

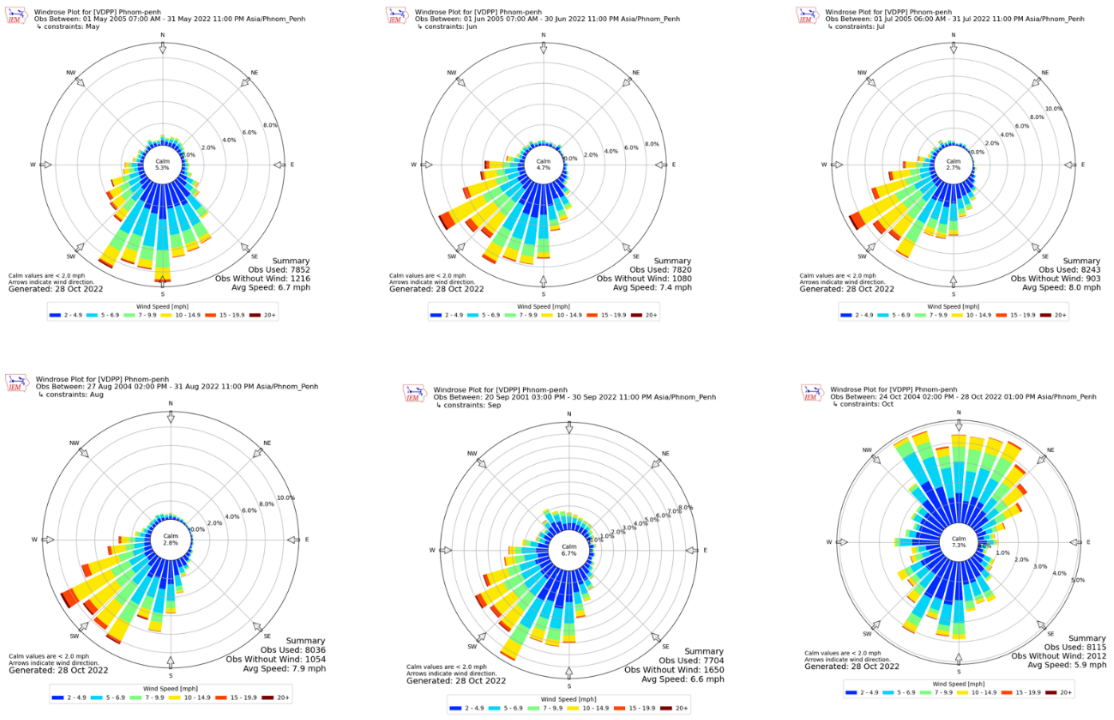
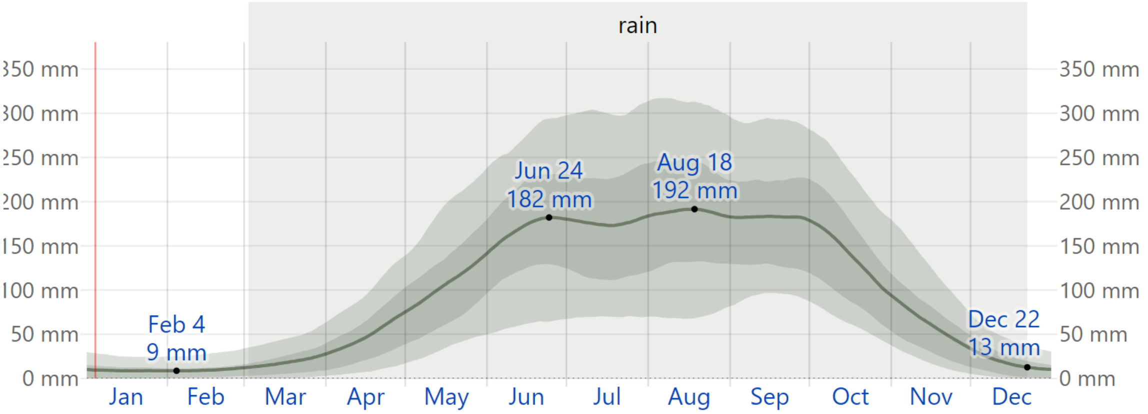


Figure 4-5: Wind rose of Phnom Penh in the rainy season.



The average rainfall (solid line) accumulated over the course of a sliding 31-day period centered on the day in question, with 25th to 75th and 10th to 90th percentile bands. The thin dotted line is the corresponding average snowfall.

Figure 4-6: Average monthly rainfall in Phnom Penh, source: Weather Spark.

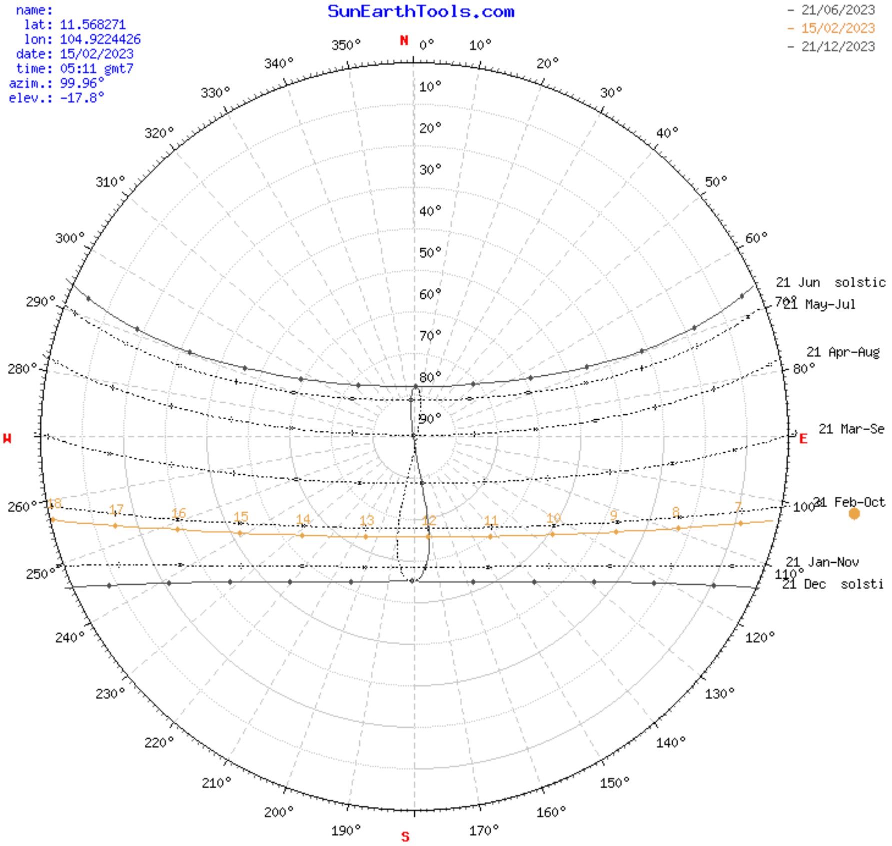


Figure 4-7: Sun path of Phnom Penh, source: Sun Earth Tool.

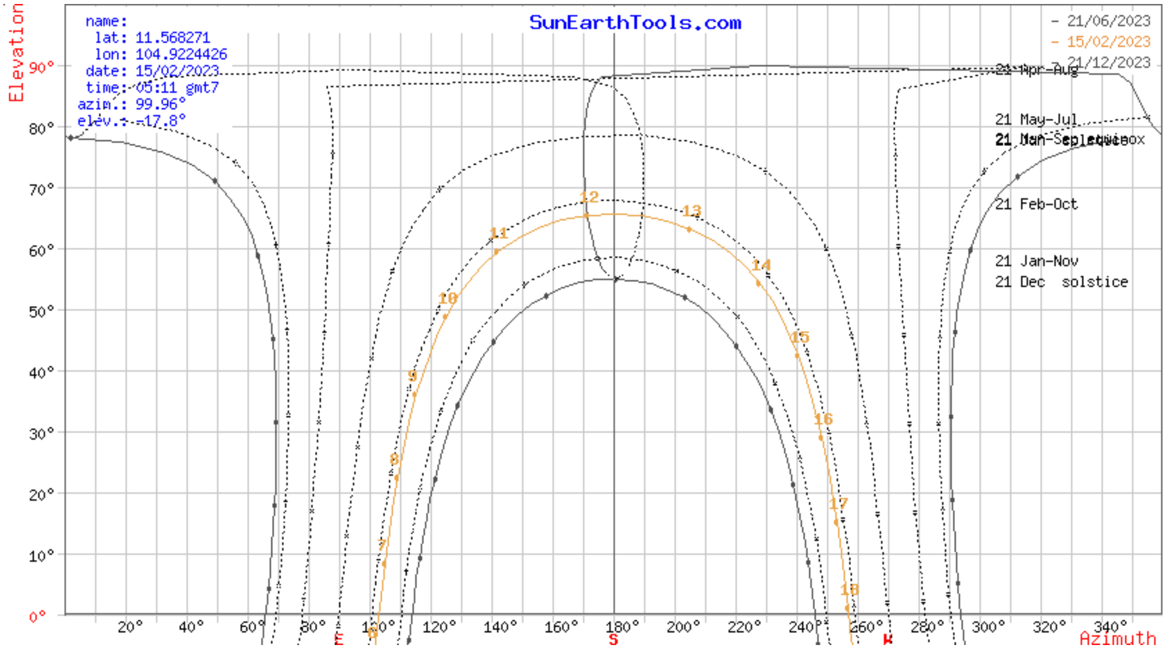


Figure 4-8: Solar elevation of Phnom Penh, source: Sun Earth Tool.

4.1.2 Residential Typologies in Cambodia

In Cambodia, 5 typologies of houses can be found throughout the country. The architectural style has been changing from the past era to now due to foreign influence, access to new technology, and lifestyle adaptation to the modern period.

- Traditional houses

The Khmer traditional house is the vernacular architecture of Cambodia. It is the common typology that can be found in most parts of the countryside of Cambodia. Similar to other traditional houses in Southeast Asia, it can be characterized by a stilted structure with a pitched roof. These houses are normally constructed with locally sourced materials such as wood, bamboo, or straw and clay roof tile. This type of house was built to accommodate the hot-humid climate of Cambodia. The elevated platform allows natural ventilation and can be used as shade for outdoor living space. The roof with a large overhang is made to protect the building from the rain and the pitch roof allows the air in the living space to always stay fresh and cold. In the modern day, this typology has been modernized by adding the ground floor built with brick to provide more living space or facilitate the business for merchant families.

Figure 4-9: Cambodian traditional house (left), modernized Cambodian traditional house (right).

- Link-house or flat

The second typology is link-house also known as flat. It was introduced during the French colonial era which took the appearance of the Chinese shophouse. This typology is commonly found the urban areas where the population is highly dense. Some houses are built link from one to another while some are built separately but in the same format. These houses are commonly built from thick brick walls of 200mm with a pitch or flat roof. In a gated community (Borey), this type of house is normally built with a mezzanine between the ground floor and first floor and identical to each other. Link house is known to be the type of house that is most accessible in the urban area and Borey.

Figure 4-10: Link house or flat in Battambang, Cambodia.

- Detached house or Villa

Also introduced in the French colonial era, this house typology is more accessible to people in the upper class. Built on ground level from the same material as the flat. This type of house can be found in the urban area or outskirts of the city. It is commonly built with the style of French colonial, New Khmer architecture, or contemporary style with elements of Khmer traditional house. A small-scale villa can also be found in the less urban areas of Cambodia as well. In Borey, this type of house is also built identically to each other and sometimes designed as semi-detached which is also known as the twin villa.

Figure 4-11: Detached house or Villa in Phnom Penh.

- Apartment

This type of house appeared in the late 2000s. The apartment can be found only in large cities such as Phnom Penh, Sihanouk Ville, and Siem Reap. The growth of high-rise apartment complexes and condos started in the 2010s toward luxury living. Studio apartments (see in Figure 4-13) which are normally built without much consideration of occupant wellbeing. It is only available for rental and can be considered the cheapest and most accessible option among university students and young workers.

Figure 4-12: Apartment complex in Phnom Penh.

Figure 4-13: Studio apartment in Cambodia.

4.2 Dwelling Thermal Comfort Survey

The global survey is a quantity approach aims to understand the current situations regarding thermal comfort of houses in Cambodia in general. In this survey, we analyze the thermal performance of buildings, characteristics of houses, and occupant behavior to improve their satisfaction. Due to the COVID-19 pandemic, the survey was published online in March

2021 via social media platforms such as Facebook and Telegram, which are among the most effective means of reaching people in Cambodia. The survey consists of questions asking about general information (sex, age, profession…), the situation of their neighborhood, information about their current houses, the thermal comfort of their houses, and their usage of air conditioning. The online survey consists of 4 parts asking about their neighborhood, general information about their houses, the thermal performance of their houses, and their adaptation to improve thermal performance including their behavior towards using air conditioners. The complete questionnaire can be found in Annex 1. Each part of the questionnaire asks about:

Part 1:

- General information about the respondents including sexes, age, and occupation
- Their neighborhood situation in terms of living quality and comfort factor

Part 2:

- Type of house they live in
- Size of the house and number of occupants
- The construction material of the house
- What they like and don't like about the house
- What they want to change about their house
- If the house was designed with expert consultation
- Focus elements when designing the house and what do they think are the most important points to have in a house

Part 3:

- Their satisfaction with the temperature inside their house
- Period when the house is hottest or coldest
- Method they use to improve their satisfaction with the temperature
- The period when they use this solution the most.
- The percentage of thermal comfort improvement by using this solution

Part 4:

- If they have air conditioner in their house
- Location of installed air conditioner
- How often and when they use the air conditioner

- Monthly energy consumption

We received 207 responses from people with 85% living in different parts of Phnom Penh and 15% of people who live in other provinces. The respondents are in their 20s to 50s working in various fields of profession. The survey was conducted at the beginning of the hottest period of the year. However, we specifically asked respondents to give us their answers based on their experience for the whole year.

The respondent shows the common typologies of houses in the urban area. The link house with two to three floors is the most typical in this area followed by the studio apartment the detached house, and finally the apartment. The first section that we are looking into from the answers of respondents to the survey is their overall opinion about their house, and what they like and dislike to identify certain house design issues. We divided the answers into their opinion on the indoor quality and outdoor quality as well as their energy consumption. In Figure 4-14, we can see the main concern is regarding the temperature inside their house which relates to thermal comfort and the green space that the house provided. As we want to focus on the thermal comfort issues, we further investigate the respondent's answers to the thermal performance of their house in this section.

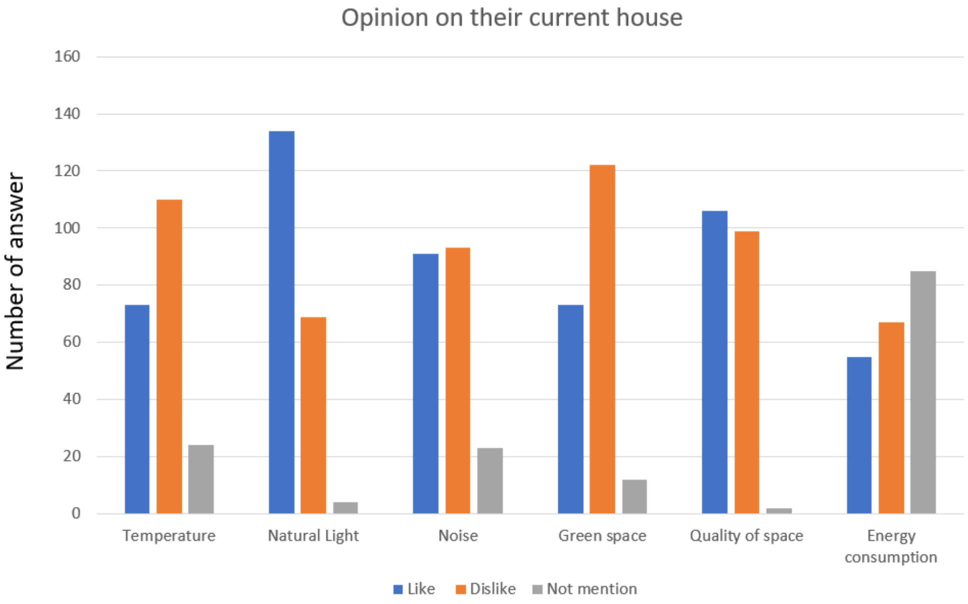


Figure 4-14: Respondent’s opinion regarding the design of their house.

From the answers, 65% of respondents live in link houses (attached houses), 12% live in villas (detached houses), 2% live in apartments and 21% live in studio apartments. Figure

4-15 shows the satisfaction percentage of thermal performance of house votes by respondents. According to their house typology, 65% of people who live in link houses, 57% who live in detached houses, 80% who live in studio apartments and 75% of those who live in apartments say that they are not satisfied with the thermal performance of their house. Figure 4-16 further demonstrates where more than 50% of them express that their house is either hot or very hot.

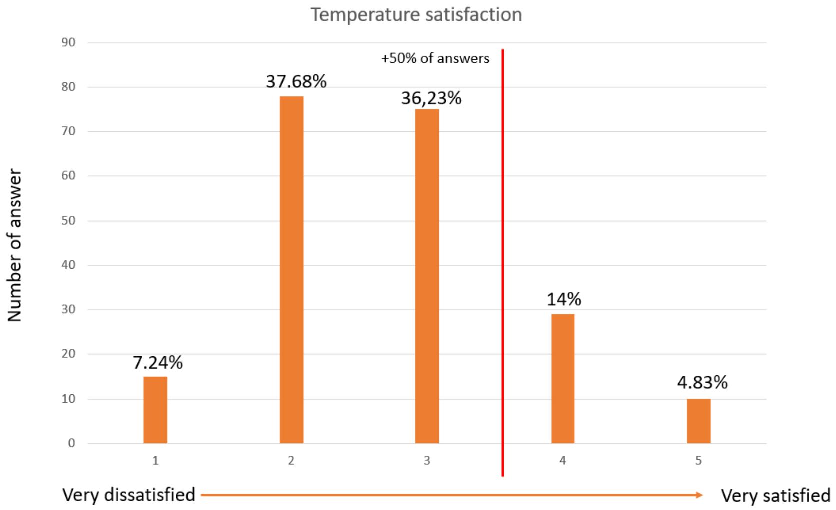


Figure 4-15: Satisfaction of respondents to their house thermal comfort.

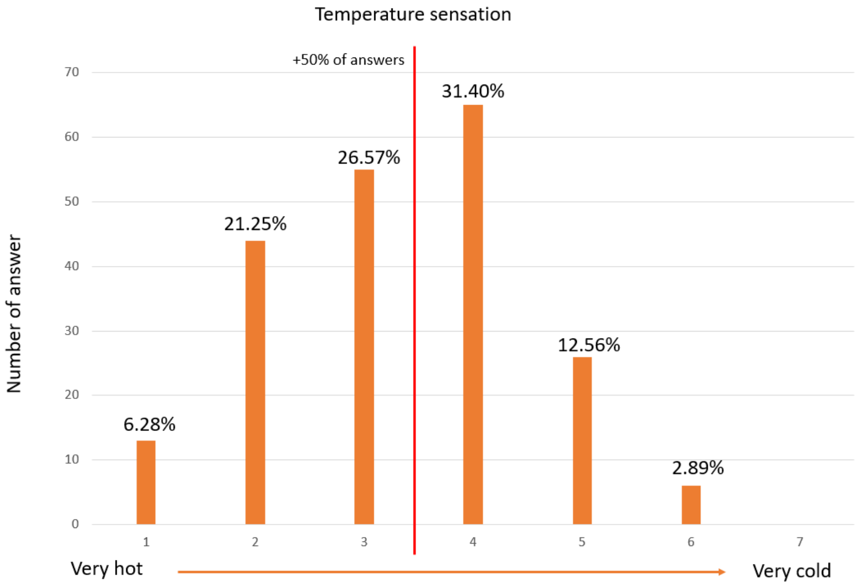


Figure 4-16: Respondent’s sensation votes of their house thermal performance.

To improve their satisfaction, cooling devices such as pedestal fans or air conditioners have become their option. Using these cooling devices can help improve their thermal satisfaction from 50 to 75% for pedestal fans and 75 to 100% for air conditioners. These solutions are mostly used at noon, during the afternoon, and at night when they go to sleep. The use of air conditioners is shown to be mostly during the night-time when they go to sleep as 80% of them have air conditioners installed only in the bedroom (Figure 4-17). This shows that to have a comfortable sleep, temperature is the most important factor.

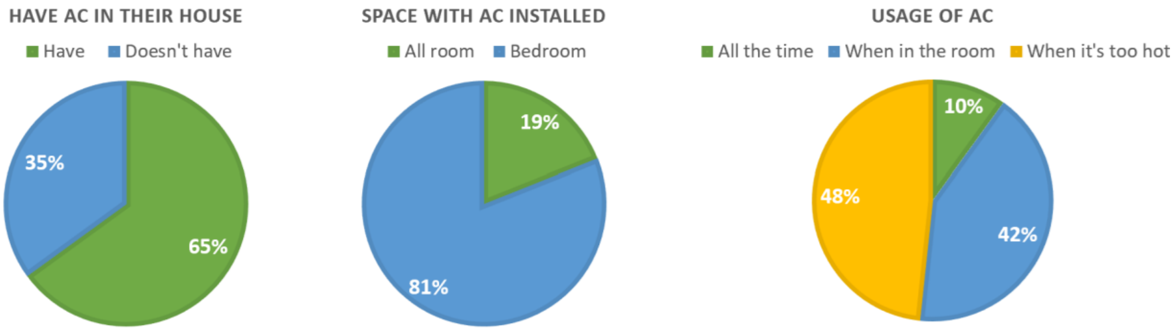


Figure 4-17: Respondents answer to the usage of air conditioners in their household.

During the daytime, when doing household activities, we can see that people can be satisfied with just the use of electric fans which indicates that in a hot humid country where temperature and humidity can't be easily adjustable, the wind is the most important factor for comfort. However, with climate change the outside wind can become more and more high in temperature. Therefore, it is questionable whether this hypothesis can remain suitable in the future. With an initial result of unsatisfied thermal comfort of buildings that we received from this global survey, we proceed to investigate further into the thermal performance of different house typologies in urban areas of Phnom Penh.

4.3 Case Study Buildings

For the purpose of this study, we chose 5 buildings that fall into 3 categories of houses, linked-house, villa, and appartement (standard and studio), as these are common house typologies derived from the survey and will continue to grow in the future. Table 4-1 shows the characteristics of each case study building and Table 4-2 show the envelope structural properties of each building.

Table 4-1: Characteristic of each case study building.

House	Type	Surface (m^2)	Number of floors	Built	Occupant
T1	Link-house	216	4	1997	4
T2	Link-house	100	1.5	2015	4
D1	Detached house/villa	236	3	2013	3-6
A1	Apartment (studio)	13.5	3	2010	3
A2	Apartment (standard)	42.5	22	2018	0

Table 4-2: Envelope structural properties of each building

Envelope	Building	Layer	Material	Thickness (m)	U-value total (W/m2 K)
External wall	All building	Innermost layer Middle layer Outermost layer	Plaster cement Brick Plaster cement	0.01 0.2 0.01	2.1
Internal wall	All building	Innermost layer Middle layer Outermost layer	Plaster cement Brick Plaster cement	0.01 0.1 0.01	2.9
Roof	T1, T2, D1, A2	1 layer	Reinforce concrete	0.12	5.3
	A1	Innermost layer Outermost layer	Plaster ceiling Zinc panel	0.02 0.01	5.87
Floor	All building	Innermost layer Outermost layer	Ceramic clay tile Reinforce concrete	0.01 0.12	2.92

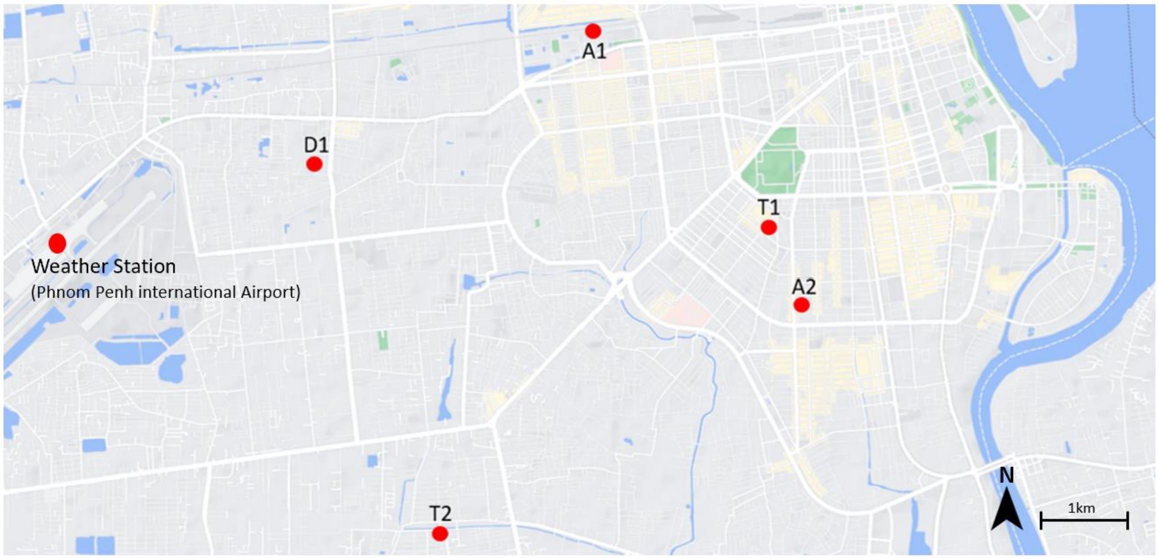


Figure 4-18: Location of 5 case study buildings and the weather station.

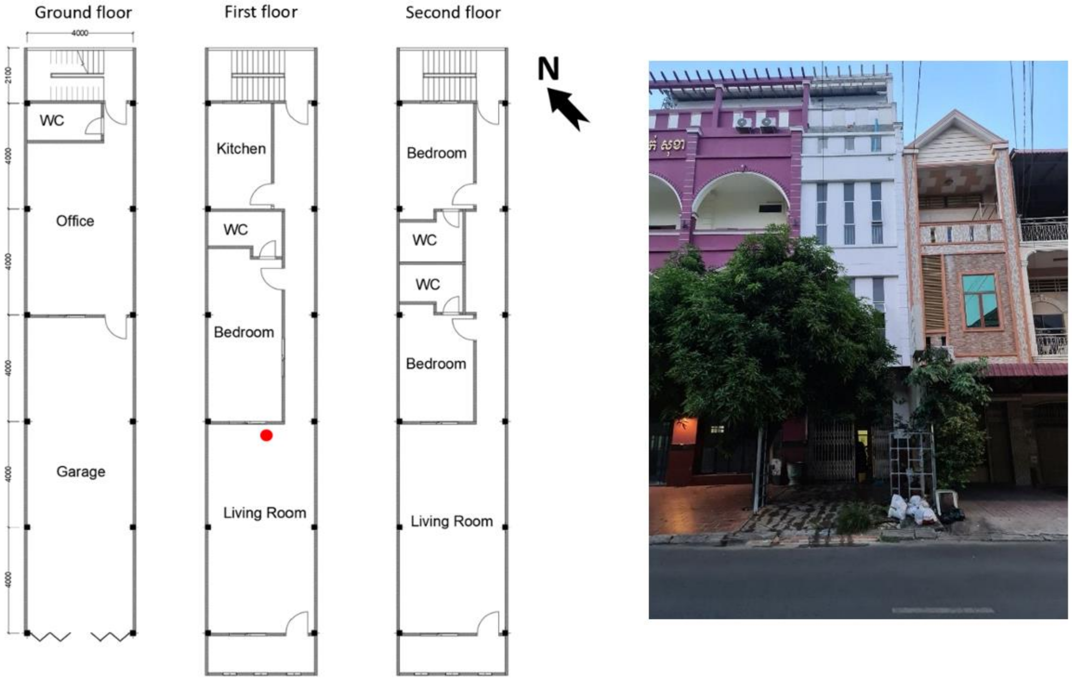


Figure 4-19: Floor plan and the surroundings of building T1 (the red dot is where the sensor was installed).

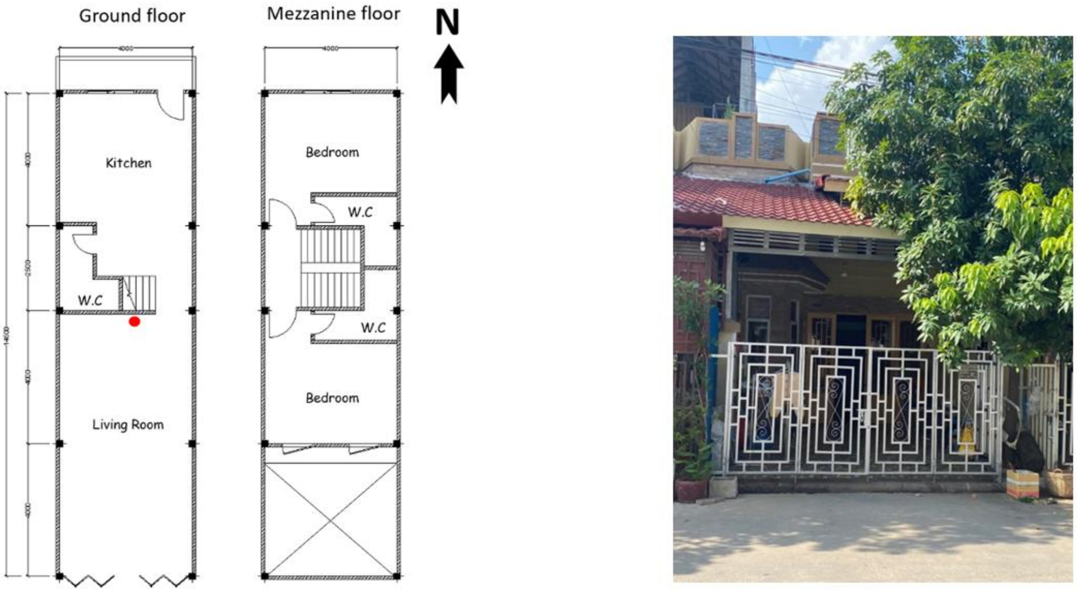


Figure 4-20: Floor plan and the surroundings of building T2 (the red dot is where the sensor was installed).

Figure 4-21: Floor plan and the surroundings of building D1 (the red dot is where the sensor was installed).

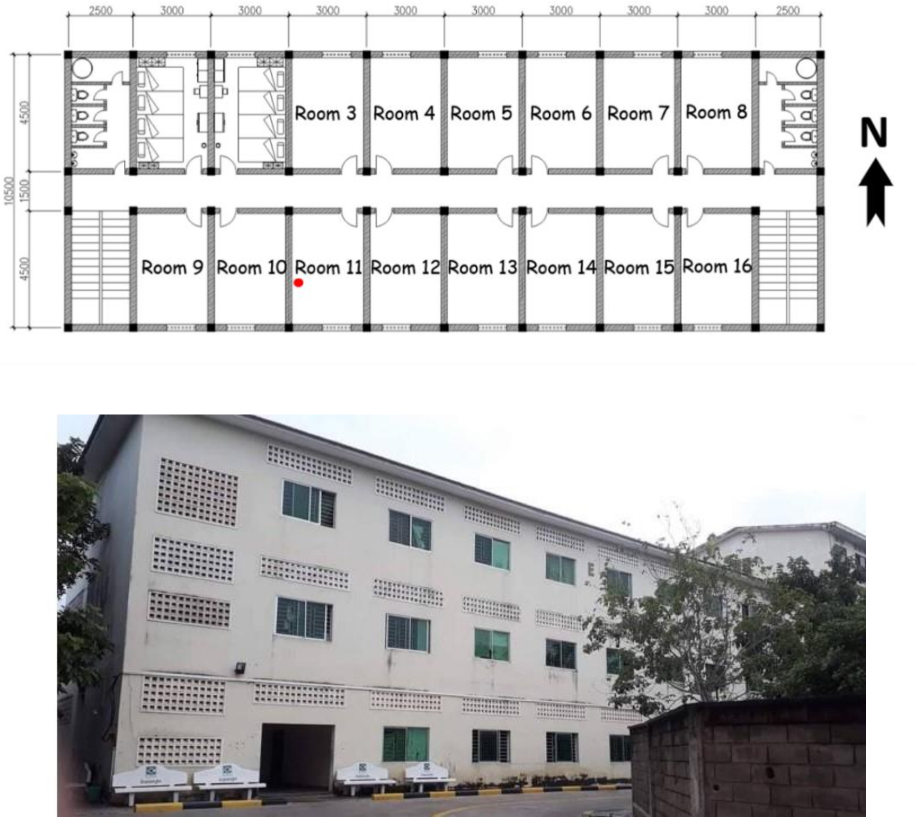


Figure 4-22: Floor plan and surroundings of building A1, room 11 is the case study unit located on 2nd floor under the roof (the red dot is where the sensor was installed).

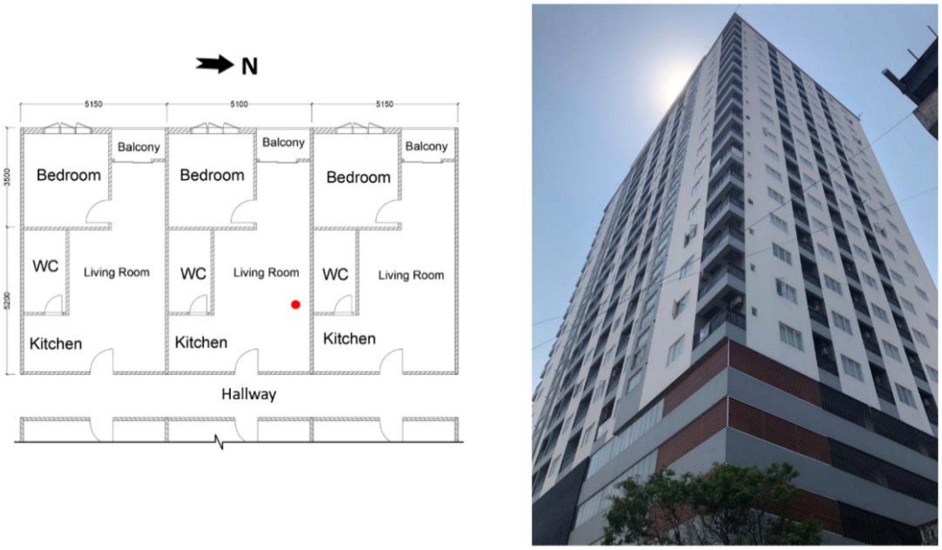


Figure 4-23: Floor plan and surroundings of building A2, the case study unit located on the 10th floor of the building facing west (the red dot is where the sensor was installed).

4.4 In-situ Measurement of Influenced Parameters

As the outdoor temperature throughout the whole year doesn't vary much, we decided to conduct the measurement for only 1 month in each season to see the impact of the season on the influential parameters. The measurements were conducted in the dry and rainy season from 01st April to 01st May and 25th June to 05th August 2021. We used EasyLog USB data logger to measure air temperature and relative humidity every 30 minutes for the whole period of the experiment. Each sensor was placed in the living room as it is the most occupied space throughout the day, and we want to investigate thermal comfort in natural ventilation conditions. During the monitoring period, the living room normally functions on natural ventilation and pedestal fans. The loggers are placed away from direct sunlight, in-house equipment (computer, television…), and placed above 1 meter from the ground. The red dot in the figure is the position of the sensor. With general high temperatures in Cambodia

For air velocity, the measurement was done using a hot-wire anemometer (Alnor Velometer) from 25th June to 05th August 2021. We did it once every week at different times of the day and in different weather conditions (sunny, windy, rain…). We measured the air velocity in the rooms that are mostly occupied such as the living room and the bedroom with 4 different ventilation conditions:

- open all the windows and doors
- open all the windows, doors, and electric fans
- close all the windows and doors
- close all the windows and doors but open the electric fan

Table 4-3: Ventilation condition for measurement of air velocity

Condition	Windows		Electric fan	
	Open	Close	Turn on	Turn off
1	x			x
2	x		x	
3		x		x
4		x	x	

Measurement in these 4 condition ventilations allows us to analyze the impact of the openings and the electric fans on air velocity, i.e., if the electric fan could make a lot of difference when all openings are opened or closed, and to see the level of airtightness of the building.

Figure 4-24: Data logger used to measure temperature and relative humidity.

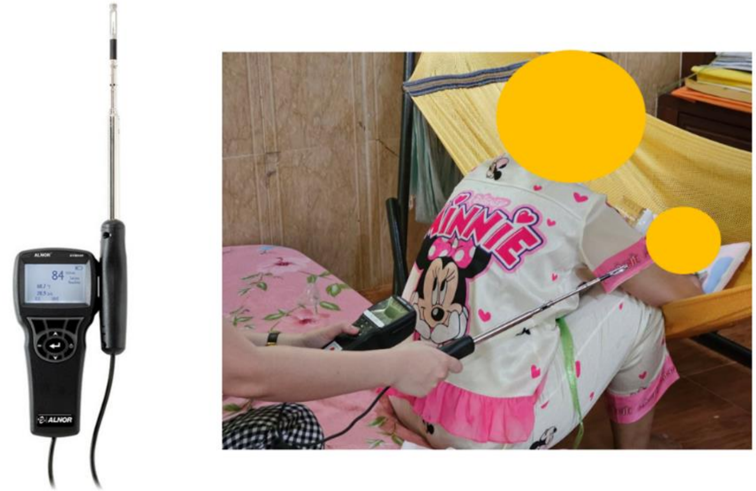


Figure 4-25: The hot wire used to measure air velocity,

4.5 Occupant Survey and Interview

Alongside the measurement, we also conducted interviews with occupants to analyze satisfaction with the thermal condition of their houses. We conduct interviews with all occupants who have lived permanently in each case study building for at least two years. The interview allows us to have a global idea of the thermal condition of buildings according to the people who live in the building, their comfort perception, the usage of fan and cooling devices, energy consumption, clothing, house design malfunction, and their behavior toward improving their thermal comfort. We also provide them with an online survey to complete about their satisfaction and sensation whenever possible. The survey answers are used to compare with the data that we get from the measurement with an attempt to identify an acceptable value of the influenced parameters that are relevant to the respondent profile. Any doubt related to the answer from the survey, was asked to occupant during the time of collecting the sensor from each house. The questions used in the interview and survey are detailed in Annex 1. Below are the most relevant questions related to thermal comfort that were asked during the interview:

- Could you describe your satisfaction and sensation of the temperature inside your house?
- What do you use to help improve your satisfaction with the temperature?
- How many percentage does this solution help you to satisfy with the thermal condition of the building?

4.6 Measurement Results

4.6.1 Air Temperature

The results of the temperature measured in all houses are presented in Figure 4-26. The temperature can vary from 27 ºC to 36 ºC in different house typologies during the monitoring period. Considering that Cambodia is a hot country all year round, this significantly shows the importance of house design impact on building thermal performance. The average air temperature of each house is between 30ºC (A2) to 32ºC (A1) in the dry season and between 30ºC (T1) to 31ºC (A1) in the rainy season which shows that the indoor climate is very uncomfortable compared to the ASHRAE standard and even tropical acceptable temperature found by studies in Chapter 1. We observe that the air temperature inside all case studies is much higher during noon and afternoon than during the night and dawn. Early morning is found to have the lowest air temperature throughout the day at around 28.5ºC to 29.5ºC. While during the afternoon the air temperature can rise to 33ºC.

Between dry and rainy seasons, there isn't a significant difference in terms of indoor air temperature in all case study buildings. This is expected as the outdoor temperature throughout the whole year doesn't vary much. The indoor air temperature follows the outdoor temperature, with the dry season having 1ºC or 2ºC higher than the rainy season. However, as the rainy season brings cooler air, due to Monsoon weather, it tends to make people feel more comfortable in the building, especially during and after the rain.

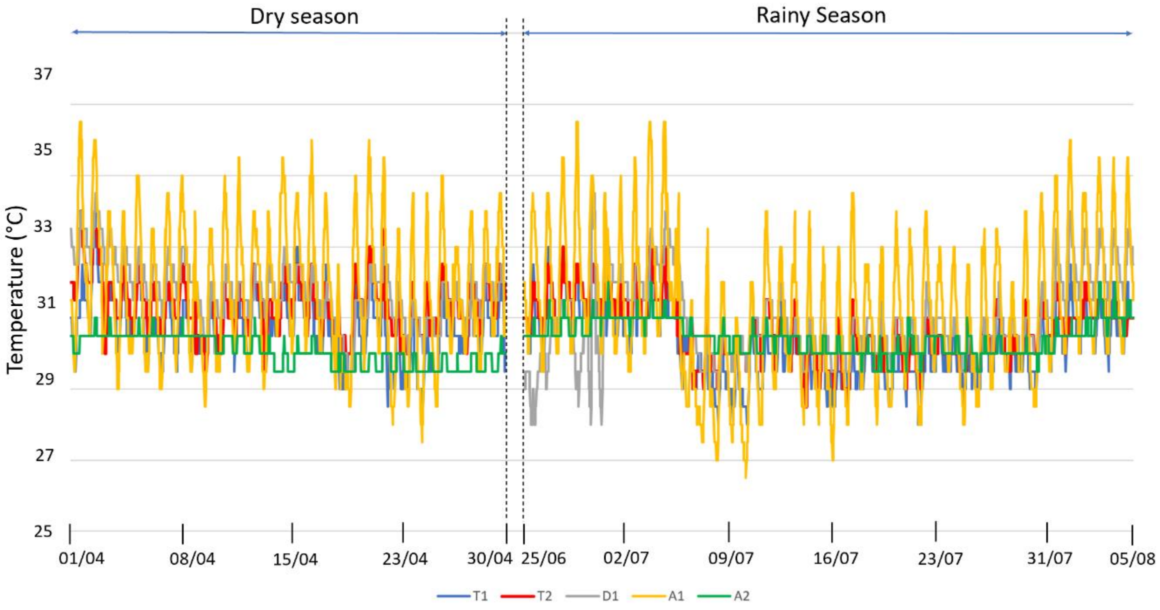


Figure 4-26: Air temperature inside all 5 case study buildings in both seasons.

Regarding the house typology, link houses seem to have the lowest air temperature followed by apartments and detached house. The apartments (A1, A2) show to have the highest and lowest (31.81ºC, 30.85ºC) average air temperatures while link houses (T1, T2) have an intermediate air temperature (30.75ºC, 31.37ºC). The detached house (D1) also has a high air temperature (31.76ºC). However, the average air temperatures in each house are still close to each other.

Within the same typology, link house (T1, T2) and apartment (A1, A2), the average air temperature remains similar to each other with a difference between 0.4ºC to 0.7ºC for house T1 and T2. House T1 that was built in 1997 always has a lower temperature than T2 that was built in 2015. The floor plan, the construction material, and the structure of both houses are the same, and both measurement sensors were placed in the living room with the same ventilation condition. Even though they belong in the same house typology, we notice some design elements that support the different monitoring results despite the microclimate condition. House T1 has 4 floors while T2 only has 1 floor and a mezzanine. Therefore, it allows the lower floor of house T1 where the living room is located to be less exposed to the sun radiation from the roof, unlike house T2 where the living room is located directly under the roof.

Contrarily, A1 and A2 have a significant difference in temperature between each other. The average air temperature in A2 is between 1ºC to 2ºC lower than in A1. Even though the difference in average air temperature isn’t high, the two houses hold the highest and lowest indoor temperatures recorded during the monitoring period. The temperature in A2 is also much more constant than in A1 as it wasn’t occupied during the measurement period. Despite being in the same house typology, many house design differences can be noticed from these two houses. House A2 was designed as a standard apartment with separate spaces for lounging and sleeping while the A1 is a studio apartment where all functions are located in the same space. Similar to the case of the link house, A2 is also situated in the middle of the building height while A1 is situated just under the rooftop, which means that A1 receives not only the heat from the façade but also from the roof. A1 doesn’t have any fixed shading device while A2 does. A2 is also at a much higher height than A1 (A1 is on the 3rd floor, and A2 is on the 10th floor).

The detached house (D1), which seems to have the high air flow among the chosen case study due to its design and the open spaces surrounding the building, however, is shown to have the second highest average temperature as it has the highest exposure to sun radiation than other houses. This shows that the type of house can’t define exactly their thermal comfort level, but it depends of course on how the house is situated, how its façade is exposed to the direct sunlight, and the architectural design concept overall.

Compared to the ASHRAE recommended comfort air temperature of 26 ºC, the average air temperature of all houses in both seasons is significantly higher than the standard at 4 to 6 ºC. Even when accounting for the standard comfort air temperature specific to tropical regions, as established in Chapter 1 which is notably higher than the international standard at around 28,5 ºC, the average air temperature observed in each of the case study houses remains unacceptably high. The temperature in all case study buildings is relatively 1 to 3ºC higher than the standard for tropical regions in both seasons.

4.6.2 Relative Humidity

The average relative humidity in the dry season is between 65% (A1) to 72% (D1) and between 67% (A1) to 70% (T1) in the rainy season which can be considered a high value. Considering that Cambodia is a humid country, the high value of indoor relative humidity in all case study buildings is expected. Figure 4-27 shows the evolution of relative humidity of all case study buildings in both seasons. The difference in indoor relative humidity is relatively low between the two seasons, even with a higher amount of rain that falls during the rainy season. In contrast, we see a more noticeable difference in relative humidity between the night and day. We observe that at a high temperature, the relative humidity decreases. This is why relative humidity during the daytime is better than in the nighttime. In the morning the relative humidity can rise to 77% and it can go down to 60% during the afternoon. The relative humidity during the day stays in the range of less than 70% and is normally higher than 70% during the night.

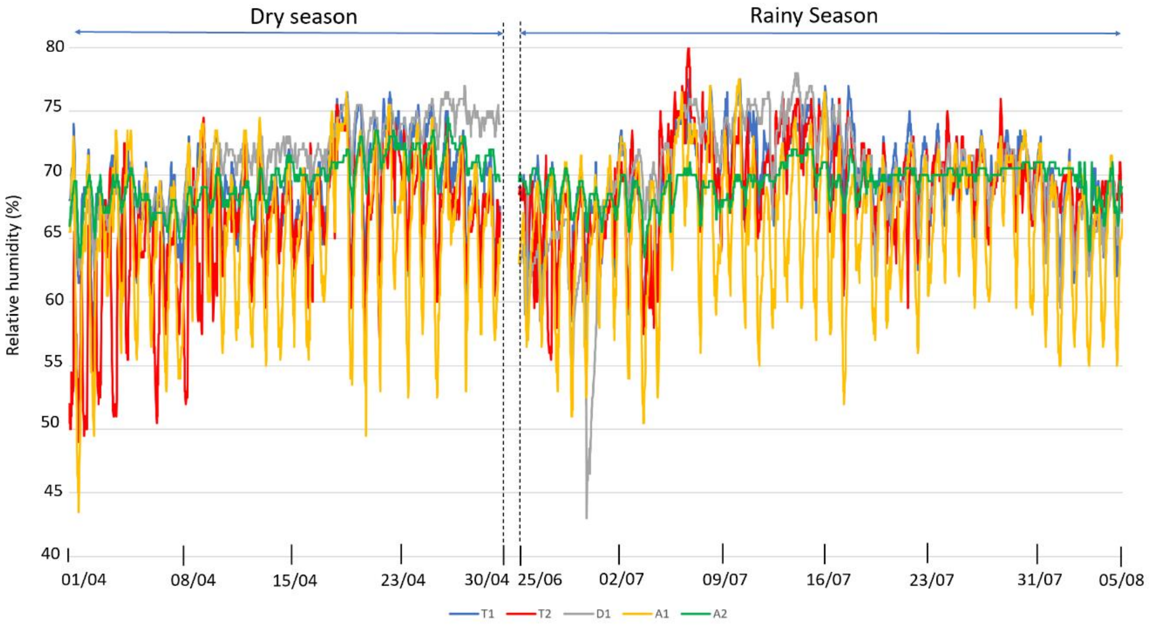


Figure 4-27: Relative humidity inside all case study buildings in both seasons.

Similar to temperature, comparing the different types of housing, the relative humidity in apartments (A1, 66%) is the lowest and the highest is in detached house (D1,72%) while the townhouse always stays in the middle (T1, 69%). However, contrasting to the air temperature, the variation of average relative humidity in all 5 case study buildings is closer to each other in the rainy season and more different in the dry season.

In the hot-humid climate region, higher relative humidity can increase the discomfort percentage rapidly as the body can't be able to sweat to cool down as quickly as it should. There isn't an exact value of relative humidity recommended for comfort as it varies with the temperature. Nevertheless, if we look at findings in the tropical region (50-70%), the relative humidity during the day can be considered to stay within the range of acceptable comfort standards. However, since the relative humidity value remains at the upper limit of the comfort range and considering that occupants tend to be more active during the day (resulting in higher metabolism rates), the elevated temperatures during this period can lead to discomfort due to the relative humidity. This discomfort may also be attributed to the clothing insulation, which restricts air circulation, as well as the low air velocity in the space. In contrast, at night, even though the relative humidity may exceed standard comfort levels, occupants are primarily asleep, and the cooler air during this time reduces the likelihood of significant discomfort.

4.6.3 Air Velocity

The result received from the measurement of relative humidity and air temperature during the dry season pushes us to investigate a step further into building thermal performance through air velocity. The interview with the occupants, which will be presented in the next section, highlighted the significance of air velocity as a critical parameter needed for further investigation. In natural ventilation conditions without the fan, the average air velocity in the living room is between 0.04 m/s (A1) and 0.13m/s (T1) on a normal sunny day and between 0.11 m/s (A1) and 0.40 m/s (D1) on a windy day (Figure 4-28). For the bedroom (Figure 4-29), air velocity on a windy day and a calm day is the same for link houses with an average of 0.02 m/s (T2). However, in apartments, the air velocity on windy days (0.24 m/s) is much higher than during calm days (0.14 m/s) due to its location on the higher floor. The detached house seems to have the best airflow of all case study buildings. Even though we can measure the air velocity in D1 for only one time due to privacy and security reasons, we pick a normal calm day for the measurement to have the most sufficient result compared to other houses.

It is observed that the air velocity in the living room is normally higher than in the bedroom in all case study buildings due to the design of the building that favors the living room with the use of natural ventilation in the bedroom. In the bedroom, the air velocity can drop to zero, indicating that the windows may have high airtightness. However, even when all openings are fully open, the air velocity in the bedroom remains close to zero. The air velocity measured in link houses and apartments for both spaces is below the standard of comfort given the temperature and relative humidity provided by the measurement in both conditions of normal and windy days. The detached house, however, has an air velocity in an acceptable range given the same conditions.

With the pedestal fan turned on, the air velocity increased by 3 to 6 times in all weather conditions, which allows the occupants to feel more comfortable with the given temperature and relative humidity. With the windows and doors closed, we notice that the air velocity with the fan stays more constant. However, occupants prefer to open the windows and door while using the fan to allow the air to circulate better and keep the space with continued fresh air. This can also be the reason why people like to use the AC during the nighttime since they have to close their windows due to their need for privacy and security. As temperature and relative humidity are similar in all case study buildings, air velocity becomes the factor that can identify the comfort level of occupants during the interview.

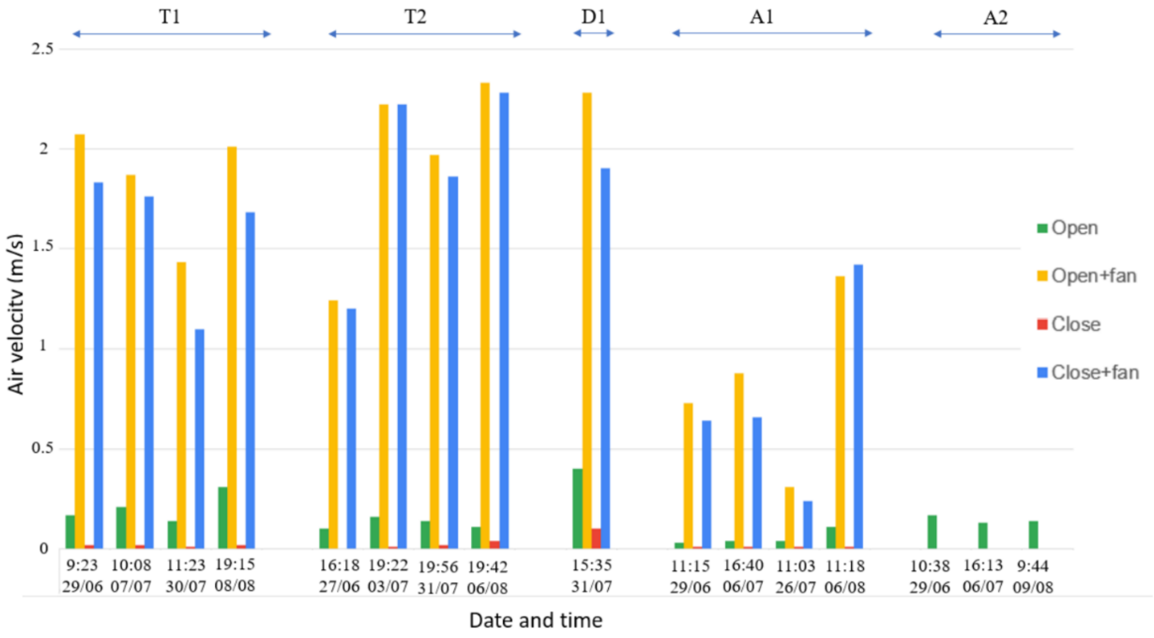


Figure 4-28: Air velocity in the living room of each case study building in different ventilation conditions.

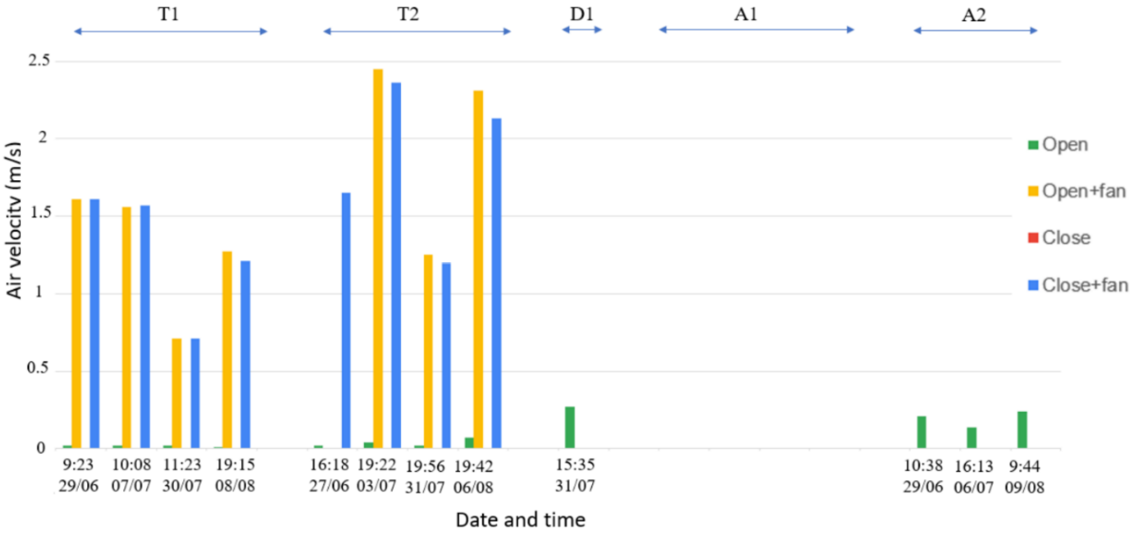


Figure 4-29: Air velocity in the bedroom of each case study building in different ventilation conditions.

4.7 Occupant Interview and Survey Results

The interview with the occupants gives an overview of their sensation and satisfaction with the thermal performance of their house as well as their behavior toward improving their comfort level. As mentioned, comfort level varies following people's adaptation, the interview result will give a more precise evaluation without being based solely on value and standard. The interviews were conducted during site visits to all the case study buildings. We visited each building multiple times (T1: permanent observation, T2: approximately 35 times, D1: 2 times, A1: approximately 10 times, and A2: 4 times). During both the placement and retrieval of the sensors, we asked the occupants similar questions to check for any changes in their responses. In addition to the interview, the survey was done during the same period of the measurement. Occupants answered a questionnaire explaining their sensation and satisfaction at that moment and their evaluations are used to compare with the data received from the measurement. This allows us to identify the exact value of air temperature and relative humidity for when they feel hot or cool, satisfied or unsatisfied.

4.7.1 Occupants Comfort Perception

We collected answers from 14 occupants which is the total number of occupants living permanently in the 4 houses as occupants in house D1 were randomly changed and house A2 wasn’t occupied during the measurement period. According to the interview, occupants describe their thermal comfort state for two seasons different from the season identified in Cambodia, a cool season from November until January and a hot season from March to June. The other months can be considered the neutral months. The comfort level of the occupant is presented in Figure 4-30 and Figure 4-31. It was found that the 4 houses don’t provide optimum comfort to all their residents as expected from the measured value of influenced parameters. The house is either hot or very hot except for houses T1 and D1 where they seem to provide an acceptable comfort range during the cool season. Even though the occupant identified two different seasons for their comfort level, the contrast in their responses between the two seasons however isn’t significant. The occupant’s satisfaction remains the majority on the dissatisfaction side during both periods. Without help from the fan or other cooling device, it is very hard for them to express their 100% satisfaction during both seasons.

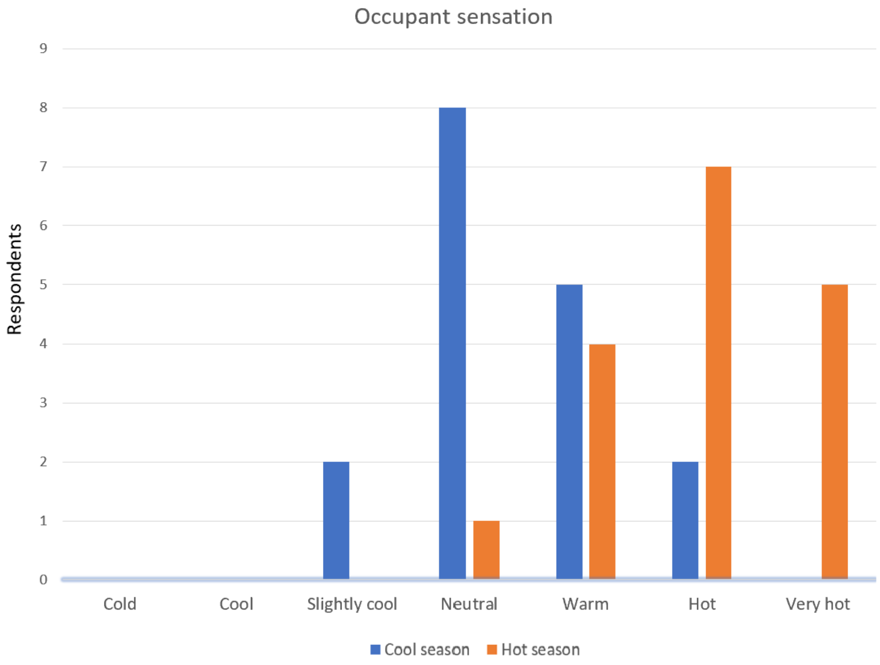


Figure 4-30: Occupant sensation vote.

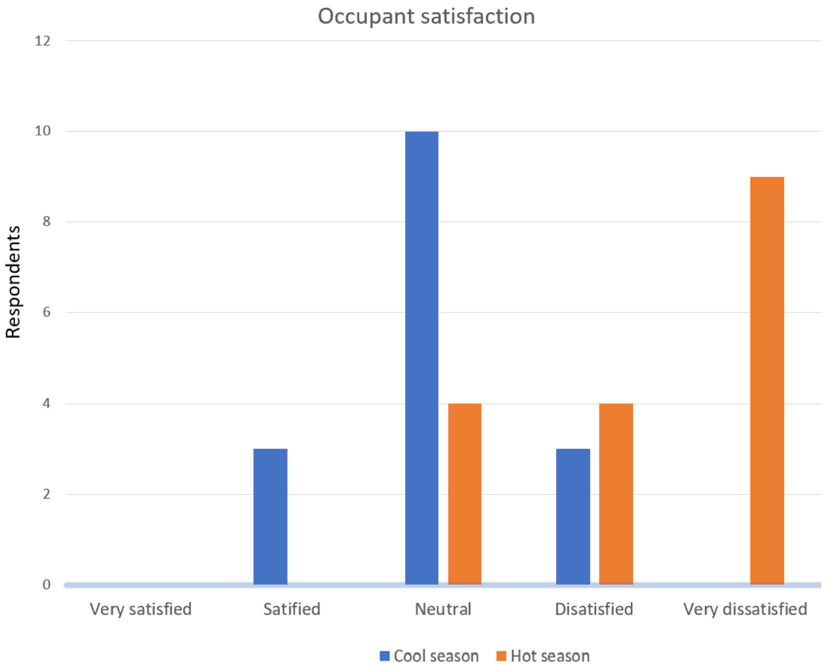


Figure 4-31: Occupant satisfaction vote.

4.7.2 Usage of Cooling Devices

To better understand their comfort perception, Table 4-4 presents the usage of fan and cooling devices that the occupants use to improve their comfort level when they stay in the space during the measurement period. As a reminder, none of the 4 houses were built with any central HVAC system. The cooling system is based solely on fans and individual AC units. Answer from occupant A1 can be categorized as the most discomfort building as they must use a fan throughout the whole day to be able to stay in the room and sometimes even with the fan, they still don’t feel satisfied. T1 and D1 can be seen to have the best thermal performance of all 4 houses as their occupants seem to have a shorter period in using electric fans and air conditioners than the other buildings. Most of the year, the temperature is bearable during the morning but as the temperature progresses throughout the day, occupants of T1, T2, and D1 find themselves turning on the electric fan from 10 AM until sunset. Air conditioners are only installed in the bedroom and are normally used only during sleeping at night to ensure comfortable sleeping time and to save energy. However, going back two years later to houses T1 and T2, we can see that there are air conditioners installed in the living room. They mentioned that during higher temperatures seasons like March to June, the use of electric fans starts early in the morning and with temperature rising at noon, they sometimes switch to air conditioners for the rest of the day.

Comparing the most 2 occupied spaces, we observed that the living room or lounge space seems to provide better thermal performance as the use of fans and air conditioners is less frequent than in the bedroom. It is due to living behavior and preference, and the house design that justify this observation. As per the respondent, they tend to open windows and doors in the living room to allow airflow. The privacy for this space isn’t as strict as other spaces in the house. In contrast, windows in the bedroom are rarely open. It is due to privacy and security reasons. Moreover, the design of the bedrooms in link houses does not facilitate effective ventilation through windows. The proximity of the houses doesn’t favor the flow of air, preventing wind from easily entering the spaces via the windows. This observation allows us to identify an important house design issue.

Table 4-4: Usage of fan and cooling devices in all 5 houses during the measurement period.

House	Occupied space	Ceiling fan (Usage frequency during occupied time)	Pedestal fan (Usage frequency during occupied time)	AC unit (Usage frequency during occupied time)
T1	Living room/ lounge	2 (-)	3 (75%)	-
	Bedroom	-	3 (60%)	1 (35%)
T2	Living room/ lounge	1 (-)	2 (85%)	-
	Bedroom	-	2 (20%)	2 (80%)
D1	Living room/ lounge	1 (-)	2 (40%)	1 (10%)
	Bedroom	-	2 (10%)	3 (80%)
A1	Bedroom and lounge	-	3 (100%)	-
A2	Living room/ lounge	-	-	1 (-)
	Bedroom	-	-	1 (-)

From the usage of the fan and AC mentioned during the interview, we observe that air velocity has become the most important factor influencing comfort as fans are used more than air conditioners when possible. With a bearable temperature of 31 degrees or less, occupants prefer to use pedestal fans in residential spaces to minimize energy consumption and for better health.

4.7.3 Acceptable Comfort Value for Influenced Parameters

The occupant survey was sent to all 17 occupants. Unfortunately, only occupants from house T1 participated in this survey. In total, we received 66 evaluations of their comfort level during the building monitoring period. There are 4 females living in house T1, aged between 25 to 35 years old. The answer was given in natural ventilation conditions without the electric fan turned on, with a metabolic rate of 1 met and clothing insulation of 0.54 clo. The evaluations that we received were completed at different times of the day and the respondents normally placed themselves near to the sensor when answering the question.

Comparing the result from the measurement to the survey, we can identify a comfort and discomfort value of temperature and relative humidity for females as shown in Table 4-5. To receive these values, we look at the time that the occupant answer the survey whether they feel satisfied or dissatisfied, and identify the value of temperature and relative humidity at that moment. Even though the number of samples is limited, we display this finding in case it could be useful information for other studies on the same topic. More than that the acceptable value found in our study also presents similarity to the finding with a larger sample in Singapore with an acceptable temperature of 28.86 ºC and relative humidity of 70% (WEBB, 1959), and in Thailand with an acceptable temperature of 28 ºC (Rangsiraksa, 2006). The interview during the measurement of air velocity also led us to define that, with fan ventilation of air speed of 1.4 to 2.33 m/s and relative humidity from 67 to 75%, the occupants can tolerate air temperature from 31.5 to 32.5ºC.

Table 4-5: Acceptable value for comfort and discomfort vote by 4 female occupants from T1 in natural ventilation conditions.

Parameter	Comfort	Discomfort
Air temperature (ºC)	29.0–30.0	31.5–34.0
Relative humidity (%)	73.0–75.0	67.5–70.0

4.8 Adaptive Comfort Model for Cambodia

In April 2024, we spend 3 days measuring the 3 parameters and PMV in house T2 again where we stay from the morning to the evening with the occupant for them to vote on their sensations. This measurement aims to identify the most influential parameter and create an adaptive comfort model in Cambodia. We allow the occupant to act as their everyday life during the monitoring period. During the measurement period, the temperature in Cambodia was the highest it had encountered before. The occupants, therefore, rely on AC for comfort throughout the day. We monitor their activities, their clothing insulation, changing from using fans to air conditioners, and verbal words to express their sensation with the thermal condition of their house. We ask 3 occupants who are 2 females in their 30s and 50s and a male in his 30s to vote on their sensation (PMV scale) every 30 minutes. Some additional questions were also asked when they changed their source of thermal comfort improvement or other related factors such as a change of clothing or getting a shower. They vote their sensation on a scale of +3 to -3 for very hot to very cold. We collected in total 12 votes for natural ventilation and 25 votes for air conditioner conditions.

There are 4 occupants who live in this house. However, during the measurement, we receive votes from only 3 occupants due to their availability. During this monitoring period, we observed that the occupants dress in the same clothing insulation of 0.54 clo and usually repeat the same activities. We calculate the average PMV vote at different times of the day, and we receive the relation between the measured parameter and PMV vote as shown in Figure 4-32.

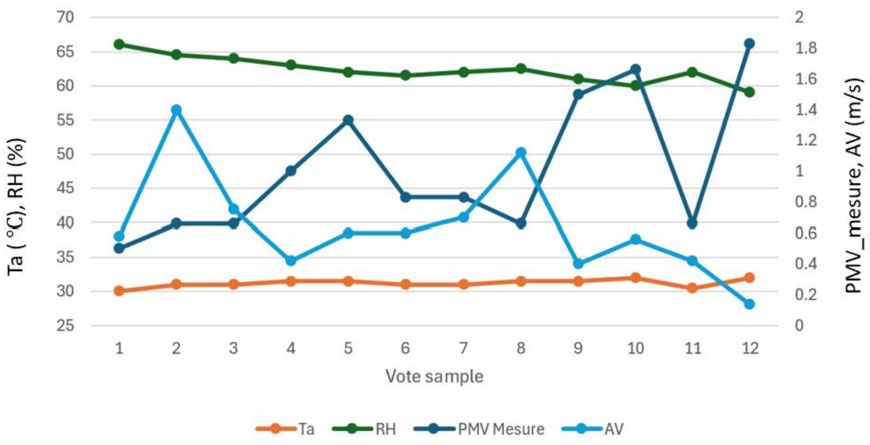


Figure 4-32: Measured parameter and PMV vote in natural ventilation (Ta: air temperature, RH: relative humidity, AV: air velocity).

It is observed that the temperature and humidity variation remain almost constant for the whole measurement period. In contrast, air velocity and PMV exhibit distinct variations. Specifically, as air velocity increases, PMV decreases, suggesting that air velocity is the most influential factor affecting occupant comfort levels which is also a finding that is noticed from the building monitoring and occupant interview. Notably, when the temperature exceeds 30 °C, the occupant either feels neutral or hot, with these perceptions being significantly influenced by changes in air velocity.

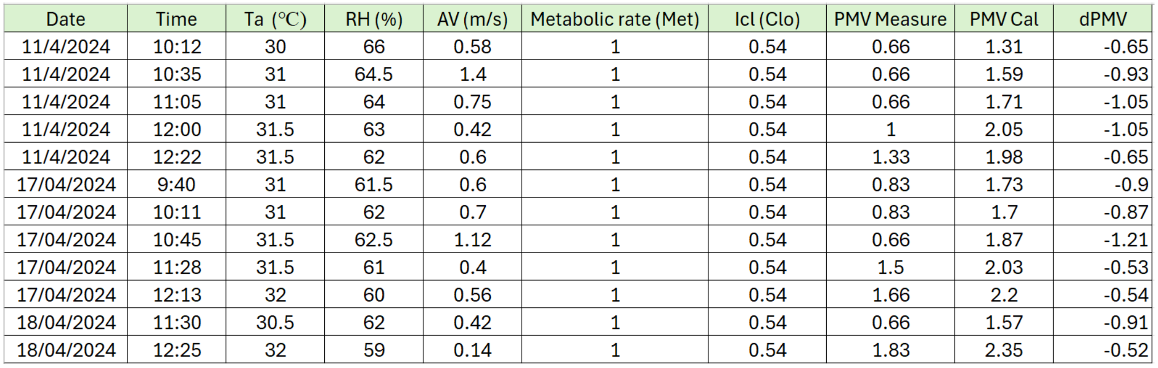
This finding result in another investigation in attempting to see the adaptability of the Fanger model for the context of Cambodia. As mentioned in Chapter 1, the Fanger model has been modified to adapt to various climate conditions around the world. The Fanger model used for the calculation of PMV is written as:

$$\begin{aligned} PMV = {} & (0.303\,exp(-0.036M) + 0.028)[M - 3.0510^{-3}(5733 - 6.99M - p_a) - \\ & 0.42(M - 58.15) - 1.710^{-5}M(5867 - p_a) - 0.0014M(34 - t_a) - \\ & 3.9610^{-8}f_{cl}((t_{cl} + 273)^4 - (t_r + 273)^4) - f_{cl}h_v(t_{cl} - t_a)] \end{aligned} \qquad \text{Eq. 4-1}$$

By using the Fanger equation above, we calculated the PMV with the measured parameter. Table 4-6 and Figure 4-33 show the result of PMV measured compared to PMV calculated in natural ventilation conditions. It is observed that the PMV calculated is always higher than the PMV measured. In the air conditioner condition (see Figure 4-34 and .

Table *4-7*), the PMV calculated is always positive whereas the PMV measured shows mostly negative value. Obviously, by using an air conditioner the occupant either feels comfortable or slightly cool as they aren’t normally adapted to using air conditioner or being in cold temperatures. This result shows that there is a bias between the PMV calculated and the PMV measured which is the real-time thermal sensation. The difference between the two values is set as dPMV which is calculated in Table 4-6 and Table 4-7) dPMV is between -0.65 to -1.21 in natural ventilation conditions and between -1.38 to -2.56 in air conditioner conditions. This shows the high adaptation of people in Cambodia to the hot climate that they experience all year round.

Table 4-6: Comparison of PMV measured and PMV calculated in natural ventilation conditions.



Date	Time	Ta (℃)	RH (%)	AV (m/s)	Metabolic rate (Met)	Icl (Clo)	PMV Measure	PMV Cal	dPMV
11/4/2024	10:12	30	66	0.58	1	0.54	0.66	1.31	-0.65
11/4/2024	10:35	31	64.5	1.4	1	0.54	0.66	1.59	-0.93
11/4/2024	11:05	31	64	0.75	1	0.54	0.66	1.71	-1.05
11/4/2024	12:00	31.5	63	0.42	1	0.54	1	2.05	-1.05
11/4/2024	12:22	31.5	62	0.6	1	0.54	1.33	1.98	-0.65
17/04/2024	9:40	31	61.5	0.6	1	0.54	0.83	1.73	-0.9
17/04/2024	10:11	31	62	0.7	1	0.54	0.83	1.7	-0.87
17/04/2024	10:45	31.5	62.5	1.12	1	0.54	0.66	1.87	-1.21
17/04/2024	11:28	31.5	61	0.4	1	0.54	1.5	2.03	-0.53
17/04/2024	12:13	32	60	0.56	1	0.54	1.66	2.2	-0.54
18/04/2024	11:30	30.5	62	0.42	1	0.54	0.66	1.57	-0.91
18/04/2024	12:25	32	59	0.14	1	0.54	1.83	2.35	-0.52

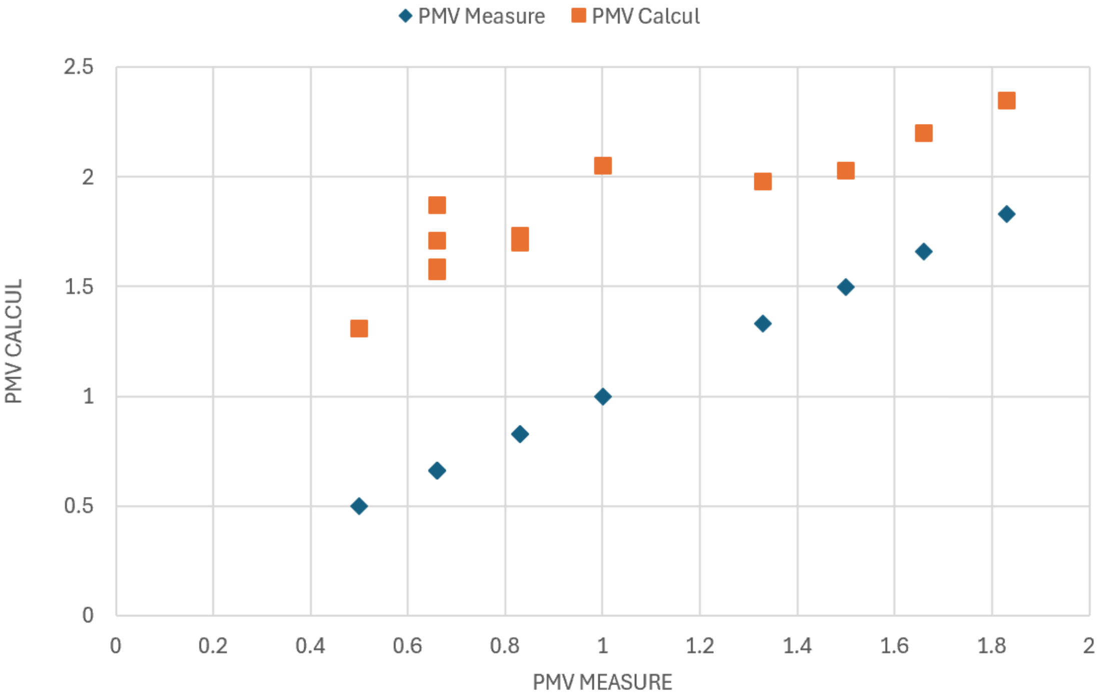


Figure 4-33: Comparison of PMV measured and PMV calculated in natural ventilation.

Table 4-7: Comparison of PMV measure and PMV calculated in air conditioner conditions.

Date	Time	Ta (°C)	RH (%)	AV (m/s)	Metabolic rate (Met)	Icl (Clo)	PMV Measure	PMV Cal	dPMV
11/4/2024	13:15	31	55	0.15	1	0.54	0	1.9	-1.9
11/4/2024	13:45	30	51	0.23	1	0.54	-0.33	1.36	-1.69
11/4/2024	13:45	30	51	0.1	1	0.54	-0.66	1.53	-2.19
11/4/2024	14:25	29.5	53	0.15	1	0.54	-0.66	1.28	-1.94
11/4/2024	14:57	29.5	53.5	0.17	1	0.54	-0.83	1.26	-2.09
11/4/2024	14:57	29.5	53.5	0.3	1	0.54	-1	1.11	-2.11
11/4/2024	15:34	29	51	0.3	1	0.54	-1.16	0.87	-2.03
11/4/2024	16:07	29	52.5	0.35	1	0.54	-1.25	0.84	-2.09
11/4/2024	16:07	29	52.5	0.15	1	0.54	-1.33	1.08	-2.41
11/4/2024	16:44	28.5	51	0.1	1	0.54	-1.5	0.95	-2.45
11/4/2024	16:45	28.5	51	0.06	1	0.54	-1.5	1.06	-2.56
11/4/2024	17:17	28.5	52.5	0.05	1	0.54	-1.5	1.07	-2.57
11/4/2024	17:19	28.5	52.5	0.35	1	0.54	-1.66	0.62	-2.28
17/04/2024	13:14	31	54	0.41	1	0.54	0.33	1.71	-1.38
17/04/2024	14:00	29.5	52.5	0.12	1	0.54	-0.5	1.32	-1.82
17/04/2024	15:12	29	52	0.12	1	0.54	-0.66	1.13	-1.79
17/04/2024	15:44	29	51.5	0.7	1	0.54	-0.83	0.61	-1.44
18/04/2024	13:23	31	55.5	0.42	1	0.54	-0.5	1.73	-2.23
18/04/2024	13:23	31	55.5	0.25	1	0.54	0.16	1.82	-1.66
18/04/2024	13:58	30	50.5	0.13	1	0.54	-0.33	1.48	-1.81
18/04/2024	13:58	30	50.5	0.16	1	0.54	-0.5	1.44	-1.94
18/04/2024	15:31	29	51	0.08	1	0.54	-0.66	1.21	-1.87
18/04/2024	15:31	29	51	0.34	1	0.54	-1	0.84	-1.84
18/04/2024	16:02	29	52.5	0.12	1	0.54	-1	1.13	-2.13
18/04/2024	16:02	29	52.5	0.2	1	0.54	-1	1	-2

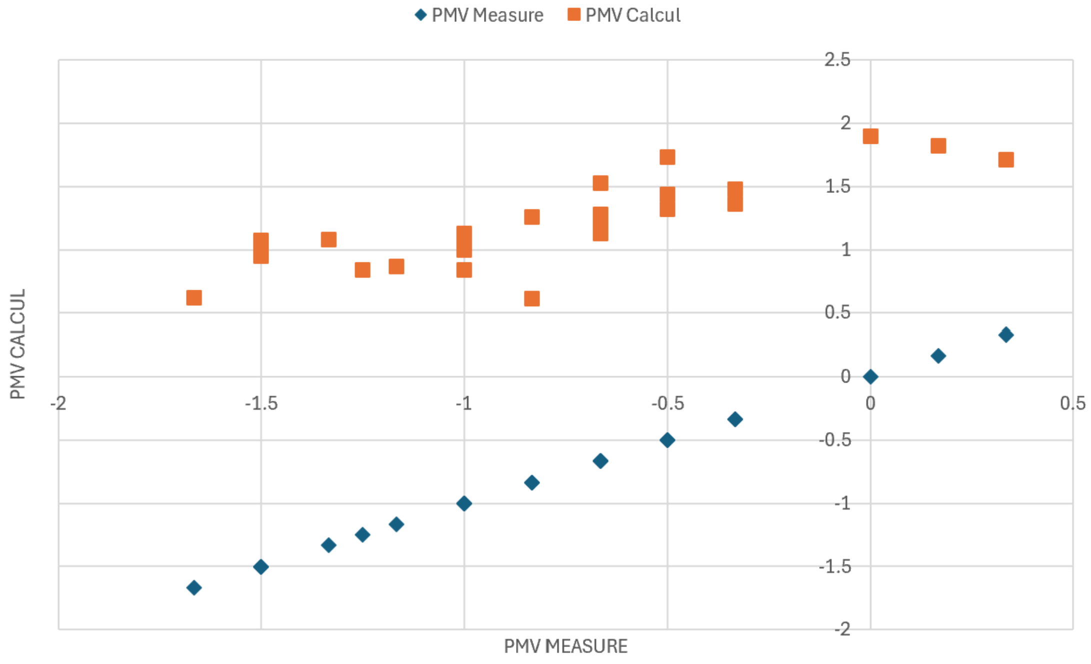


Figure 4-34: Comparison of PMV measured and PMV calculated in air conditioner conditions.

The difference in PMV found between the measured and those calculated by Fanger leads us to identify an adaptive model by using a corrective coefficient. We therefore can write that the PMV adaptive as:

$$PMV_{adqptive} = PMV_{calculated} - dPMV$$

Eq. 4-2

dPMV in this case is the corrective coefficient of the most influential parameter that the variation of PMV follows.

4.8.1 Natural Ventilation Conditions

We identify the corrective coefficient by using a multilinear regression model on the calculated and measured PMV. The table below shows the summary result of the regression model.

Table 4-8: Summary of regression model run.

R= 0.97, R^2= 0.95				
	Coefficient	Standard error	t stat	P value
Ta	0.018	0.004	4.497	0.0011
AV	0.39	0.178	2.220	0.0506

From this result, we can therefore identify the corrective coefficient in natural ventilation as

$$dPMV = 0.018Ta + 0.39AV$$

Eq. 4-3

The PMV adaptive, therefore can be written as:

$$PMVadaptive = PMVcalculated - (0.018Ta + 0.39AV)$$

Eq. 4-4

Or

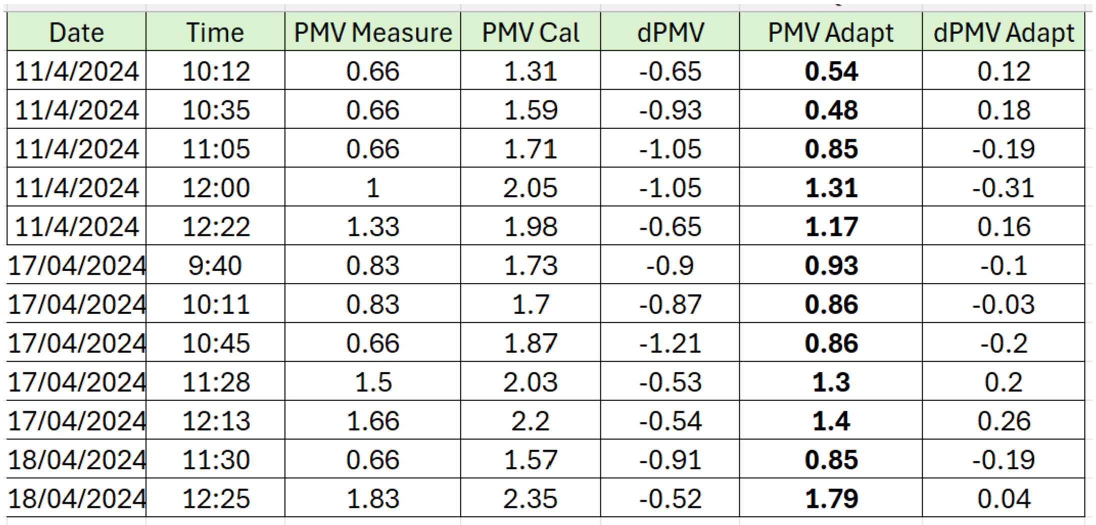
$$PMV\ adaptive = (0.303\,exp(-0.036M) + 0.028)[M - 3.0510^{-3}(5733 - 6.99M - p_a) - 0.42(M - 58.15) - 1.710^{-5}M(5867 - p_a) - 0.0014M(34 - t_a) - 3.9610^{-8}f_{cl}((t_{cl} + 273)^4 - (t_r + 273)^4) - f_{cl}h_v(t_{cl} - t_a)] - (0.018Ta + 0.39AV)$$

Eq. 4-5

As a reminder, the PMV adaptive is based on a sample size of only 3 people (2 females and 1 male). We don’t establish this finding as the standard PMV adaptive for Cambodia.

Further investigation with a much larger sample size is needed to make it a reliable PMV adaptive for Cambodia. The table below compares the PMV adaptive calculated using equation 4.5 to the PMV measured. We can see that the difference between dPMV adapt is much smaller compared to dPMV calculated. This finding will be used as our adaptive model to analyze building thermal performance in the simplified method that will be presented in Chapter 6.

Table 4-9: Comparison of PMV measured, PMV calculated and PMV adapt.



Date	Time	PMV Measure	PMV Cal	dPMV	PMV Adapt	dPMV Adapt
11/4/2024	10:12	0.66	1.31	-0.65	**0.54**	0.12
11/4/2024	10:35	0.66	1.59	-0.93	**0.48**	0.18
11/4/2024	11:05	0.66	1.71	-1.05	**0.85**	-0.19
11/4/2024	12:00	1	2.05	-1.05	**1.31**	-0.31
11/4/2024	12:22	1.33	1.98	-0.65	**1.17**	0.16
17/04/2024	9:40	0.83	1.73	-0.9	**0.93**	-0.1
17/04/2024	10:11	0.83	1.7	-0.87	**0.86**	-0.03
17/04/2024	10:45	0.66	1.87	-1.21	**0.86**	-0.2
17/04/2024	11:28	1.5	2.03	-0.53	**1.3**	0.2
17/04/2024	12:13	1.66	2.2	-0.54	**1.4**	0.26
18/04/2024	11:30	0.66	1.57	-0.91	**0.85**	-0.19
18/04/2024	12:25	1.83	2.35	-0.52	**1.79**	0.04

4.9 Current House Design Issues

Houses in the gated community, which is the most accessible option for people living in the city were designed by the developer without the involvement of the occupants themselves. As mentioned in the problem statement, the house design benefits the developer rather than the occupants who are the long-term users of the building. Consequently, the design lacks the essence of providing a comfortable living environment due to the pricing of the land.

As seen from the dwelling comfort survey, people tend to use air conditioners in their bedrooms for comfortable sleep. The building design therefore follows this trend of lifestyle. More than that, the living room can also be used for small businesses where there are people coming in and out often. Therefore, the use of air conditioners is sometimes not quite accommodated with this condition. The open plan living room for maximum natural ventilation to use with a ceiling fan or pedestal fan is more suitable for the lifestyle of Cambodians.

From the monitoring of the building's thermal performance and interviews with occupants, we can identify several issues of the current house design that impact its thermal performance. This issue is commonly seen in houses in gated communities, especially for link houses which can be identified from house T2. Starting from the surrounding environment of house design, there is a notable deficiency in parking and green space. Due to security concerns, some residents are compelled to use their living rooms to park their cars and motorbikes. The lack of green space poses a significant problem, as these houses typically lack backyards or small courtyards for greenery. This absence of garden space adversely affects the provision of natural ventilation within the building. Additionally, the proximity between houses raises privacy issues, preventing occupants from fully utilizing their windows for natural ventilation. The prevalent design of sliding glazed windows allows only 50% of the window area to open, while still permitting 100% solar heat gain. While the use of glazing is intended to maximize natural light, the close spacing of houses inhibits effective light penetration through the windows. In Cambodia's hot climate, it is recommended that windows be opened as much as possible to maximize ventilation and natural light. However, the traditional use of louvers, which facilitate natural ventilation, is becoming increasingly rare, being replaced by glazing to accommodate air conditioner use.

The design of link houses with mezzanines creates an environment reminiscent of a cave. The low height between doesn't allow stack ventilation or prevents natural light from adequately penetrating the space. Typically, link houses are quite long, ranging from 12 to 18 meters in length. Consequently, the central part of the house, often comprised of the corridor or stairwell, tends to be dark and humid. The design with a flat or gable roof is common. However, the design of the gable roof (see Figure 4-35) is normally positioned directly above the ceiling without any gab, the roof transforms into a heat box during the day, making the space below, usually the bedroom, unbearably hot for sleeping at night.

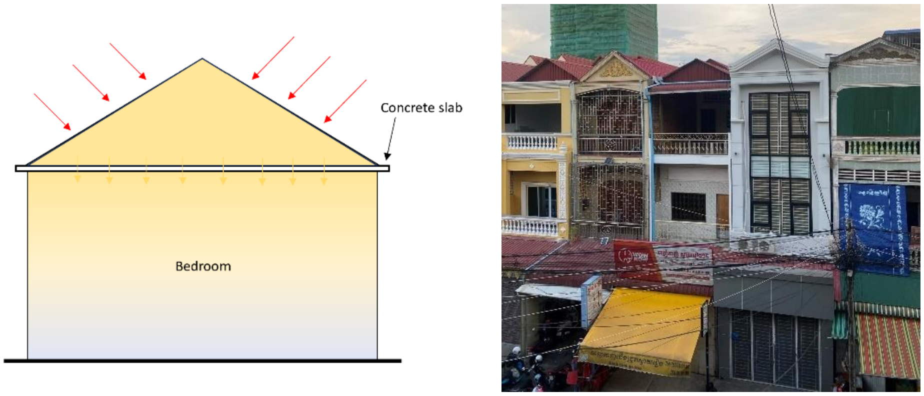


Figure 4-35: Example of house design with a gable roof that transforms into a heat box.

On the other hand, the design of detached houses in gated communities, which is the case for D1 seems to have an overall better design for comfort. However, it still lacks the surrounding green space and normally overlooks the integration of shading devices. Creating a more pleasant surrounding environment that could benefit a microclimate for the building doesn't seem to be on the agenda of developers of these gated communities.

The design of studio apartments which is the most popular dwelling option for students and young workers (the case of A1) possesses the most issues in terms of a comfortable living environment. Green spaces and parking spaces weren't normally made accessible for this type of accommodation. The design for studio apartments is generally made by the owner without consultation with architects. Hence, to maximize the use of land, building comfort wasn't a priority. This house typology is normally designed with an open corridor and the apartment attached between the corridor and the neighboring building. This design doesn't allow the space to have enough windows or sometimes no windows at all. In that case breeze bricks are installed for air circulation. The apartment surface is normally too small for its occupation and no exhaust fans are installed for indoor air quality. The security and privacy design for studio apartments are also quite low.

Overall, the design the design the house doesn't respond to the hot and humidity conditions and the living lifestyle of Cambodia which of course explains its weak thermal performance. The current house design outlines problems in all design aspects starting from surrounding environments to floor plan design to envelope design. This design flaw necessitates a reevaluation of architectural strategies to improve ventilation, create a surrounding microclimate, and reduce solar gain while maintaining natural light, ventilation, and overall indoor thermal comfort improvements.

4.10 Chapter Conclusion

In this chapter, we take a look into the thermal performance of common house typology in the urban area of Cambodia. The building's indoor climate usually follows the outdoor weather conditions. Even with two significant seasons, the impact of these seasons isn't high on building thermal performance. The poorly designed houses result in weak thermal performance for both dry and rainy seasons. The temperature in these houses is relatively higher than acceptable for comfort standards. The high humidity causes even more discomfort in these houses. The design trend of current houses also wasn't accommodating the natural ventilation which is a potential factor to help improve the comfort level. Occupants have no choice but to resort to using pedestal fans and air conditioners to improve their indoor environment quality. Several house design issues are noticed in different house typologies from the monitoring and occupant interview results, giving a potential resource to develop a bioclimatic design guideline that is suitable for the climate and living conditions of Cambodia.

We are able to identify the comfort and discomfort value of influenced parameters that could be a useful finding for another research study on the same topic. An adaptive comfort model for PMV calculation is also a valuable finding that will be an input for the simplified method which will be presented in Chapter 6.

All the findings above led us to reflect on design strategies and methods that can be used to assist architects in improving the thermal performance of the building during the design process.

CHAPTER 5

BIM MODEL AND BPS FOR ANALYSIS BUILDING THERMAL PERFORMANCE

This chapter explores the efficacy of BIM and BPS in analyzing thermal comfort within buildings. A BIM model will be developed for each case study building using Revit, followed by thermal performance simulations conducted in DesignBuilder. A calibration model will be employed to ensure the accuracy of the simulation results by aligning them closely with measured data.

The author's experiences with BIM and BPS methodologies will be critically analyzed to assess their effectiveness in evaluating building thermal performance. Additionally, their potential as decision support tools during the architectural design process will be examined.

5.1 Building Performance Simulation

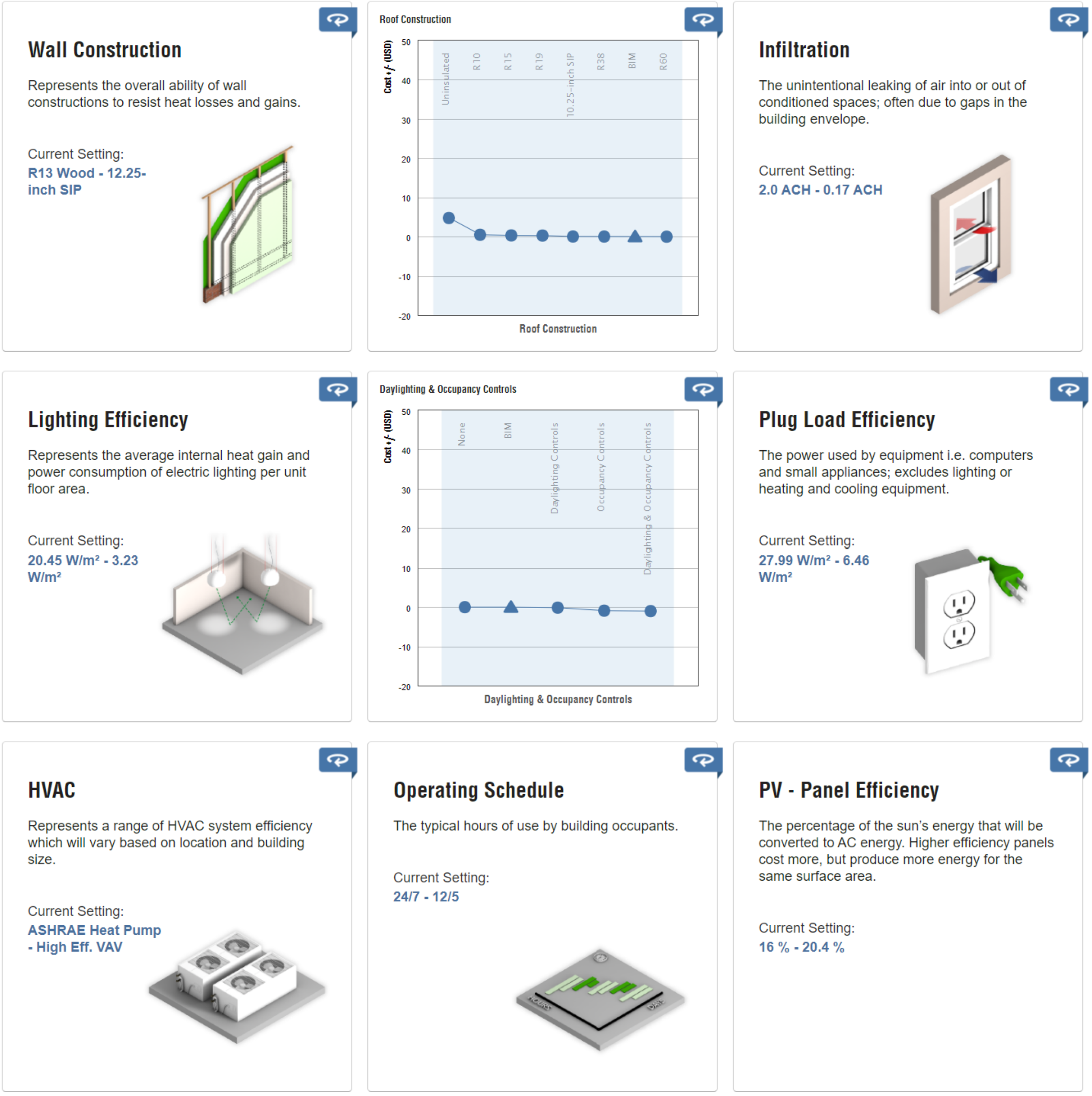
The BPS is a method used to analyze building thermal performance for new-built buildings. It can predict the building's thermal performance for various design criteria. In a way, it works as a decision support tool for architects and designers regarding building design strategies and the application of active system (Østergård et al., 2016). For our study, the role of BPS is to validate the effectiveness of the proposed bioclimatic design guidelines, which you will see in Chapter 7, and to investigate its efficiency as a tool for decision support during the design process for the context of Cambodia.

As BIM starts to integrate more and more into the design world, we would like to do BPS using the BIM model. The author, an architect, put herself as a test subject for 3 energy software that works with the BIM model. The chosen software is Revit Energy Analysis link with Insight, Green Building Studio, and DesignBuilder. Two of the three engines are very similar to each other as a quick analysis tool developed by Autodesk. DesignBuilder is a BPS tool with more complete output data for building thermal performance. For this study, we don’t intend to validate the potential of each tool, rather, we aim to identify what would be the most suitable tool for practical use in the context of Cambodia.

5.1.1 Revit Energy Analysis – Insight

Revit energy analysis (REA) is the first tool used to do the simulation of building performance. It is a plugin in Revit that can transform the BIM model to a gbXML file and then link with Insight to simulate the building energy performance. We decided to test this tool first, as it can be directly simulated using the BIM model within the same modeling software. The BIM model already contains the thermal properties of the building material and then was generated to be an energy model by adding a few parameters related to energy such as building location, occupancy, HVAC system, and the type of building.

The results that we receive from Insight, which is a simulation engine combined with the REA focus solely on the energy consumption of the building. The data that we received from the building analysis gave an insight into the energy consumption of building elements such as wall window ratio (WWR), wall material, window glazing, window shading, roof construction, and the active system such as the HVAC system. In this result, Insight also proposes design alternative criteria to reduce energy consumption, e.g., construction material, building orientation, and installation of solar panels... as seen in Figure 5-1. The final result focuses on calculating the cost of energy consumption for example in the case of house T2, the annual energy consumption cost is 42USD/m^2/year.



Wall Construction

Represents the overall ability of wall constructions to resist heat losses and gains.

Current Setting:
R13 Wood - 12.25-inch SIP

Infiltration

The unintentional leaking of air into or out of conditioned spaces; often due to gaps in the building envelope.

Current Setting:
2.0 ACH - 0.17 ACH

Lighting Efficiency

Represents the average internal heat gain and power consumption of electric lighting per unit floor area.

Current Setting:
20.45 W/m² - 3.23 W/m²

Plug Load Efficiency

The power used by equipment i.e. computers and small appliances; excludes lighting or heating and cooling equipment.

Current Setting:
27.99 W/m² - 6.46 W/m²

HVAC

Represents a range of HVAC system efficiency which will vary based on location and building size.

Current Setting:
ASHRAE Heat Pump - High Eff. VAV

Operating Schedule

The typical hours of use by building occupants.

Current Setting:
24/7 - 12/5

PV - Panel Efficiency

The percentage of the sun's energy that will be converted to AC energy. Higher efficiency panels cost more, but produce more energy for the same surface area.

Current Setting:
16 % - 20.4 %

Figure 5-1: Result from REA and Insight for house T2.

The result from Insight is useful for the case of new building design and renovation projects where the architect aims to explore various materials and make minor design adjustments, such as changes in shading elements or building orientation. Additionally, since simulations can be conducted directly within Revit, Insight significantly reduces the time required for each simulation when modifications are made to the building design.

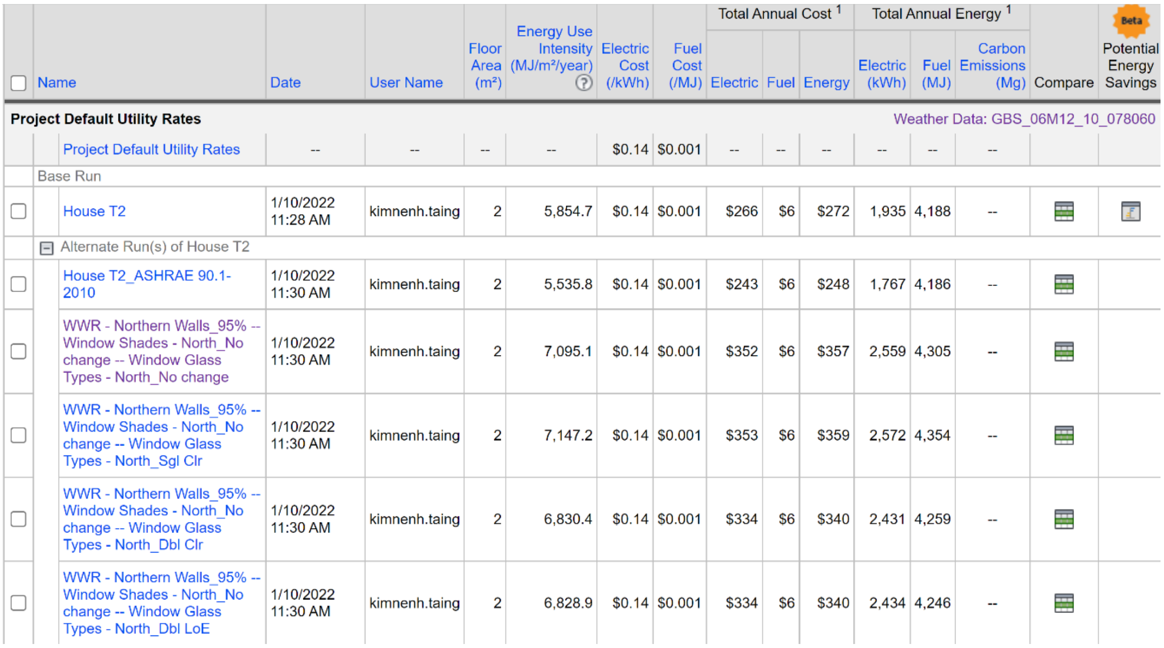
However, the result given as energy cost is hard to analyze as the energy price is different from one country to another. The alternative design options proposed in the results are also limited, as the construction materials or design criteria suggested by the software may not be available or may be restricted to certain locations. Furthermore, the total energy consumption cost provided by the software combines the energy required for heating, cooling, lighting, and hot water, making it difficult for architects to analyze building performance or design criteria based on this result. Consequently, identifying effective design modifications can be challenging when relying on such aggregated data.

While energy consumption data can be used to predict the overall energy performance of the building, it is not suitable for model calibration when assessing building thermal performance, particularly in the context of this study. For calibration purposes, we consider air temperature data from measurements to be more accurate and reliable for model comparison. Since our study goal is to achieve the highest possible accuracy in model calibration, using energy consumption data alone is inadequate. Consequently, Green Building Studio, another Autodesk platform is tested.

5.1.2 Green Building Studio

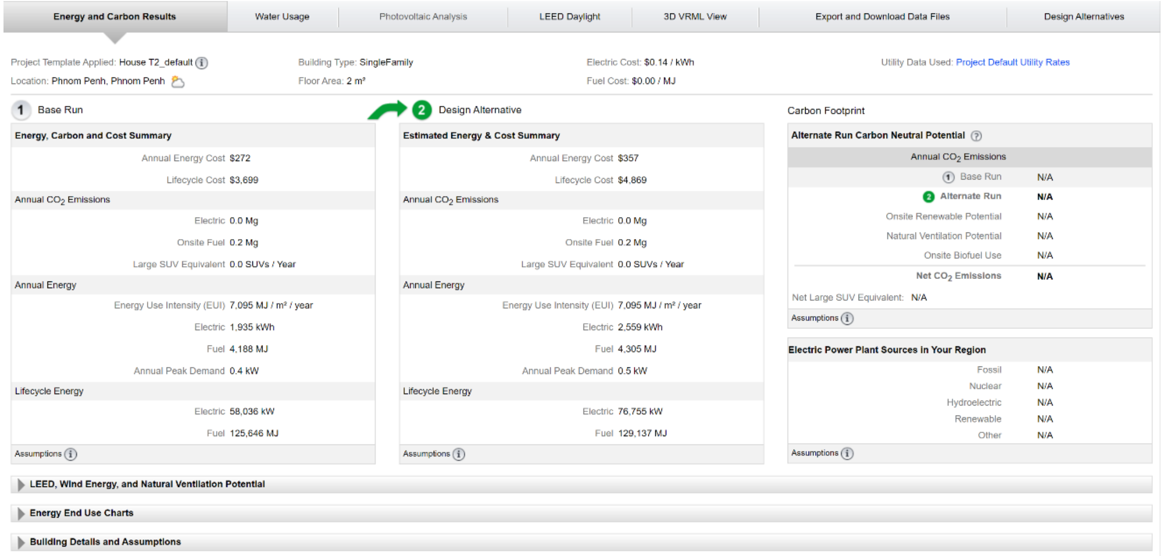
Green Building Studio (GBS) is an Autodesk cloud-based building performance analysis platform that uses DOE-2 simulation engine to provide energy use, water use, and carbon emission results. In GBS, the analytical model (gbXML) generated from the BIM model in Revit can be used to simulate building performance. Similar to Insight, the result we receive also focuses on total annual energy consumption as seen in Figure 5-2. GBS also provides many design alternatives related to wall window ratio (shade, orientation, size, and material), building orientation, material of building envelope, air infiltration, lightning, HVAC system, operating schedule…

Compared to Insight, GBS offers deeper insights into each design alternative proposed by the tool. For each alternative, GBS provides detailed simulation results related to energy, carbon footprint, water usage, photovoltaic potential, and LEED analysis, as illustrated in Figure 5-3. Additionally, users can customize these design alternatives directly within the platform. While Insight and GBS share many similarities, likely due to their common development origins, GBS extends its capabilities further by offering more comprehensive building performance analysis and green building certification support. Furthermore, its ability to work directly with BIM models and provide customizable design options makes it an effective decision support tool in the early design phase. However, for our study, the results from GBS are not suitable for ensuring that the BIM and BEM models created are well-calibrated, which is why it has not been selected as our simulation tool.



☐	Name	Date	User Name	Floor Area (m²)	Energy Use Intensity (MJ/m²/year) ⓘ	Electric Cost (/kWh)	Fuel Cost (/MJ)	Total Annual Cost [1]			Total Annual Energy [1]			Compare	Beta Potential Energy Savings
								Electric	Fuel	Energy	Electric (kWh)	Fuel (MJ)	Carbon Emissions (Mg)		
Project Default Utility Rates															Weather Data: GBS_06M12_10_078060
	Project Default Utility Rates	--	--	--	--	$0.14	$0.001	--	--	--	--	--	--		
Base Run															
☐	House T2	1/10/2022 11:28 AM	kimnenh.taing	2	5,854.7	$0.14	$0.001	$266	$6	$272	1,935	4,188	--	▦	▦
⊟ Alternate Run(s) of House T2															
☐	House T2_ASHRAE 90.1-2010	1/10/2022 11:30 AM	kimnenh.taing	2	5,535.8	$0.14	$0.001	$243	$6	$248	1,767	4,186	--	▦	
☐	WWR - Northern Walls_95% -- Window Shades - North_No change -- Window Glass Types - North_No change	1/10/2022 11:30 AM	kimnenh.taing	2	7,095.1	$0.14	$0.001	$352	$6	$357	2,559	4,305	--	▦	
☐	WWR - Northern Walls_95% -- Window Shades - North_No change -- Window Glass Types - North_Sgl Clr	1/10/2022 11:30 AM	kimnenh.taing	2	7,147.2	$0.14	$0.001	$353	$6	$359	2,572	4,354	--	▦	
☐	WWR - Northern Walls_95% -- Window Shades - North_No change -- Window Glass Types - North_Dbl Clr	1/10/2022 11:30 AM	kimnenh.taing	2	6,830.4	$0.14	$0.001	$334	$6	$340	2,431	4,259	--	▦	
☐	WWR - Northern Walls_95% -- Window Shades - North_No change -- Window Glass Types - North_Dbl LoE	1/10/2022 11:30 AM	kimnenh.taing	2	6,828.9	$0.14	$0.001	$334	$6	$340	2,434	4,246	--	▦	

Figure 5-2: GBS result of T2.



Project Template Applied: House T2_default ⓘ
Location: Phnom Penh, Phnom Penh
Building Type: SingleFamily
Floor Area: 2 m²
Electric Cost: $0.14 / kWh
Fuel Cost: $0.00 / MJ
Utility Data Used: Project Default Utility Rates

① Base Run

Energy, Carbon and Cost Summary

Annual Energy Cost	$272
Lifecycle Cost	$3,699
Annual CO_2 Emissions	
Electric	0.0 Mg
Onsite Fuel	0.2 Mg
Large SUV Equivalent	0.0 SUVs / Year
Annual Energy	
Energy Use Intensity (EUI)	7,095 MJ / m² / year
Electric	1,935 kWh
Fuel	4,188 MJ
Annual Peak Demand	0.4 kW
Lifecycle Energy	
Electric	58,036 kW
Fuel	125,646 MJ

Assumptions ⓘ

② Design Alternative

Estimated Energy & Cost Summary

Annual Energy Cost	$357
Lifecycle Cost	$4,869
Annual CO_2 Emissions	
Electric	0.0 Mg
Onsite Fuel	0.2 Mg
Large SUV Equivalent	0.0 SUVs / Year
Annual Energy	
Energy Use Intensity (EUI)	7,095 MJ / m² / year
Electric	2,559 kWh
Fuel	4,305 MJ
Annual Peak Demand	0.5 kW
Lifecycle Energy	
Electric	76,755 kW
Fuel	129,137 MJ

Assumptions ⓘ

Carbon Footprint

Alternate Run Carbon Neutral Potential ⓘ

Annual CO_2 Emissions	
① Base Run	N/A
② Alternate Run	**N/A**
Onsite Renewable Potential	N/A
Natural Ventilation Potential	N/A
Onsite Biofuel Use	N/A
Net CO_2 Emissions	**N/A**

Net Large SUV Equivalent: N/A

Assumptions ⓘ

Electric Power Plant Sources in Your Region

Fossil	N/A
Nuclear	N/A
Hydroelectric	N/A
Renewable	N/A
Other	N/A

Assumptions ⓘ

LEED, Wind Energy, and Natural Ventilation Potential

Energy End Use Charts

Building Details and Assumptions

Figure 5-3: GBS alternative design result.

5.1.3 DesignBuilder

DesignBuilder is an energy simulation software developed in the UK using the Energy Plus simulation engine to perform analysis including energy and comfort, HVAC, daylighting, cost, design optimization, CFD, BREEAM/LEED credits... The software is popular among researchers in building performance as it provides detailed results of parameters related to factors such as temperature, relative humidity, PMV, etc. More than that the software can model the building directly in the software or import a BIM model (gbXML) to conduct the simulation. In this software, the result can be simulated annually, monthly, or hourly which compelling with the data that we have from the measurement facilitates the calibration process. In terms of input parameters such as weather data, the software provides:

- Location-Specific Weather Data: The software has a built-in library of weather data limited to specific locations. This likely means it provides pre-loaded weather information for various geographic regions, which can be used directly in simulations.
- Custom Weather Data Input: Despite the location-specific of the built-in weather data, the software allows users to input their weather data. This is particularly useful if users have measured or obtained weather data independently, enabling them to perform simulations with more accurate or localized information.

This flexibility is beneficial for users who need to run simulations in locations that are not covered by the software's library or who require more precise data than what the default library offers for model calibration. More than that, the result from simulation in DesignBuilder, as hourly temperature or relative humidity, is easy to use for the model calibration using the hourly data that we have from the measurement.

Due to its ability to work with BIM models, its accessible weather data input, and the quality of results it provides, DesignBuilder has proven to be the most suitable tool for conducting simulations of case study buildings in our research.

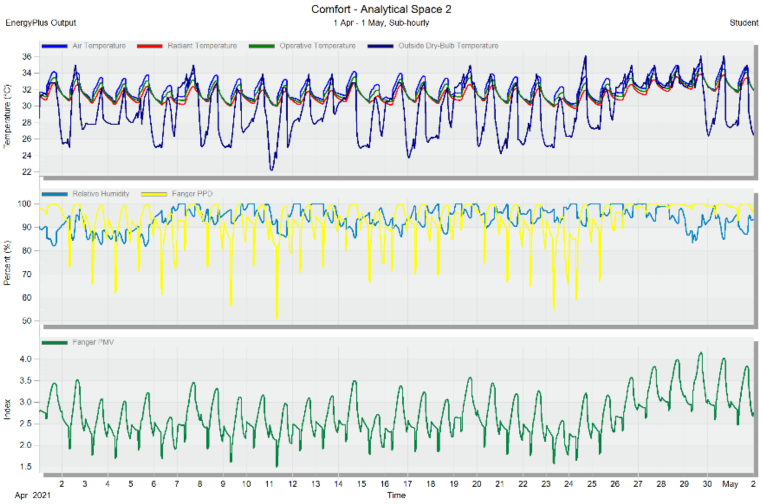


Figure 5-4: Result received from the DesignBuilder for thermal comfort parameters.

5.2 BIM to BEM Model

Out of 5 case study buildings, we chose 3 buildings to continue with the BIM model which are T2, D1, and A1. As T1 and T2, A1 and A2 are in the same category of residential buildings. We chose T2 as it was built more recently than T1 and also is the typical Borey House that is popularized these days. Since A2 was unoccupied during the measurement period and we lacked access to the building's full floor plan, we chose A1 instead to enable a more accurate analysis of thermal performance in the simulation compared to the measurement results.

The BIM model is created in the software Revit. With Revit, a 3D model can be generated directly when the 2D plan is finished. Parameters such as geometric data of the building and construction materials are included in the 3D model to make a BIM model. In the same software, we create an analytical model by adding the location of the building, building type, and operating schedule. The analytical model already has different thermal zones. For Insight this model can be directly used to do the simulation. In our case, this model is later exported as a gbXML file keeping necessary information from the BIM model to conduct thermal performance simulation. This file is imported into DesignBuilder to create a complete energy model by adding a few more parameters as shown in Figure 5-5.

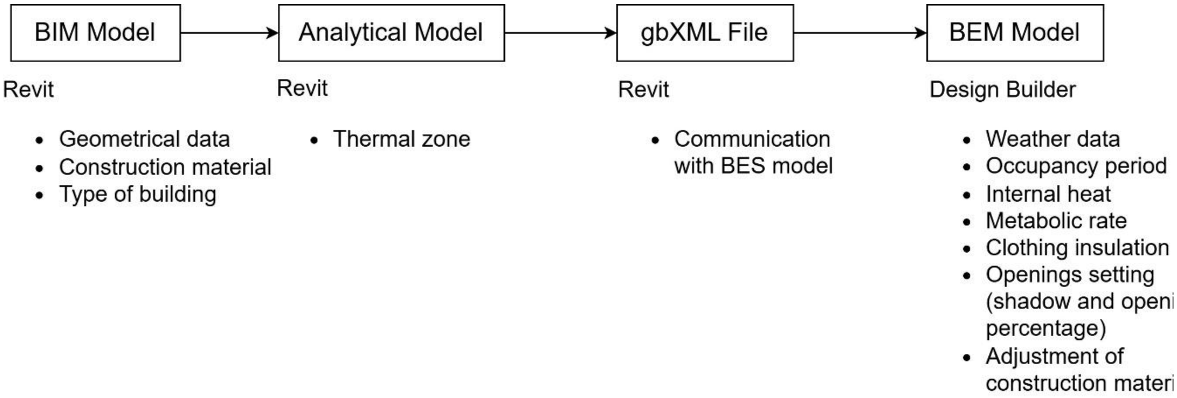


Figure 5-5: Schema evolution from BIM model to BEM model.

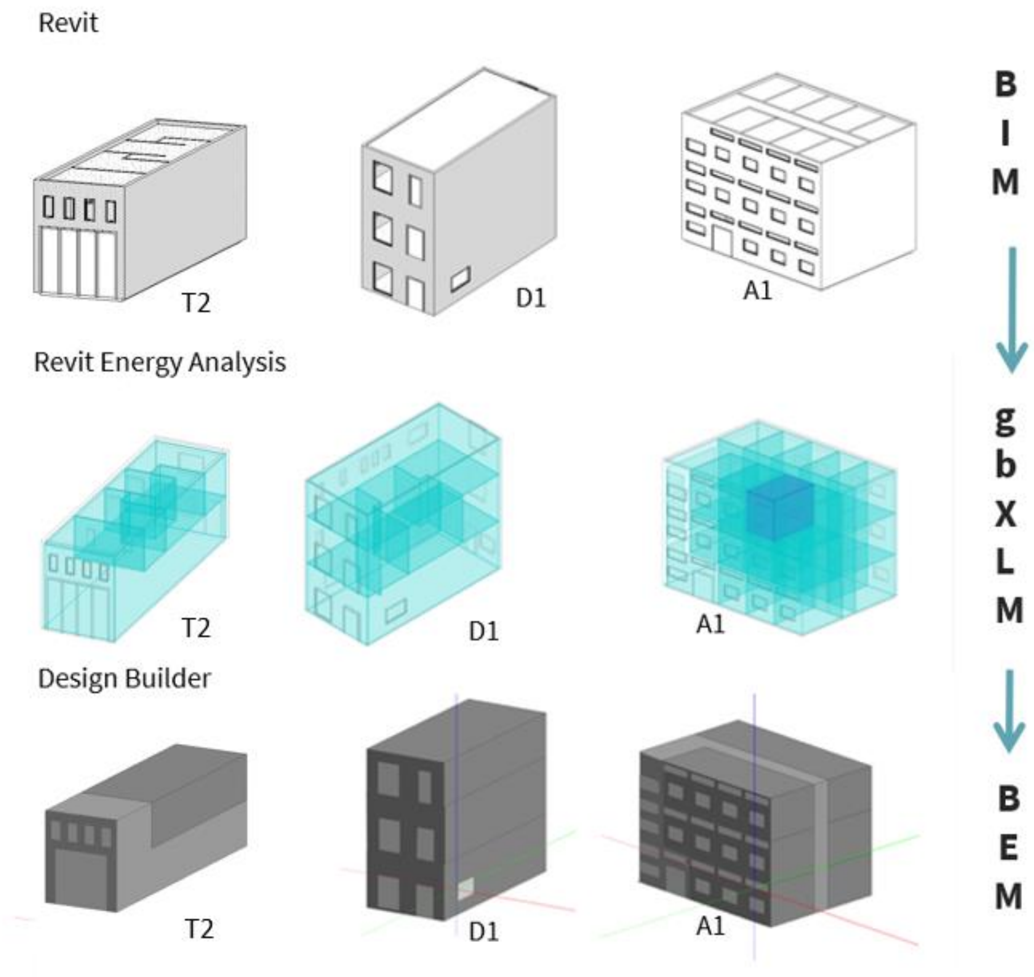


Figure 5-6: From BIM model in Revit to BEM in DesignBuilder.

5.3 Simulation and Calibration

For existing buildings, simulation data can be used to analyze the whole year of building thermal performance to reduce the amount of in-situ measurement. These simulation data, however, can vary from the real-time data due to faults in data input or building modeling inaccuracy. The calibration method of the numerical model is recognized as an important factor in defining the accuracy of the simulation result. In this case, the measurement data from the case study building is compared to the simulation result after calibrating to see how accurate the simulation model is.

Calibration can be performed for multiple runs to receive simulation data as close to the measurement data as possible. The procedure of calibration goes through several stages. First, the site location of specific weather data needs to be collected to ensure an accurate weather data input. The collected weather data is then joined into a single data file that is suitable for the simulation engine and then put into the weather tape. For our case, the weather data that we use is from OneBuilding which derived data from NOAA (National Oceanic and Atmospheric Administration). Weather data in NOAA are derived from the weather station located at Phnom Penh International Airport. Second, the building model needs to be loaded into the simulation software. In this case, the input building numerical model is already completed in Revit based on information collected from the site visit and the as-built architectural plan. The simulation results are then compared with the measurements. During the calibration run, uncertain input parameters or variables can be modified including building physical properties, material thermal properties, occupancy schedule, opening control, HVAC system… The simulation is considered calibrated when the residual from the simulation result reaches an acceptable range defined by some standard such as ASHRAE.

According to ASHRAE, a statical approach using two statical indicators - Normalized Mean Bias Error (NMBE) and Coefficient of Variation of Root Square Mean Error CV(RMSE) are used to verify the calibration. These two indicators can be defined as below:

NMBE (Normalized Mean Bias Error):

$$NMBE\ (\%) = \frac{\sum_{i=1}^{n}(t_{im}-t_{is})}{(n-1)\overline{t_m}} \times 100 \qquad \text{Eq. 5-1}$$

CV(RMSE) (Coefficient of Variation of Root Square Mean Error):

$$CV(RMSE)(\%) = \sqrt{\frac{\sum_{i=1}^{n}(t_{im}-t_{is})^2}{(n-1)\overline{t_m}}} \times 100 \qquad \text{Eq. 5-2}$$

Where t_{im} is the measurement temperature at i-hour, t_{is} is the simulation temperature at i-hour, t_m is the average value from the measurement temperature and n is the total number of data.

NMBE measures the average deviation between the simulated and actual data, normalized by the actual data. It reveals whether the simulation systematically overpredicts or underpredicts the outcomes. A high NMBE suggests a significant systematic bias in the model, potentially due to errors in input data or assumptions. For instance, incorrect weather data, inaccurate equipment schedules, or faulty energy consumption profiles might lead to such bias. CV(RMSE) assesses the dispersion of simulation errors relative to the mean of the actual data. It gives a sense of how well the simulation model captures the variability of the actual performance. A low CV(RMSE) indicates that the model's predictions are closely aligned with the actual data, implying high accuracy in the variability aspect. A simulation showing a low CV(RMSE) but a high NMBE might suggest that while the model closely matches the pattern of actual performance (low variability), it consistently overestimates or underestimates the values (high bias). This could be a sign of issues with the input data or systematic errors in the model setup. Conversely, a simulation with a high CV(RMSE) and a low NMBE means the model does not exhibit significant bias (low NMBE), but the predictions are not consistently close to the actual values (high variability). This situation might arise when the inputs are accurate, however, the model fails to capture the full range of real-world influences, such as varying occupant behavior, which is difficult to simulate precisely (Claridge, 2003).

According to ASHRAE an acceptable calibrated model for hourly simulation has to have a value of NMBE smaller than 10% and CVRSME smaller than 30% (ASHRAE, 2014). In this study, a linear regression model was also used alongside these two indicators to enhance the reliability of the calibration.

5.3.1 Calibration of Link House (T2)

The measurement data of temperature is used for calibration purposes. The BIM model imported into DesignBuilder is verified for geometry errors and material thermal properties. Some imported material is correct, and some are made for adjustment. Using temperature data from the living room is quite challenging for the calibration as the occupancy period can be varied and the control of the openings is random. For future studies, calibration using data from the bedroom would be easier as those two factors are more constant. The calibration starts from run #1. In reality, the calibration runs took around 20 trials and errors and took about 45 hours. However, some run results weren’t significant or didn’t have any change at all. Therefore, only the 5 most significant runs are presented. Table 5-1 presents the trial and errors of calibration run from start to final calibration indicating adjustments made in each trial and what was noticed from this adjustment, along with the improved CV(RSME) and NMBE as it gets closer to zero.

Table 5-1: Calibration runs for house T2.

Run	CV(RSME) (%)	NMBE (%)	Input parameter adjustment	Result observed
#1	6.5	3.74	Use import material from the BIM model	The temperature variation is large and the overall temperature is lower than the measurement
#2	4.16	2.71	- Verify and re-input the material properties - Turn on equipment power density to 0.004 w/m^2, scheduled for 24/7	The temperature variation is smaller but the overall temperature is still low
#3	3.55	2.21	- Change equipment power density to 1W/m^2 - Open only 50% of openings	The nighttime temperature rises higher, the daytime stay almost the same
#4	3.28	-1.14	- Change equipment schedule to 8h-18h every day	The temperature during the daytime rises too high
#5	2.33	-0.13	- Change the equipment power density to 0.05 W/m2	The daytime temperature is a bit lower and closer to the measurement

In run#1, the BEM model is imported into DesignBuilder and directly simulated keeping the material that was input in the BIM model and with some parameter input in the activities panel. We can see that the interoperability between the BIM model and the BEM model is very poor in our case, as all the input material in the BIM model was imported into something else. For example: the wall layer is input as 3 layers in the BIM model in Revit and turns out to be 5 layers in the BEM model in DesignBuilder. Similar cases are seen for the roof and floor. After changing the material properties, we can see the simulation result stays in a similar range as the measurement, and the CV(RSME) is getting lower. We can notice the improvement of simulation results with adjustment of input parameters from calibration run #1 to run #5. Figure 5-8 compare the simulation temperature of run#1 and run#5 to the measurement. Another method used to calibrate the model is linear regression analysis which is presented in Figure 5-7 where we can graphically assess the accuracy and correlation of the model.

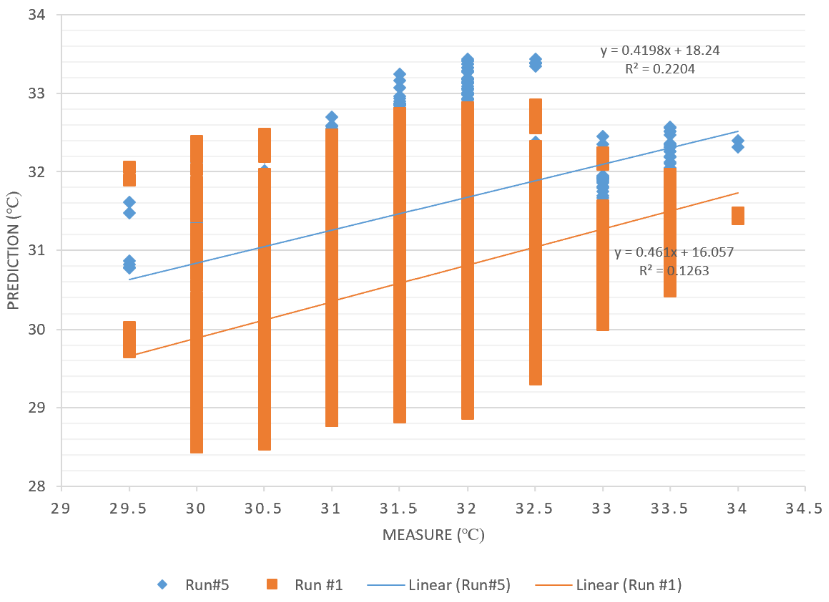


Figure 5-7: Linear regression analysis of run #1 vs run #5 for house T2

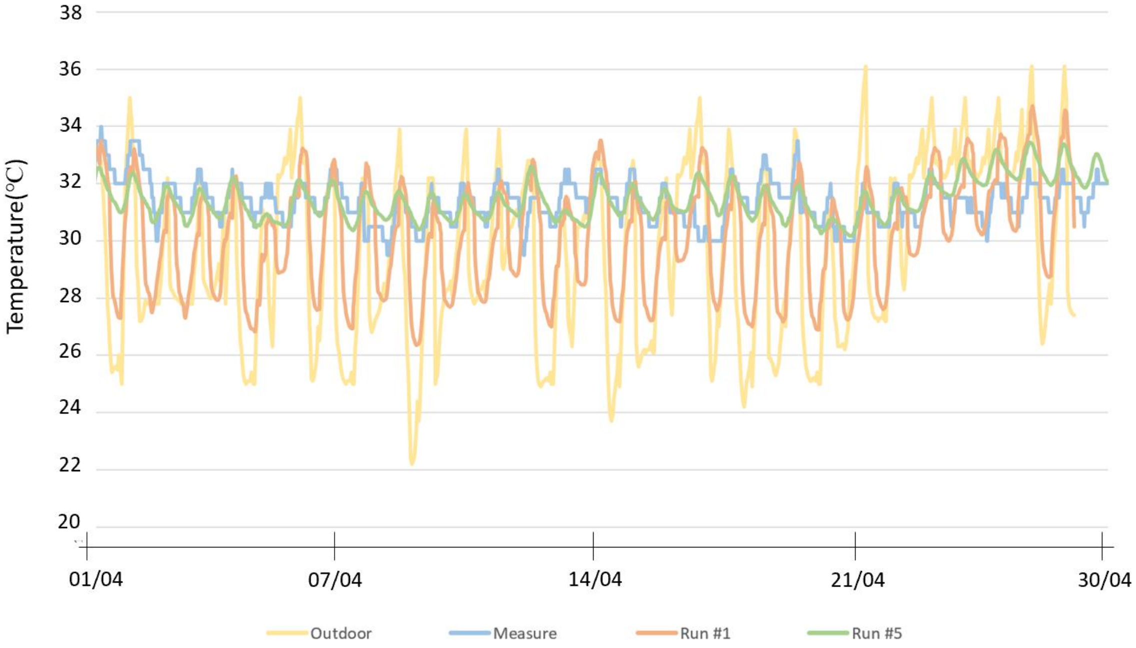


Figure 5-8: Measurement temperature and simulation temperature after calibration for house T2

Both statical indices and the linear regression analysis show the improvement of the numerical model from run#1 to run#5. The statical indices are in the acceptance range as per the standard of ASHRAE. However, the linear regression analysis shows an R^2 of 0.24 and a slope of 1.18 which is way too low compared to the acceptable range recommended by AHSRAE (2009) (R^2 of 0.9 or greater, slope between 0.75 and 1.25). This indicates that the calibration isn't well correlated with the measurement. Although the R^2 value is low, the acceptable results from two statistical indices indicate that the numerical model neither overestimates nor underestimates real-time values, demonstrating its reliability. Based on the value of NMBE and CV(RSME), this model can be considered calibrated per ASHARE standard. However, the low value of R^2 demonstrates that the model shouldn't be used to predict building thermal performance or assess thermal comfort in real-time. Nevertheless, it can still be utilized for further simulations, such as comparing the impact of different design scenarios on thermal performance, which is the primary objective of our study. Table 5-2 presents all input parameters for the final calibration run.

Table 5-2: Input parameters for simulation of house T2 in final calibration.

Categories	Input model	Value
Construction	External wall Partition wall Roof Floor Airtightness Schedule	U value = 2.1(W/m^2K) U value = 2.9 (W/m^2K) U value = 5.3 (W/m^2K) U value = 2.92 (W/m^2K) Model filtration: 0.7 (ac/h) 24/7
Activities	Household size Building surface Density Occupancy schedule Summer clothing Metabolism level Computers	4 100 m^2 0.04 person/m^2 8h00-18h00 everyday 0.5 clo 0.85 met 0.05 (W/m^2)
Opening	U value Total solar transmission Light transmission	5.89 (W/m^2K) 0.72 0.68
Lightning	Normalized power density Schedule	5 (W/m2-100lux) 8h00-18h00 everyday
HVAC	Mechanical ventilation DHW Heating Cooling Natural ventilation	No No No No 8h00-18h00 everyday

Using the input parameters in the table above, we simulated the relative humidity of the space. The result shows a higher value of statistic indices than the temperature with NMBE of -12.87 which is a bit higher than the ASHRAE standard. However, the CV(MSE) is in the standard of ASHRAE with a value of 16.77. The relative humidity from the simulation is generally higher than the measurement. This could be due to random occupancy during the daytime, the use of pedestal fans that can’t be input in the BEM model, and absorption by the wall material and wood furniture. The higher difference is noted during the nighttime when the room is unoccupied and outdoor temperatures drop. Even though we set the occupancy in the space to be only during the daytime, the model doesn’t seem to consider this factor during the simulation as we attempted to modify this factor multiple times, and the result is still the same. The variation of relative humidity depends on the activities in the space which is hard to input in the model, especially for a living room space where activities happen randomly. Relative humidity was proven in the previous chapter to be not as highly influence on thermal comfort as temperature for Cambodia. Therefore, the result of relative humidity from the simulation won’t be discussed in the later chapter and won’t be used to evaluate the thermal performance of buildings with the application of bioclimatic design strategies.

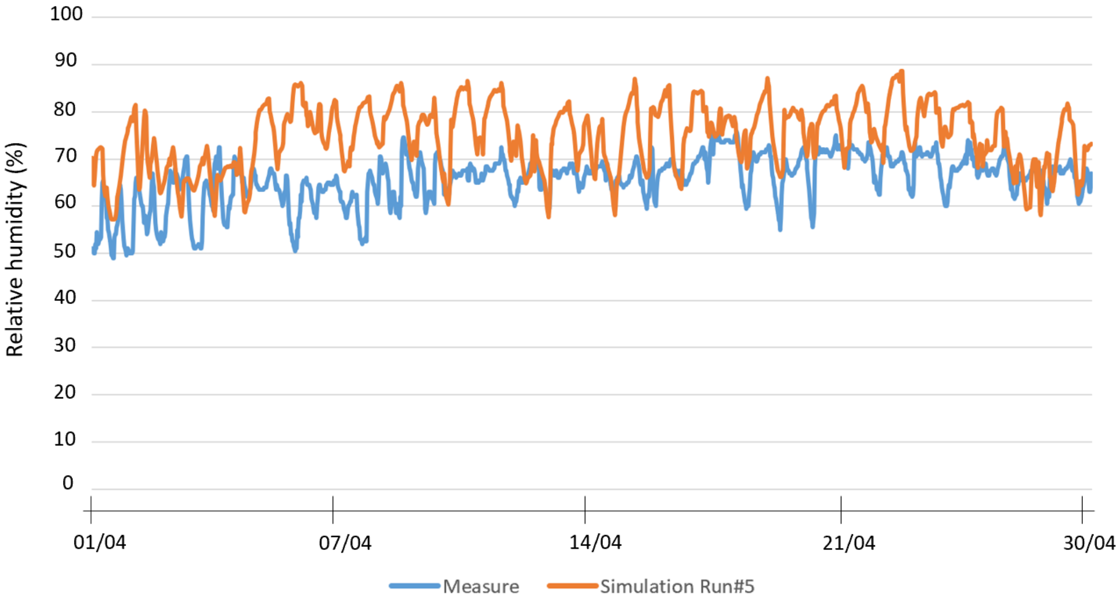


Figure 5-9: Relative humidity from measurement and simulation after calibration of house T2.

5.3.2 Calibration of Detached House (D1)

Temperature from the monitoring of the living room in D1 is chosen to conduct the calibration. Even though we already get the hang of using DesignBuilder from the calibration of T2, the calibration of D1 is much more challenging. As a detached house, even a slight change in the outdoor environment can impact the indoor thermal performance. More than that, during the monitoring period, the occupancy of house D1 was also not constant. The occupant randomly changed from 3 to 6 people. During the interview and site observation, we also noticed that the occupant behavior varies throughout the day in terms of opening windows which is a factor that is hard to define in the simulation. In reality, the calibration process took about 15 trials and errors and around 20 hours. Table 5-3 presents the summary of the 3 runs that show the most significant improvement of the result.

Table 5-3: Calibrations run for house D1

Run	CV(RSME) (%)	NMBE (%)	Input parameter/ adjustment	Result observed
#1	7.74	2.41	- Verify and re-input material property - Turn on equipment with a power density of 0.05W/m^2	The temperature variation is large, and it is either higher or lower than the measured
#2	5.76	1.61	- Turn off the equipment - Change occupation from 6 to 3 people - Change air tightness from 0.7 ac/h to 1ac/h	The temperature variation is smaller, the day temperature drops but the night temperature stays low
#3	4.86	0.94	- Turn on equipment with 0.004 W/m^2, schedule 24/7	The nighttime temperature rises higher

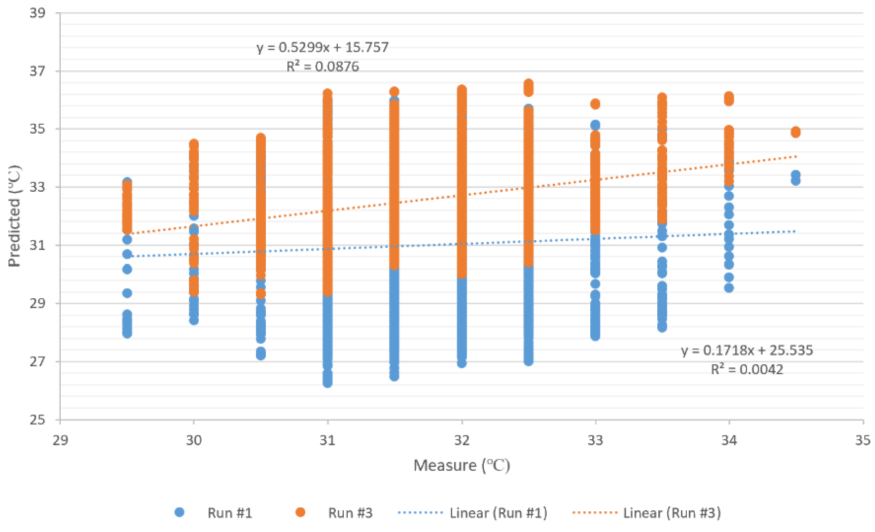


Figure 5-10: Linear regression analysis of run #1 vs run #3 for house D1.

Even though the calibration process for D1 is shorter than T2, the result for T2 is much better than D1. Of course, we can see the improvement from run #1 to run #3 but the linear regression analysis (R^2=0.08, slope 0.52) was much lower than the acceptable range for ASHRAE. However, further runs of the calibration don't show any improvement. Therefore, we decided to stop the calibration at run #3 where CV(RSME) and NMBE are the closest to zero. We notice the high CV(RSME) compared to NMBE which indicates that the model can't capture the random behavior change of the occupant (the random change of occupants, the control of openings functionality,…). Similar to the previous case, based on the ASHRAE standard, the model can be considered calibrated. However, with a value of R^2 even lower than T2, this model definitely shouldn't be used for analysis of the thermal performance of the actual building.

As in this study, the calibrated model is intended to be used for the comparison of the building before and after the application of bioclimatic design strategies and as the two statistical indices are in the acceptable standard by ASHRAE, this numerical model can still be used. Nevertheless, the analysis of the result from this model needs to be more cautious, especially during the last week of the simulation period where the difference between simulation and measurement temperature is high. Figure 5-11 illustrates the temperature of measurement and the calibration where we can see some correlations at the beginning of the month and more and more different towards the end. Table 5-4 presents the final input parameters for simulation run #3.

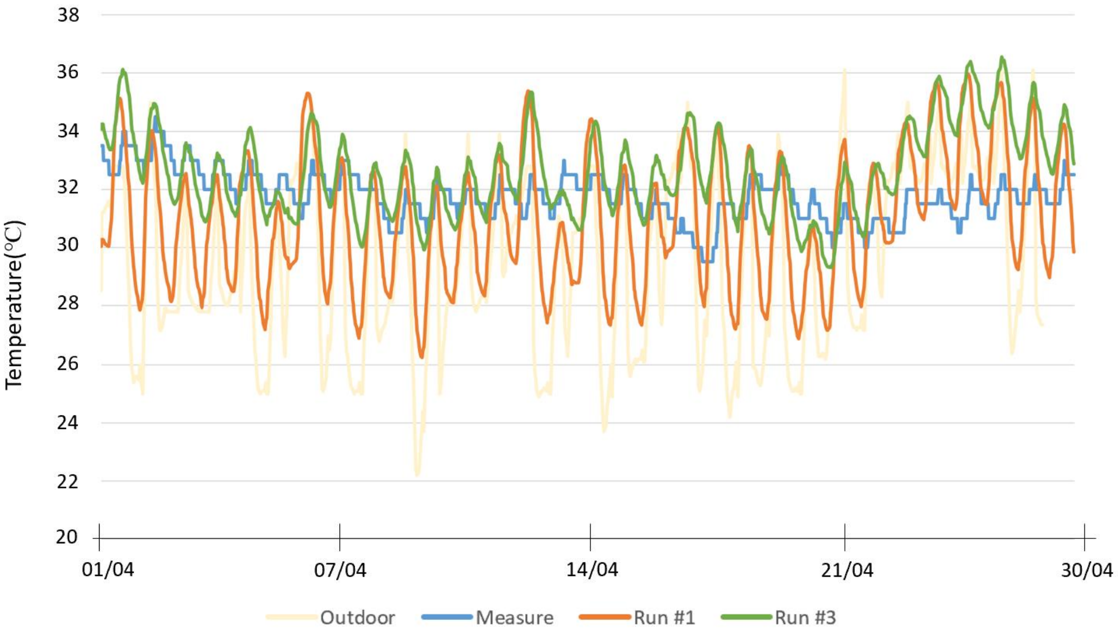


Figure 5-11: Measurement temperature and simulation temperature after calibration for house D1.

Table 5-4: Input parameters for simulation of house D1 in final calibration.

Categories	Input model	Value
Construction	External wall Partition wall Roof Floor Airtightness Schedule	U value = 2.1(W/m^{2}K) U value = 2.9 (W/m^{2}K) U value = 5.3 (W/m^{2}K) U value = 2.92 (W/m^{2}K) Model filtration: 1 (ac/h) 8h00-18h00 everyday
Activities	Household size Building surface Density Occupancy schedule Summer clothing Metabolism level Computers	3 236 m^2 0.012 person/m^2 24/7 0.5 clo 0.85 met 0.004 (W/m^2)
Opening	U value Total solar transmission Light transmission	5.77 (W/m^{2}K) 0.62 0.57
Lightning	Normalized power density Schedule	5 (W/m2-100lux) 8h00-18h00 everyday
HVAC	Mechanical ventilation DHW Heating Cooling Natural ventilation	No No No No 8h00-18h00 everyday

The simulation results for the relative humidity of D1 demonstrate improved statistical indices, with an NMBE of 10.03 and a CV(RMSE) of 4.3, both of which fall within the acceptable range of the ASHRAE standard. However, it is observed that the simulated relative humidity fluctuates more compared to the measured values, sometimes being either higher or lower than the actual measurements. This increased variability could be attributed to the influence of a fan, which may help maintain a more stable relative humidity in reality. Given the correlation between the simulated and measured data, we do not recommend using the results of relative humidity from this simulation for further analysis, despite the statistical indices being within acceptable limits.

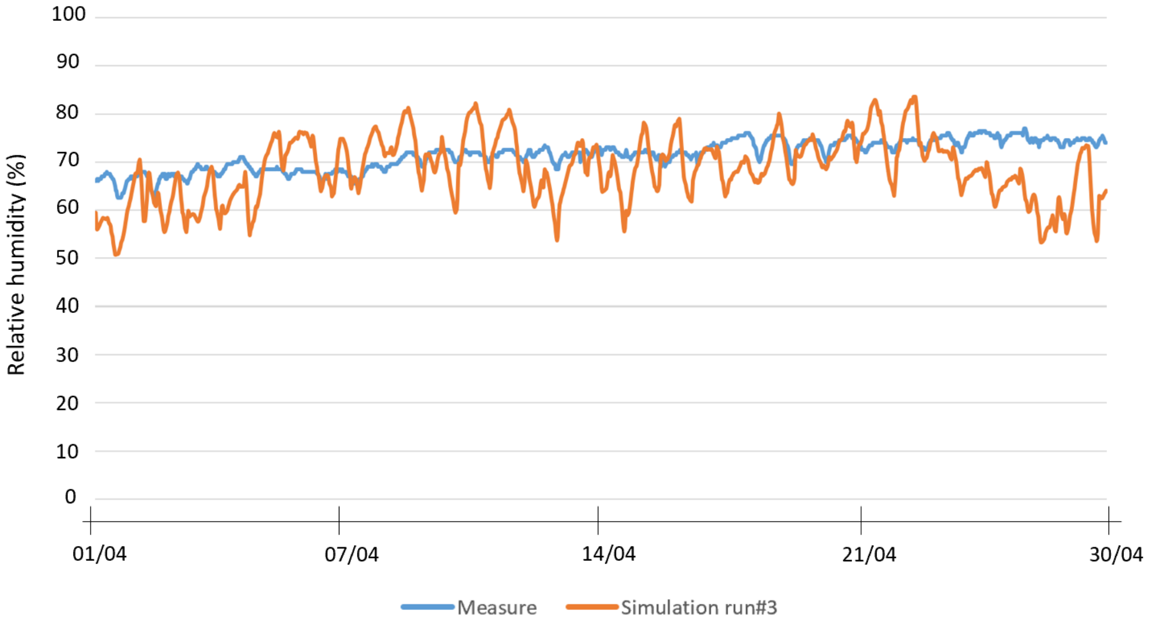


Figure 5-12: Relative humidity from measurement and simulation after calibration of house D1.

5.3.3 Calibration of Apartment (A1)

After the calibration of T2 and D1, we are able to identify certain input parameters that need to be adjusted, which could be helpful for the calibration of A1. For house A1, the occupant number is more constant than for house D1. However, the occupant behavior that could produce internal gain can't be defined easily. Given that this is a studio apartment, the occupant uses the space for multiple activities, including cooking and working. Additionally, the occupant is an architect who operates several computers, which generate significant heat. The occupant in house A1 works from home for most of the time. Therefore, the heat generated by the computers in the room likely fluctuated, especially when combined with the heat from cooking. These fluctuations in internal heat gains present challenges in accurately defining the input for internal gains, making it difficult to calibrate the simulation model effectively. Even though we already have some experience with the calibration from T2 and D1, the calibration of this house still presents a lot of difficulties. The calibration runs through 10 trials and errors in reality. Table 5-5 presents 3 runs with the most significant output.

Table 5-5: Calibrations run for house A1

Run	CV(RSME) (%)	NMBE (%)	Input parameter/ adjustment	Result observed
#1	9.07	-6.7	- Verify and re-input material property - Turn on equipment with a power density of 0.5 W/m^2	The variation is small and the overall temperature is higher compared to the measured
#2	8.68	-5.22	- 100% open for all openings - Schedule natural ventilation to 24/7	The variation is better, the nighttime temperature drops but the daytime temperature is still high
#3	7.24	-2.74	- Turn down equipment power density to 0.05 W/m^2	The daytime temperature drop

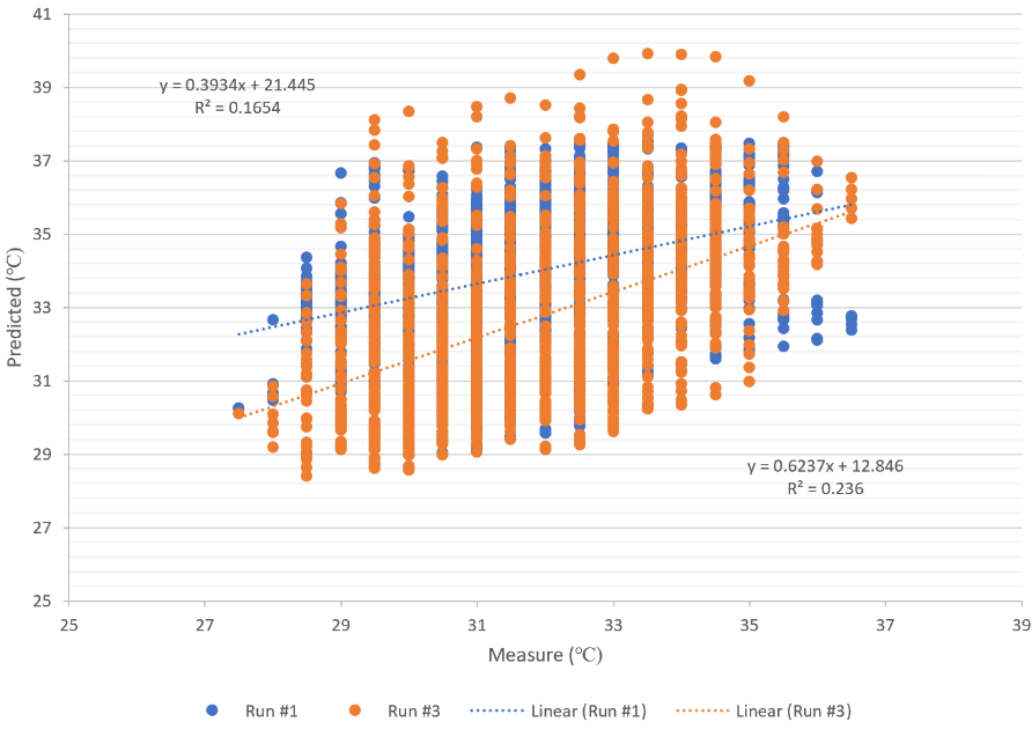


Figure 5-13: Linear regression analysis of run #1 vs run #3 for house A1.

Despite having the largest statistical indices compared to the other two buildings, the evolution of temperature between run#3 and measurement in Figure 5-14 seems to correlate well with an average error smaller than 3%. The linear regression also shows a similar value of R^2 and slope compared to house T2. Similar to house D1, more calibration runs don't seem to improve the two statistical indices and the value of R^2. Similar to T2, the numerical model doesn't duplicate the actual building, however as the CV(RMSE) and NMBE are in the acceptable range, the model can be used for further simulations but can't be used for prediction of actual building thermal performance.

Following the calibration of all three case study buildings, it appears that the difference between measured and simulated temperatures predominantly occurred during the final week, likely influenced by the outdoor temperature input, as this period showed elevated outdoor temperatures compared to previous weeks. Simulations consistently showed higher temperatures compared to measurements, possibly due to limitations in the model, which does not account for surrounding environmental factors. Additionally, during the measurement period, several holiday days coincided with a lockdown beginning mid-month. This may indicate that some occupants were away during this time, potentially visiting family over the holidays and remaining there during the lockdown, which would contribute to the lower recorded temperatures in the final week.

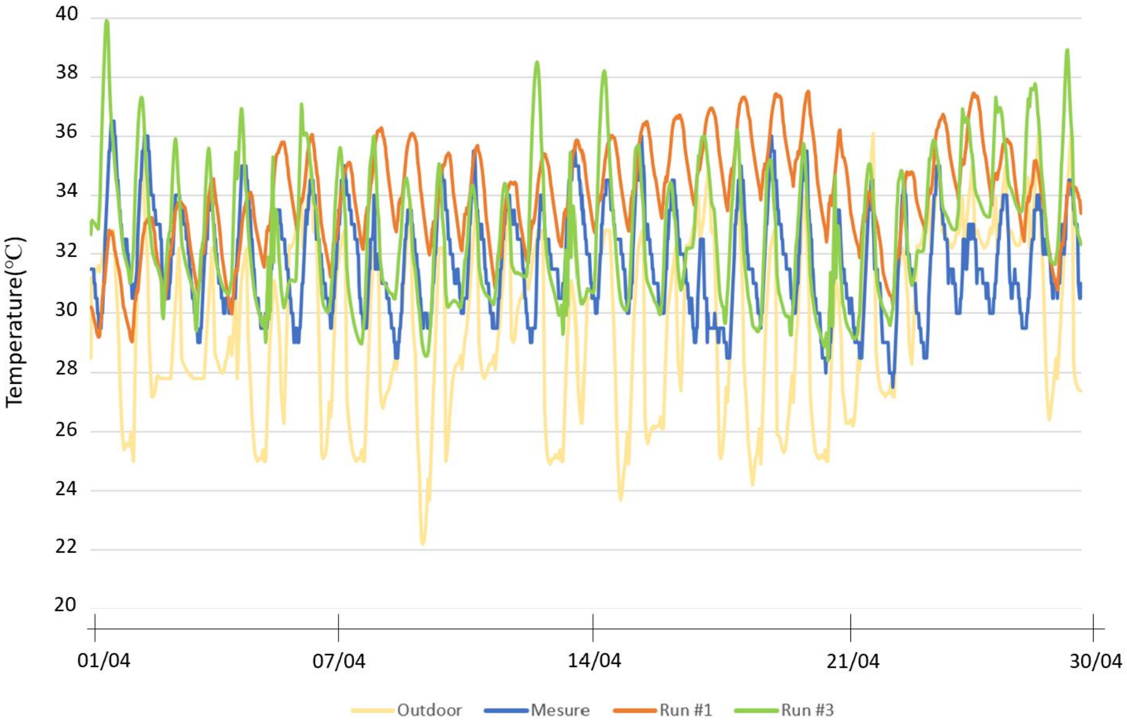


Figure 5-14: Measurement temperature and simulation temperature after calibration for house A1.

Table 5-6: Input parameters for simulation of house A1 in final calibration.

Categories	Input model	Value
Construction	External wall Partition wall Roof Floor Airtightness	U value = 2.1(W/m^2K) U value = 2.9 (W/m^2K) U value = 5.87 (W/m^2K) U value = 2.92 (W/m^2K) Model filtration: 0.7 (ac/h)
Activities	Household size Building surface Density Occupancy schedule Summer clothing Metabolism level Computers	3 per room 913.5 m^2 0.22 person/m^2 24/7 0.5 clo 0.85 met 0.05 W/m^2
Opening	U value Total solar transmission Light transmission	5.89 (W/m^2K) 0.72 0.68
Lightning	Normalized power density Schedule	5 (W/m2-100lux) 8h00-18h00 everyday
HVAC	Mechanical ventilation DHW Heating Cooling Natural ventilation	No No No No 24/7

The simulation results for the relative humidity of A1 show better performance compared to the other houses. The fixed occupancy pattern and the permanently open window in A1 likely contribute to this improved outcome. Nevertheless, the measured relative humidity remains lower than the simulated values, likely due to the effect of the pedestal fan. Despite this difference, the statistical indices indicate that the simulation results are acceptable, with an NMBE of -0.11 and a CV(RMSE) of 11.05, both of which fall within the standard of ASHRAE.

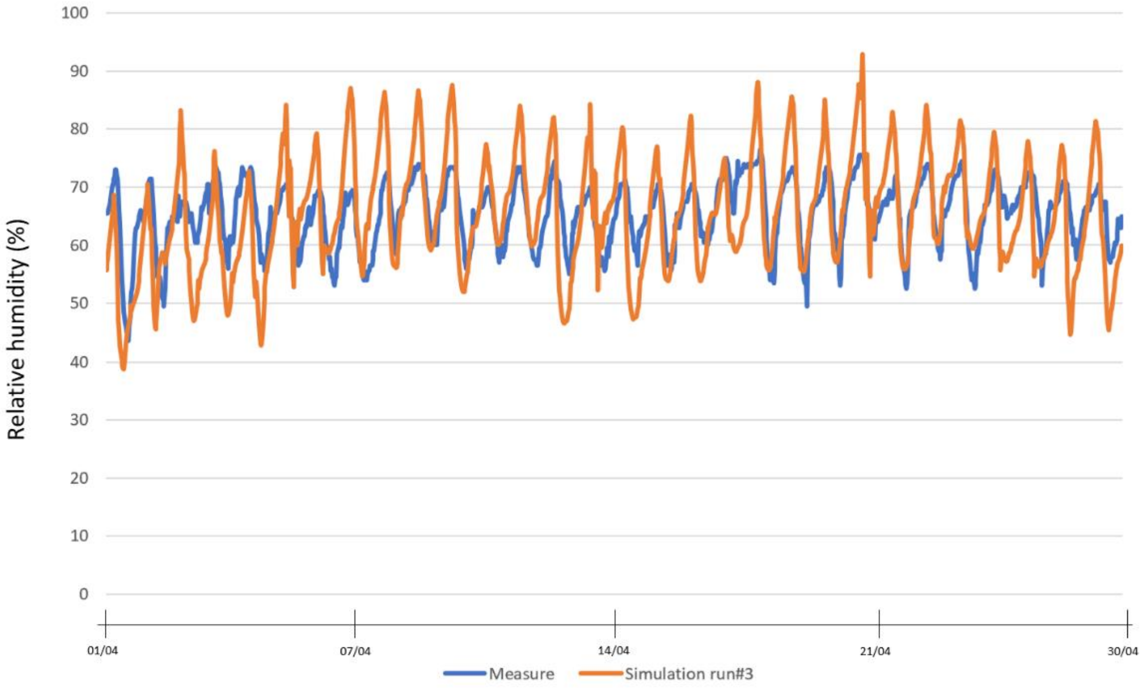


Figure 5-15: Relative humidity from measurement and simulation after calibration of house A1.

5.4 BIM Model and BPS as Decision Support Tools

As mentioned earlier in this chapter, in this phase of the methodology, the researcher put herself in place as an architect during the design process to see the effectiveness of using BIM and BPS as decision support tools. Using BIM with RAE-Insight and GBS has proved to be efficient in terms of analyzing the energy consumption of buildings and proposing alternatives for building materials and active systems. The simulation process using these two tools is relatively straightforward, requiring minimal parameter re-entry and consuming little time. Moreover, their ability to integrate directly with BIM models allows architects and designers to easily modify building designs and immediately run simulations to assess the impact of these changes. Considering these features, RAE-Insight and GBS are well-suited for decision support during the early design phase.

However, despite their strengths, these tools may not be ideal for use in Cambodia. The alternative design options they suggest may not be suitable or available in the Cambodian context such as the construction material, HVAC system, solar panel... By default, the energy cost calculations in Insight are based on data from the U.S. Energy Information Administration. Although these settings can be adjusted to fit the building's location, the available options only cover certain countries, excluding Cambodia. Additionally, for architects and designers who prioritize thermal comfort, these tools do not provide sufficient information to evaluate that aspect effectively.

For the use of BPS software that produces sufficient results for thermal comfort such as DesignBuilder, the challenge relies on the time and expertise needed for the simulation. For our study, the modeling of each building takes on average around 4 hours and the simulation took around 20 hours. As a reminder, the author has prior experience with Revit and DesignBuilder, which provided some familiarity with the software used in this study. Considering that architects aren’t normally familiar with the BPS tool, the time and effort needed to conduct simulation and calibration could be quite extensive. More than that, given the numerous trials and errors required to calibrate the model, the reliability of this type of simulation for analyzing the performance of newly constructed buildings is also questionable.

When using BPS as a decision support tool for architects during the design process, it can certainly be beneficial for making informed design choices. However, if BPS is used to test different design strategies, the required time could potentially double. The interoperability between models is low, meaning that any modifications necessitate rerunning the entire simulation process. In both professional and educational environments, where design timelines are often tight, this approach may not be efficient, particularly during the early design phase. To ensure a smooth architectural design process, a separate team dedicated to performing BPS might be necessary.

Using a BIM model to conduct BPS rather than a standard 3D model did not demonstrate significant advantages in this study. Although the BIM model contains much of the data required for simulation, many of these inputs still need to be re-entered in the simulation tool to ensure accuracy. For instance, the modifications made to the wall materials and layers in the BIM model were not successfully transferred to the BEM model in DesignBuilder. Upon investigation, it was found that the gbXML file contained only the original wall type from the Revit library, disregarding any alterations made within the Revit environment. Currently, BIM models cannot be directly linked to BPS tools, meaning that any changes made in the BIM model require reimporting into the BPS tool and rerunning the entire simulation process.

BIM models would be far more effective if they could be directly integrated with BPS tools, allowing any changes in the BIM model to be automatically reflected in the simulation. If architects are already using BIM for drawing and modeling, conducting BPS with the BIM model wouldn’t necessarily extend their design process. However, without this direct integration, the potential benefits of using BIM for BPS are limited.

5.5 Chapter Conclusion

BIM models and various building simulation tools were evaluated for their efficiency as decision support tools for architects, particularly in terms of building thermal performance analysis. Tools like RAE-Insight and GBS prove useful for building energy analysis, offering design alternatives related to building materials, active systems, and photovoltaic systems. These tools are particularly suitable during the early design phase, though they may not be ideal for the context of Cambodia and the analysis of building thermal performance.

While BIM models are effective when combined with RAE and GBS, their advantages are less clear when used in conjunction with Building Performance Simulation (BPS). The simulation process often requires extensive calibration, involving many trials and errors to achieve a calibrated model. In our case, even after numerous adjustments to input parameters, the models did not calibrate well. This time-consuming process raises questions about the reliability of BPS as a decision support tool for architects, especially in the early stages of the design process.

Despite these challenges, BIM models and BPS can still serve as valuable decision-support tools. However, further research is needed to determine how BIM and BPS can be effectively integrated into the design process and to identify the most appropriate phases of the design process for their implementation. This is especially important in the context of Cambodia, where expertise in BIM, BPS, and related resources is still developing.

CHAPTER 6

TOOLS AID DECISION MAKING: BIM MODEL, BPS AND SIMPLIFIED TOOL

This chapter presents findings on methods that aid decision-making in building thermal performance analysis. The investigation regarding the use of BIM, BPS, and bioclimatic design in the AEC sector in Cambodia is conducted. The current architectural design process, which integrates these three approaches, is identified and evaluated, highlighting malpractices and proposing more effective methodologies. A simplified tool, Esad, is proposed as a decision support tool for architects and designers. This tool facilitates the analysis of various design strategies to achieve optimal building thermal comfort from the early design phase.

A part of this chapter was presented at the international conference PLEA 2024 in Wroclaw, Poland, and published in the same conference proceeding.

Taing, K., Reiter, S., Han, V., & Leclercq, P. (2024). Integration of BIM and BES in sustainable architecture design process: case study of a developing country. PLEA 2024: (RE)THINKING RESILIENCE. The Book of Proceedings, p 657.

6.1 BIM and Bioclimatic Design Awareness in Cambodia

The first step toward analyzing the use of BIM in designing a bioclimatic building for Cambodia is through a survey on awareness and practice of these two approaches in the current ACE sector in Cambodia. A survey is put in place to understand the current situation of awareness and application of BIM and bioclimatic design in the ACE sector in Cambodia. The survey was done online in April 2021 during the period of COVID lockdown through Facebook as it is one of the most active platforms to reach out to people. Telegram is another platform that is also used to publish this survey. In Facebook and Telegram, some groups or pages or channels gather architects and engineers together. The surveys are sent and posted in those groups to reach as many people as possible. The questionnaire used in the survey can be found in Annex 1. In general, the questions ask about:

- The profile of the responders
- How many years they have experience in the field
- Their awareness of BIM and bioclimatic design
- The practice and contribution of BIM and bioclimatic design in their project.

We received 106 responses from people with different backgrounds such as architects, civil engineers, contractors, urban planners, lecturers, and students from 3rd year engineering degrees to doctoral degrees in the field of ACE. They work in private companies, government organizations, research laboratories, and freelance projects with the majority of 1 to 5 years of experience in the field.

In terms of bioclimatic design awareness, 34% of respondents who are familiar with or have knowledge of this concept are predominantly architects and civil engineers holding a master's or PhD degree. After reviewing the definition of bioclimatic design provided in the survey, 5% of respondents indicated that they had applied this approach in their projects, although they were not aware of its technical terminology. As shown in Figure 6-1 the number of architects who are both knowledgeable about and have practiced bioclimatic design is two to four times higher than that of civil engineers, which is expected given that bioclimatic principles are more involved in the architectural design phase. However, it is noteworthy that some civil engineers have also implemented this approach in their projects, suggesting collaboration between civil engineers and architects during the design process. Figure 6-2 further illustrates the general project objectives when bioclimatic design is incorporated into a project. In applying bioclimatic design, certain principles are practiced more frequently than others, as shown in Figure 6-2.

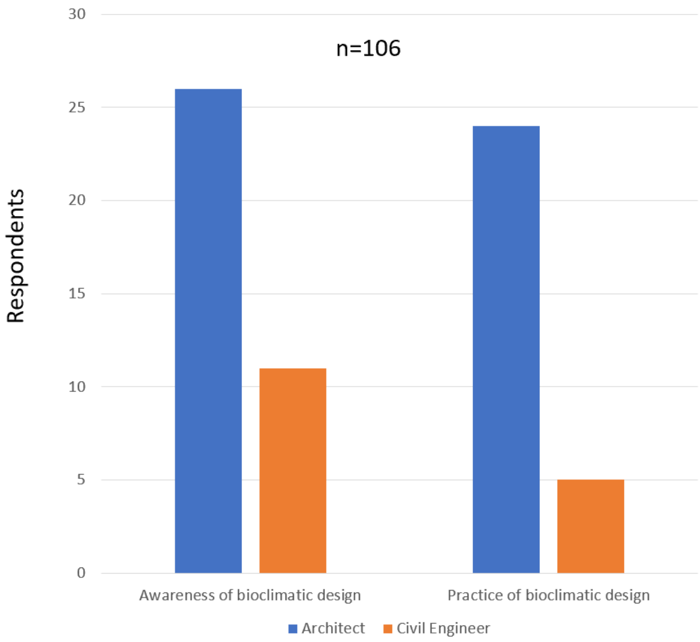


Figure 6-1: Awareness and practice of bioclimatic design in Cambodia.

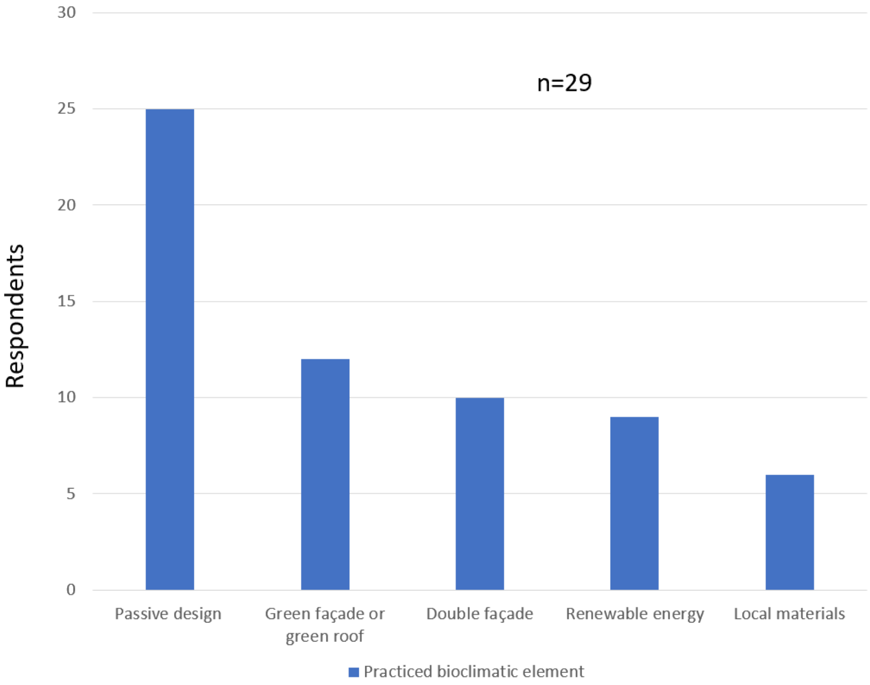


Figure 6-2: Bioclimatic strategies that are practiced by respondents.

In the application of bioclimatic design, certain goals are expected to be achieved by the project which likely contributes to sustainability, occupant well-being, and construction cost. We provided 7 options for respondents to choose as the project goal upon integration of bioclimatic design. ‘Lower energy consumption’ turned out to be the most important goal chosen by the respondents followed by ‘improve thermal comfort’ and ‘reduce environmental problems’ then ‘support of local materials’ while ‘lower construction cost’ and ‘improve quality of space’ are chosen by only 2 respondents.

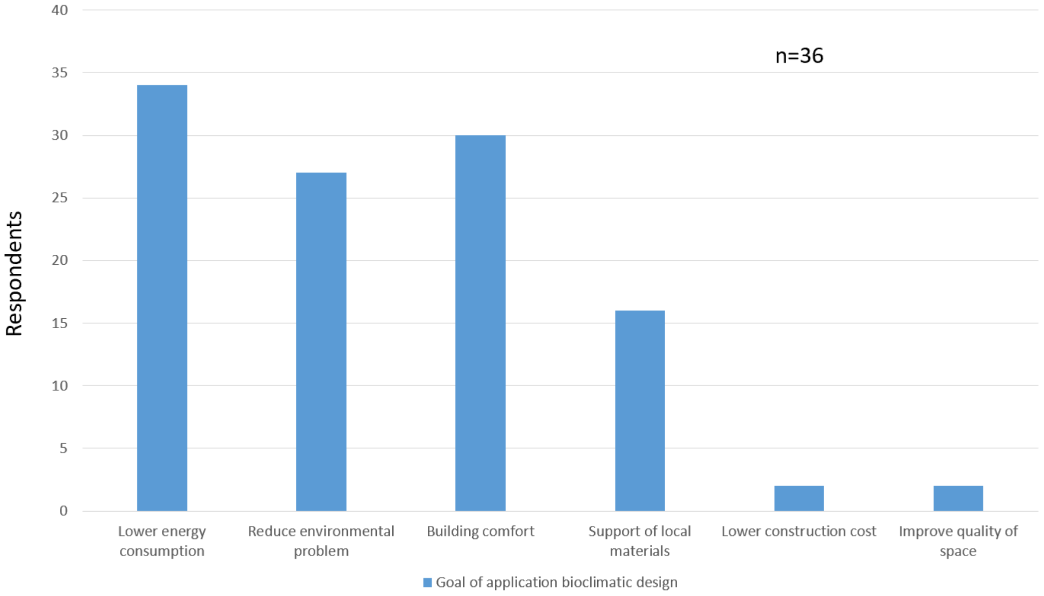


Figure 6-3: Goal for the application of bioclimatic in the projects.

Concerning BIM, 80% of respondents, including architects, civil engineers, and students in both fields, have heard of or are familiar with the term. In contrast to bioclimatic design, there is a greater awareness of BIM among civil engineers than among architects. This indicates that BIM is more practiced in the construction phase where plans and construction planning need to be executed. Despite higher awareness of BIM compared to bioclimatic design, only 34% of respondents have implemented BIM in their projects. This suggests that the complexity of BIM or lack of expertise and resources may be a significant factor limiting its application. We notice that 17% of the respondents who know about BIM are still in the learning process of this approach. More than that the practice of BIM focuses majority on modeling rather than other benefits that BIM could provide as seen in Figure 6-5. This emphasis on modeling is further reflected in the choice of BIM software, with the majority of respondents using Revit, a BIM software designed to facilitate building drawing and modeling (see Figure 6-6).

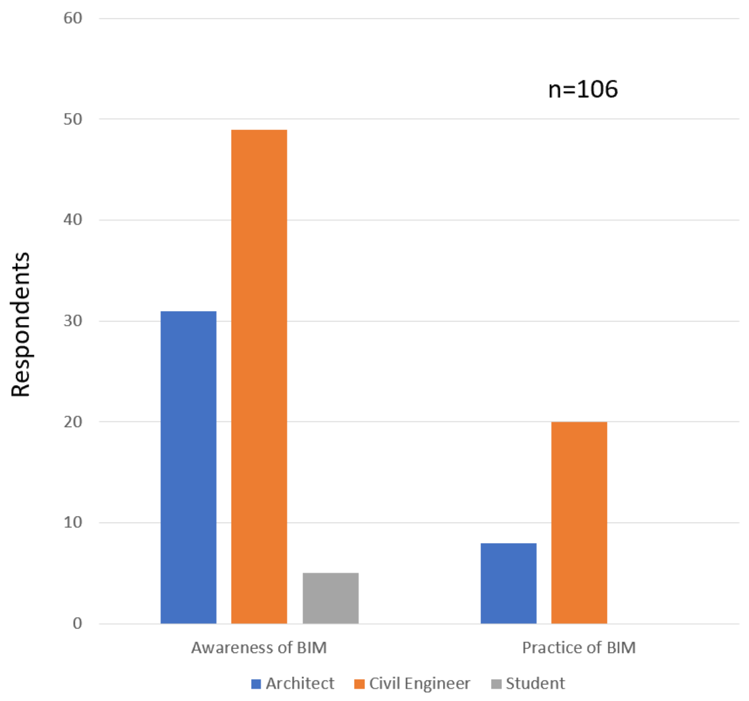


Figure 6-4: Awareness and practice of BIM in the project in Cambodia.

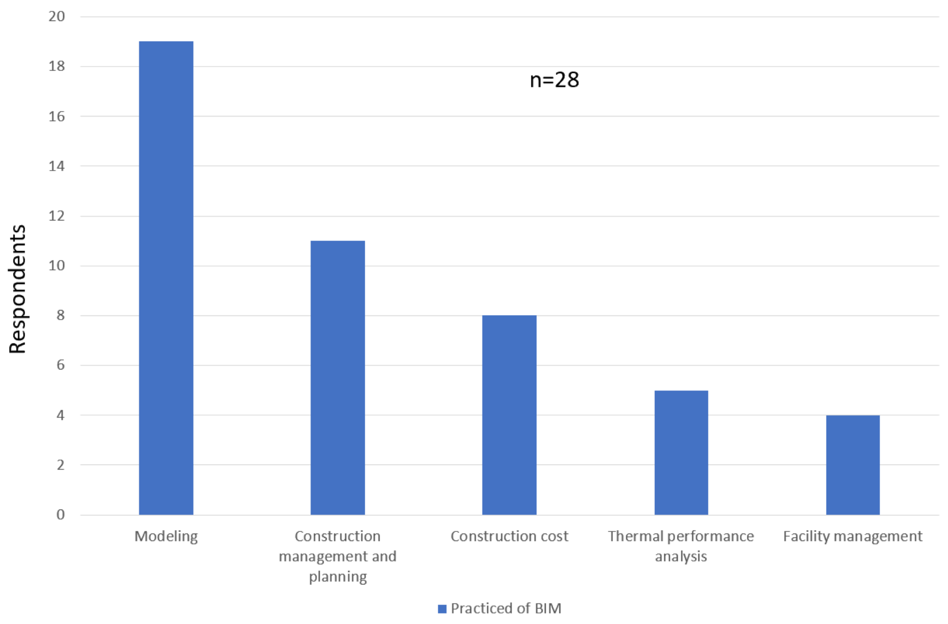


Figure 6-5: The focus of the practice of BIM.

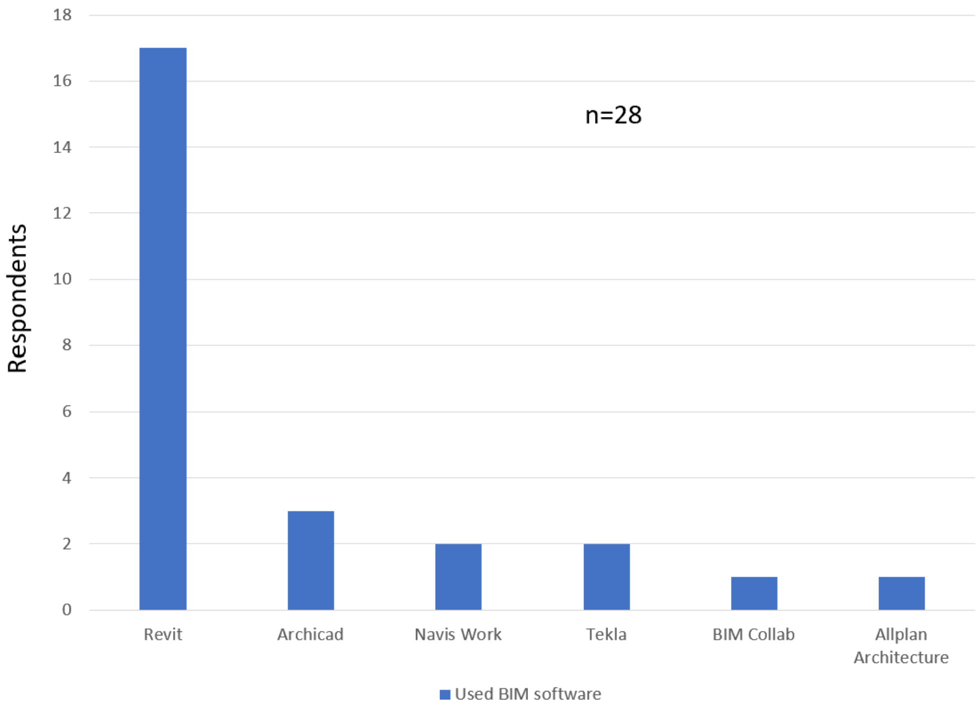


Figure 6-6: BIM software that is used by the respondents.

When asking them to define BIM, people still mistake BIM as just software for 3D modeling or just Revit. This misconception contributes to the higher percentage of BIM usage being directed toward building modeling. The detailed modeling capabilities of Revit facilitate time savings for civil engineers by streamlining the creation of detailed drawings for structural elements. In contrast, the lower utilization rates of Tekla and BIM Collab indicate that BIM is not extensively employed for collaborative purposes, such as clash detection and coordination among stakeholders.

This survey allows us to have an initial idea about the limitations of awareness and current practice of BIM and bioclimatic design in the ACE sector in Cambodia. For bioclimatic design, which is a term that was first mentioned in 1953, it is a surprise that the awareness and the practice of this approach remain relatively low compared to BIM which is a term that just appeared in the last decade.

The limitation of practice bioclimatic design in the project could be one of the reasons for the low thermal performance of current houses in Cambodia. This observation underscores the prevalent trend among architects to prioritize the aesthetic and cost of construction over the comfort of building which is a long-term investment.

6.2 Architectural Design Process Interview

The response from the survey pushes us to investigate the practice of BIM and bioclimatic design in more detail. These findings highlight the need for a more detailed exploration of how BIM is being applied and how bioclimatic design principles are being integrated within the architectural design processes. Our qualitative research method is based on semi-structured interviews, aiming to better understand the practice of using BIM and BPS in the architectural design process in Cambodia. The applied method includes 7 rigorous research steps: (1) selection of the architectural firms to be interviewed, (2) development of an interview guide, (3) exploratory interview to correct and validate the interview guide, (4) realization and recording of the interviews, (5) complete transcription of the interviews and anonymization of the answers, (6) analysis of the content of the interviews, and finally (7) the interpretation of the results of the study and the development of its conclusions.

A guide for the interview is developed to keep the interview in line with our objectives. The complete questionnaire used for the semi-interview is presented in Annex 2. It consists of questions asking on subjects such as:

- The development of their design process from one design phase to another.
- The tools that they use during their conception phase.
- The focus goal/element of sustainable design or bioclimatic design in their project
- The implementation of BIM and BPS in their project including the advantages, disadvantages, limitations…
- The method that they use to evaluate building thermal performance if BPS isn't practiced in their company.
- The project that they design with the requirement to obtain green building certification.
- The overall design timeline combines all the steps of design, tools used at each step, collaboration, and decision-making.

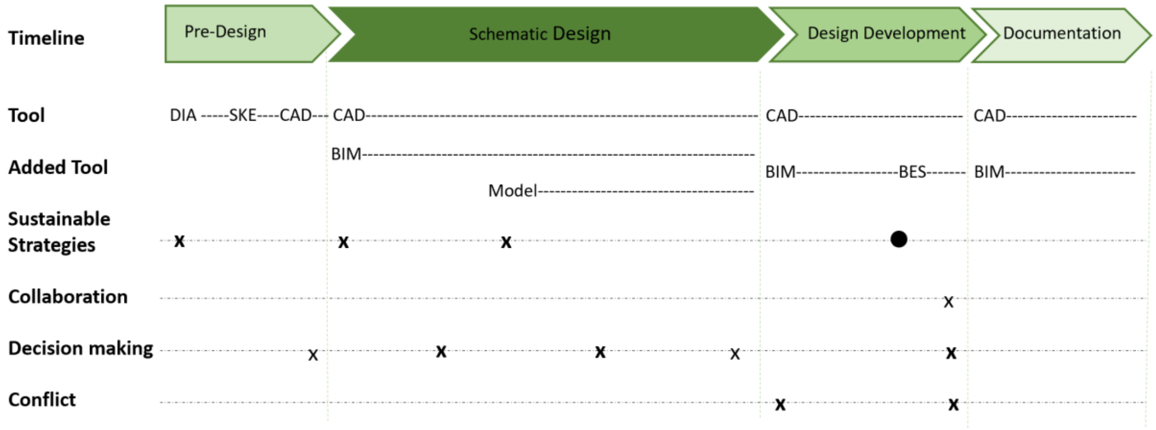
Below are the requirement criteria for each company that we interviewed:

- Practice sustainable design in their project.
- Have at least 5 years of experience in the field.
- Have at least 5 architects working in their company.
- Have a head office or mainly working on projects in Cambodia.

As evidenced by the survey, the number of architects familiar with or actively practicing bioclimatic design and sustainable strategies remains limited. Consequently, it has been challenging to identify companies in Cambodia that fully implement these principles and meet the criteria for participation in the interviews, while also being willing to share their experiences. Out of the 17 companies contacted via email, 10 responded positively, agreeing to participate in the interview process. Each company was assessed against our criteria, based on the projects that they have designed, as well as information available on their websites, including their vision and mission statements.

We conducted interviews with 10 companies, comprising 8 architectural offices, 1 architectural and construction firm, and 1 energy consulting firm. Each interview involved 1 or 2 architects from the respective companies, with three of the participants also serving as founders. These founders play a pivotal role in promoting sustainable design practices, as well as the integration of BIM and BPS within their projects. Overall, we collected in total 8 hours and 17 minutes of audio recordings, along with 64 pages of responses to 18 interview questions and an additional 10 pages of supplementary notes.

Figure 6-7 illustrates the identified overall architectural design process where it follows the traditional 4 phases design process. This diagram describes the design phases, tools used, and the collaboration between the various actors involved in the projects. The detail of each aspect is discussed in the section below.



Tool : DIA= Diagram, SKE= Sketch, BIM= Building Information Modeling, BES= Building Energy Simulation, CAD=Computer-Aid-Design
● = Strategies verification, **X** = Action Made, x = Possible action made

Figure 6-7: Identified the overall design process currently practiced in Cambodia.

6.2.1 Design Timeline

In Cambodia, both types of project delivery are practiced: design bit-build and design-build (Keth et al., 2023). For small projects such as residential buildings, however, the design-build method is more popular. In design-build projects, all stakeholders collaborate closely compared to traditional design-bid-build methods. Additionally, this type of project is frequently undertaken by firms that specialize in both architectural design and construction, allowing them to streamline the process from conception to completion.

The design timeline varies significantly based on the type of project and the level of client involvement. In Cambodia, local architectural firms primarily design small projects, including residential, small commercial, and public buildings, while large-scale or high-rise projects are typically handled by international companies. Consequently, the firms we interviewed primarily engage in the design of residential and small commercial buildings. In terms of working and design protocol, each company follows its approach according to its available resources. The design work is mostly collective design where each actor's task varies according to their skill (conception, drawing, modeling, graphic…). What we can see in similarities between each company is the evolution of the conception phase. All companies follow the general architectural design process which starts from pre-design to schematic design to design development. During the design process, we can see both "*engineering design*" and "*cognitive*" approaches are practiced. From the interview, two types of design processes can be identified which show some similarity to these two approaches:

- Phase Design: this approach to the design process emphasizes addressing specific design elements or the production of distinct plans and models in sequential phases. The process is organized progressively, focusing on individual aspects such as functionality, building envelope, and structural components allowing for a structured development from one phase to the next. This approach is more on a linear timeline similar to the "*engineering design*" approach.
- Detail Design: this design approach integrates all design aspects—functionality, envelope, and structure—into a cohesive whole. The combined elements are developed concurrently, refining each aspect to achieve a comprehensive final design at an increased level of detail.

All companies practice these two approaches, however, 5 companies frequently practice the *Detail Design*, and 4 other companies often practice the *Phase Design* approach. Although four companies indicate that the Phase Design approach is their primary method, the *Detail Design* approach is also occasionally employed. Typically, in the programming phase, all aspects of the building design are outlined and conceptualized. From this point, both approaches may be implemented based on project specifics and client requirements. For instance, some clients may request a review of the floor plan before progressing to façade design and other building elements. Therefore, the *Phase design* approach needs to be employed.

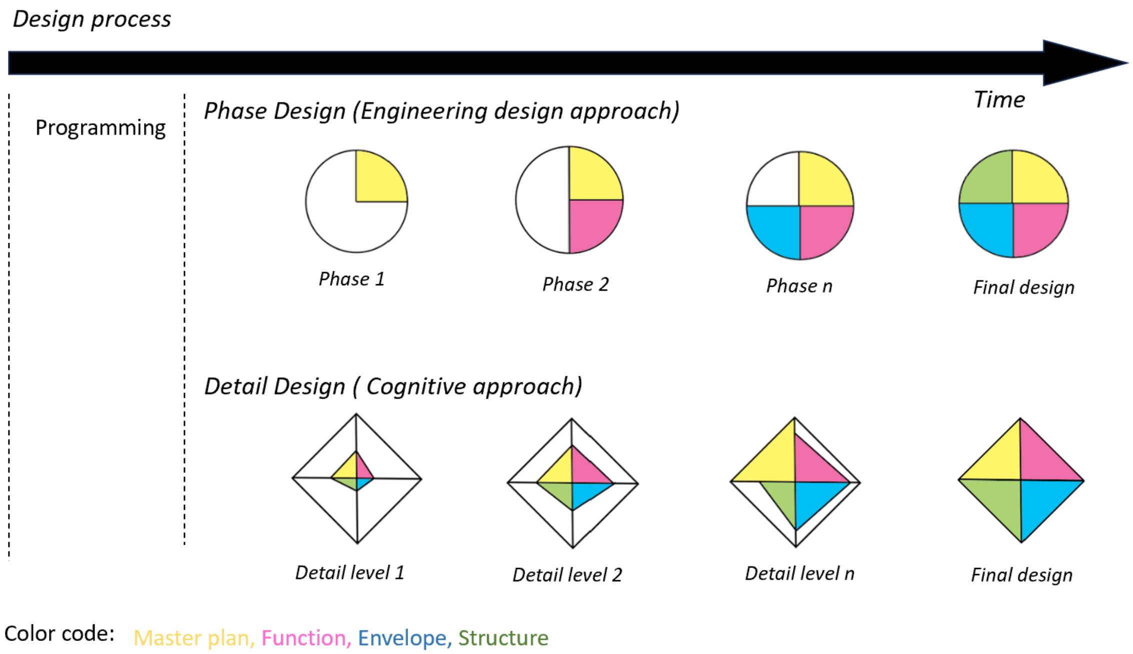


Figure 6-8: Two types of the identified design phases.

In terms of integration of sustainable strategies, some companies establish their goal early in the design phase while others start integrating along the way of their conception evolution. Their main sustainability goal usually focuses on building comfort, usage of local materials, and energy efficiency (Figure 6-9). To achieve this goal, passive design strategies for natural ventilation and light are normally applied in their project along with the active system that is more adapted to the context of Cambodia. Rain protection design is also a high priority as well in building design. However, with the constraints of design and construction time, these goals are sometimes achieved or hard to obtain, especially for commercial buildings. We can see that companies that meet our criteria mostly design residential spaces where sustainable design is attainable.

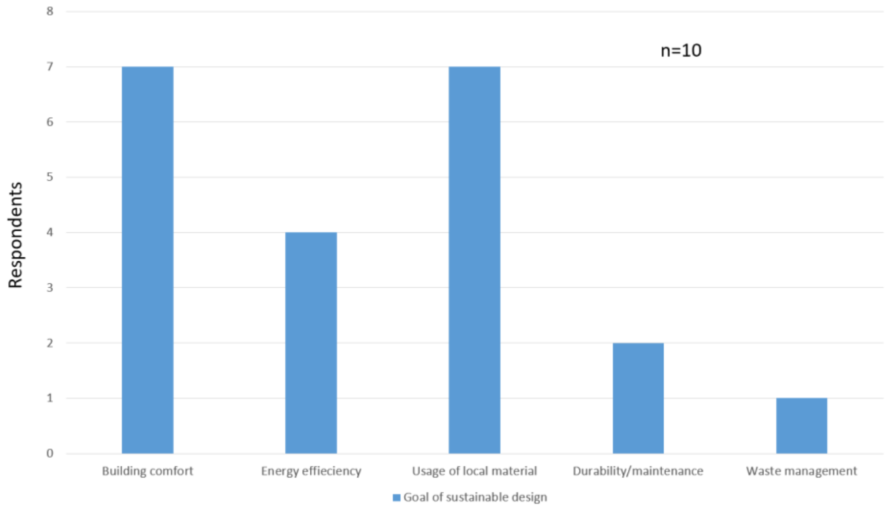


Figure 6-9: The focus of sustainable design strategies in the project.

For three companies, the choice of materials was made from the pre-design phase to ensure the possibility of using local materials and the design of the envelope of the building follows the possibility of chosen materials. The architects express that the projects that aim to obtain green building certificates are likely to achieve the sustainability goal set in the early design phase. The application of sustainable design strategies is usually based on experience and exchange with clients and stakeholders. Currently, there is no specific guideline that architects can follow to ensure good thermal performance for their buildings yet.

In Cambodia, architectural firms are typically responsible for the building design, while construction companies implement these designs without significant collaboration between the two entities. The building design is generally completed before being handed over to structural and MEP engineers for detailed considerations regarding structural integrity and HVAC systems. Consequently, collaboration between these professionals tends to occur primarily at the latter stages of the design process. At this stage, if errors are encountered, which is often the case in building design and construction without collaboration between stakeholders, modifications require significant time and effort. This issue is frequently addressed by both architects and engineers.

6.2.2 Design Tools

Basic architectural design tools such as CAD remain the primary tools used by all companies. As the company interviewed focuses on residential and average-sized buildings with light complexity, the use of sketching and CAD remains reliable for their needs. Figure 6-10 illustrates the design tool used throughout the design process.

We can divide their utilization of these tools into 4 categories:

- Brainstorming: the tool used to brainstorm ideas and the first design of the project.
- Drawing: plan drawing in 2D, more detail of building design in 2D.
- Modeling: creating 3D models, building forms, and envelope design.
- Visualization: building analysis based on visualization, test of the space design, effectiveness of shading device, light analysis…

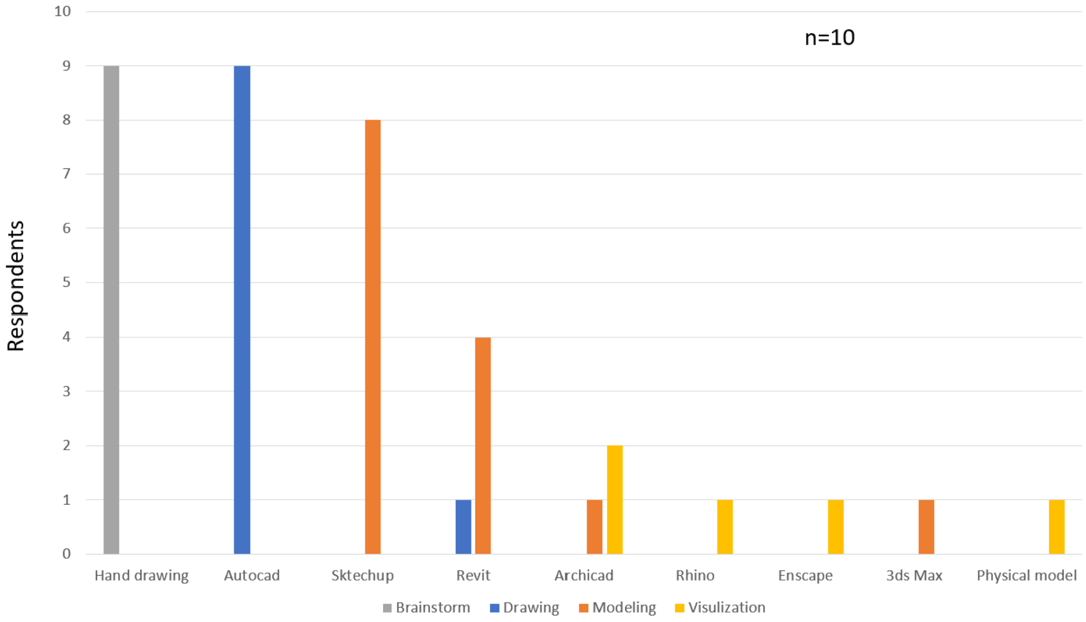


Figure 6-10: Design tool used for different types of production.

We can see in Figure 6-10 that 5 companies are using BIM software, however only 4 companies interviewed declare that they have integrated BIM and BPS into their design processes. For one company, Archicad is used only for modeling and visualization purposes. Among the 4 companies utilizing BIM, two companies practice BIM regularly, while the other two use BIM primarily when projects require to obtain green building certifications. One of the companies that practice BIM regularly is a company that has both architectural design and construction. The purpose of using BIM is therefore could be indicated to facilitate from building design to the building construction phase. This highlights the limited adoption of BIM in the architectural domain in Cambodia. For the company that regularly utilizes BIM, the technology is employed to create models for energy consumption simulations in the later stages of the design phase, as well as to visualize shading and lighting in building designs. Additionally, BIM is used for cost estimation, planning, and coordination among stakeholders. We can see the application of each tool in the design phase as in Figure 6-7.

Some architects mentioned that using BIM can prolong the design process due to the lack of experts in Cambodia and because designing a villa is not complex enough to necessitate BIM. Typically, villa designs in Cambodia do not integrate HVAC systems. Lighting and air conditioning are typically the only MEP-related components incorporated in these projects. Therefore, collaboration multidisciplinary isn’t seen as necessary in the architectural design phase.

During the design development phase where most of the design aspects have been finalized, BPS is utilized to simulate the building's energy and thermal performance. These simulations are sometimes employed to persuade clients of the validity of certain architectural design choices and to analyze the building's performance to meet green building certification requirements. In essence, BPS is used to verify whether the proposed design achieves optimal building performance. The result from BPS provides architects with a lesson to see whether their applied sustainable design strategies are effective.

BPS isn’t practiced directly by the architect. Companies that utilize BPS either have an internal department with experts in building performance analysis or rely on services from energy consulting firms. We interviewed an architect who works in one of the consultant companies where many architectural firms have used their services. The role of the consultant company is important for the design process only for projects that require certification from the green building certificate. Sometimes, the consultant company is able to work with their client (the architect) from the beginning of the project and some at the end of the design process where the design aspect is already finalized. For the role of architect interviewed for the consultant company, they evaluate the building design if it fits with the requirements for the green building certificate that the client wants to achieve and propose design solutions to help them obtain their goal. We aren’t able to identify the name of the BPS tool or software used by the interviewed companies, as the architects we spoke to were not directly involved in the BPS process.

6.2.3 Conclusion of the Interview

For residential building design, it is highlighted that the use of CAD is still reliable, and BIM isn’t a necessity just yet. As stated above, the practice of BIM can also complicate the design process if any actor lacks proficiency in using it. Nonetheless, utilizing BIM solely as a drawing and modeling tool can offer significant advantages in terms of creating detailed models, floor plans, and analysis of certain design elements. As technological advancements continue to shape the future, the adoption of BIM within the construction sector of developing countries, such as Cambodia, is inevitable.

The integration of BIM and BPS into the architectural design process, particularly as a decision support system from the early design phase, presents significant potential but also reveals several challenges in current practice, especially in contexts like Cambodia:

- **Multidisciplinary collaboration in the early design phase**: BIM is being utilized from the early stages of the design process. However, the collaboration between stakeholders typically begins only towards the end of the design process. This late-stage involvement limits the ability of stakeholders to influence and impact the design, reducing the overall effectiveness of BIM in facilitating collaborative decision-making and project coordination. The lack of early collaboration hinders the opportunity to address potential issues or to integrate valuable input from various stakeholders, such as engineers, contractors, and facility managers, who could contribute to more robust and coordinated design solutions.

- **BPS integration as a verification tool**: BPS requires detailed data inputs, which are often not available or are too vague during the preliminary design phase. More than that as BPS isn't used by architects or is conducted by consulting companies, BPS tends to be integrated later in the design process, when many design decisions have already been finalized. Conducting BPS at a later stage limits its utility in informing design decisions. If simulations reveal issues or inefficiencies, making changes to the design is more challenging, costly, and time-consuming because many elements have already been locked in.

- **Lack of BIM and BPS application as decision support tools**: In Cambodia, the use of BIM and BPS is not widely practiced as decision support tools. Instead, they are often used in a more isolated manner, with BIM focusing on 3D modeling and documentation, and BPS being applied sporadically, mainly for compliance rather than for design optimization. This separation reduces the potential benefits of using BIM and BPS together to inform and guide design decisions from the early stages. Without integration, the decision-making process misses the opportunity to use simulation data to optimize the design for performance, cost, and sustainability.

6.3 Architectural Design Process Observation

Due to privacy reasons, the company we interviewed did not permit us to observe the design process during their project. Consequently, we conduct our observations at a university in Cambodia during a school project designed by architectural engineering students. This approach also enabled us to compare the results from the interview in the professional setting to the design process of students in the educational environment.

This observation aims to identify a long-term architectural design process for complex buildings including the tools used for bringing conception to life, the resources and methods applied for building analysis, the integration of bioclimatic strategies to achieve building comfort, and the decision-making processes of designers.

The objectives of this observation are to:

- Identify a design process timeline integrated aspect bioclimatic.
- Identify tools that designers use to create their concepts.
- Identify the phase/step of concept development: shape, orientation, function, façade, material, solar protection, green façade, structure …
- The technical and theoretical aspects that designers implement to achieve each target of the bioclimatic concept.
    - Target 1: Natural ventilation
    - Target 2: Sun protection
    - Target 3: Rain protection
    - Target 4: Space arrangement
    - Target 5: Green façade
    - Target 6: Water feature
- Identify motif use for decision-making of conception in their project.
- Identify the design collective between actors.

6.3.1 Data Collection

We conducted an observational study involving four groups of fourth-year students enrolled in the Bachelor's degree program in Architectural Engineering at ITC. The study took place during their Architectural Studio course, which focused on the design of a government building complex of a provincial hall that consists of 5 to 6 buildings with functions such as a ministry building, administrative building, conference hall, staff dormitory... Each group comprised five members, with some students working individually on specific buildings and others collaborating in pairs. The course spanned 16 weeks, with the design phase starting in week 3 and finishing in week 11. However, as shown in Table 6-1 the schedule imposed by the professor wasn't well respected due to unexpected activities happening during that period that resulted in the design phase starting at week 4 and finalizing at week 13.

Table 6-1: Expected and occurring activity of the design process during the Architectural Studio course.

Week	Expected Activity (Schedule by professor of the course)	Occur activity
Week 01	Project introduction	Project introduction
Week 02	Case studies and site analysis presentation	Case study and site analysis presentation
Week 03	Programming in detail (Master plan)	Bioclimatic course
Week 04	Floor plan	Programming in detail (Master plan)
Week 05	Floor plan	Floor plan
Week 06	Elevation	Floor plan
Week 07	Elevation	Floor plan and elevation
Week 08	Master plan and 3D modeling	Elevation
Week 09	Technical detail	Elevation
Week 10	Project finalization	Elevation and technical detail
Week 11	Project submission and presentation	Technical detail
Week 12	Physical modeling	Project finalization
Week 13	Physical modeling	Project submission and presentation
Week 14	Physical modeling	Physical modeling
Week 15	Physical modeling	Physical modeling
Week 16	Physical modeling submission	Physical modeling submission

Students were given the freedom to choose the province and utilize the existing town hall site for their project. The size of the site assigned to each group varied between 2 to 10 hectares. Based on the chosen site size, the required building complex ranged from 5 to 6 buildings, including two main buildings common to all groups: the town hall and the ministry building. Additional buildings incorporated into the project could include a conference hall, an administrative building, staff dormitories, a small museum, and a residence for the governor. This project did not impose strict requirements regarding the surface, programming, and functionality of the buildings, allowing students flexibility in their designs.

Prior to the commencement of the design phase, students attended a theoretical session lasting three hours on the principles of bioclimatic design. This session aimed to equip students with the knowledge to incorporate these principles into their projects.

The initial data collection was conducted through observations and questionnaires administered during each project review session with the professors. However, after two weeks of employing this approach, it became evident that the data obtained was insufficient to provide a comprehensive understanding of their project design progress, particularly the design collective and decision-making. Consequently, the data collection methodology was refined and expanded to include:

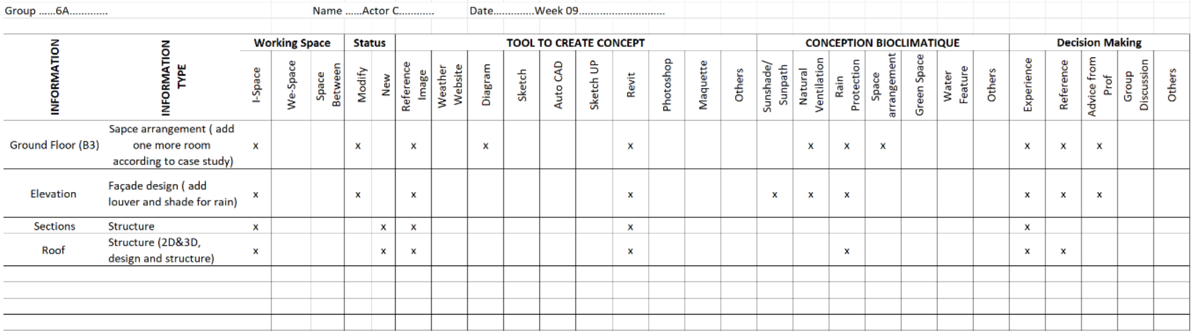
- Weekly observation during the project review.
- A progression sheet for students to complete about their design process as shown in Figure 6-12.
- Semi-structured interviews during and at the end of their project design for an insight into collaborative work and the overall design process.
- Join their telegram group to see their exchange (communication) and information sharing.

Weekly observations are still conducted during the project review sessions with the course professor but don’t act as the primary data collection. We observe the group interaction when explaining their concept design for each building and the way they answer questions and accept feedback from the professor. After each review session, students were asked to complete a project progress sheet where we could see their design process. This method aimed to gain deeper insights into their conceptualizations and creative processes throughout the design phase. At the end of the project, a semi-structured interview was conducted by group with all members simultaneously.

Figure 6-11: The weekly project review with the professor.

The creation of the progression sheet is to obtain information about the design progress and process as much as possible. Figure 6-12 present an example of a progression sheet completed by the student. In this sheet, completed information is divided into 7 categories:

- Information: to know about the type of plan/model and building that they are working on in that week.
- Information type: to know more details of what/why/how certain elements are changed in that plan.
- Working space: the collaboration between actors.
- Status of their production: if the plan continues to be modified or was given up and created new or finalized to be documented.
- Tools that are used to create conceptions or productions of that week.
- Bioclimatic element that integrates into that plan.
- Methods that help with their final decision-making to choose that plan to present to their professor for that week.



Group ……6A…………

Name ……Actor C…………

Date…………Week 09…………………………

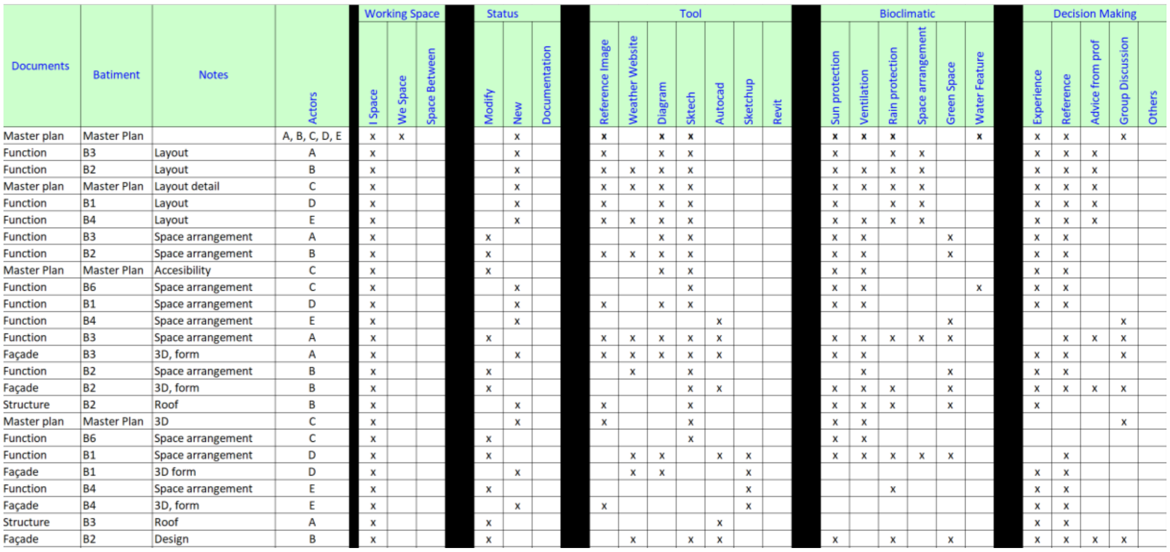
		Working Space			Status		TOOL TO CREATE CONCEPT										CONCEPTION BIOCLIMATIQUE							Decision Making				
INFORMATION	INFORMATION TYPE	I-Space	We-Space	Space Between	Modify	New	Reference Image	Weather Website	Diagram	Sketch	Auto CAD	Sketch UP	Revit	Photoshop	Maquette	Others	Sunshade/ Sunpath	Natural Ventilation	Rain Protection	Space arrangement	Green Space	Water Feature	Others	Experience	Reference	Advice from Prof	Group Discussion	Others
Ground Floor (B3)	Sapce arrangement (add one more room according to case study)	x			x		x		x				x					x	x	x				x	x	x		
Elevation	Façade design (add louver and shade for rain)	x			x		x						x				x	x	x					x	x	x		
Sections	Structure	x				x	x						x											x				
Roof	Structure (2D&3D, design and structure)	x				x	x						x						x					x	x			

Figure 6-12: Example of observation grid given to students to complete each week (progress sheet of actor C in group 6 for week 09).

6.3.2 Observation Results

- **Vireli: Method visualization of the results**

We collected a total of 224 pages of the progression sheet and 12 pages of answers during the interview. Collected data are analyzed in a platform called **Vireli** (Visualisation de ressources et livrables) developed by the author and Aurélie Jeunejean, a colleague at LUCID specific for this study where data are encoded into an Excel sheet and translated into a graph as shown in Figure 6-15. The encoding in Excel was done by group and by week. In total 242 rows with 33 columns were encoded into Excel for the 4 groups. All encoding sheets can be found in Annex 3.



Documents	Batiment	Notes	Actors	Working Space			Status			Tool							Bioclimatic						Decision Making				
				I Space	We Space	Space Between	Modify	New	Documentation	Reference Image	Weather Website	Diagram	Sktech	Autocad	Sketchup	Revit	Sun protection	Ventilation	Rain protection	Space arrangement	Green Space	Water Feature	Experience	Reference	Advice from prof	Group Discussion	Others
Master plan	Master Plan		A, B, C, D, E	x	x			x		x		x	x				x	x	x			x	x	x		x	
Function	B3	Layout	A	x				x		x		x	x				x		x	x			x	x	x		
Function	B2	Layout	B	x				x		x	x	x	x				x	x	x	x			x	x	x		
Master plan	Master Plan	Layout detail	C	x				x		x	x	x	x				x	x	x	x			x	x	x		
Function	B1	Layout	D	x				x		x		x	x				x		x	x			x	x	x		
Function	B4	Layout	E	x				x		x	x	x	x				x	x	x	x			x	x	x		
Function	B3	Space arrangement	A	x			x					x	x				x	x			x		x	x			
Function	B2	Space arrangement	B	x			x			x	x	x	x				x	x			x		x	x			
Master Plan	Master Plan	Accesibility	C	x			x					x	x				x	x					x	x			
Function	B6	Space arrangement	C	x				x					x				x	x				x	x	x			
Function	B1	Space arrangement	D	x				x		x		x	x				x	x					x	x			
Function	B4	Space arrangement	E	x				x						x							x					x	
Function	B3	Space arrangement	A	x			x			x	x	x	x	x			x	x	x	x	x			x	x	x	
Façade	B3	3D, form	A	x				x		x	x	x	x	x			x	x					x	x		x	
Function	B2	Space arrangement	B	x			x				x		x					x			x		x	x			
Façade	B2	3D, form	B	x			x						x	x			x	x	x		x		x	x	x	x	
Structure	B2	Roof	B	x				x		x			x				x	x	x		x		x				
Master plan	Master Plan	3D	C	x				x		x			x				x	x								x	
Function	B6	Space arrangement	C	x			x						x				x	x									
Function	B1	Space arrangement	D	x			x				x	x		x	x		x	x	x	x	x			x			
Façade	B1	3D form	D	x				x			x	x			x								x	x			
Function	B4	Space arrangement	E	x			x								x				x				x	x			
Façade	B4	3D, form	E	x				x		x					x								x	x			
Structure	B3	Roof	A	x			x							x									x	x			
Façade	B2	Design	B	x			x				x		x	x			x		x		x		x	x	x	x	

Figure 6-13: Encoding in Excel for group 2A

In Vireli, all information related to a specific week's production is organized into what is called a "*production bubble*" as illustrated in Figure 6-14. Each bubble corresponds to one architectural plan or model that was worked on during that week. Within each bubble, there are sections detailing the information collected concerning that specific production. The bubble provides insights into the tools used and the bioclimatic aspects integrated into the plan.

To aid in visualization, each bubble is color-coded to represent the type of plan or model produced that week: yellow for site integration design (master plan), pink for functional design (floor plan), blue for envelope design (elevation plan), and green for structural design (section and detail plan). This color-coding allows for a quick understanding of the design phase by simply looking at the overall timeline. Additionally, the number of bubbles in each week indicates the level of progress or activity, highlighting the weeks with the most advancements or actions.

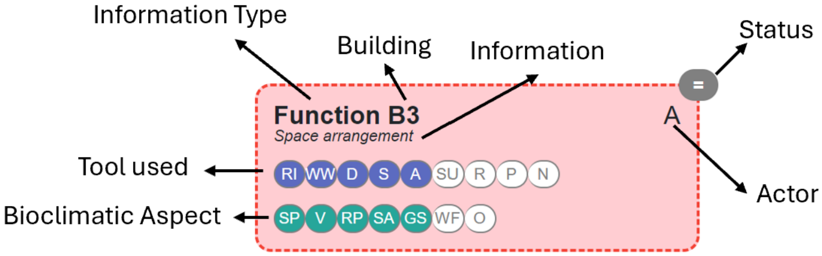


Figure 6-14: Information present in each bubble in Vireli.

Legends:

- Information type: what kind of plan that they have worked on in that week which includes Master Plan, Function, Façade, and Structure.
- Information: detail about changing of concept on that plan/model
- Tool: Reference images, weather websites, diagrams, sketch, Autocad, SketchUp, Revit, Photoshop, and others
- Bioclimatic aspect: Sun protection, natural ventilation, rain protection, space arrangement, green space/façade/roof, water feature, others
- Status: + Create new, = Modify, x Documentation

Each colored tool and bioclimatic aspect means that that tool and bioclimatic is used and integrated to create that production. As there are multiple buildings in the project, the name of the building could let us know the progress of each building and how actors work together between buildings. The decision-making information isn’t presented in Vireli. In each bubble, multiple actors can be presented as collaboration between actors happens. The figure below shows the look of platform Vireli, which in this case presents the design process of group A2.

Filters

Data file

Magic Graph 2A csv

Actors

☑ A ☑ B ☑ C ☑ D ☑ E

Documents

☑ Master plan ☑ Function ☑ Structure ☑ Façade

Batiments

☑ Master Plan ☑ B1 ☑ B2 ☑ B3 ☑ B4 ☑ B5 ☑ B6

Status

☑ Modify ☑ New ☑ Mise au propre

Figure 6-15: Architectural design process of group 2A visualized using Vireli.

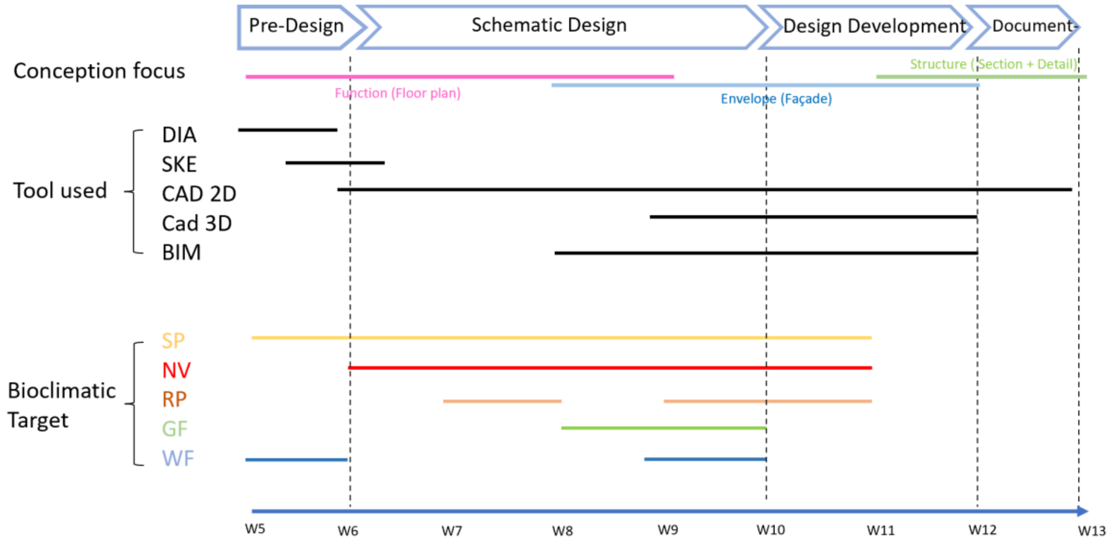
- **Overall design timeline**

Figure 6-16 show the design progress imported in Vireli (each design timeline can be found in Annex 3) for all 4 groups. Looking at the 4 graphs we can notice several points:

- Increased activity is observed during the middle stages of the design phase.
- The design process does not follow a linear progression through the design phases.
- A correction loop begins from the middle phase of the design process.
- Groups 2A and 6A tend to work more independently, whereas Groups 5A and 7A collaborate in pairs, as evidenced by the number of productions each group provides each week. As each bubble represents a plan/model, the team that works individually would produce a higher amount of plan while the team working in pairs shows a lower number of production (lower number of bubbles) as two or more members working to produce the same plan.

Figure 6-16: Design progress of the 4 groups observed visualized in Vireli

An analysis of these four design timelines reveals an architectural design process that aligns with the traditional four-phase architectural design process, but with an emphasis on development by conception/ design aspect phase, as illustrated in Figure 6-17. In this graph, we can see the evolution of their conception focus from function to façade to structure as well as the tool used and the bioclimatic target they integrated into their project at each design stage. The details of each category of design aspect will be discussed in the later section.



DIA: Diagram, SKE: Sketch, SP: Sun protection, NV: Natural ventilation, RP: Rain protection, GF: Green façade, roof or green space, WF: Water feature (creating microclimate)

Figure 6-17: Overall architectural design process identified from the student observation.

6.3.3 Conception Phase

The design process for all groups follows the weekly theme of the review scheduled for the project. This schedule leads their design focus to divide into 6 phases: brainstorming, master plan, floor plan, elevation plan, section and detail plan, and documentation.

The project begins with a pre-design phase, referred to here as the brainstorming phase, during which design activities have not yet commenced. In this phase, the focus is on analyzing the building site, reviewing case studies, developing an overall concept for the project, and dividing tasks, specifically, assigning the design of each building to individual team members.

Once the site location is selected, the team enters the first design phase, starting with the master plan. In this phase, the team collaborates to create a master plan that meets the needs of all members. The master plan provides a general overview of the building's size, its placement on the site, and how the site can be integrated to enhance the building's design. Typically, the master plan is developed during the first week of the design process and is revisited and modified at the end of the design phase to accommodate and complement changes in the final building design.

The floor plan is the next design phase where all the functionality design happens. The design of the floor plan for each group focuses on the functionality of the building, building circulation flow, space arrangement to allow ventilation and light, privacy, and security. Some technical details (where the plumbing system should be placed) and some structural elements (size of column and beam) are also thought of for less risk of error at the final design stage. At this point, the building volumetry is generated from the floor plan to facilitate the next design phase. Normally, this phase takes the longest period in the whole design process as most of the ideas and conceptions are executed.

The next design phase aims to produce the elevation plan. They focus their design on the façade design, what type and where the opening should be incorporated into the building, and choosing material for their façade design. The façade design reflects both the influence of the site (master plan design) and the building’s aesthetic, in this case emphasizing a traditional style and symmetry. The façade design aims to shield the building from the sun and the rain while allowing ventilation and connection to the outdoor space.

In the structure and detail plan phase, they focus on the roof design (type of roof, material used), new building technology, and the structural detail (technical drawing) of the building. Typically building structures in Cambodia is quite simple, especially in the case of student projects. The building structures are normally reinforced concrete with a beam-column system with occasional use of pre-stressed concrete. As mentioned, the overall idea of the structural system and elements has already been thought of since the design of the floor plan. However, the end of the design process is when the structural elements design gets more detailed and all technical elements are added to the plan. The everchanging plan causes the master plan to be modified at the end to accommodate the size of the building and certain landscape elements such as plants are identified to complement the building design.

The final phase, documentation, is where the design is completed and compiled for submission to the professor. At this stage, minimal adjustments to the building design may occur, though they are uncommon. The student's focus shifts primarily toward representing their design through renderings, posters, or videos.

We notice a correction loop at the start from week 09 to week 11. When the design element gets more detail, some initial designs and ideas can’t be executed. The modification in façade design for example the changing of opening for location for the building façade impacts the design of space arrangement in the floor plan. Certain technical elements added at the last design stage sometimes can also impact the floor plan or elevation, creating a correction loop. The everchanging building design causes the master plan to be modified at the end to accommodate the size of the building and certain landscape elements such as plants are identified to complement the building design. As a result, the design phase doesn't follow 100% with the provided schedule assigned for the project review at the beginning.

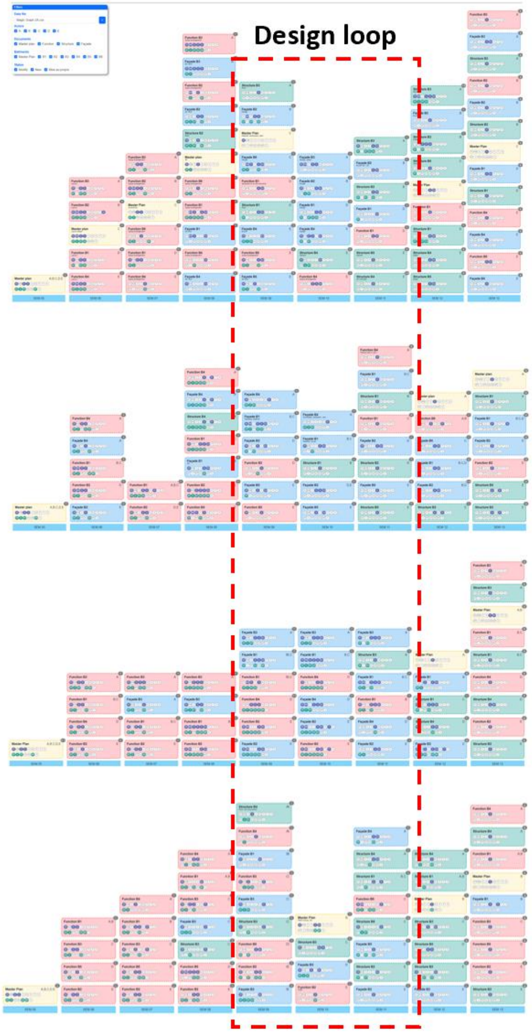


Figure 6-18: A correction loop is noticed in all 4 groups.

In terms of decision-making, there are no guidelines or decision support tools to help students feel completely confident about their design choices. Plug-in in design tools such as SketchUp and Revit for shading analysis is commonly used to help with decision-making for façade design. Feedback from professors and discussion within their group act as a decision support for their design. If the feedback from the professor still isn't acceptable to them, they keep changing their design which is also one of the reasons that create the correction loop as well. This normally causes delays in project design and sometimes limits the output that is produced by the student's creativity in the educational environment.

Comparing the results from the interview, we observe similarities between the design phases in professional and educational environments, particularly in the progression from master plan to functional design to the building envelope. In educational settings, the *Phase Design* approach is predominantly employed, with the design phase structured around a weekly project review theme due to the constraints of a rigorous academic schedule. Conversely, professional environments demonstrate flexibility by incorporating both *Detail Design* and *Phase Design* timelines. The selection of either approach is determined by the specific requirements of the project and the preferences of the client, allowing for a more tailored and responsive design process.

6.3.4 Design Tools

All the basic design tools such as hand drawing and CAD tools are being used in this project. The use of design tools follows the step of their design phase. They start with sketches and diagrams to brainstorm ideas, divide functionalities, identify the surface for each space, and create the first draft of their building design (overall concept, floor plan…).

CAD 2D which in this case is Autocad is the main tool used throughout the design process. First, the floor plan transforms from sketch into Autocad for a correct scale of space. Different versions of floor plans are created in Autocad for review with the professor before finalizing and exporting into SketchUp. The floor plans from Autocad are imported into SketchUp to create a 3D model for better visualization of the building façade and to help save time to create perspective views. SketchUp is easier to use for building envelope design as it gives a 3D view of the building. The model is also tested with different façade designs in SketchUp to visualize the effectiveness of the shading device (visualize the shadow of the shading device on the openings). For the elevation phase, SketchUp and Autocad are being used back and forth for the loop of plan modification between the floor plan and the elevation plan.

The use of BIM isn’t asked for in this project. However, we can see some students start adapting BIM software during their design process. Two groups (2 members from each group) out of the 4 groups used Revit in their design phase. The use of Revit which is a BIM software started as early as the use of Autocad. The intention of using Revit is mainly for simultaneously creating 2D plans and 3D modeling. Similar to SketchUp, it is also used for visualizing the design in terms of shading and natural light of building design as well. During the interview, they mentioned that Revit can help them to fasten the design of the building façade. With Revit, they don’t have to go back and forth between Autocad and

SketchUp which can save some time in modifying the plan. However, whether the choices of 3D modeling tool, the correction loop between floor plan and elevation still can be noticed.

Toward the end of the design phase, Autocad is extensively used to create the required project plans with the correct scale and to ensure that all design aspects are accurately represented. The 3D model, initially used for visualizing the building envelope, is then exported back into Autocad to generate elevation, section, and detail plans. This process is similarly applicable to teams using Revit, where the 3D model is also leveraged to produce detailed construction documents.

The application of each tool in each design phase is illustrated in Figure 6-19. The 4 categories of design tools used identified from the interview can also be seen categorized in a similar way from the observation:

- Brainstorming: reference image, diagram, and hand drawing
- Drawing: CAD 2D, Revit
- Modeling: CAD 3D, Revit
- Visulization: CAD 3D, Revit

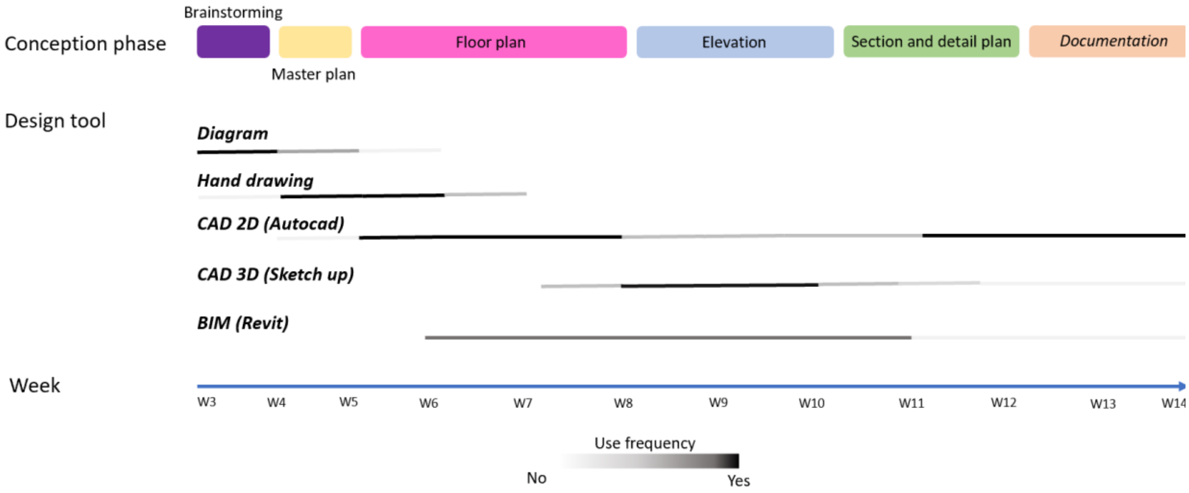


Figure 6-19: Illustration of frequency of design tool used for conception.

6.3.5 Integration of Bioclimatic Strategies

At the beginning of the design process, all groups set a goal to achieve maximum building comfort by implementing bioclimatic design strategies. However, specific elements of these design strategies to meet the goal of building comfort are not identified at this initial stage. Throughout the design process, the focus on integrated bioclimatic strategies evolved according to their conceptual phase. Sun protection and natural ventilation emerged as the two primary passive design elements prioritized throughout the design process. Additionally, efforts are made to incorporate landscape design to benefit the building, including the creation of a microclimate around the building. Green façade is primarily integrated into façade design as shading devices. Natural ventilation is more effectively incorporated into both the floor plan and façade design, utilizing elements such as louvers and strategic space arrangement. Other aspects of passive design are addressed within the floor plan and building envelope. However, the structural design phase does not appear to focus on bioclimatic design considerations.

While there is a clear understanding of some passive strategies, there is also noticeable confusion. For instance, while the teams effectively highlight how their designs enhance natural ventilation, they face challenges in analyzing sun path data to design appropriate shading devices. Consequently, they rely more on visualization tools to assess shading options and select the most suitable design based on these results. Regarding energy or thermal performance analysis, students cannot currently conduct thorough analyses using these methods. Their building analysis through visualization primarily focuses on natural light and shading.

Initially, there is a strong emphasis on incorporating passive design principles, with every design decision considering its impact on building comfort. However, toward the end of the design process, as the correction loop starts presenting, the focus shifts to addressing structural, functional, and aesthetic concerns. As a result, the passive design principles integrated at the beginning of the process are often abandoned in favor of these other priorities.

6.3.6 Collective Design

In this group project, which involves designing multiple buildings, the workload was divided among members, with some working individually on specific buildings and others collaborating in pairs. At the beginning of the design process, the group worked collaboratively to develop the master plan, ensuring that the final design was agreed upon by all members. Following the development of the master plan, design tasks were assigned to individual group members or pairs based on the specific buildings.

The study identifies three types of collective design approaches observed throughout the design process, two of which align with those discussed in the literature review and one that is novel and not previously documented. The three collective design approaches identified are:

- **Co-design**: where two members work on the same building by dividing their work and discussing building design from the start till the end (including decision-making and validation), practice in all groups except 2A.

- **Design distribution**: where each actor works individually on designing their building and design decisions made individually, practice in group 2A.

- **Design coordination**: where members work individually on their building design but ask their team members for ideas on certain design aspects and validation, practice in groups 5A and 6A.

During this design process, particularly starting from the elevation phase, in order to get a good design production and be on time with the deadline, they mentioned during the interview that they tend to divide their work based on their skill which allows us to see 3 profiles of actor:

- **The all-rounder**: mostly the member who has the most reliable skill in all aspects (design, software, building analysis…) where they verify the 2D plan and master plan to be coherent and make sure that everything has good quality and correct. Throughout the design process, this actor profile also normally helps with decision-making and validation.

- **The skilled**: a member that has the most expertise whether in modeling, rendering, or graphics, they focus on these tasks.

- **The supporter**: which is rarely seen in a group, this actor provides all information needed concerning their building to the other actors.

Each group works differently in terms of the collaboration method of collective design work. However, the tools for their collaboration and coordination are very similar. The table below shows the software related to the collaboration that was used during the design process. The tools they use for collaboration don’t impact their design process from one to another.

Table 6-2: Tools used for collaboration purposes

Type of collaboration	Tools
Model/ data sharing	No
Communication	Telegram, Messenger
Production Stockage	Individually, Google Drive

We can see that the design process from one group to another is similar concerning the design phase and tool used. However, the work coordination and collaboration can be very different. There is no protocol or method that all groups can follow to have a workflow that is effective in their design production.

6.4 Integration of BIM and BPS in the Design Process

BIM software is starting to adapt for practice in both professional and educational environments for architectural design, even though it is still limited. Even though BIM and BPS are expected to be more cooperative in the design process in the future, BIM and BPS practice currently don’t benefit the architects in terms of decision support in the early design phase to achieve bioclimatic building. The complexity of the BIM model and BPS would prolong the design process as mentioned in the interview. More than that, BPS does not seem to be suitable to be used directly by architects to help them analyze their building design and act as a decision support for design strategy choices.

It is noted that BIM and BPS are not yet adaptable solutions for decision-making support during the early design process in Cambodia. This is due to the need for expertise and extensive data, both of which are currently limited in the country. To better align with the existing architectural design processes in both professional and educational environments, a simplified method or tool should be developed. This tool would facilitate informed decision-making for achieving optimal indoor thermal comfort, designed for use by non-experts and without requiring large amounts of input data. While BIM and BPS can still play a role, their application would be more appropriate for complex buildings and in the later stages of the design process, where more detailed data is available. A proposed architectural design process integrating these two approaches will be presented in Chapter 7.

6.5 Esad: Decision Support for Analysis of Building Thermal Performance at the Early Design Phase

A simplified tool for the analysis of building thermal performance at the early design phase is proposed in this section. Esad (Exel sheet aid design) aims to help architects and designers make informed decisions when choosing design strategies to achieve optimum building thermal comfort. The tool is in the form of spreadsheets where you can input general building data such as building geometry, construction material, occupancy, and horizontal shadow which are the data that are normally known at the early design phase.

In the context of building thermal comfort, indoor temperature is a critical parameter in architectural design. Furthermore, as identified in Chapter 4, air velocity significantly influences occupant comfort levels, particularly in the Cambodian context. In designing buildings for Cambodia, solar heat gain and natural ventilation emerge as key factors impacting both indoor temperature and air velocity. Consequently, the calculations within Esad are oriented towards showing the effects of solar gain and airflow in buildings. Specifically, two critical factors are evaluated to demonstrate these impacts: indoor temperature and the PMV, employing an adaptive PMV model that prioritizes the influence of air velocity.

The output from Esad is not intended to provide architects with real-time temperature or PMV data for specific structures. Instead, it serves as a comparative tool, enabling architects to evaluate various design strategies and identify those that may enhance thermal comfort, thus supporting informed decision-making processes.

The first calculation is centered on determining the indoor temperature of the building. This analysis aims to assess the effects of solar gain resulting from various window positions, the building's orientation, and the incorporation of horizontal shading devices. Given that the calculation is designed for conditions of natural ventilation, a non-steady-state energy balance is typically employed to account for the variability of the outdoor environment over time. However, this approach entails a complex calculation process that is generally utilized in BPS tools.

Contrasting to BPS, Esad is intended for simplified and expedited calculations, without the objective of producing real-time temperature results. Therefore, we opted for a steady-state approach, which streamlines the calculation process by reducing the number of parameters required and utilizing data readily available to architects during the early design phase. This approach still allows for the assessment of the impacts of solar gain and airflow on indoor temperature. To account for temperature fluctuations between day and night, the calculation is structured to provide hourly assessments.

For the calculation of indoor temperature in steady state approach, we take the energy balance equation from the European Standard EN ISO 13790 (ISO13790, 2008) which includes equations 6-1, 6-2, and 6-5. The equation used for the calculation of ventilation rate equations 6-3 and 6-4 is taken from European Standard prEN 15242 (PrEN15242, 2006).

$$T_i = \frac{\sum IFA + Q_i + T_e(\sum H_V t + \sum H_T t)}{(\sum H_V t + \sum H_T t)} \qquad \text{Eq. 6-1}$$

Where

T_i : Indoor temperature (°C)

T_e : Outdoor temperature (°C)

Q_i : Internal gain (MJ)

H_V: Coefficient of lost by transmission from ventilation (W/K)

H_T : Coefficient of lost by transmission from transition of the wall and roof (W/K)

I : Solar radiation total during the calculation period on a surface (MJ/m^2)

F : Reduction factor by shadow

A : Collective surface of effective opening (m^2)

t : Duration of calculation (Ms)

$$H_v = \varphi_a . C_a . V_v \qquad \text{Eq. 6-2}$$

Where :

$\varphi_a . c_a$: Heat capacity = 1200J/(m^3.K)

V_v : Ventilation rate/airflow (m^3/s)

$$\mathrm{V_v = 3{,}6\,.\,500\,.\,Aow.\,V^{0.5}} \qquad \text{Eq. 6-3}$$

$$\mathrm{V = Ct + Cw.\,Vmet^2 + Cst.\,Hwindow.\,abs(\,t_i - t_e)} \qquad \text{Eq. 6-4}$$

Where:

Aow : window opening area (m^2)

Ct =0.01 takes into account wind turbulence

Cw= 0.001 takes into account wind speed

Cst= 0.0035 takes into account the stack effect

Hwindow : free area height of the window (m)

Vmet : meteorological wind speed at 10 m height (m/s)

t_i : room air temperature

t_e : outdoor air temperature.

$$H_T = \sum_j A_j \;.\, U_j \qquad \text{Eq. 6-5}$$

Where:

A_j : Effective surface (m^2)

U_j : Coefficient of thermal transmission, Uvalue ($W/m^2.K$)

For the calculation of the shadow factor, we focus more on the horizontal shading as it is more effective and can be defined in the building design. The equation used for calculating the shadow is written by the author as below:

$$F = 1 - \frac{(tan\,\alpha).L}{H+h} \qquad \text{Eq. 6-6}$$

α: the elevation angle of the sun

L: length of the shading device (m)

H: height of the window or opening (m)

h: height of the shading device from the window or opening (m)

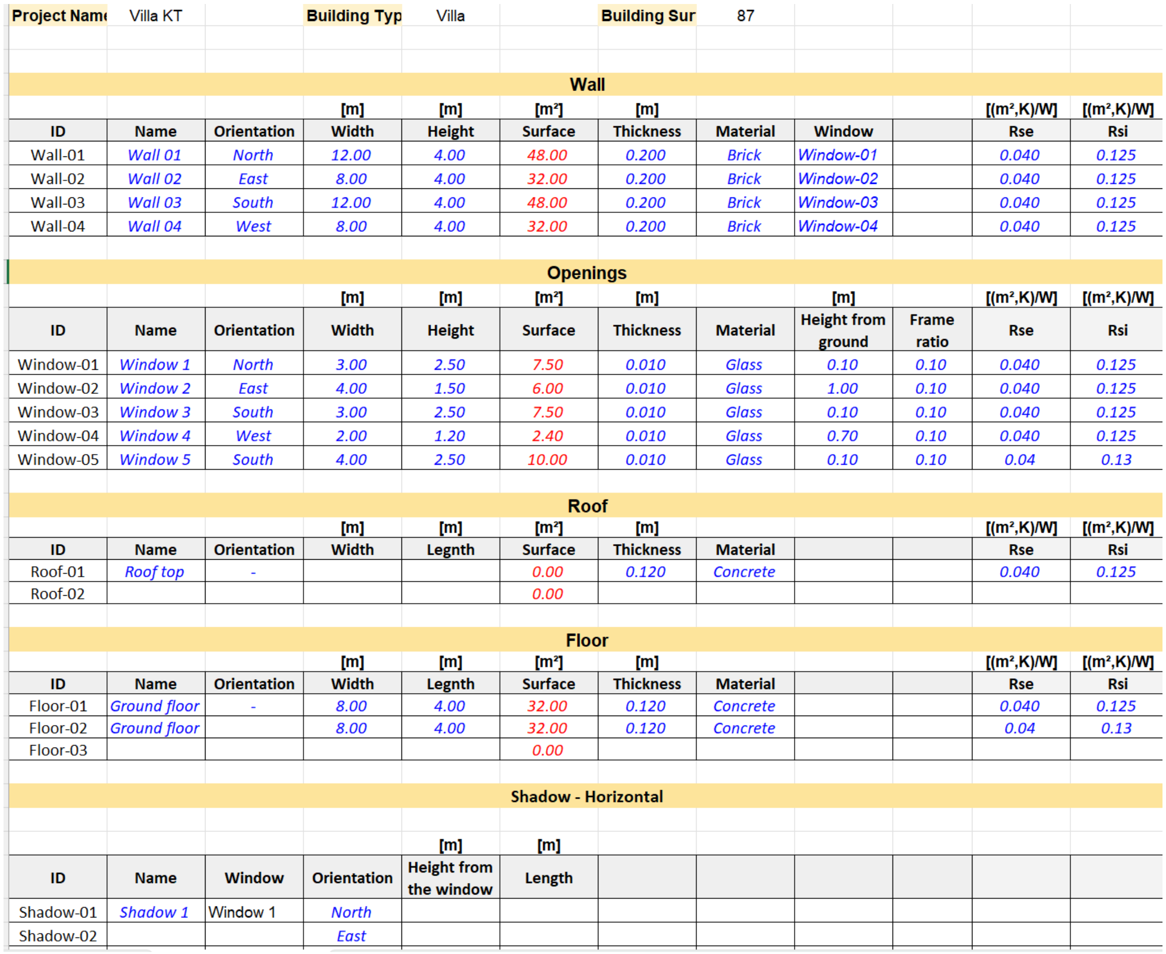
For the calculation of the PMV, we take the equation of PMV adaptive found in Chapter 4 (equation 4.5). The usage of this equation for the calculation favors the importance of air velocity for the comfort of occupants making it adaptive to the context of Cambodia. These two factors calculation approach emphasizes the importance of solar gain and air velocity in building design, ensuring that design choices are more suitable for the specific climatic conditions in Cambodia. By incorporating these factors, the tool enhances the adaptability of architectural designs to the local context, promoting better thermal comfort for occupants.

The outdoor weather data used for the calculation is the same weather data that was used for the case study building simulation in DesignBuilder. The TYMX file was transformed into an Excel sheet with all the data needed for the calculation including temperature, humidity, solar radiation, solar azimuth, sun elevation, air velocity, wind direction…

To begin the calculation, data on building geometry, internal gain (occupant, house equipment), and shading device need to be completed. The first sheet is the Encoding data sheet where architects and designers can input all necessary data needed for the calculation. Figure 6-20 present the Encoding sheet of Esad that is divided into 5 categories to be completed:

- Wall: all the exterior walls that could have heat transfer with outdoor.
- Opening: all the exterior openings including windows and doors that can receive solar heat gain and airflow.
- Roof and floor.
- Horizontal shadow: horizontal shading device design for the building including roof overhang.
- Activities: number of occupants and equipment that produce heat used in the building.

For the building envelope, Esad includes a column where users can select materials for their envelope from options that are commonly used in Cambodia. Currently, the calculation is based on single-layer walls or roofs, meaning it does not account for multi-layered constructions, such as insulated walls. Given that insulation is not yet widely adopted in building design in Cambodia, this limitation is unlikely to pose significant issues in the current context. For each essential element in the tool, a fixed unit value is provided to guide users and help avoid errors in the calculation. The ID and name of these elements are independent of the calculation, allowing users to choose any name they prefer without affecting the results.



Project Nam	Villa KT		**Building Typ**	Villa		**Building Sur**	87

Wall

			[m]	[m]	[m²]	[m]				[(m²,K)/W]	[(m²,K)/W]
ID	**Name**	**Orientation**	**Width**	**Height**	**Surface**	**Thickness**	**Material**	**Window**		**Rse**	**Rsi**
Wall-01	Wall 01	North	12.00	4.00	48.00	0.200	Brick	Window-01		0.040	0.125
Wall-02	Wall 02	East	8.00	4.00	32.00	0.200	Brick	Window-02		0.040	0.125
Wall-03	Wall 03	South	12.00	4.00	48.00	0.200	Brick	Window-03		0.040	0.125
Wall-04	Wall 04	West	8.00	4.00	32.00	0.200	Brick	Window-04		0.040	0.125

Openings

			[m]	[m]	[m²]	[m]		[m]		[(m²,K)/W]	[(m²,K)/W]
ID	**Name**	**Orientation**	**Width**	**Height**	**Surface**	**Thickness**	**Material**	**Height from ground**	**Frame ratio**	**Rse**	**Rsi**
Window-01	Window 1	North	3.00	2.50	7.50	0.010	Glass	0.10	0.10	0.040	0.125
Window-02	Window 2	East	4.00	1.50	6.00	0.010	Glass	1.00	0.10	0.040	0.125
Window-03	Window 3	South	3.00	2.50	7.50	0.010	Glass	0.10	0.10	0.040	0.125
Window-04	Window 4	West	2.00	1.20	2.40	0.010	Glass	0.70	0.10	0.040	0.125
Window-05	Window 5	South	4.00	2.50	10.00	0.010	Glass	0.10	0.10	0.04	0.13

Roof

			[m]	[m]	[m²]	[m]				[(m²,K)/W]	[(m²,K)/W]
ID	**Name**	**Orientation**	**Width**	**Legnth**	**Surface**	**Thickness**	**Material**			**Rse**	**Rsi**
Roof-01	Roof top	-			0.00	0.120	Concrete			0.040	0.125
Roof-02					0.00						

Floor

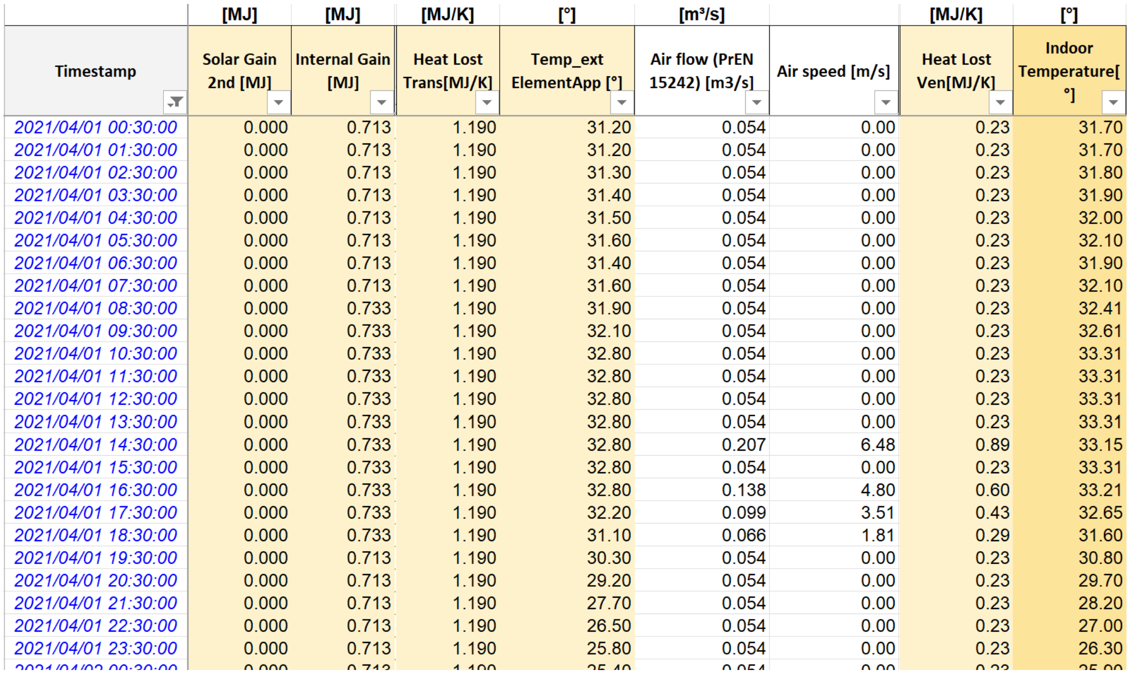
			[m]	[m]	[m²]	[m]				[(m²,K)/W]	[(m²,K)/W]
ID	**Name**	**Orientation**	**Width**	**Legnth**	**Surface**	**Thickness**	**Material**			**Rse**	**Rsi**
Floor-01	Ground floor	-	8.00	4.00	32.00	0.120	Concrete			0.040	0.125
Floor-02	Ground floor		8.00	4.00	32.00	0.120	Concrete			0.04	0.13
Floor-03					0.00						

Shadow - Horizontal

				[m]	[m]
ID	**Name**	**Window**	**Orientation**	**Height from the window**	**Length**
Shadow-01	Shadow 1	Window 1	North		
Shadow-02			East		

Figure 6-20: Encoding sheet of Esad.

Three sheets are available to users where they present the result of the building's thermal performance. Figure 6-21 presents the sheet that shows the calculation result of the indoor temperature. In this sheet, users can also find the calculation of solar gain, internal gain, heat lost by transmission, and the calculation of airflow enabling architects to see the effect of their design strategies on different parameters that impact on temperature. The users have the option to pick any month of the year that they would like to perform their analysis. The figure below is the result calculated for house T2 in April which is considered the hottest month in Cambodia. We also provided a sheet with results in the graph for easy assessment of the result as shown in Figure 6-22. Figure *6-23* shows the sheet that presents the calculation result of the PMV using the PMV adaptive equation for Cambodia. The result of the PMV is also presented in a graph for easy evaluation as well.



	[MJ]	[MJ]	[MJ/K]	[°]	[m³/s]		[MJ/K]	[°]
Timestamp	Solar Gain 2nd [MJ]	Internal Gain [MJ]	Heat Lost Trans[MJ/K]	Temp_ext ElementApp [°]	Air flow (PrEN 15242) [m3/s]	Air speed [m/s]	Heat Lost Ven[MJ/K]	Indoor Temperature[°]
2021/04/01 00:30:00	0.000	0.713	1.190	31.20	0.054	0.00	0.23	31.70
2021/04/01 01:30:00	0.000	0.713	1.190	31.20	0.054	0.00	0.23	31.70
2021/04/01 02:30:00	0.000	0.713	1.190	31.30	0.054	0.00	0.23	31.80
2021/04/01 03:30:00	0.000	0.713	1.190	31.40	0.054	0.00	0.23	31.90
2021/04/01 04:30:00	0.000	0.713	1.190	31.50	0.054	0.00	0.23	32.00
2021/04/01 05:30:00	0.000	0.713	1.190	31.60	0.054	0.00	0.23	32.10
2021/04/01 06:30:00	0.000	0.713	1.190	31.40	0.054	0.00	0.23	31.90
2021/04/01 07:30:00	0.000	0.713	1.190	31.60	0.054	0.00	0.23	32.10
2021/04/01 08:30:00	0.000	0.733	1.190	31.90	0.054	0.00	0.23	32.41
2021/04/01 09:30:00	0.000	0.733	1.190	32.10	0.054	0.00	0.23	32.61
2021/04/01 10:30:00	0.000	0.733	1.190	32.80	0.054	0.00	0.23	33.31
2021/04/01 11:30:00	0.000	0.733	1.190	32.80	0.054	0.00	0.23	33.31
2021/04/01 12:30:00	0.000	0.733	1.190	32.80	0.054	0.00	0.23	33.31
2021/04/01 13:30:00	0.000	0.733	1.190	32.80	0.054	0.00	0.23	33.31
2021/04/01 14:30:00	0.000	0.733	1.190	32.80	0.207	6.48	0.89	33.15
2021/04/01 15:30:00	0.000	0.733	1.190	32.80	0.054	0.00	0.23	33.31
2021/04/01 16:30:00	0.000	0.733	1.190	32.80	0.138	4.80	0.60	33.21
2021/04/01 17:30:00	0.000	0.733	1.190	32.20	0.099	3.51	0.43	32.65
2021/04/01 18:30:00	0.000	0.733	1.190	31.10	0.066	1.81	0.29	31.60
2021/04/01 19:30:00	0.000	0.713	1.190	30.30	0.054	0.00	0.23	30.80
2021/04/01 20:30:00	0.000	0.713	1.190	29.20	0.054	0.00	0.23	29.70
2021/04/01 21:30:00	0.000	0.713	1.190	27.70	0.054	0.00	0.23	28.20
2021/04/01 22:30:00	0.000	0.713	1.190	26.50	0.054	0.00	0.23	27.00
2021/04/01 23:30:00	0.000	0.713	1.190	25.80	0.054	0.00	0.23	26.30

Figure 6-21: The sheet presents the calculation of indoor temperature (calculation using the geometry of house T2, the house has full shading on the openings).

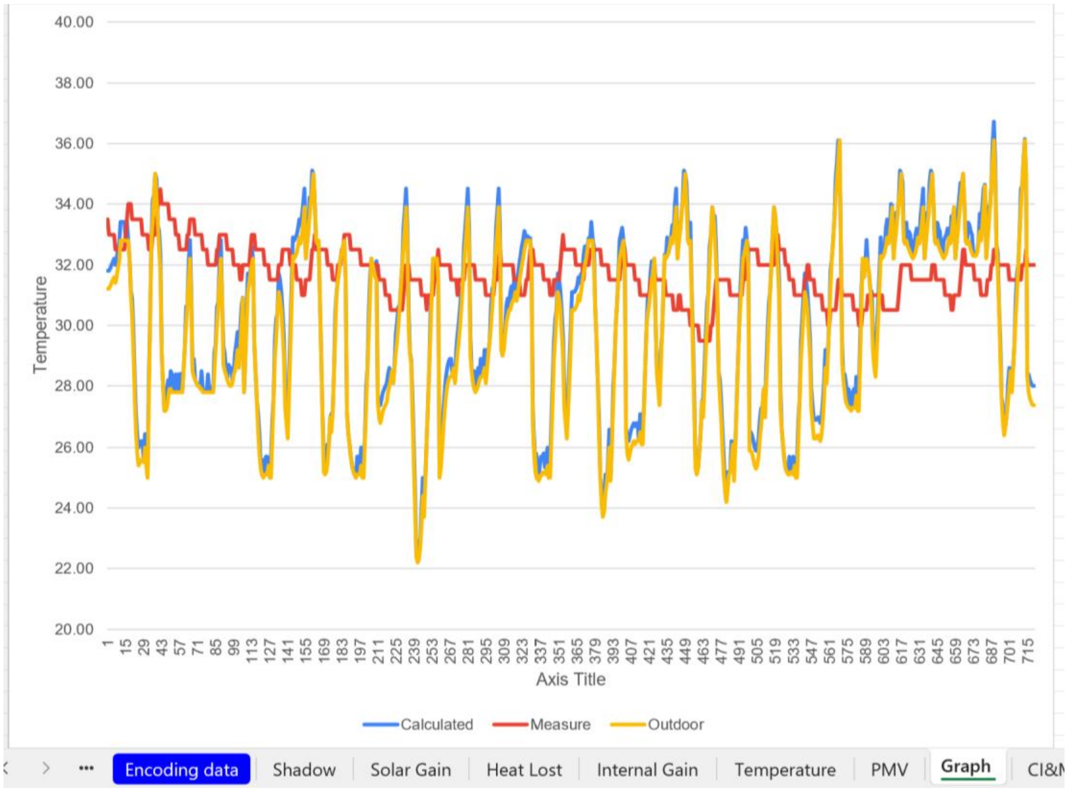
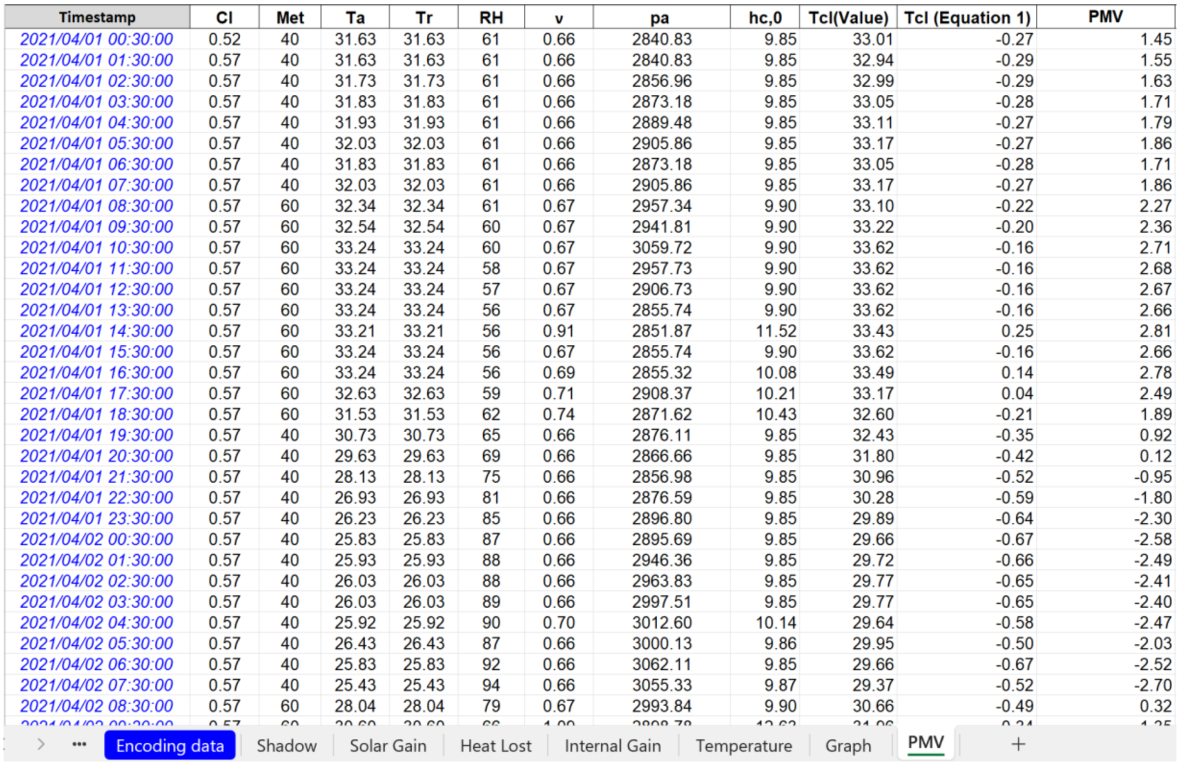


Figure 6-22: The sheet presents a graph of the indoor temperature.



Timestamp	Cl	Met	Ta	Tr	RH	v	pa	hc,0	Tcl(Value)	Tcl (Equation 1)	PMV
2021/04/01 00:30:00	0.52	40	31.63	31.63	61	0.66	2840.83	9.85	33.01	-0.27	1.45
2021/04/01 01:30:00	0.57	40	31.63	31.63	61	0.66	2840.83	9.85	32.94	-0.29	1.55
2021/04/01 02:30:00	0.57	40	31.73	31.73	61	0.66	2856.96	9.85	32.99	-0.29	1.63
2021/04/01 03:30:00	0.57	40	31.83	31.83	61	0.66	2873.18	9.85	33.05	-0.28	1.71
2021/04/01 04:30:00	0.57	40	31.93	31.93	61	0.66	2889.48	9.85	33.11	-0.27	1.79
2021/04/01 05:30:00	0.57	40	32.03	32.03	61	0.66	2905.86	9.85	33.17	-0.27	1.86
2021/04/01 06:30:00	0.57	40	31.83	31.83	61	0.66	2873.18	9.85	33.05	-0.28	1.71
2021/04/01 07:30:00	0.57	40	32.03	32.03	61	0.66	2905.86	9.85	33.17	-0.27	1.86
2021/04/01 08:30:00	0.57	60	32.34	32.34	61	0.67	2957.34	9.90	33.10	-0.22	2.27
2021/04/01 09:30:00	0.57	60	32.54	32.54	60	0.67	2941.81	9.90	33.22	-0.20	2.36
2021/04/01 10:30:00	0.57	60	33.24	33.24	60	0.67	3059.72	9.90	33.62	-0.16	2.71
2021/04/01 11:30:00	0.57	60	33.24	33.24	58	0.67	2957.73	9.90	33.62	-0.16	2.68
2021/04/01 12:30:00	0.57	60	33.24	33.24	57	0.67	2906.73	9.90	33.62	-0.16	2.67
2021/04/01 13:30:00	0.57	60	33.24	33.24	56	0.67	2855.74	9.90	33.62	-0.16	2.66
2021/04/01 14:30:00	0.57	60	33.21	33.21	56	0.91	2851.87	11.52	33.43	0.25	2.81
2021/04/01 15:30:00	0.57	60	33.24	33.24	56	0.67	2855.74	9.90	33.62	-0.16	2.66
2021/04/01 16:30:00	0.57	60	33.24	33.24	56	0.69	2855.32	10.08	33.49	0.14	2.78
2021/04/01 17:30:00	0.57	60	32.63	32.63	59	0.71	2908.37	10.21	33.17	0.04	2.49
2021/04/01 18:30:00	0.57	60	31.53	31.53	62	0.74	2871.62	10.43	32.60	-0.21	1.89
2021/04/01 19:30:00	0.57	40	30.73	30.73	65	0.66	2876.11	9.85	32.43	-0.35	0.92
2021/04/01 20:30:00	0.57	40	29.63	29.63	69	0.66	2866.66	9.85	31.80	-0.42	0.12
2021/04/01 21:30:00	0.57	40	28.13	28.13	75	0.66	2856.98	9.85	30.96	-0.52	-0.95
2021/04/01 22:30:00	0.57	40	26.93	26.93	81	0.66	2876.59	9.85	30.28	-0.59	-1.80
2021/04/01 23:30:00	0.57	40	26.23	26.23	85	0.66	2896.80	9.85	29.89	-0.64	-2.30
2021/04/02 00:30:00	0.57	40	25.83	25.83	87	0.66	2895.69	9.85	29.66	-0.67	-2.58
2021/04/02 01:30:00	0.57	40	25.93	25.93	88	0.66	2946.36	9.85	29.72	-0.66	-2.49
2021/04/02 02:30:00	0.57	40	26.03	26.03	88	0.66	2963.83	9.85	29.77	-0.65	-2.41
2021/04/02 03:30:00	0.57	40	26.03	26.03	89	0.66	2997.51	9.85	29.77	-0.65	-2.40
2021/04/02 04:30:00	0.57	40	25.92	25.92	90	0.70	3012.60	10.14	29.64	-0.58	-2.47
2021/04/02 05:30:00	0.57	40	26.43	26.43	87	0.66	3000.13	9.86	29.95	-0.50	-2.03
2021/04/02 06:30:00	0.57	40	25.83	25.83	92	0.66	3062.11	9.85	29.66	-0.67	-2.52
2021/04/02 07:30:00	0.57	40	25.43	25.43	94	0.66	3055.33	9.87	29.37	-0.52	-2.70
2021/04/02 08:30:00	0.57	60	28.04	28.04	79	0.67	2993.84	9.90	30.66	-0.49	0.32

Figure 6-23: The sheet presents the calculation of adaptive PMV (result using the geometry of house T2).

In Figure 6-22, we notice that the temperature calculated by the tool closely aligns with the outdoor temperature. In this calculation, we assume that all windows are fully open, allowing 100% of their surface area to be exposed and that all openings are completely shaded from direct solar radiation (as in house T2). Under these conditions, with all windows open and no additional solar gain, the indoor temperature from the calculation mirrors the outdoor temperature. For a simple building design that relies on natural ventilation and does not use any mechanical methods to remove heat, the indoor temperature should theoretically be higher than the outdoor temperature due to heat gains from solar radiation and building occupancy. However, indoor temperatures can remain lower than outdoor temperatures if windows are kept closed during the day to retain the cooler air from dawn until the morning. Unfortunately, this is one of the factors that Esad can’t show in the result which results in the indoor temperature always staying higher than the outdoor temperature in Esad.

However, if architects have two design options with variations in opening orientation, opening size, shading devices, or wall and window thickness and materials, they can assess how these adjustments impact the building’s thermal performance, providing them with informed decision support. As mentioned earlier, the temperature calculations are intended to assess the impact of design choices concerning solar gain. Figure 6-24 and Figure 6-25 illustrate the impact of various design choices on the building's thermal performance, with a particular focus on temperature increases resulting from solar gain. These figures highlight the effects of shading device configurations and window placement on indoor temperature. When shading devices are not used, the indoor temperature increases significantly, illustrating the critical role of shading in maintaining thermal comfort. Additionally, it is observed that south-facing windows generate more heat gain than north-facing windows.

In this scenario, even with a relatively small window surface area of just 4 square meters, the impact of design decisions is already noticeable. The lack of shading devices leads to a marked increase in indoor temperature, and the orientation of windows further captures the heat gain. If the window area were larger, the effect would be even more pronounced, underscoring the importance of careful consideration of both shading strategies and window placement in building design to optimize thermal performance.

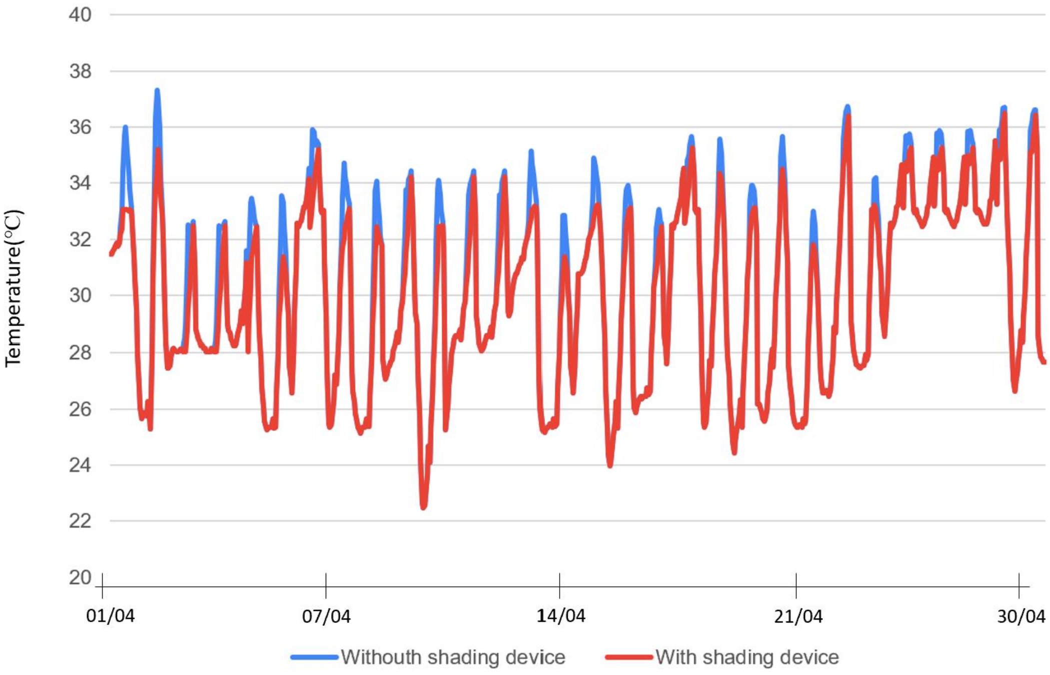


Figure 6-24: Indoor temperature calculated with and without the shading device.

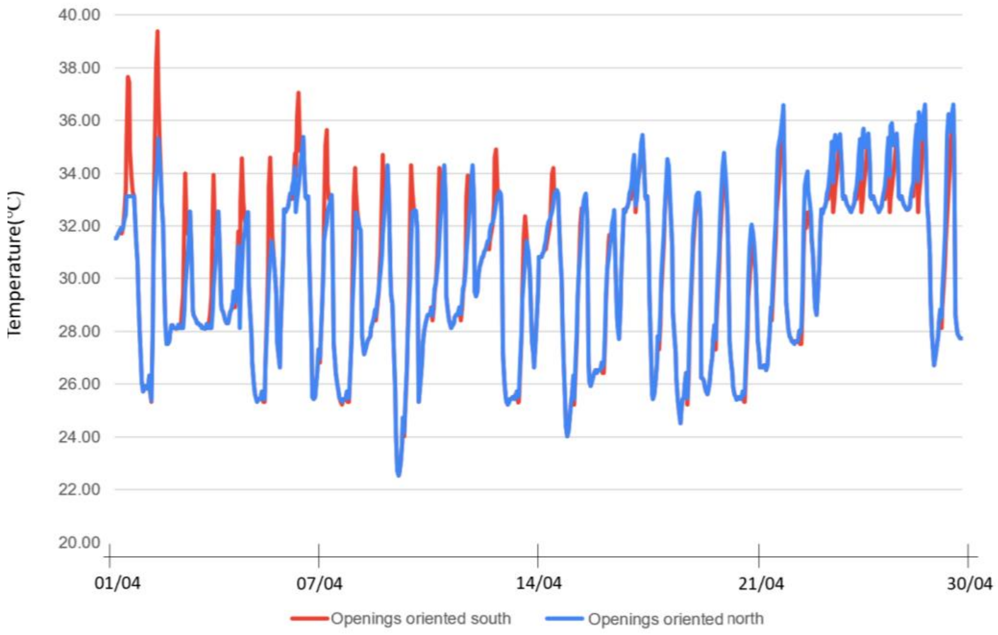


Figure 6-25: Indoor temperature with window change orientation from south to north.

More than the result of temperature, Esad also calculated PMV with a focus on seeing the effect of openings on natural ventilation. As the direction of the prominent wind is the same as the orientation with exposure longer to the sun for Cambodia, the result of PMV could help architects further evaluate their design choices (e.g., the window placement is good for sun protection but not good for airflow). In Figure 6-26 and Figure 6-27, we can see the comparison of PMV between the two orientations of the window placement. Placing the window to the south gives an average temperature of 30.28 ℃ while the window placed to the east gives an average temperature of 30.08 ℃. However, despite having a higher average temperature, the building design with the window facing south has an average PMV of 0.65 while the other building design has an average PMV of 0.7 which is reasonable as the south is the prominent wind direction. The architect can probably keep the window to the south orientation and find solutions to lower temperatures with horizontal shading or integrating other design strategies. The calculation of PMV that is adaptive to the context of Cambodia, therefore, could help the designer to have a deeper and better analysis of the impact of their different design choices.

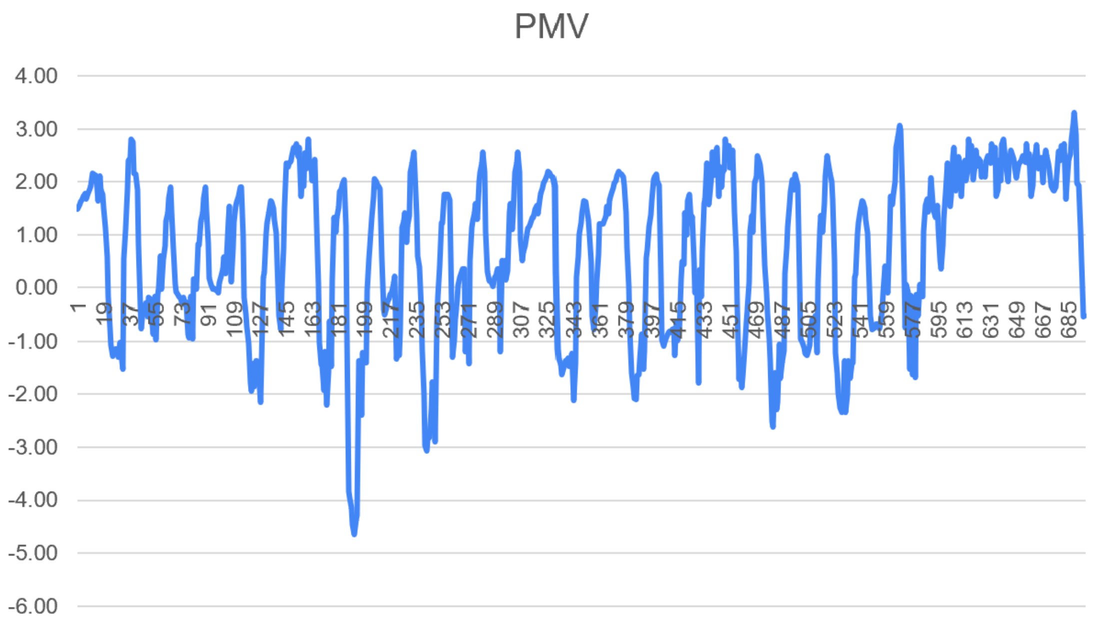


Figure 6-26: PMV when the window is placed on the east facade.

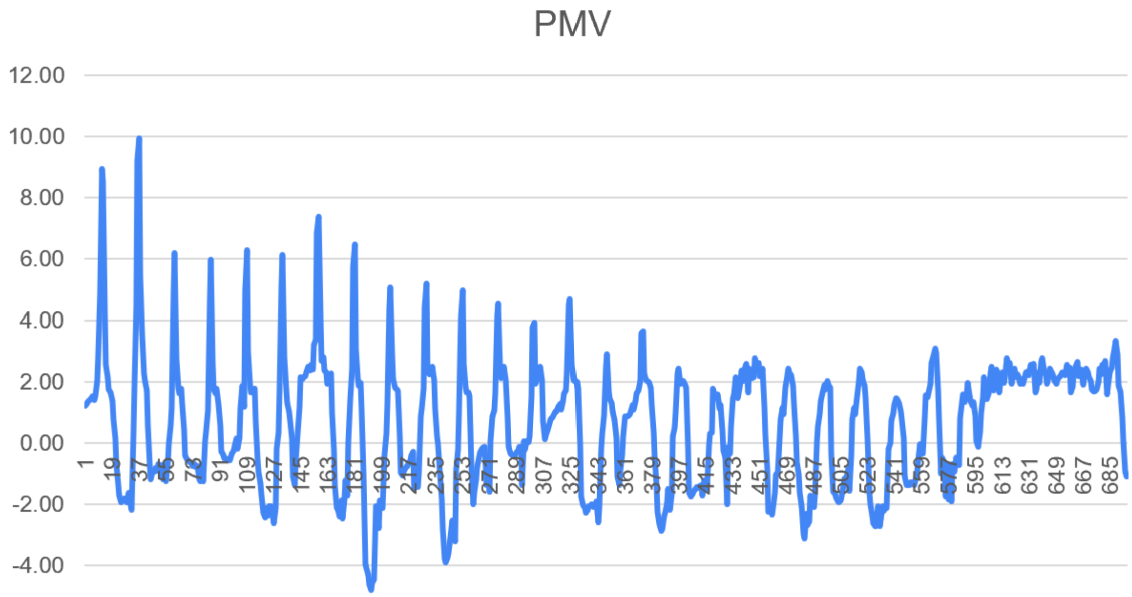


Figure 6-27: PMV when the window is placed in the south facade.

6.6 Strength and Limit of Esad

Esad is designed to serve as a decision support tool for architects and designers during the early design phase, helping them make informed choices about building design strategies based on the calculation of parameters that influence thermal comfort. This version of Esad successfully achieves that objective. It is user-friendly and straightforward, making it accessible to both experts and non-experts in the building design environment. More than that, Esad also adopted the calculation which focuses on factors that are the most important for building design in Cambodia. The calculation of both temperature and PMV gives architects numerous ways to evaluate their design strategy for informed decision-making. Esad also proves that applying bioclimatic design strategies can effectively lower building temperatures and achieve a better PMV. The inclusion of adaptive PMV calculations also makes this tool particularly suitable for projects in Cambodia, further proving that Esad can be a reliable decision support tool for architects.

The simplicity in terms of calculation in Esad limits this tool from analysis of building thermal performance in real-time. As seen in the previous section, the temperatures shown in Esad tend to closely align with outdoor temperatures. For instance, when calculating for house T2, the results significantly differ from actual measurements and more advanced simulations. This discrepancy is understandable, given the many factors influencing thermal performance. Even with simulation tools, considered among the most reliable methods for thermal performance analysis, accurate results often require calibration through multiple trials and errors. Esad's calculations are much simpler than those produced by simulation software, and several key factors affecting indoor temperature cannot be accounted for. These include the control of openings, shading from the surrounding environment, stack effect, nighttime cooling, and more. As a result, while Esad provides a basic estimation of thermal comfort, its results should be interpreted with an understanding of these limitations.

Another limitation of Esad is its inability to account for the complexity of building designs that incorporate certain advanced strategies. For example, bioclimatic design strategies that involve creating microclimates through the integration of ponds, or the use of double façades, green façades, or green roofs, cannot be accurately calculated in Esad. These factors are challenging to model even in more sophisticated BPS tools. One limitation of ESAD, when compared to the BPS, is its inability to perform multizonal calculations. This feature is particularly significant for architects, especially when making decisions regarding spatial arrangements. Due to the complexity of the equations involved, this functionality is not yet feasible in ESAD’s current version. However, extending this capability is a key objective for future developments of the tool.

Esad is primarily focused on fundamental aspects of building design, such as orientation, the position of openings, and the U-value of building materials. Since it is intended for quick calculations during the early design phase, adding more complex factors would increase the required input data and extend the time needed for calculations, potentially making it as time-consuming as detailed simulations. As it was designed to be used since the early design process, the minimal data requirement for calculation Esad makes it the most suitable tool for informed decision-making in this design phase.

This is the first version of Esad which can be further developed into a more comprehensive tool or platform, where more technical calculations and detailed data inputs can be incorporated. This would enhance its usefulness in the architectural design process.

6.7 Chapter Conclusion

In this chapter, the findings through two methods enable us to identify the current architectural design process in Cambodia and how BIM and BPS are integrated. The use of these two approaches in building design to achieve sustainability is still limited in this context. Even though we see an increase in the practice of BIM slowly in the construction sector, it is more useful for stakeholder collaboration and project management. The practice of BIM and BPS in Cambodia currently doesn’t act as decision support for architects to achieve sustainable design or optimal thermal performance in their buildings. They are used more for the purpose of achieving the green building certificate. The complexity of these two methods makes it hard to integrate them since the early design phase.

Esad, a decision support tool, in the form of spreadsheets is proposed as a tool to assist architects in achieving sustainability and thermal comfort in building design by analyzing the thermal performance of various design strategies. Although Esad has certain limitations in some aspects of analyzing building thermal performance, it serves effectively as a decision-support tool for architects from the early stages of the design process. It offers an efficient alternative to time-consuming tasks such as detailed modeling, simulation, and calibration, reducing the need for repetitive iterations in the design process.

BPS still can be integrated into the design process. However, it is recommended to integrate at the later stages of the design phase where the building has more details and certain design elements have already been evaluated using Esad to avoid running unnecessary simulations. Combining Esad in the early design phase and BPS in the later stage with integrating the BIM model during the early design phase would help architects and designers achieve optimal comfort for their building without prolonging the design process.

CHAPTER 7

DESIGN STRATEGIES AID DECISION MAKING: BIOCLIMATIC DESIGN GUIDELINE

In this chapter, we present a bioclimatic design guideline developed based on an analysis of Cambodia's climate, existing adaptable bioclimatic design strategies, and the local living context. This guideline is intended as decision support material to be used with Esad. Its effectiveness has been validated through usability testing conducted during the design process, as well as through building thermal performance simulations of bioclimatic building scenarios created from the test results.

7.1 Bioclimatic Design Guidelines for Cambodia (BDGC)

BDGC aims to provide architects with informed decision-making during the design process focusing on achieving low indoor temperatures, optimizing protection from direct sunlight, and maximizing natural airflow within buildings. In the context of building design, crucial factors such as temperature, humidity, sun path, wind speed, wind direction, and rainfall must be carefully considered. These elements significantly influence design decisions related to building orientation, the positioning of openings, space arrangement, shading devices, and construction materials.

In a hot-humid climate like Cambodia's, the goal is to design buildings that minimize direct sun exposure, maximize natural ventilation, reduce relative humidity, and allow for the possibility of keeping openings accessible during the rainy season to maintain fresh air circulation. To ensure the guideline is appropriately tailored to Cambodia's context, it is necessary to analyze the country's climatic conditions, examine the characteristics of traditional houses and their associated way of living, and identify suitable bioclimatic design strategies practiced in other countries with similar climates. This comprehensive approach ensures that the guideline is both relevant and effective in promoting comfortable and bioclimatic building designs in Cambodia.

7.1.1 Analyzing Climate Conditions of Cambodia

The monsoon weather in Cambodia makes it to have two significant seasons. However, in terms of temperature, relative humidity, and wind the variation between the two seasons isn’t high or noticeable. From analyzing the weather data presented in Chapter 4, we note some information that is crucial for the creation of the guideline:

- High solar elevation throughout the year (see Figure 4-8).
- Sun moves from east to west through the north axis for 4 months and through axe south for 8 months (see Figure 4-7).
- Solar is at its highest elevation when moving through the north axis while at its lowest elevation when moving through the south axis (see Figure 4-7 and Figure 4-8).
- The daytime period is similar between the two seasons when the sun normally rises at 6:00 am and sets at 6:30 pm (see Figure 4-7).
- Dominant wind between southwest and northeast, while stronger wind comes from the southwest with high humidity and northeast wind has less humidity (see Figure 4-4 and Figure 4-5).
- Heavy rain with an angle due to the wind (see Figure 4-6).

7.1.2 Characteristics of Cambodian Houses

Cambodian houses are normally welcome with a spacious living room. The living room is the first thing you see when entering a Cambodian house which is a semi-private space where the owner welcomes their guest into the house. Cambodians love to have big gatherings at home so the living room is always big in space and airy.

The kitchen is a private space for the family. Cambodians always think that the kitchen is a dirty space, so it is normally placed at the back of the house. There is usually a wall to separate private and semi-private spaces so that the guests won't see the kitchen directly as they enter the house. As Cambodian food has a strong smell, the kitchen is sometimes designed as a closed space and placed to avoid the direction of wind flow into other parts of the house or having a separate kitchen outside the house.

A big entrance door is always a must in Cambodian houses to welcome guests, for gatherings, for business purposes for townhouses, and to let maximum airflow as they live in a hot country. Traditionally, the entrance door means bringing a lot of luck and money into the family. For Feng Shui reasons, the entrance door and back door shouldn't be placed in the same direction. Each house has to have a space where they can put a small shrine for the house deity. It is normally placed face to the entrance door in the living room space. Some houses also have a shrine for their ancient family as well which is normally placed near or on top of the house deity shrine.

Privacy and security are very important for Cambodians. Bedrooms are mostly located at the end of the main living quarters in the private section and equipped with an ensuite bathroom for privacy reasons and convenience. The window is also normally designed to provide maximum security with wood or metal frames in the inside layer. In a traditional house, openings are designed as a casement window style with louvers of wood material. On the façade, close to the roof, there are normally breeze brick installed or openings designed for stack effect. The roof is also designed in pitch style with at least a 0.5 meter overhang for ventilation and protection of the façade from sun and rain. The window design in the current house is normally sliding with glazing material. An example of a contemporary house in Cambodia can be seen in the case study building T1 and D1. Below is an example of a contemporary traditional house that illustrates most of the characteristics presented above.

Figure 7-1: Plan and interior of a contemporary traditional house in Kratie Province.

7.1.3 Passive Cooling Strategies Practice in Tropical Region

From existing design strategies as presented briefly in Chapter 1, bioclimatic design strategies for hot humid tropical climates focus on passive cooling which includes designing the building to allow maximum ventilation and minimum direct sun radiation. And that includes design strategies such as:

- Creating a microclimate surrounding the building using water and vegetation to lower the outdoor temperature (Hosham & Kubota, 2019; Mv & Korovin, 2020).
- Positioning openings to create cross ventilation to enhance natural ventilation inside the building (Stasi et al., 2024).
- Creating stack or chimney effect to enhance natural ventilation and ensure lower temperature at the ground level through roof, courtyard, and stack ventilation (Rezadoost Dezfuli et al., 2023; Wahab & Ismail, 2012; Yusoff et al., 2010).
- Designing openings that would allow maximum ventilation to improve building thermal performance (Kitagawa et al., 2021).
- Design a roof that would promote natural ventilation and provide maximum sun protection such as double ventilated roof or green roof (Arch et al., 2010; Dareeju et al., 2011).
- Integrating shading devices to reduce direct solar radiation into the building through horizontal and vertical shading devices or vegetation (Leu & Boonyaputthipong, 2023; Zune et al., 2021).

- Using vertical landscapes such as green façades to provide shade to the external wall and reduce radiant temperature (Mohammad Shuhaimi et al., 2022; Rupasinghe & Halwatura, 2020).
- Using high heat resistance material to reduce the heat transfer from outdoors into the building (Jannat et al., 2020).

7.1.4 BDGC

Taking the analysis of the climate and living conditions as mentioned above and to answer the identified house design issue in Chapter 4, the guidelines aim to provide design strategies for maximum natural ventilation and minimum solar gain. This guideline focuses on using bioclimatic and passive design strategies for minimum household energy consumption. Figure 7-2 explains in more detail how all BDGC elements are put together. The 18 recommended elements are put together based on:

- Analysis of climate in Cambodia
- Bioclimatic strategies that have been practiced in the traditional and current buildings in Cambodia
- Bioclimatic strategies studied by other researchers in a similar climate
- Strategies used by students during the observation and mentioned by the architect during the architect interview
- Grouping according to the design phase identified from the observation and interview to facilitate its implementation into each design phase.

Following the design step as mentioned in Chapter 6, the guideline is divided into 5 categories for each design step such as:

- Building implementation: building orientation and microclimate
- Floor plan design: space arrangement and space composition
- Façade design: openings and shading devices
- Roof design
- Construction material

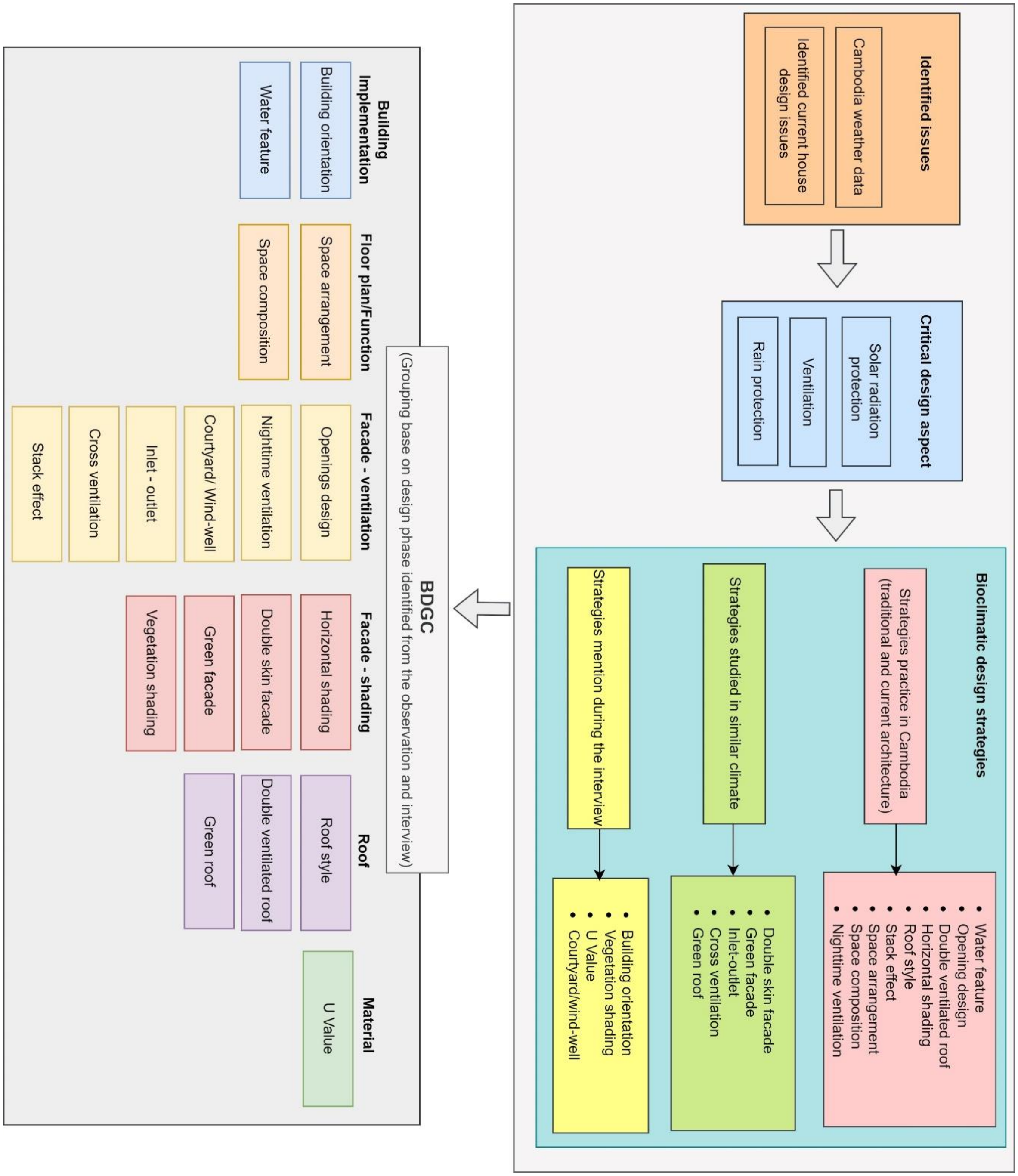


Figure 7-2: Diagram explains the creation of BDGC.

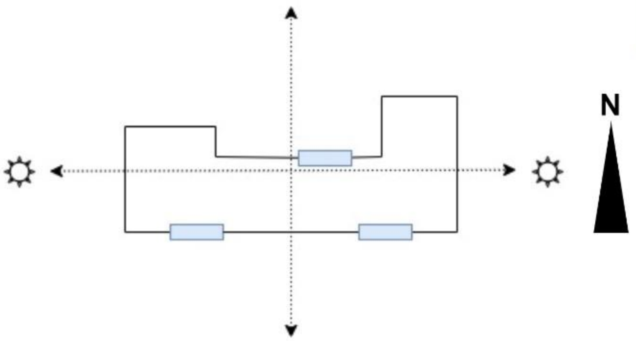
This is a simple guideline that focuses on recommending bioclimatic strategies that aim toward users at any level of experience in building design, especially in the context of Cambodia. The guideline is intended to be used as decision support material for architects and designers during the design process to achieve bioclimatic buildings (optimum comfort with minimum energy consumption). The guidelines are presented below:

7.1.4.1 Building Implementation

- **Building orientation**

The orientation of a building significantly influences the levels of solar radiation and wind exposure impacting the structure. Given Cambodia's proximity to the equator, the sun traverses from east to west, moving through a northern axis for four months and through a southern axis for eight months. Throughout the year, solar elevation in Cambodia remains high; however, it reaches its peak elevation during its passage along the northern axis, whereas along the southern axis, it is at a comparatively lower elevation. Consequently, solar radiation is less intense on the building façade when the sun is aligned with the northern axis, directing more radiation toward the horizontal surfaces, such as roofs.

In the afternoon, temperatures reach their highest point due to the accumulation of heat throughout the day. During this period, the sun's position shifts between the south and west, and a façade toward these directions would be especially vulnerable to additional heat gain. Therefore, west and south could be considered the orientations that should be avoided for sun protection. It is recommended to orient the building's long side along a north-south axis or at a 45° angle toward east orientation to reduce exposure from the sun and benefit from the wind direction.



- **Creating a microclimate surrounds the building**

Given Cambodia's consistently high temperatures throughout the year, creating a microclimate around buildings is highly recommended to enhance comfort. This can be achieved by incorporating elements like water bodies and various types of trees, which contribute to shading, temperature reduction through evaporation, and localized air movement.

A water feature, such as a pond or swimming pool, can be strategically placed on the north or east side of the building. This positioning helps to freshen the air and lower its temperature during the dry season when the dry wind flows from the east and north. Trees should be planted on the west or south sides of the building to provide maximum shade, reducing heat exposure during the hottest parts of the day. Additionally, trees with big leaves such as banana trees which are easy to grow in Cambodia can also help generate localized wind patterns, further contributing to a cooler and more comfortable indoor environment. As a country prone to high populations of insects and flies, the placement of water bodies should be carefully considered to minimize mosquito breeding. It is recommended that water features should take the form of either swimming pools or natural ponds with fish or other elements to promote water movement, as these options help to prevent mosquito populations from thriving.

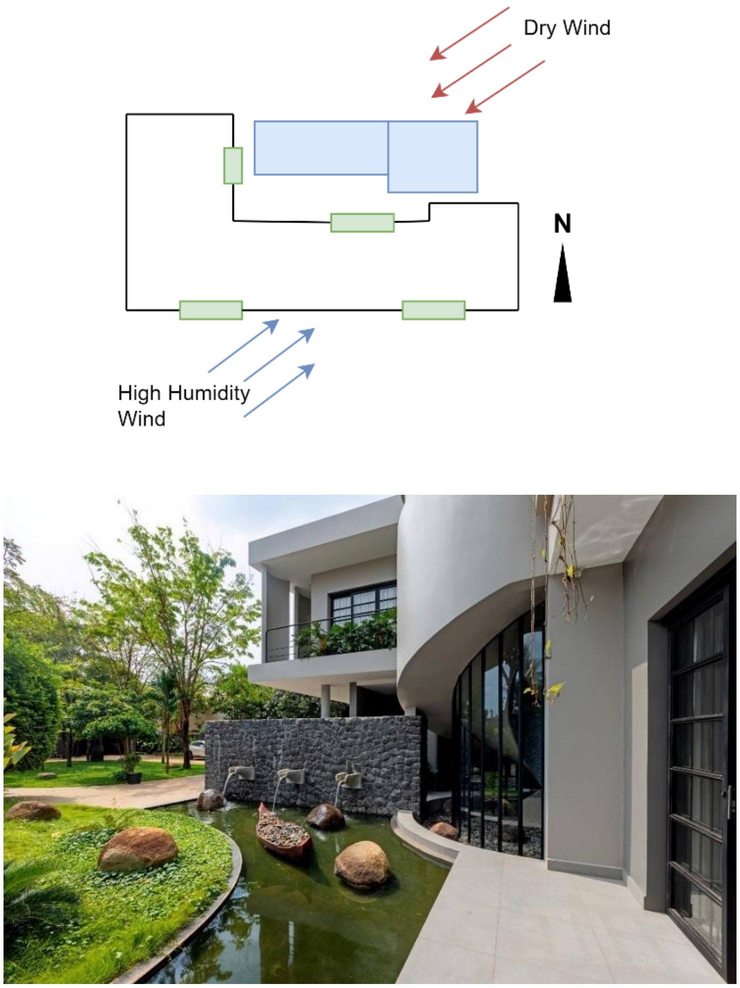


Figure 7-3: Example of integration of water feature to create microclimate surrounding the building, source: UAD Architects.

7.1.4.2 Floor Plan Design

- **Space arrangement**

Space arrangement is crucial in determining which areas of a building should be exposed to sunlight and which should be shielded from it. For this purpose, spaces within the building can be categorized into two types: frequently occupied spaces and rarely occupied spaces.

Frequently occupied spaces, such as living rooms, bedrooms, and offices, are areas where people spend a significant amount of time. These spaces should be designed to receive ample natural light while still being protected from excessive solar radiation to ensure comfort. On the other hand, rarely occupied spaces, like storage rooms, bathrooms, and garages, can be placed in locations with more exposure to direct sunlight to act as solar protection for the living space. By arranging these spaces thoughtfully, the building can maintain a comfortable indoor environment while optimizing energy efficiency.

- **Living space**

Living space is recommended to be placed away from direct sunlight and in the direction of prominent wind to allow maximum ventilation and minimum solar heat gain. For Cambodia, the prominent wind direction is between southwest and northeast and high solar exposure is south and west. The living space should be placed toward east and north orientation.

- **Storage space**

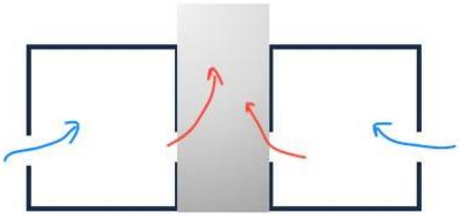
Storage and service space that isn’t occupied regularly such as a car garage, toilette, or laundry room should be put at an orientation that has strong direction sunlight to act as an insolation to protect living space from the heat. For Cambodia's climate, the west and south are a suitable orientation for such space.

- **Space composition**

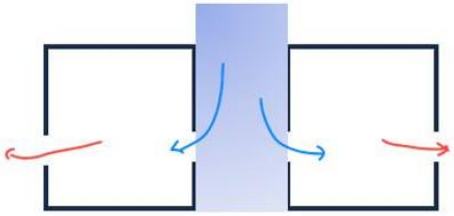
In hot and humid climates, building design should prioritize open spaces that facilitate effective wind flow. To enhance natural ventilation and maintain a comfortable indoor environment, building design should avoid compact and enclosed layouts. Instead, design spaces to be light and airy with minimal interior walls and doors. This openness allows for better air circulation and helps keep indoor spaces cooler. In the context of Cambodia, where food odors can be particularly strong, it's practical to design the kitchen with adequate separation or ventilation to manage these smells while still allowing for overall open and airy living spaces. Design space for furniture arrangement to avoid obstructing airflow through openings and create pathways for air to circulate freely.

- **Wind well (Courtyard effect)**

For fully attached buildings, such as apartment complexes or link houses, integrating features like wind wells can enhance natural ventilation and light entry through courtyards or stairwells. A courtyard combined with trees and water bodies can create a microclimate provided in the building as well. Courtyard space can benefit the building during both day and nighttime. During the day, the courtyard helps dissipate heat from the surrounding areas, reducing heat buildup within the building and creating a shading for openings toward the courtyard. The presence of trees and water surfaces can further cool the air through shading and evaporation. At night, when the outdoor temperature drops, the courtyard space becomes cooler which allows cool air into the building through opening toward the courtyard. This effect helps to ventilate and refresh indoor spaces, maintaining a comfortable environment until mid-morning.



Daytime effect



Nighttime effect

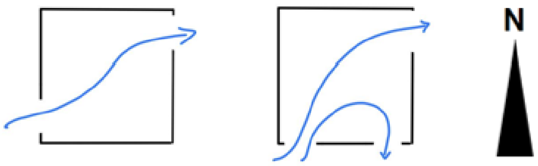
7.1.4.3 Façade Design

- **Openings design and placement**

Openings can determine the wind flow, the light, and solar gain into the building. To maximize the wind flow into the building through openings, the designing of the opening involves its position on the wall, orientation, size, and design style.

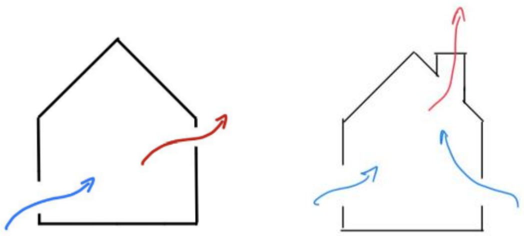
- **Cross ventilation**

To maximize natural ventilation and enhance indoor comfort in hot and humid climates like Cambodia, openings should be strategically positioned. Openings should be placed along the prominent wind directions, which are southwest and northeast in Cambodia. This alignment allows for effective capture of prevailing winds and improves airflow throughout the building. Design the building layout to facilitate cross ventilation. Position windows and other openings on opposite sides of the building to enable air to flow through and reach all corners. This approach helps ensure a consistent and comfortable indoor environment.



- **Stack Effect**

In a country with high temperatures, the stack or chimney effect is a design strategy that can ensure cool air at ground level. The stack effect happens when the cool air comes into the building through the window at a lower level and pushes hot air out of the building through openings at a higher level or the roof. Creating a stack effect by placing an opening space favorably louver at the top of the wall to extract hot air and keep the air at the living level fresh. The practice of this method has existed for decades in house design in Cambodia but has recently disappeared due to the accommodation of air conditioners.

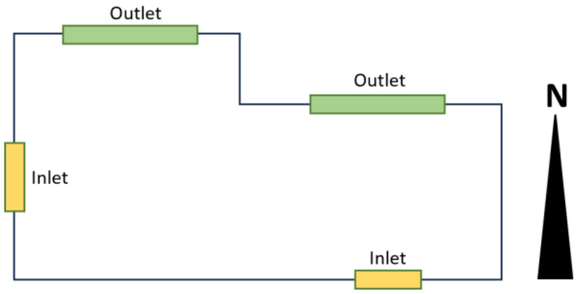


- **Nighttime ventilation**

During the night, when outdoor temperatures are cooler, it’s crucial to position windows so they can be opened safely, addressing privacy and security concerns. As the heat stored within the building envelope begins to transfer to the indoor atmosphere, it is crucial to have windows positioned in such a way that they can be opened during the nighttime to facilitate the expulsion of this accumulated heat. Natural ventilation during the night not only contributes to improved sleep quality but also maintains a fresh indoor environment throughout the morning.

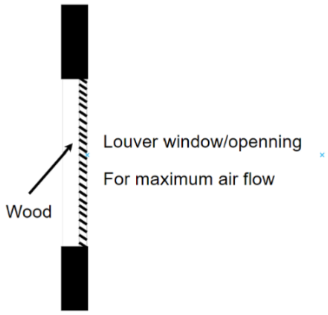
- **Size: Inlet and outlet**

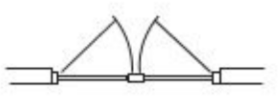
The design of openings should ensure that the outlet is wider than the inlet to create sufficient wind pressure, thereby enhancing wind speed within the building. With dominant winds coming from the south and west, openings oriented in these directions should function as inlets. Consequently, these inlets should be smaller in size compared to outlets positioned in other orientations. This configuration maximizes the efficiency of natural ventilation by optimizing wind flow and pressure differentials throughout the building.



- **Design**

The design of the opening is very important to ensure maximum benefit from it. The opening should be designed to allow natural ventilation during the rainy period as well. This design will help reduce the humidity inside the building during the rain. The casement window design with louvers is recommended and also practiced in traditional houses. As a tropical country, different types of insects and flies can enter the building. The design of the openings should consider this factor to avoid insects entering the house, especially during the night.



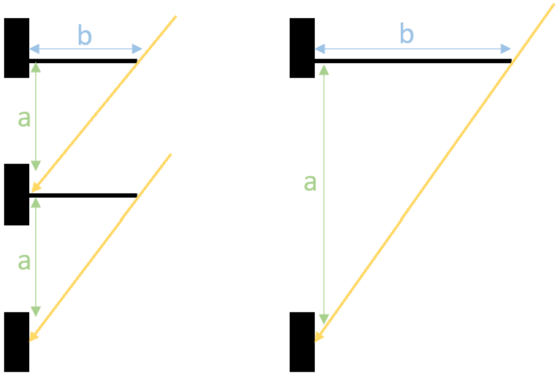


- **Shading**

Shading is a critical element in protecting buildings from excessive solar radiation. For walls exposed to significant sunlight, it is essential to incorporate appropriate shading measures. Shading can be achieved through various methods such as shading devices (fixed or removable), the surrounding environment (building or vegetation), and the design of the building façade/skin. While shading should be implemented wherever feasible, in situations where site constraints limit the options, prioritizing the shading of the west and south-facing orientation is highly recommended due to its exposure to intense afternoon sunlight.

- **Horizontal Shading**

A fixed horizontal shading device is advantageous for ensuring consistent shading, as the sun's elevation in Cambodia remains relatively high throughout the year. To achieve optimal shading, the length of the shading device should exceed the height of the window, taking into account its distance from the window.



Maximum shading : b>a

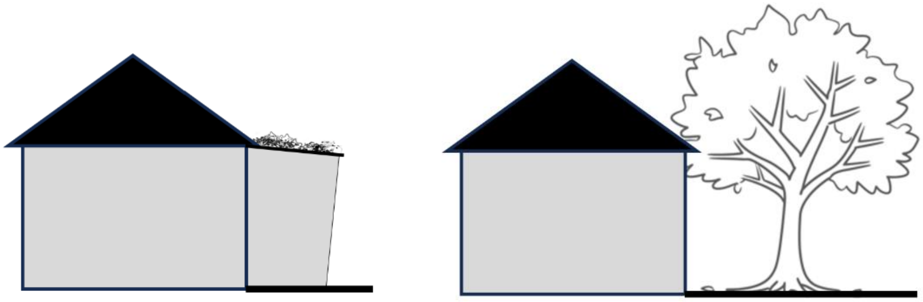
- Double façade

A double façade can function as an effective shading device for a building. The outer layer should be designed to facilitate ventilation into the inner layer. It is recommended to use louvers set at an angle of 30 to 60 degrees to ensure both natural ventilation and protection from rain. These louvers can be oriented either horizontally or vertically and should be equipped with automatic rotation mechanisms to optimize shading while minimizing view obstruction.

Figure 7-4: Example of using louver to create a double facade, source: Architectuul.

- Vegetation shading

Vegetation can serve as both a shading device and a means to create a microclimate around a building. Tall vegetation, which allows for unobstructed airflow while providing shade at the upper levels, is particularly effective. Additionally, vegetation can be planted directly on building walls to function as a green façade. This approach not only provides shading but also acts as an insulating layer, contributing to improved thermal performance.



- **Green façade**

Green façade is a type of façade design that has started to cooperate more and more in building design for sun protection. In Cambodia, due to the high heat, a green façade is rarely installed in large-scale or high-rise buildings due to the need for maintenance. For residential buildings, however, we see more and more green façade start to cooperate in the building design. The design normally consists of a planter box with ivory-type plants planted from the balcony to go down on top of the building façade. This allows easy maintenance for the homeowner.

Figure 7-5: Green facade design in a residential building in Phnom Penh, source: Bloom Architecture.

7.1.4.4 Roof Design

- **Roof with slope**

Using a sloped roof design, such as a double gable or double shed roof, can facilitate a stack effect within the building. The dual layers of such roofs create a space that allows hot air to escape, thereby enhancing natural ventilation. This type of roofing is also characteristic of traditional architectural styles. Additionally, sloped roofs with large overhangs are effective in protecting the building from rain and facilitating efficient rainwater evacuation.

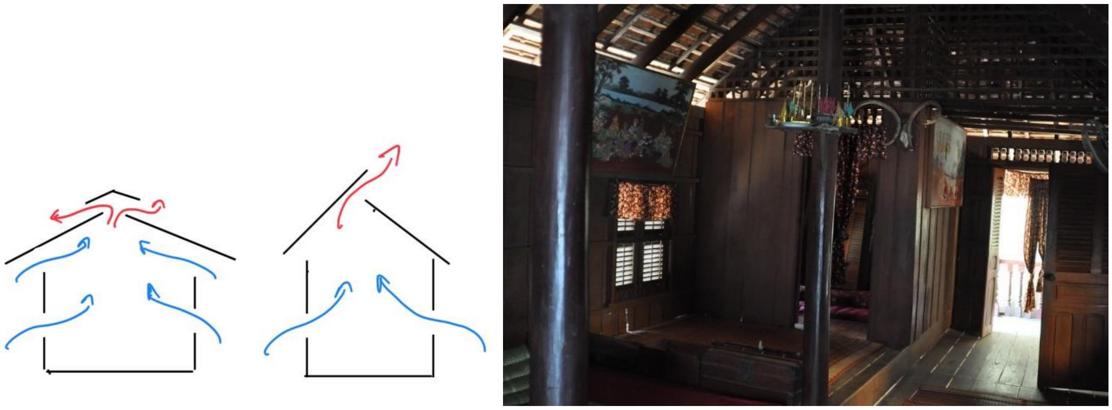


Figure 7-6: Example of slope roof in a traditional house.

- **Double ventilated roof**

A double-layer roof provides both solar protection and ventilation between its layers. The outer layer shields the inner layer from direct sunlight, while the air circulating between the layers helps to lower the temperature of the inner surface. This configuration ensures that the space beneath the roof maintains a lower temperature, or a temperature comparable to the space below it. This roofing design is widely utilized in Cambodia.

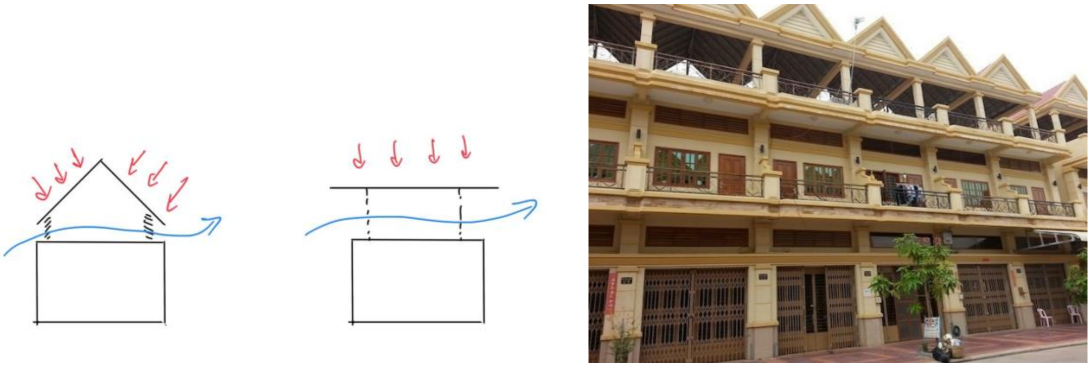


Figure 7-7: Example of double-ventilated roof in Phnom Penh.

- **Green roof**

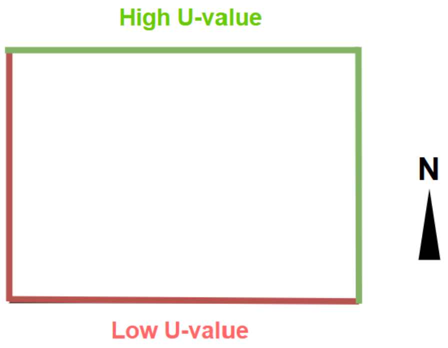
If the designer wants to design a flat roof, using a green roof is recommended. Green roofs provide an additional layer of insulation, shielding the structure from direct solar radiation while also enhancing the surrounding environment by introducing green space. In

Cambodia, the incorporation of green roofs is more commonly observed in larger-scale buildings, such as commercial structures and apartment complexes, rather than in single-family homes. This trend is driven by the need to create green spaces in densely built environments, where land is often limited.

Figure 7-8: Integration of green roof in a residential building in Siem Reap, Cambodia, source: UAD Architects.

7.1.4.5 Construction Materials

The U-value is a crucial parameter in selecting construction materials to ensure optimal thermal performance of buildings. A lower U-value indicates a material's greater effectiveness in minimizing heat transfer from the exterior to the interior, which is particularly beneficial in hot climates. Material with a high U-value such as glass shouldn’t be used in the orientation with exposure during the afternoon to the sun such as west and south and the roof. Materials with a low U-value should be applied to walls and openings oriented towards the west or south for slower heat transfer as the temperature keeps rising throughout the day. For optimum thermal comfort, a study in Singapore shows that the U-value of the material shouldn’t exceed 2.5W/m^{2}K (Wang et al., 2007).



7.2 Application of BDGC: Usability Test

The objective of this test is to identify the usability of BDGC for the architect to design a building that achieves maximum thermal comfort in the preliminary design phase and the design process that integrates the BDGC. We aim to assess the effectiveness and applicability of BDGC in achieving thermal comfort and to understand its role in supporting architects' decision-making processes.

7.2.1 Test Preparation

- **Test setup**

The test setup involves choosing participants with different profiles and divided into groups working on different building types (linked-house and detached house), preparing documents provided during the test (original building plans, design requirements for the new design, BDGC, and weather data), and the question for the pre and post-test questionnaire (see Annex 2).

- **Data collection**

The data collection for this usability test is conducted through two primary methods: questionnaires and observation utilizing the BDGC card and the think-aloud protocol. A comparative analysis is performed on the responses from the questionnaires administered before and after the test to evaluate how BDGC aids architects during the design process. These responses enable us to assess the guideline’s effectiveness in achieving building thermal comfort and its impact on architects' confidence in designing bioclimatic buildings. During the observation phase, participants are asked to interact with the BDGC card as they incorporate guideline elements into their building designs, while also engaging in the think-aloud protocol during individual testing. This observation data provides insights into how participants engage with BDGC, the decision-making processes they employ, and the challenges they encounter when using the guideline.

Pre-workshop questions are related to:

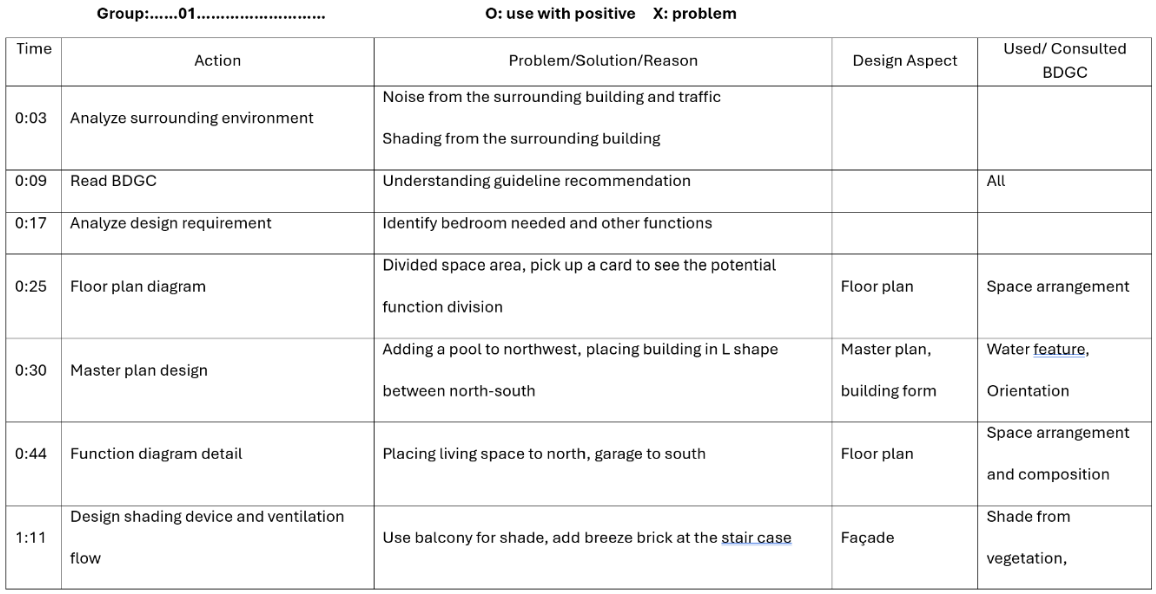
- Participant experience with design building with comfort goal
- Participant experience with any design guideline and methodology to achieve building comfort
- Tool and method used to analyze building thermal performance and decision support overall

Post-workshop questions are:

- Ability of BDGC to provide informed decision-making to the participant
- Their confidence in the final building design in achieving comfort with the use of BDGC
- Participant satisfaction with BDGC

For the observation of the design process during the usability test, an observation sheet (Figure 7-9) is created to note down:

- The evolution of the design phase.
- The interaction of participants with BDGC.
- Where in the design aspect and when in the design phase BDGC is applied.
- Why and how BDGC is applied and its impact on the design aspect.
- The number of BDGC elements that are used in each test and integrated into the final design.
- Any problem encountered by the participants when using BDGC card.



Group:……01……………………… **O: use with positive X: problem**

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 BDGC	Understanding guideline recommendation		All
0:17	Analyze design requirement	Identify bedroom needed and other functions		
0:25	Floor plan diagram	Divided space area, pick up a card to see the potential 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 detail	Placing living space to north, garage to south	Floor plan	Space arrangement and composition
1:11	Design shading device and ventilation flow	Use balcony for shade, add breeze brick at the stair case	Façade	Shade from vegetation,

Figure 7-9: Example of observation grid completed during the usability test.

- **Experiment 0**

Experiment 0 was implemented before conducting the actual usability test to ensure that the protocol used for the test and all the materials provided during the test are suitable and can allow us to manage the design process observation.

7.2.2 Data Collection

7.2.2.1 Test Procedure

The workshop is structured into six sessions, accommodating five groups and two individuals. Each session lasts up to four hours and follows a specific sequence: it begins with a pre-workshop questionnaire, followed by a briefing on the BDGC, an explanation of the test objectives, and an overview of the materials provided. Participants, who are either architects or architectural engineering students, then proceed with the design process. As the focus is on preliminary design, participants create their final building designs by hand, either on paper or using a tablet, without any computer assistance. The session concludes with a post-workshop questionnaire and feedback from the participants.

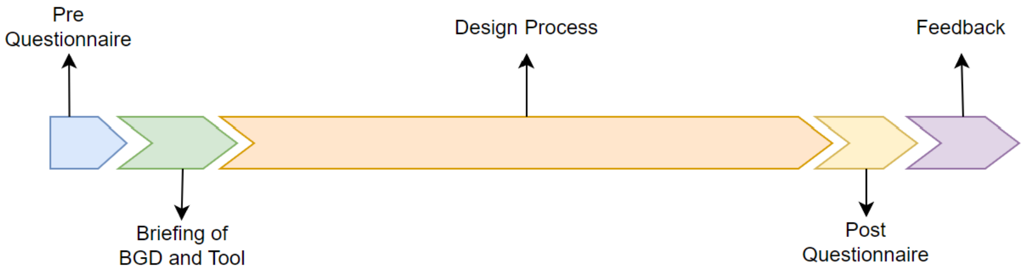


Figure 7-10: Workshop procedure.

Figure 7-11: Usability test procedure.

7.2.2.2 Participant Profile

The test was conducted with participants of architects and architectural engineering students who were divided into 5 groups and 2 individual tests. Each group has 3 members. The student groups consist of 3 students from year 4 and year 5 in engineering degree. The architect groups consist of 3 architects with 2 to 6 years of experience in the field of architectural design. Individual tests are with architects who have more than 5 years of experience in building design. The table below specifies the profile of all members in each group and the building type they were given for redesign.

Table 7-1: Profile of participant in the usability test.

Group	Profile	Building Redesign
Test 1	2 Architectural students, year 5 1 Architectural student, year 4	D1
Tests 2 and 3	2 Architectural students, year 5 1 Architectural student, year 4	T2
Test 4	2 Architects with 6 years of experience 1 Architect with 3 years of experience	D1
Group 5	2 Architects with 5 years of experience 1 Architect with 2 years of experience	T2
Test 6	1 Architect with 6 years of experience	D1
Test 7	1 Architect with 5 years of experience	T2

7.2.2.3 Design Requirements

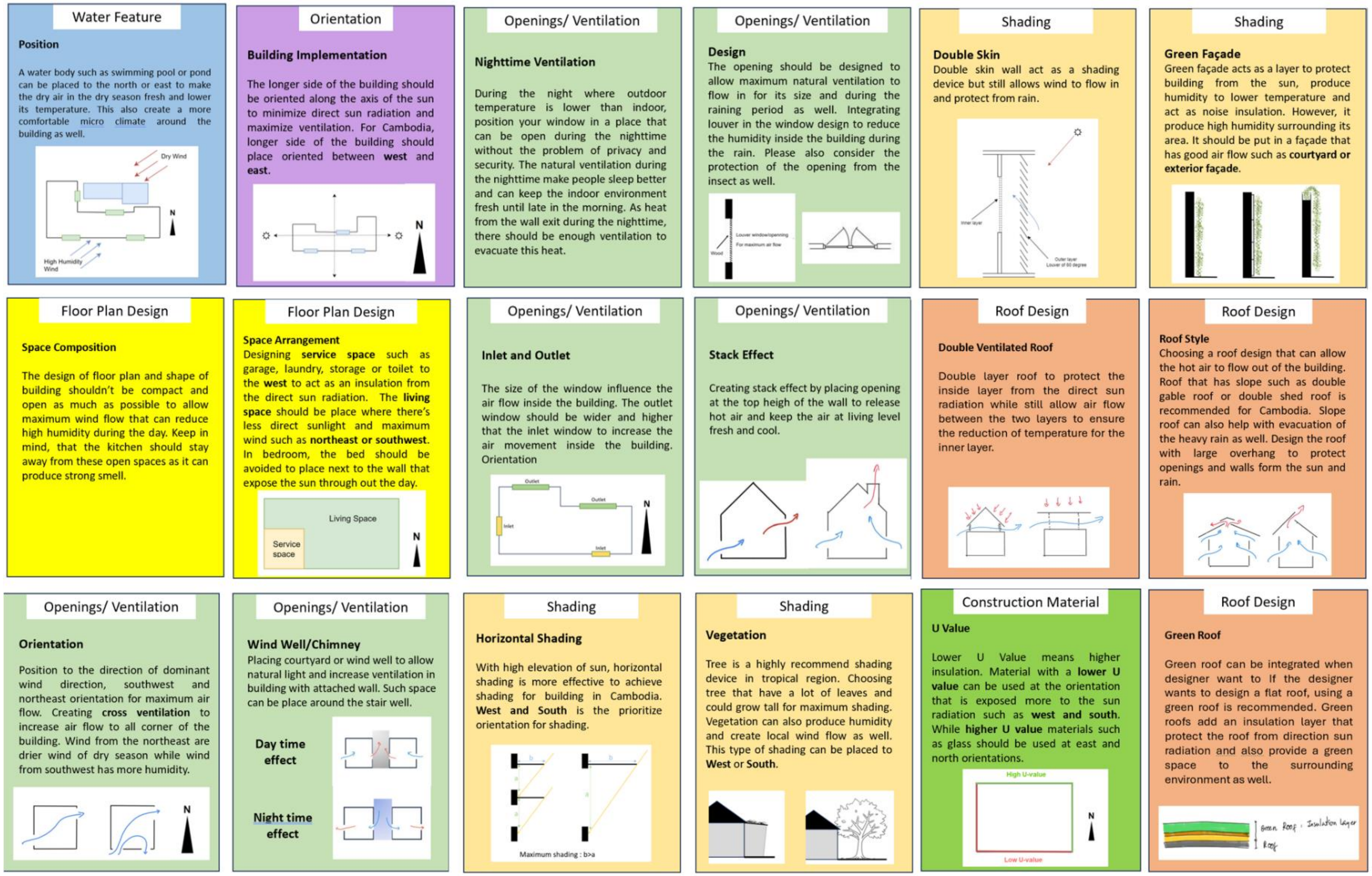
Participants are tasked with redesigning one case study building, either T2 or D1, to enhance their thermal comfort and suitability for the climate conditions and lifestyle of Cambodians. Each house requires specific functional modifications to better accommodate residential needs. Detailed documentation supporting this test, including the redesign guidelines, can be found in Annex 4. The table below outlines the design requirements for the redesign of each house.

Table 7-2: Design requirements for each building.

House T2	House D1
- House for 3-4 people - Minimum 2 bedrooms (with bathroom attached) - Living room - Kitchen - Dining area - A space for the house shrine (1m2 on elevation) - Toilet for guests - Garage for 1 car or 2 motorbikes	- House for 5-6 people - Minimum 3 bedrooms (with bathroom attached) - Living room - Kitchen - Dining area - A space for the house shrine (1m2 on elevation) - Toilet for guests - Storage or laundry room - Garage for 1 car and 2 motorbikes

7.2.2.4 Design Guideline Provided for the Test

The guidelines provided during the test are in the form of a card as seen in Figure 7-12 with diagrams or images and a complete BDGC guideline as presented in section 7.1.4. The color used for each card is to group certain elements that belong to the same category together for better usage and quick access for the participants. Other documents such as Cambodia weather data are also provided for the participants for better analysis of their design strategies. All documents provided during the test can be found in Annex 4.



Water Feature

Position

A water body such as swimming pool or pond can be placed to the north or east to make the dry air in the dry season fresh and lower its temperature. This also create a more comfortable micro climate around the building as well.

Orientation

Building Implementation

The longer side of the building should be oriented along the axis of the sun to minimize direct sun radiation and maximize ventilation. For Cambodia, longer side of the building should place oriented between **west** and **east**.

Openings/ Ventilation

Nighttime Ventilation

During the night where outdoor temperature is lower than indoor, position your window in a place that can be open during the nighttime without the problem of privacy and security. The natural ventilation during the nighttime make people sleep better and can keep the indoor environment fresh until late in the morning. As heat from the wall exit during the nighttime, there should be enough ventilation to evacuate this heat.

Openings/ Ventilation

Design

The opening should be designed to allow maximum natural ventilation to flow in for its size and during the raining period as well. Integrating louver in the window design to reduce the humidity inside the building during the rain. Please also consider the protection of the opening from the insect as well.

Shading

Double Skin

Double skin wall act as a shading device but still allows wind to flow in and protect from rain.

Shading

Green Façade

Green façade acts as a layer to protect building from the sun, produce humidity to lower temperature and act as noise insulation. However, it produce high humidity surrounding its area. It should be put in a façade that has good air flow such as **courtyard or exterior façade**.

Floor Plan Design

Space Composition

The design of floor plan and shape of building shouldn't be compact and open as much as possible to allow maximum wind flow that can reduce high humidity during the day. Keep in mind, that the kitchen should stay away from these open spaces as it can produce strong smell.

Floor Plan Design

Space Arrangement

Designing **service space** such as garage, laundry, storage or toilet to the **west** to act as an insulation from the direct sun radiation. The **living space** should be place where there's less direct sunlight and maximum wind such as **northeast or southwest**. In bedroom, the bed should be avoided to place next to the wall that expose the sun through out the day.

Openings/ Ventilation

Inlet and Outlet

The size of the window influence the air flow inside the building. The outlet window should be wider and higher that the inlet window to increase the air movement inside the building. Orientation

Openings/ Ventilation

Stack Effect

Creating stack effect by placing opening at the top heigh of the wall to release hot air and keep the air at living level fresh and cool.

Roof Design

Double Ventilated Roof

Double layer roof to protect the inside layer from the direct sun radiation while still allow air flow between the two layers to ensure the reduction of temperature for the inner layer.

Roof Design

Roof Style

Choosing a roof design that can allow the hot air to flow out of the building. Roof that has slope such as double gable roof or double shed roof is recommended for Cambodia. Slope roof can also help with evacuation of the heavy rain as well. Design the roof with large overhang to protect openings and walls form the sun and rain.

Openings/ Ventilation

Orientation

Position to the direction of dominant wind direction, southwest and northeast orientation for maximum air flow. Creating **cross ventilation** to increase air flow to all corner of the building. Wind from the northeast are drier wind of dry season while wind from southwest has more humidity.

Openings/ Ventilation

Wind Well/Chimney

Placing courtyard or wind well to allow natural light and increase ventilation in building with attached wall. Such space can be place around the stair well.

Day time effect

Night time effect

Shading

Horizontal Shading

With high elevation of sun, horizontal shading is more effective to achieve shading for building in Cambodia. **West and South** is the prioritize orientation for shading.

Shading

Vegetation

Tree is a highly recommend shading device in tropical region. Choosing tree that have a lot of leaves and could grow tall for maximum shading. Vegetation can also produce humidity and create local wind flow as well. This type of shading can be placed to **West** or **South**.

Construction Material

U Value

Lower U Value means higher insulation. Material with a **lower U value** can be used at the orientation that is exposed more to the sun radiation such as **west and south**. While **higher U value** materials such as glass should be used at east and north orientations.

Roof Design

Green Roof

Green roof can be integrated when designer want to If the designer wants to design a flat roof, using a green roof is recommended. Green roofs add an insulation layer that protect the roof from direction sun radiation and also provide a green space to the surrounding environment as well.

Figure 7-12: BDGC cards provided during the usability test.

7.2.3 Usability Test Results

7.2.3.1 Pre-test Questionnaire and Answer

The pre-test questionnaire allows us to know the experience of participants regarding designing a comfortable building. As seen in Figure 7-13, 95% of participants have experience designing a comfortable building. However, as shown in Figure 7-14 they based their design strategies on theories they studied at school, strategies learned from the internet, or on their experiences. They typically focus on single design factors such as green façades/roofs, shading devices, or ventilation, which do not cover all aspects of building design. Apparently, there is no specific design method or guideline available to aid architects in achieving high thermal performance or bioclimatic buildings. Consequently, their design strategies rely primarily on theoretical knowledge from literature and personal experience. As illustrated in Figure 7-15, only 35% of the participants have previously used any decision support tools, such as energy simulation or design software plugins, to analyze building thermal performance. These tools were typically employed to simulate energy performance or visualize the effects of shading and light Figure 7-16. However, detailed simulations of building performance were not conducted by the participants themselves but by other team members in their company. While the participants did perform visualization using design plugins, 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, participants expressed a lack of confidence in claiming that their buildings would provide adequate comfort.

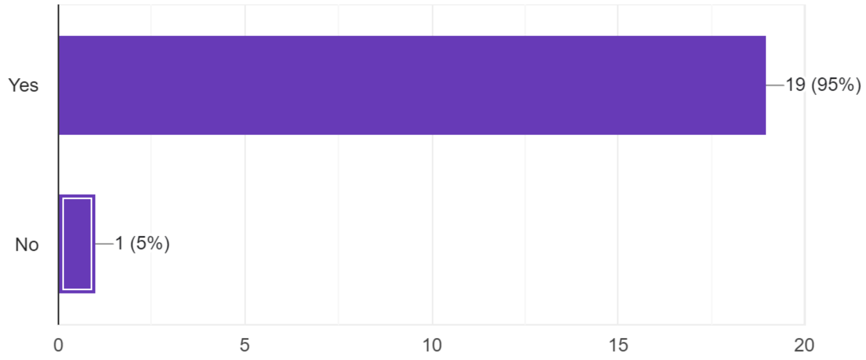
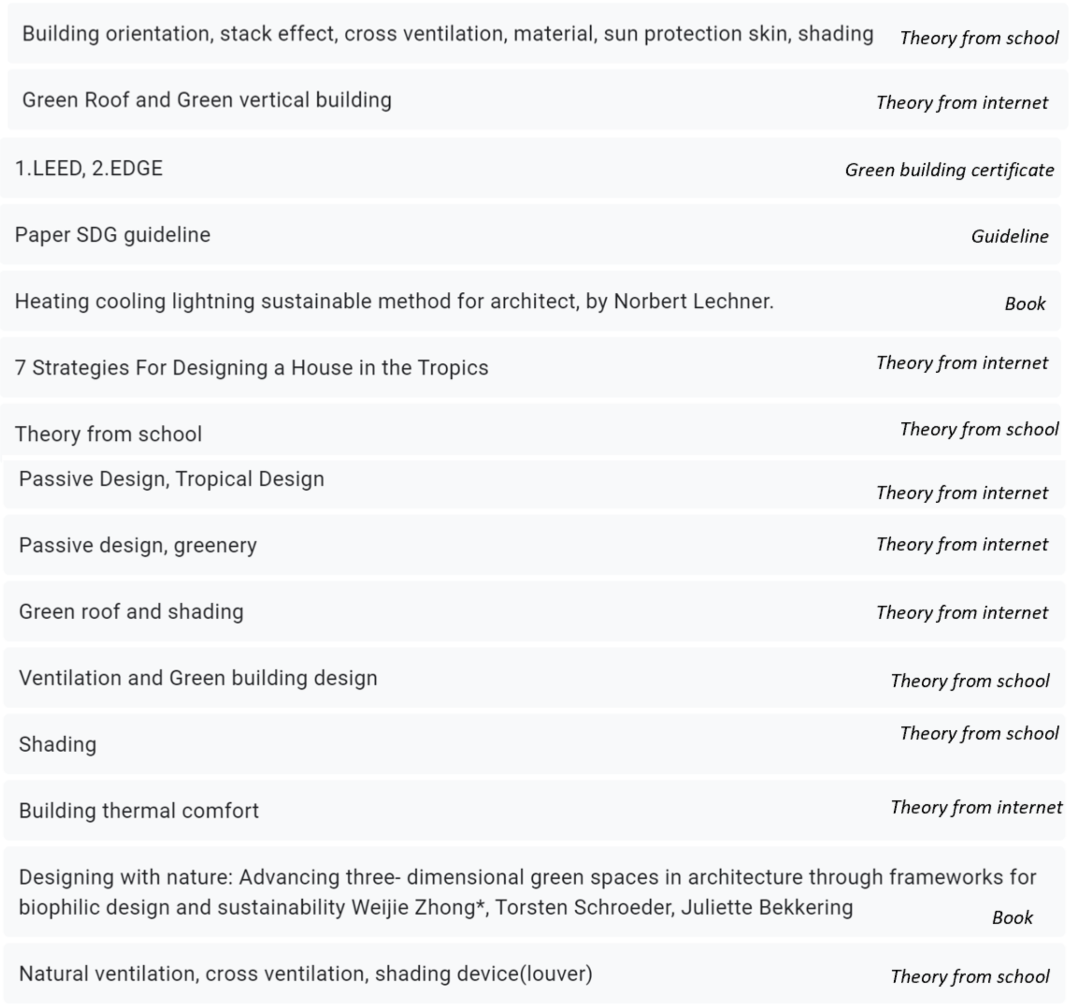


Figure 7-13: Participant's response to the question 'Have you ever designed a comfortable building before?'.



Building orientation, stack effect, cross ventilation, material, sun protection skin, shading	*Theory from school*
Green Roof and Green vertical building	*Theory from internet*
1.LEED, 2.EDGE	*Green building certificate*
Paper SDG guideline	*Guideline*
Heating cooling lightning sustainable method for architect, by Norbert Lechner.	*Book*
7 Strategies For Designing a House in the Tropics	*Theory from internet*
Theory from school	*Theory from school*
Passive Design, Tropical Design	*Theory from internet*
Passive design, greenery	*Theory from internet*
Green roof and shading	*Theory from internet*
Ventilation and Green building design	*Theory from school*
Shading	*Theory from school*
Building thermal comfort	*Theory from internet*
Designing with nature: Advancing three- dimensional green spaces in architecture through frameworks for biophilic design and sustainability Weijie Zhong*, Torsten Schroeder, Juliette Bekkering	*Book*
Natural ventilation, cross ventilation, shading device(louver)	*Theory from school*

Figure 7-14: Participants respond regarding guidelines that they have used to achieve building comfort during the design process.

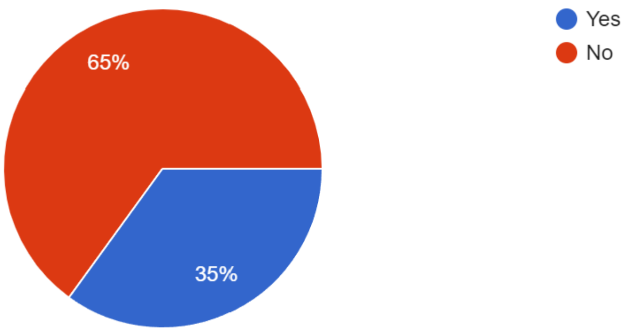


Figure 7-15: Participants respond to experience using tools to help analyze building thermal performance during the design process.

Autocad, SketchUp and V-ray

Insight by Autodesk

Ecotech software

Shading projector V7, SketchUp

Data logger, Phoenix, Ecotect

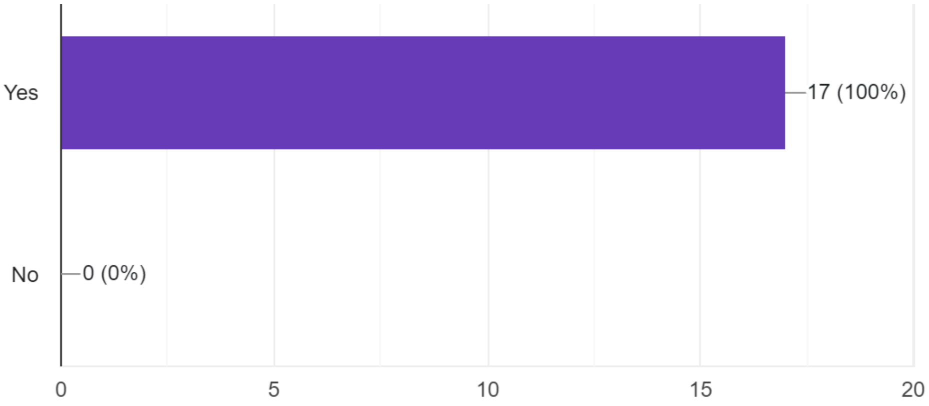
Figure 7-16: Thermal performance analysis tool that participants have used.

7.2.3.2 Post-test Questionnaire Answer

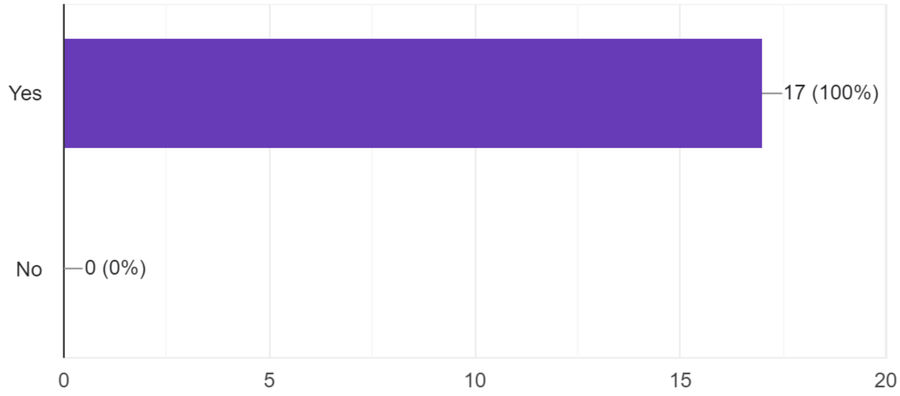
After finishing re-designing the building, participants were asked to complete the post-test questionnaire. From the answer, we can see 95% of participants use BDGC to help them in decision-making of redesigning certain aspects of the house and it allows them to feel confident in achieving building thermal comfort. All of the participants are satisfied with BDGC and the way that it is categorized according to the design phase and the problem it intends to solve (maximize natural ventilation, building shading…). They agree that BDGC can be utilized from the early design process, particularly after the pre-design phase where site analysis is completed, and design requirement is identified. All of them express their interest in using BDGC in their future project.

Below you can review the participant's answer to post-test questions.

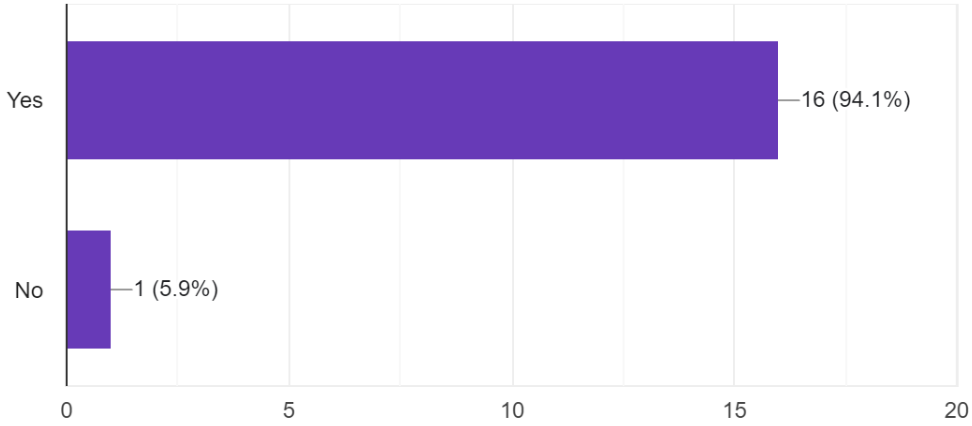
- Q1: Does the design guideline help your decision-making in redesigning the house?



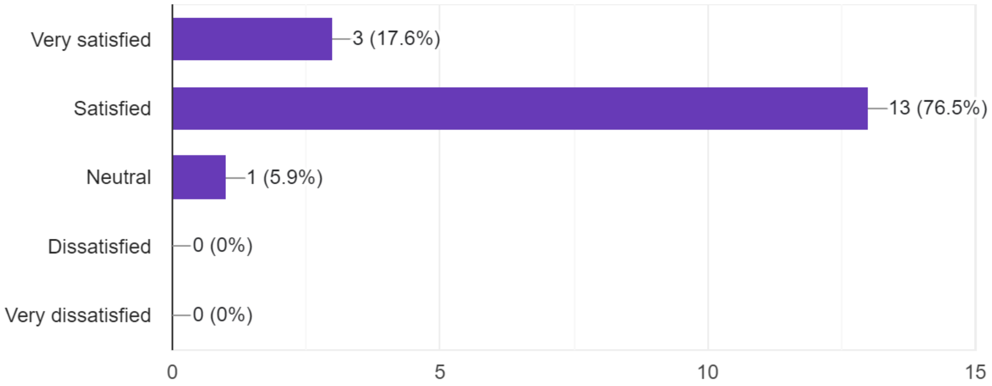
- Q2: Does the design guideline allow you to achieve the goal of designing a comfortable house?



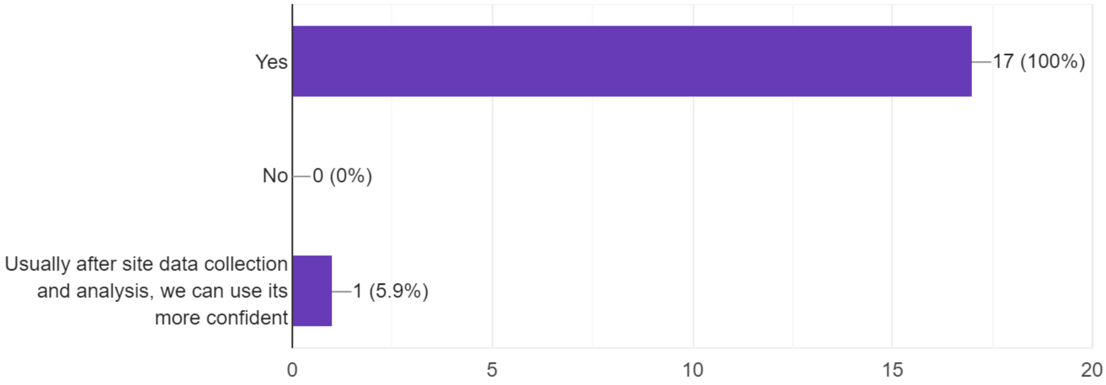
- Q3: Does the guideline allow you to have confidence in your final design to be a comfortable house?



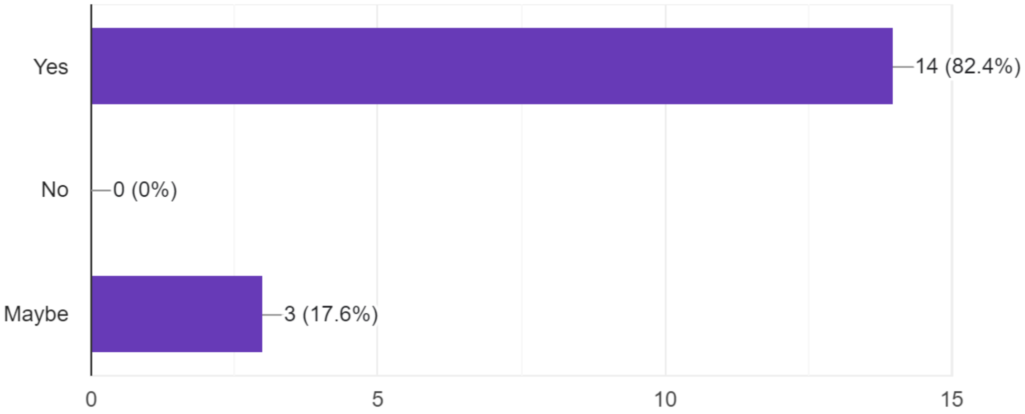
- Q4: Please state your satisfaction with the design guideline provided.



- Q5: Do you agree that BDGC has been useful since the early design phase?



- Q6: Will you use BDGC for your future project?



Responses to Questions 3 and 6 revealed some areas of participant concern, as indicated by several negative feedback points. One participant shared that while the BDGC provided her with increased confidence in achieving thermal comfort in her building designs, having access to a tool that allows for the calculation of specific parameters or visualization of design impacts would give her complete confidence in reaching optimal thermal performance. This feedback highlights the potential value of integrating Esad with BDGC, as Esad could offer additional insights and reinforcement for design decisions.

Furthermore, three participants expressed tentative interest in using BDGC in future projects. However, their uncertainty appears to stem from challenges with the guideline being available only in English and a perception that many of BDGC’s recommended elements are already familiar to them.

7.3 Bioclimatic Design Scenarios and Validation of BDGC

7.3.1 Bioclimatic Design Scenarios for Residential Buildings in Cambodia

From the usability test, we are able to collect 7 bioclimatic design scenarios of residential buildings in Cambodia for both linked and detached houses that can be used as an example of bioclimatic buildings. Below we present the two scenarios of link house and one scenario of detached house. Other scenarios will be presented in the next section.

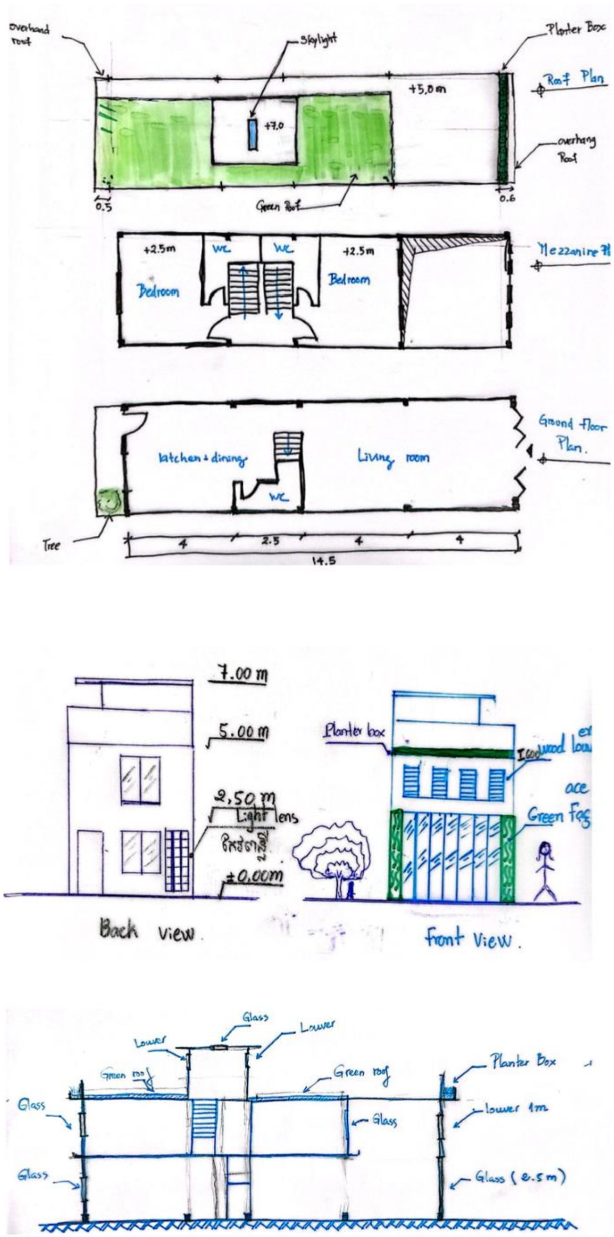


Figure 7-17: Bioclimatic link-house scenario 3

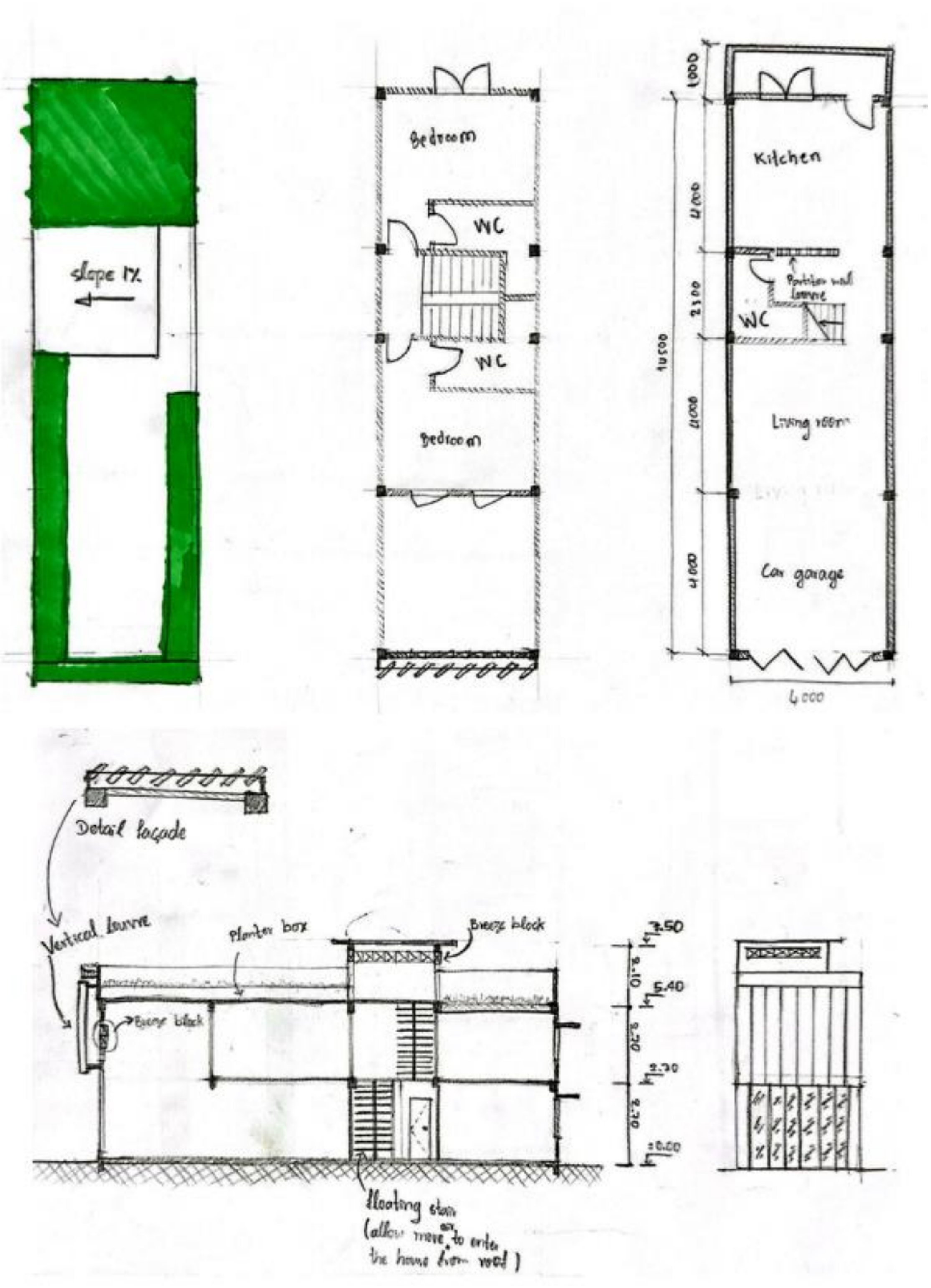


Figure 7-18: Bioclimatic link-house scenario 4

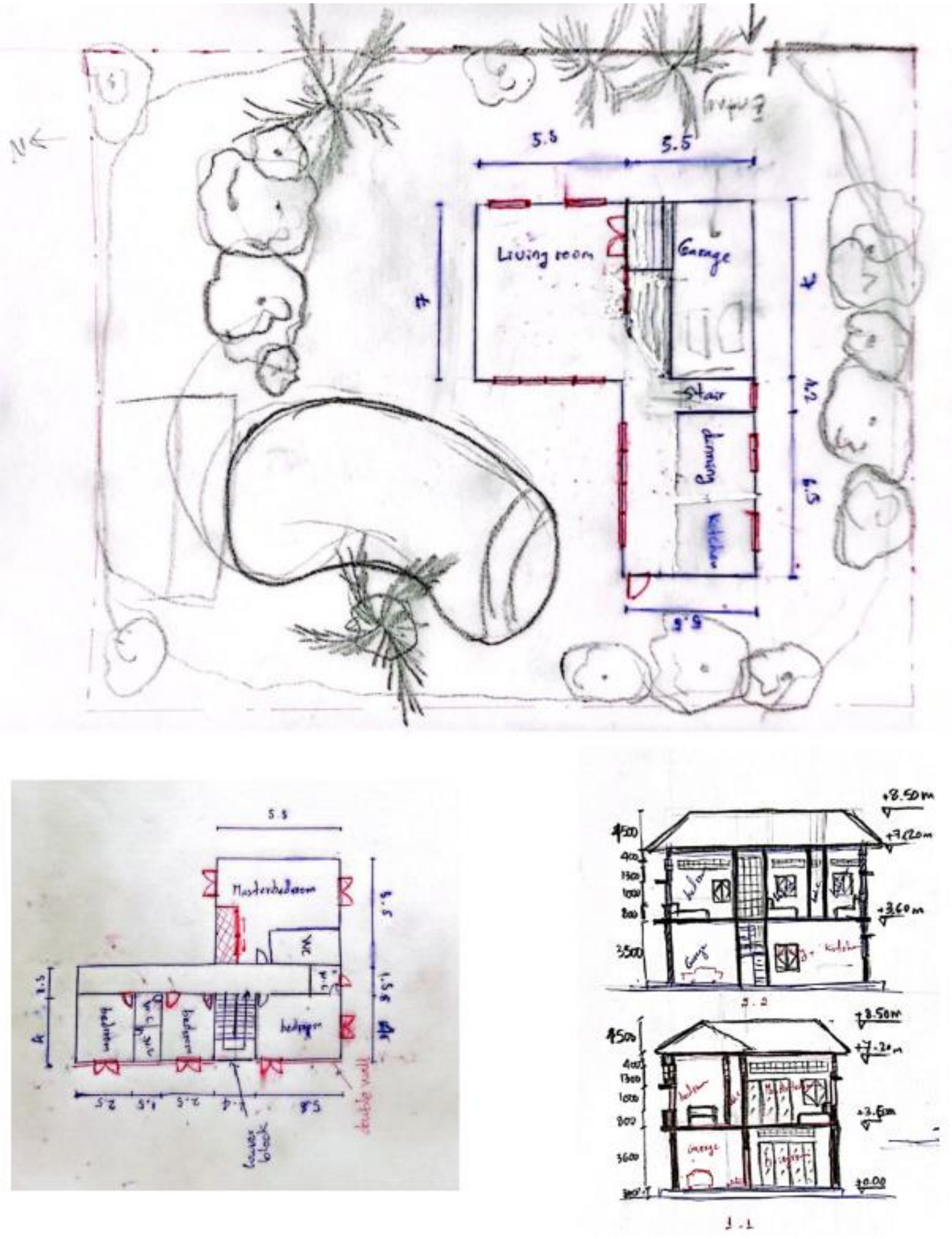


Figure 7-19: Bioclimatic detached house scenario 3.

We chose 4 building scenarios from the usability (2 scenarios for link house and 2 scenarios for detached house) where we can see the most differences in building design from the original case study building. We take the calibrated model of the case study building and modify its design following the design scenarios received from the usability test. The simulations of the bioclimatic buildings are conducted in DesignBuilder to compare the thermal performance of the case study building and the bioclimatic scenarios houses to validate the ability of BDGC to help architects improve building thermal performance. After that, the 4 building scenarios will be tested in Esad for their thermal performance and to evaluate the effectiveness of Esad for providing informed decisions of building design that integrated bioclimatic strategies.

7.3.2 Test 5: Link House (Scenario 1)

- **Design process**

The testing process for this group commences with a thorough review of the requirements for the new design and an identification of the problems inherent in the original building. They proceed by defining the goals they aimed to achieve with their redesign. Subsequently, they analyze the weather data provided and design guidelines, taking particular note of those elements that appear relevant and applicable for addressing the identified issues in the new design. They mention some design elements in the guidelines they have known about and used to practice in their project before. They select specific guidelines to inform their redesign process, integrating these recommendations with their own expertise and experiences. Throughout the redesign process, all three participants remain actively engaged. The collaborative interaction among the participants facilitates a consensus-driven decision-making process, ensuring that each choice is collectively agreed upon. In instances of uncertainty, they refer back to the guidelines for clarification, direction, and making decisions.

They identify that the original design of the building doesn’t provide enough natural light and natural ventilation, lacks green space, and has low ceiling height. Upon this issue identification, this group chose 9 BDGC elements to cooperate in their building redesign. They aim to create a house that would allow ventilation as much as possible and have enough natural light and sun protection on the front façade and the roof. To achieve this purpose, they chose the following BDGC elements:

1. Space composition: enlarging the building by 1 meter in width and reducing it to 2 meters in length to allow more open space and a building length so that light and wind can go through every corner of the building.

2. Space arrangement: eliminating the mezzanine and turning it into a whole floor plan to allow wind and light directly to the master bedroom. The arrangement of the ground floor was kept the same as the original to accommodate the living lifestyle of Cambodians.
3. Stack effect: placing louver above all exterior windows. The floor height was added by 1 meter to accommodate the new design.
4. Wind well: using the staircase as the wind well to maximize airflow.
5. The design of the window: modifying by enlarging its size to allow more airflow, and by using a casement window in the front part of the house to maximize airflow when opened.
6. Horizontal shading: using the balcony as a sun shading device to protect the back window from direct sun radiation and rain.
7. Vegetation for shading: adding greenery onto the roof and the balcony for green space as well as sun protection for the roof and the front windows.
8. Double skin façade: adding a vertical louver for maximum protection from the sun added to vegetation on the balcony.
9. Orientation: this card was used to consult the orientation of the building but the original orientation is kept as the building was already designed following the recommended orientation by BDGC.

A bioclimatic design strategy is integrated into the design that isn’t included in the BDGC. The top floor is added to another bedroom at the back for guests and to work as a sun protection layer for the below bedroom when it isn’t in use which acts as a double roof.

Table 7-3: The noticeable changing design parameter between the original design and bioclimatic scenario 1.

Design element	Original design	Link house scenario 1
Habitable area	104m^2	155m^2
Number of floors	1 floor and a mezzanine	2 floors
Opening area	13m^2	20m^2
Total height of the building	7 meters	10.8 meters

When comparing the bioclimatic building scenario 1 to the original design, the difference in surface area is relatively minor, as the architects chose to eliminate the mezzanine and add a guest bedroom. The increase in surface area is not solely intended to implement bioclimatic strategies; rather, it aims to create a comfortable living space that aligns with Cambodian standards by incorporating a guest bedroom. On the other hand, the bioclimatic building is significantly taller than the original, having been transformed into a two-story structure to facilitate the integration of louvers designed for bioclimatic purposes.

Figure 7-20: The floor plan and section of bioclimatic design for link house scenarios 01.

- **Thermal performance simulation**

The simulation of the bioclimatic building follows the process of simulation of the case study building. The case study building in Revit is modified to become a bioclimatic building according to the information we have from the usability test. The model is then exported as a gbXLM file and imported into the calibrated BEM model of the case study building for the simulation in DesignBuilder. The setting of activities, lightning, and HVAC, is kept the same with the simulation of the case study building to ensure its result is changed solely based on the modified building geometry and design.

Table 7-4: Input parameter for the simulation of link house scenario 1.

Categories	Input parameters	Value
Construction	External wall Partition wall Roof Floor Airtightness Schedule	U value = 2.1(W/m^{2}K) U value = 2.9 (W/m^{2}K) U value = 5.3 (W/m^{2}K) U value = 2.92 (W/m^{2}K) Model filtration: 0.7 (ac/h) 24/7
Activities	Household size Building surface Density Occupancy schedule Summer clothing Metabolism level Air velocity DWH Computers	4 *155 m^2 *0.025 person/m^2 24/7 0.5 0.85 8h00 – 18h00 everyday Non-applicable 0.5 (W/m^2)
Opening	U value Total solar transmission Light transmission	5.89 (W/m^{2}K) 0.72 0.68
Lightning	Normalized power density Schedule	5 (W/m2-100lux) 8h00-18h00 everyday
HVAC	Mechanical ventilation DHW Heating Cooling Natural ventilation	No No No No 8h00-18h00 everyday

*: modified parameter compared to input parameter for original design simulation

On average, the temperature inside the bioclimatic house is observed to be 2 to 4 °C lower than that of the original design, as determined through simulation. Additionally, the temperature variation within the bioclimatic house is greater than that of the original house. This increased variation is likely attributed to the nocturnal cooling effect, where the design's wind wells facilitate a significant decrease in temperature during the night. Compared to the acceptable comfort temperature for tropical regions, the average temperature from the bioclimatic scenario stays in the acceptable range. The building is overall 49% stay in the comfortable temperature range (below 29.5 °C) for this simulation period.

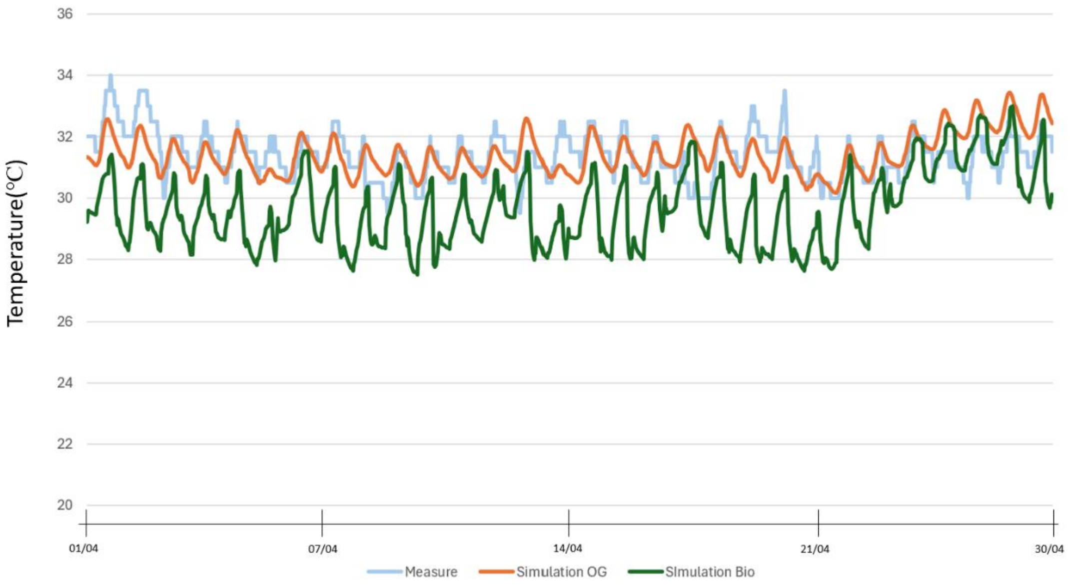


Figure 7-21: Temperature of link house scenario 1 compared to measure and simulation data in DesignBuilder.

7.3.3 Test 7: Link House (Scenarios 2)

This scenario is proposed by an individual test, with the design process being slightly shorter than in the group sessions, as the designer was solely responsible for all decision-making. The test begins with a review of the project and the redesign requirements, followed by a detailed reading of the guidelines. Similar to the previous group test, the architect identifies issues such as insufficient natural light and ventilation in the original building design, as well as a ceiling height that would hinder proper air circulation. The architect systematically evaluates the quality of the current design by referencing the elements in the guideline (e.g., assessing the building's orientation using the guideline criteria and verifying the position of the window)

Below are the guideline elements that are used for this bioclimatic scenario:

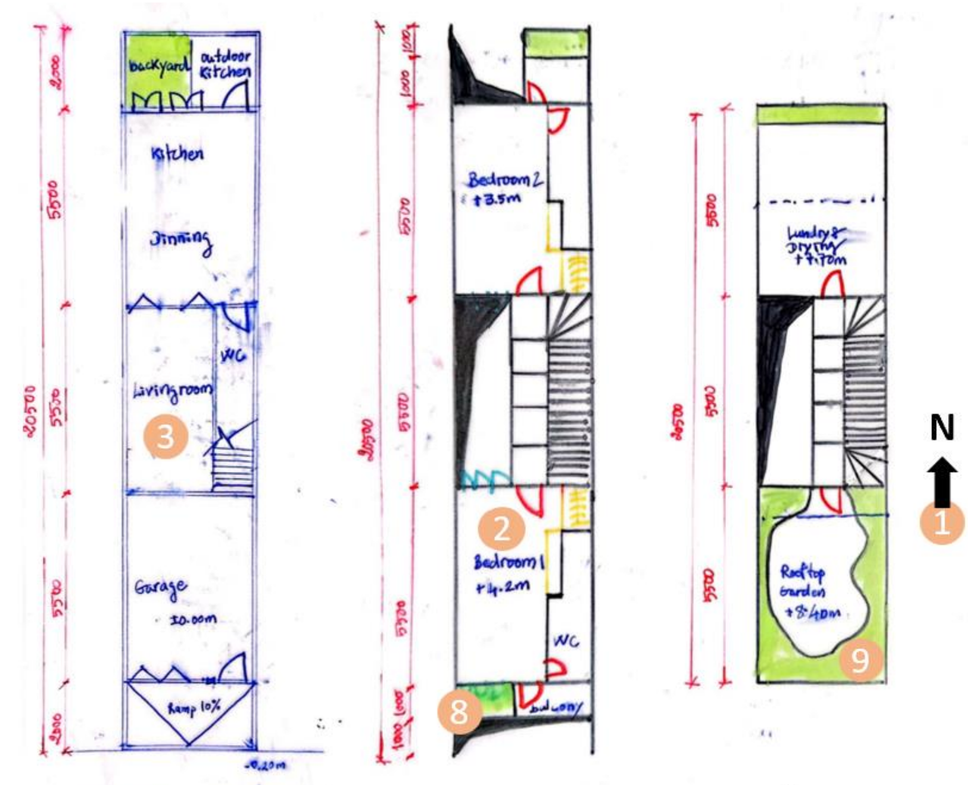
1. Orientation: verify the orientation of the building.
2. Space arrangements: placing the living space in the wind well and the night space with an exterior opening.
3. Space composition: the living space is in an open concept from the living room to the kitchen.
4. Cross ventilation: placing multiple windows in the bedrooms facing each other to create cross ventilation.
5. Nighttime ventilation: benefit from the wind as well as an outdoor for ventilation during the nighttime.
6. Wind well: using the living room next to the stairs as the wind well.
7. Stack effect: applying louvers at the top of the wind well and on top of the window for stack effect.
8. Vegetation shading: placing a small backyard and green space on the balcony for shading.
9. Green roof: apply a green roof on the flat roof.
10. Horizontal shading: using the balcony as a shading device for the entrance door and the outdoor kitchen.

Besides the use of BDGC elements, the architect also incorporates an outdoor kitchen to adapt to the usage of Cambodians as well.

Table 7-5: The noticeable changing design parameter between the original design and bioclimatic scenario 2.

Design element	Original design	Link house scenario 2
Habitable area	104m^2	135m^2
Number of floors	1 floor and a mezzanine	2 floors
Opening area	13m^2	19.1m^2
Total height of the building	7 m	11.4m

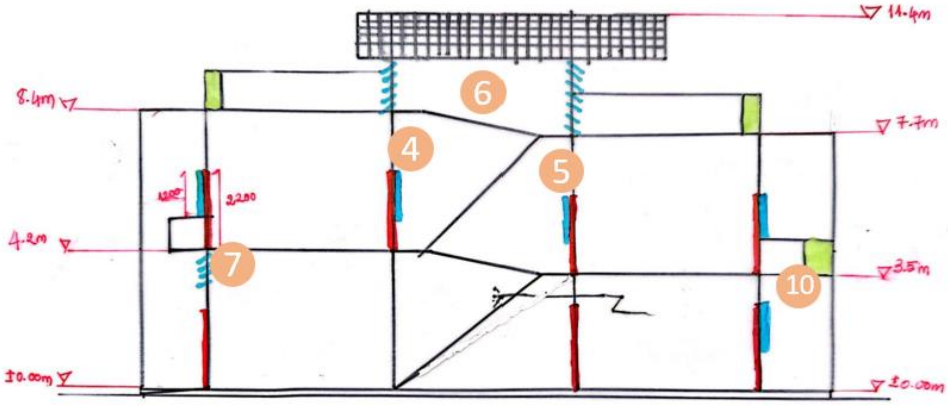
Like scenario 1, scenario 2 also features only minor changes in building surface area. The surface area of scenario 2 is even smaller and closer to the original design, as the architect chose not to expand the width of the building but instead prioritized incorporating bioclimatic strategies through its length. However, the height of the building differs significantly, as the floors are designed at varying levels to maximize space and enhance airflow throughout the structure.



Ground floor

First floor

Terrace



Section

Figure 7-22: Bioclimatic building scenario 2 for link house.

- **Thermal performance simulation**

The simulation for this building scenario follows the same process as applied in the previous scenario. However, the green roof introduced in this scenario cannot be modeled. Consequently, the temperature comparison between this scenario and the previous one must account for this variable. The table below presents the input parameters for the simulation.

Table 7-6: Input parameter for the simulation of link house scenario 2.

Categories	Input parameters	Value
Construction	External wall Partition wall Roof Floor Airtightness Schedule	U value = 2.1(W/m^{2}K) U value = 2.9 (W/m^{2}K) U value = 5.3 (W/m^{2}K) U value = 2.92 (W/m^{2}K) Model filtration: 0.7 (ac/h) 24/7
Activities	Household size Building surface Density Occupancy schedule Summer clothing Metabolism level Air velocity DWH Computers	4 *135 m^2 *0.029 person/m^2 24/7 0.5 0.85 8h00 – 18h00 everyday Non-applicable 0.5 (W/m^2)
Opening	U value Total solar transmission Light transmission	5.89 (W/m^{2}K) 0.72 0.68
Lightning	Normalized power density Schedule	5 (W/m2-100lux) 8h00-18h00 everyday
HVAC	Mechanical ventilation DHW Heating Cooling Natural ventilation	No No No No 8h00-18h00 everyday

*: modified parameter compared to input parameter for original design simulation

Based on the simulation results in DesignBuilder, bioclimatic building scenario 2 demonstrates a lower temperature relative to the original design. Additionally, temperature variation in this scenario appears greater than that observed in the base case model. In this scenario, the living room is positioned directly within the wind well, allowing it to consistently receive fresh air, which might contributes to temperature reduction. The open layout connecting the living room and kitchen further enhances ventilation between these spaces. Furthermore, the extended side walls beyond the front façade provide vertical shading, which also aids in reducing temperature. Incorporating the green roof, which could not be included in the simulation, would likely further reduce the temperature in this scenario.

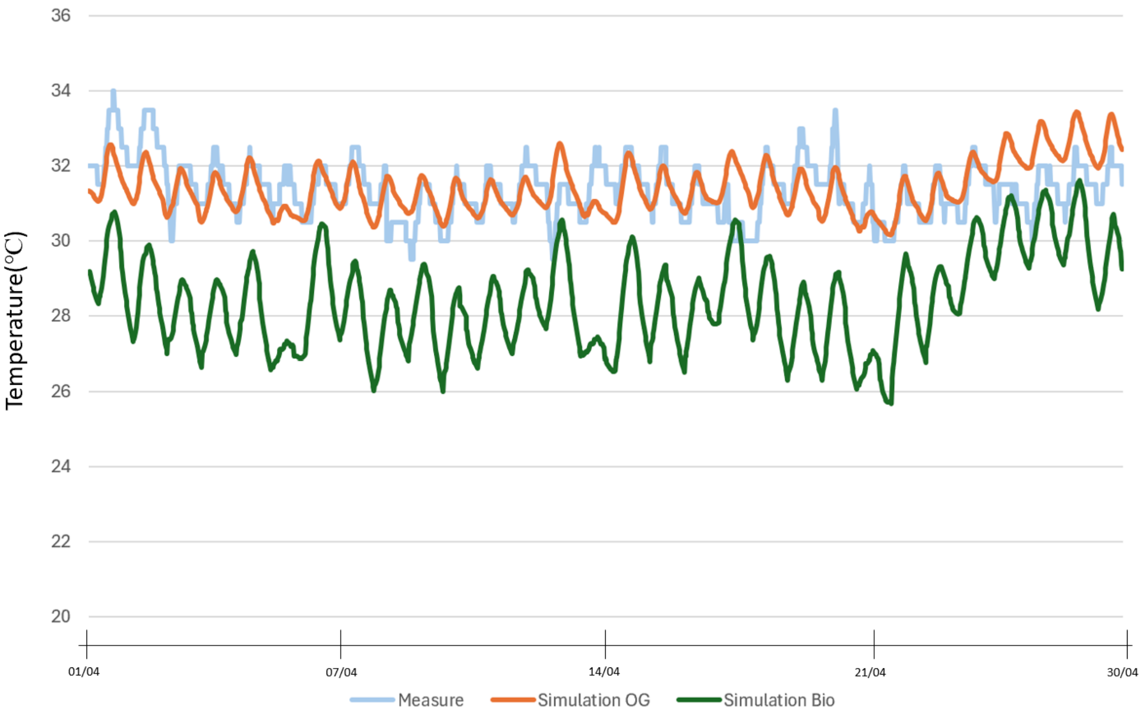


Figure 7-23: Temperature of link house scenario 2 compared to measure and simulation data

- **Comparison of BDGC card used in the two scenarios**

We see the similarities between scenarios 1 and 2 given the constraint of the site. There is wind-well cooperation in both scenarios for maximum ventilation and natural light. Given the length of the house, the middle part has a potential that light and wind can't reach. Placing a stair wind well would help to resolve this problem and act as a division between private and semi-private spaces. The use of vertical shading for the double skin effect and the green roof are also similarities in both scenarios. At the same time, we notice a few differences in terms of cooperation of green space where scenario 2 can be seen to have more green space, the height of the floor, the organization of space, and the fact that scenario tries to benefit from the wind well for the bedroom as well. This shows that even with a very high constraint site, BDGC doesn't limit the creativity and design style of each architect.

These similarities and differences in design are reflected in the result of the simulation of building temperature in Design Builder. We can see a higher temperature in scenario 1 than in scenario 2 due to the placing of the living room directly in the wind well and the composition of space.

7.3.4 Test 4: Detached House (Scenarios 1)

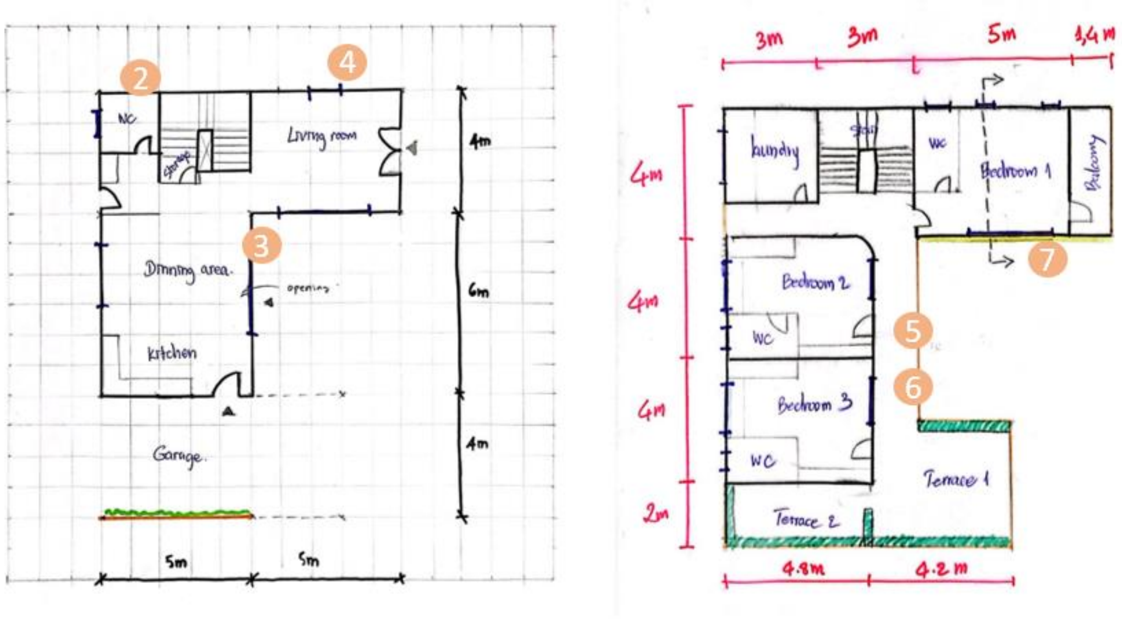
For this team, the test begins with a thorough review of all materials provided. They examine the conditions of the surrounding buildings to assess the impacts of shading, privacy, and noise. They noticed that the land plot was well-situated, benefiting from some shading provided by a neighboring house. While they consider the house to be generally well-designed, they identify a lack of adequate shading and features to enhance natural ventilation. Upon identifying these issues, the team consults the guidelines to find suitable solutions, selecting those that align with their aesthetic vision for the building.

Despite loving the land plot, they don't spend much time designing the master plan. They start the design by creating a diagram of the requirements for the new house. The overall diagram allows them to easily divide space to fit the circulation flow as well as living comfort. The integration of BDGC started in this design stage. The BDGC that they cooperate in their design are:

1. Orientation: following the recommendation from BDGC to put the longer length of the building toward the north.
2. Space arrangement: placing the living space toward the north and south and the service space to the west and east.
3. Opening design: choosing a casement window for maximum ventilation.
4. Opening size: designing openings to accommodate the inlet and outlet purpose to increase airflow.
5. Horizontal shading: placing balcony and big terrace for shading on the openings and walls.
6. Double skin façade: placing a lover façade on the first floor to create a shading for the bedroom but still allow fresh air.
7. Green façade: placing green façade on the wall towards the west to protect against sun radiation.
8. Vegetation shading: using surrounding trees to provide shade for openings.
9. Roof style: using a roof style that allows a stack effect. The overhang from the roof also acts to protect the sun and rain on the walls as well.

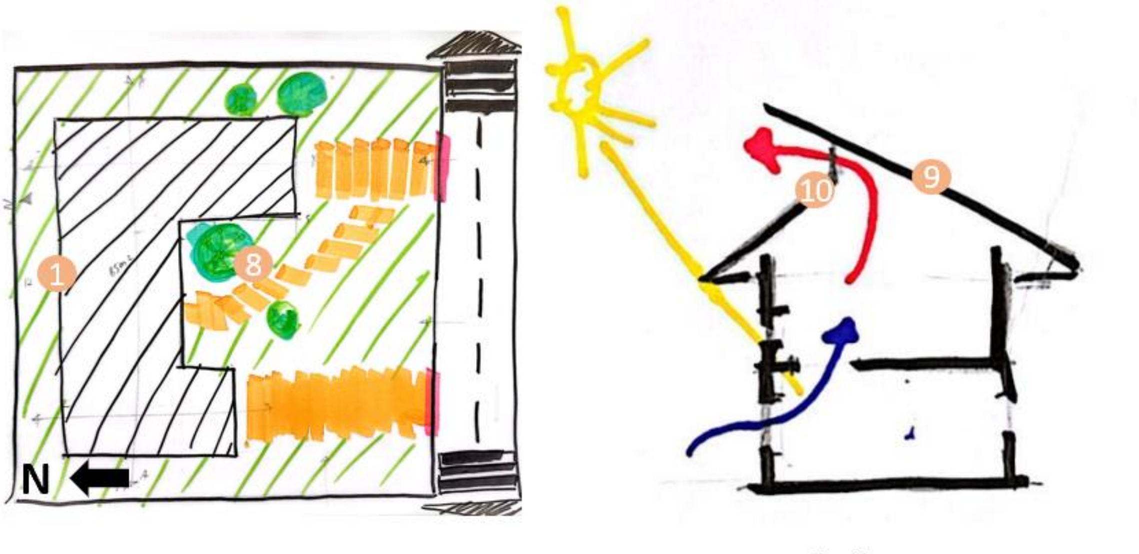
10. Wind well: using an opening from the roof to create a wind well through the stairs.

We noticed that at first, they chose green roofs as their roof design option. However, as their conception evolved they decided to change to a gable roof to fit better with the style of their building.



Ground floor

First floor



Master plan

Section

Figure 7-24: Bioclimatic design scenario 1 for the detached house.

The bioclimatic scenario is notably smaller than the original design, which is intriguing given that bioclimatic scenarios for link houses typically feature a larger surface area than their original counterparts. This reduction is primarily attributed to the elimination of one bedroom, leading to a decrease in the building's overall surface area, number of floors, and height. This modification is not specifically driven by bioclimatic considerations but rather arises from design requirements stipulating that the building must contain a minimum of two bedrooms. Despite the significant reduction in the surface area, the total opening surface area remains larger, indicating that additional openings have been incorporated to enhance ventilation which results from the recommendation from BDGC.

Table 7-7: The noticeable changing design parameter between the detached house's original design and bioclimatic scenario 1.

Design element	Original design	Detached house scenario 1
Habitable area	236m^2	144m^2
Number of floors	3 floors	2 floors
Opening area	32.6m^2	35m^2
Total height of the building	10.5m	8.5m

- **Thermal performance simulation**

In this simulation, which follows the same process as the other two buildings, we weren't able to model the trees that surrounding the building as well as the green façade.

Table 7-8: Input parameter for the simulation of detached house scenario 1.

Categories	Input parameters	Value
Construction	External wall Partition wall Roof Floor Airtightness Schedule	U value = 2.1(W/m^{2}K) U value = 2.9 (W/m^{2}K) U value = 5.3 (W/m^{2}K) U value = 2.92 (W/m^{2}K) Model filtration: 1 (ac/h) 24/7
Activities	Household size Building surface Density Occupancy schedule Summer clothing Metabolism level	5 *144 m^2 *0.034 person/m^2 24/7 0.5 clo 0.85 met

	Computers	0.004 (W/m^2)
Opening	U value	5.77 (W/m^{2}K)
	Total solar transmission	0.62
	Light transmission	0.57
Lightning	Normalized power density	5 (W/m2-100lux)
	Schedule	8h00-18h00 everyday
HVAC	Mechanical ventilation	No
	DHW	No
	Heating	No
	Cooling	No
	Natural ventilation	8h00-18h00 everyday

*: modified parameter compared to input parameter for original design simulation

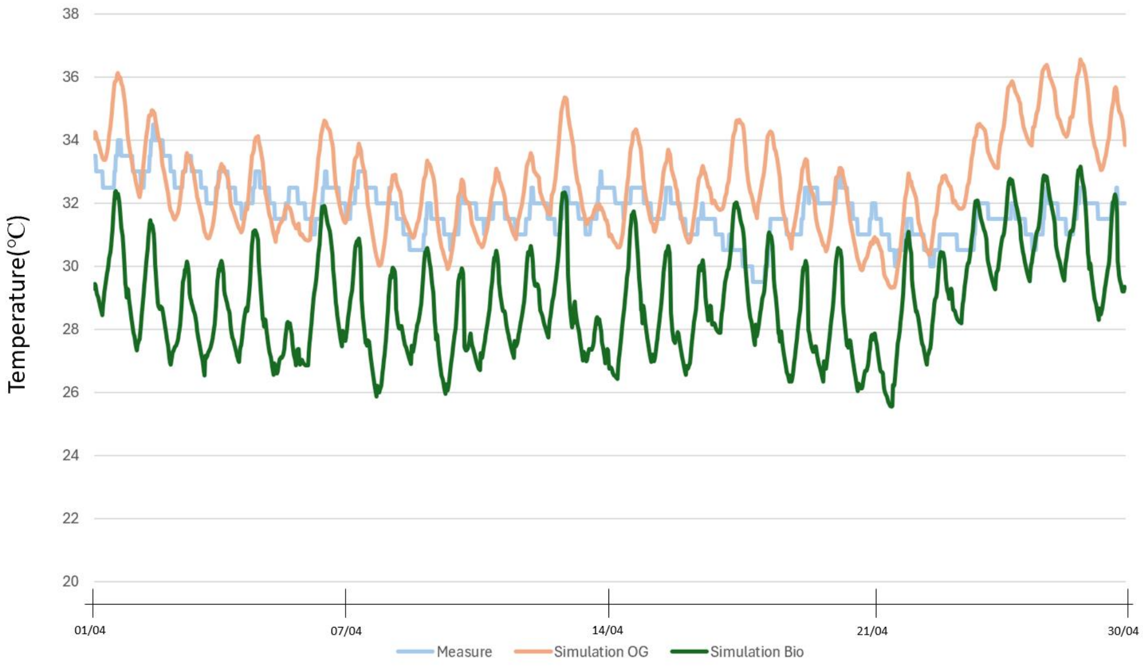


Figure 7-25: Temperature of detached house scenario 1 compared to measure and simulation data.

The average temperature in the bioclimatic building is 2 to 3 °C lower than the average simulated temperature in the original building design. The temperature variation is also greater than what was observed in the simulation and measurement. The difference in temperature during the daytime is more consistent than at nighttime, indicating that bioclimatic integration has a more significant impact on nocturnal cooling. This effect is particularly noticeable in this building typology due to its detached design, where even minor changes in the outdoor environment can rapidly affect the indoor climate. The building is well-shaded, thanks to its shape and floor plan design.

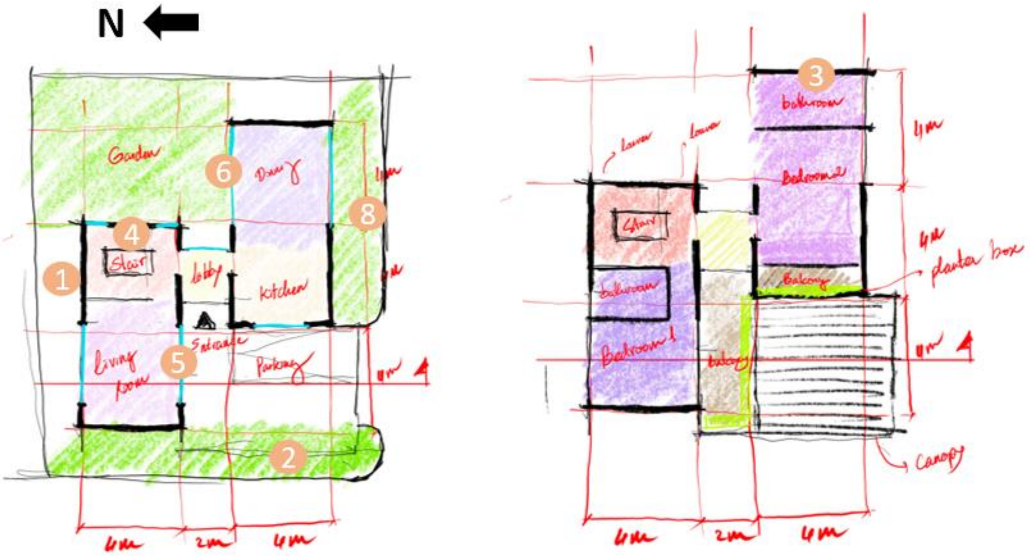
7.3.5 Test 6: Detached House (Scenarios 2)

This scenario is proposed by an individual test. Similar to other teams, he initiates the test by identifying issues within the current house design. He acknowledges that the existing design is straightforward and considers comfort to some extent. However, certain aspects can be enhanced to ensure optimal thermal comfort within the building. Key factors such as the building's orientation and its surrounding environment are what he finds significantly influence the design. He notes that the current master plan does not advantageously serve the building; the house is situated close to the neighbor while the opposite side faces an undeveloped area. Additionally, the house lacks sufficient shading, both from natural sources like trees and from the shading devices of the building itself. There is also an absence of interaction between indoor and outdoor spaces in the present design. These addressing issues are the primary focus of his new design proposal.

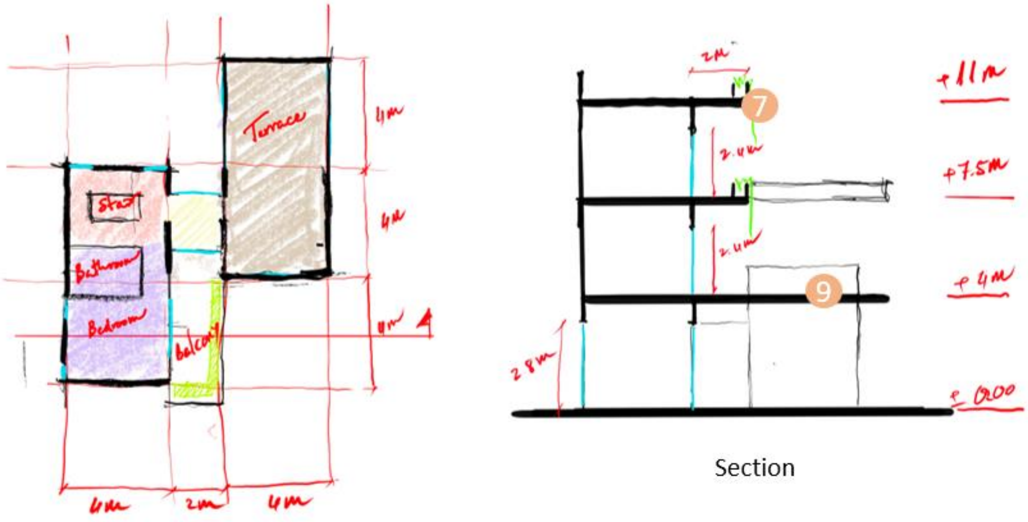
Nine elements of BDGC are used for the new design such as:

1. Orientation: placing the building at the orientation north to allow maximum airflow and benefit from using the tree as shading
2. Creating microclimate: placing green space surrounding the building to create a colder and calmer environment.
3. Space arrangement: placing living space toward north and south for maximum airflow and shading from the green space outside and contrast for the service space.
4. Wind well: placing permanent openings at the staircase to create a wind well in this space.
5. Cross ventilation: placing windows perpendicular and across from each other for maximum airflow.
6. Opening design: choosing bay windows for the ground floor that can be fully open to allow maximum airflow and create indoor-outdoor living.
7. Green façade: adding a planter box to the balcony to create vertical shading to windows using the vegetation.
8. Vegetation shading: use the surrounding tree for shading the dining area that has a huge opening.
9. Horizontal shading: using balcony and canopy as shading devices to protect the openings from sun radiation and rain.

As an individual test, the design process for this test is shorter than the group as he doesn't have to collaborate or need agreement from other team members for decision-making. With many experiences working on projects that focus on comfort, he is familiar with most of the guideline's elements and has practiced them in his project before. However, he still finds the BDGC useful when in doubt in designing certain elements and to have an overall idea of the design goal. Figure 7-26 is the bioclimatic design scenario 2 for the detached house proposed by test 5.



Ground floor First floor



Second floor Section

Figure 7-26: Bioclimatic design scenario 2 for the detached house.

Table 7-9: The noticeable changing design parameter between the detached house's original design and bioclimatic scenario 2.

Design element	Original design	Detached house scenario 2
Habitable area	236m^2	200m^2
Number of floors	3 floors	3 floors
Opening area	32.6m^2	59.25m^2
Total height of the building	10.5m	8.5m

Scenario 2 also features a smaller building surface, similar to scenario 1, even though the number of bedrooms remains unchanged. In examining the original plan, it becomes apparent that the bedrooms were designed significantly larger than the standard sizes typically found in Cambodia. In this scenario, the total opening surface area is doubled, as numerous openings and louvers have been added to facilitate cross ventilation and the wind well effect. Additionally, bay windows have been incorporated to enhance the creation of an indoor-outdoor living experience.

- **Thermal performance simulation**

The modeling and simulation process is the same as the other houses. However, with the design including a lot of trees around it, we weren’t able to incorporate this design aspect into the simulation model.

Table 7-10: Input parameter for the simulation of detached house scenario 2.

Categories	Input parameters	Value
Construction	External wall Partition wall Roof Floor Airtightness Schedule	U value = 2.1(W/m^{2}K) U value = 2.9 (W/m^{2}K) U value = 5.3 (W/m^{2}K) U value = 2.92 (W/m^{2}K) Model filtration: 1 (ac/h) 24/7
Activities	Household size Building surface Density Occupancy schedule Summer clothing Metabolism level Computers	5 *200 m^2 *0.025 person/m^2 24/7 0.5 clo 0.85 met 0.004 (W/m^2)

Opening	U value	5.77 (W/m^{2}K)
	Total solar transmission	0.62
	Light transmission	0.57
Lightning	Normalized power density	5 (W/m2-100lux)
	Schedule	8h00-18h00 everyday
HVAC	Mechanical ventilation	No
	DHW	No
	Heating	No
	Cooling	No
	Natural ventilation	8h00-18h00 everyday

*: modified parameter compared to input parameter for original design simulation

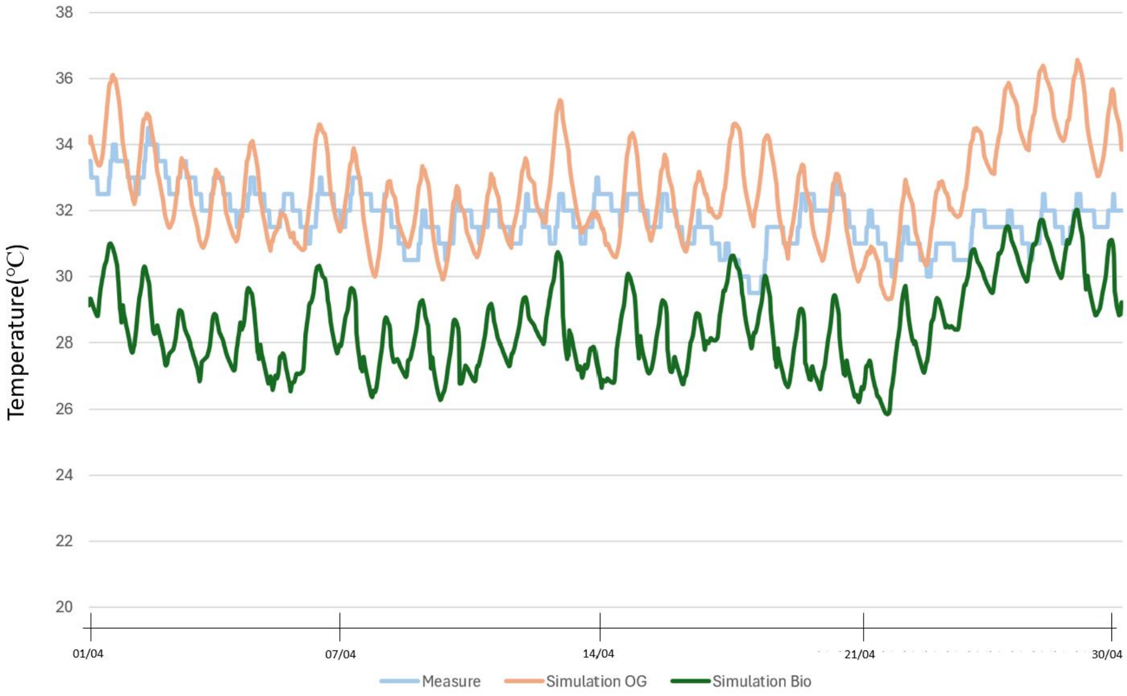


Figure 7-27: Temperature of detached house scenario 2 compared to measure and simulation data.

The average temperature of scenario 2 is similar to scenario 1 with 3 to 4 °C lower than the average temperature simulated in the original design. We see a variation of temperature between day and night in the bioclimatic house that is more difference compared to simulation and measured of the original design. That means adding louvers, the opening design, and the placement of the opening allow natural ventilation letting the house refresh during the nighttime.

- **Comparison of the BDGC card used in the two scenarios**

Comparing scenario 2 to scenario 1, we can notice a lot of similarities and differences between the two scenarios. We can see some similarities in the shape of the house, the organization of living space where they try to divide between semi-private and private space, using garage space as a shading area, and the fact that they try to connect indoor-outdoor space. However, other than that the house style is unique to each other. In terms of roof style, the number of floors and the design of night space are very different from each other. Scenario 1 uses the roof to create stack ventilation while scenario 2 uses the louver to create wind well in the stair area. Scenario 1 focuses on using green façades for the shading while scenario 2 uses the surrounding tree and balcony for shading. The surface area of scenario 1 is also smaller and closer to the original design as well. Nevertheless, both scenarios try to cooperate as much as possible with the design that allows natural ventilation and low, and sun protection. The creation of a microclimate using a water body isn’t a popular choice in both scenarios due to its complication in maintenance as mentioned by the participants.

The simulation results from DesignBuilder indicate that Scenario 1 exhibits a lower average temperature compared to Scenario 2. Despite the variety of design strategies implemented, the temperature difference between the two scenarios is relatively small, ranging from 0.5 to 1°C. The reduced temperature observed in Scenario 2 may be attributed to the presence of additional shading devices compared to Scenario 1. Conversely, during nighttime, Scenario 1 shows a slightly lower temperature, potentially due to the more effective space composition design that facilitates better airflow from the wind well at the staircase.

7.3.6 Apartment

Due to the size and complexity of this building, the duration of 4 hours wouldn’t be enough to conduct the usability test sufficiently like other buildings. Therefore, the apartment building (A1) wasn’t picked to undergo the redesign in the usability test. However, as we want to see how our guidelines can be applied in a more complex building, a bioclimatic design scenario is proposed by the author following the guidelines. We try to cooperate as much as possible with the design elements recommended by BDGC. For this redesign, we don’t evaluate the design process of this redesign but only the applicability of BDGC and its effectiveness on building thermal performance.

Several issues that can be addressed from the original design of the apartment are:

- Lack of shading to protect the building from the sun

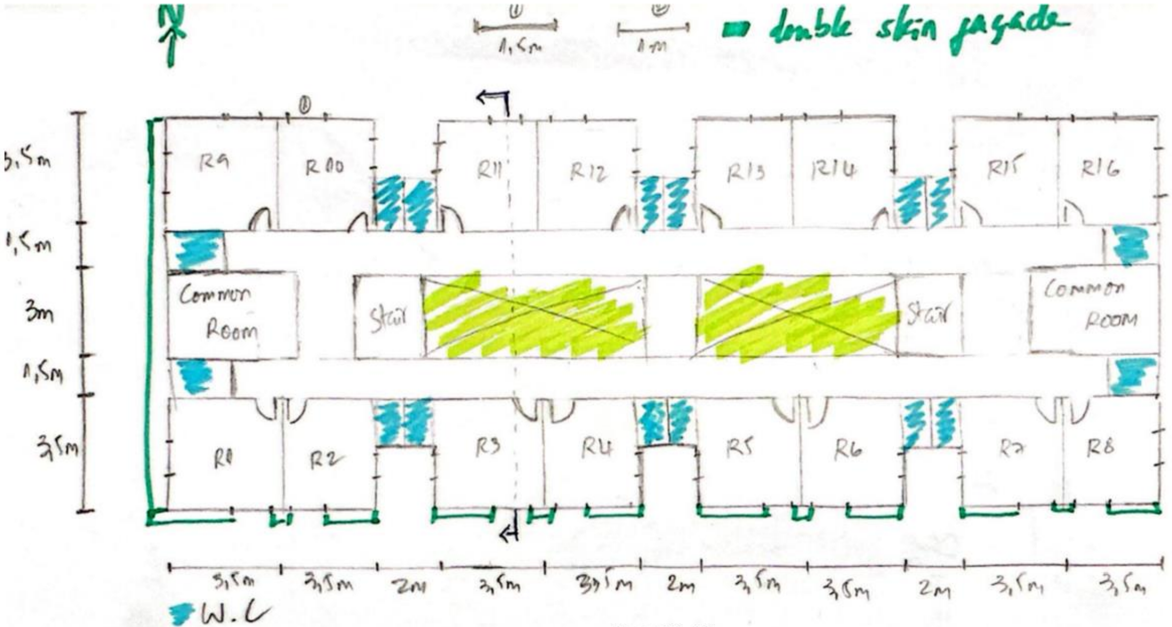
- The design of the window doesn’t allow maximum ventilation (slide glass window)
- The high occupancy inside each room
- Lack of kitchen and bathroom that doesn’t accommodate the privacy and comfortable living for Cambodian standard
- Lack of green space

Several design elements already cooperate with the recommendation from the BDGC:

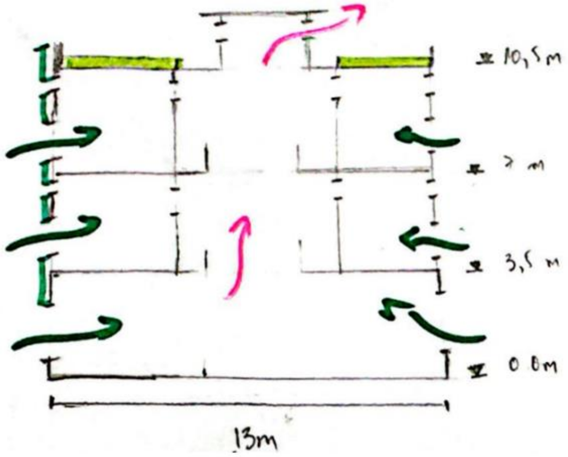
- The orientation of the building
- Cooperation of louvers to create a stack effect

For the redesign of the apartment to be a bioclimatic building, we focus on cooperating with more shading devices and creating a microenvironment surrounding the building. The redesign of this building using 10 elements from BDGC:

1. Water features: placing a pond on the ground floor to help extract heat, preventing it from rising to the upper floors to reduce indoor temperatures.
2. Wind well: adding a central courtyard into the building design to facilitate natural ventilation by channeling airflow through the structure.
3. Stack effect: adding louvers above windows and along walls facing the hallway to enhance the stack effect, which promotes vertical air movement, aiding in passive cooling.
4. Openings orientation: placing large windows on the north and south sides of the building to maximize ventilation, while windows on the west and east sides create cross-ventilation, improving airflow throughout the building.
5. Openings design: choosing casement window style to allow a greater surface area for airflow, optimizing natural ventilation.
6. Green façade: cooperating indirect green facades to provide shading for the building's exterior walls, reducing solar heat gain and improving indoor thermal comfort.
7. Horizontal Shading: The space between the green façade and the wall offers horizontal shading for the windows. Additionally, the small gaps between rooms create shaded areas for side windows, ensuring cooler air enters the building.
8. Green Roof: adding a rooftop garden to mitigate heat on the upper floor while also offering functional space for occupants, such as a vegetable garden.
9. Inlet - outlet: Although the variation in window size is due to indoor space design and not intentionally optimized for ventilation, the openings still provide some benefit by contributing to airflow dynamics.



Foor 01-02



Section

Figure 7-28: Bioclimatic design scenario 2 for the apartment.

The total surface area of the bioclimatic scenario is significantly larger than that of the original design, despite the room sizes remaining relatively similar. This increase can be attributed to the incorporation of a courtyard, which facilitates ventilation and shading as recommended by the BDGC, as well as the addition of a kitchen to meet comfortable Cambodian living standards. The opening surface area in each room is notably larger, considering the minimal changes made to the overall room dimensions. The room design allows for the integration of more openings without substantial alterations to the room's surface area. This demonstrates that implementing bioclimatic design strategies does not necessarily require an increase in overall building size.

Table 7-11: The noticeable changing design parameter between the original design and the bioclimatic scenario of the apartment.

Design element	Original design	Apartment bioclimatic scenario
Habitable area of each room	13.5 m^2	14.25 m^2
Total surface per floor	304.5 m^2	442 m^2
Number of floors	3 floors	3 floors
The surface of the opening of the whole building	132m^2	232m^2
Openings surface of each room	2.75 m^2	4.25m^2
Total height of the building	10.5 m	10.5m

- **Thermal performance simulation**

In this simulation, building parameters such as the pond in the courtyard and the green façade weren't able to cooperated in this model.

Table 7-12: Input parameter for the simulation of the apartment.

Categories	Input parameters	Value
Construction	External wall Partition wall Roof Floor Airtightness Schedule	U value = 2.1(W/m^2K) U value = 2.9 (W/m^2K) *U value = 5.3 (W/m^2K) U value = 2.92 (W/m^2K) Model filtration: 1 (ac/h) 24/7
Activities	Household size Building surface Density Occupancy schedule Summer clothing Metabolism level Computers	3 person per room *1326 m^2 *0.21 person/m^2 24/7 0.5 clo 0.85 met 0.004 (W/m^2)
Opening	U value Total solar transmission Light transmission	5.77 (W/m^2K) 0.62 0.57
Lightning	Normalized power density Schedule	5 (W/m2-100lux) 8h00-18h00 everyday

HVAC	Mechanical ventilation DHW Heating Cooling Natural ventilation	No No No No 24/7

*: modified parameter compared to input parameter for original design simulation

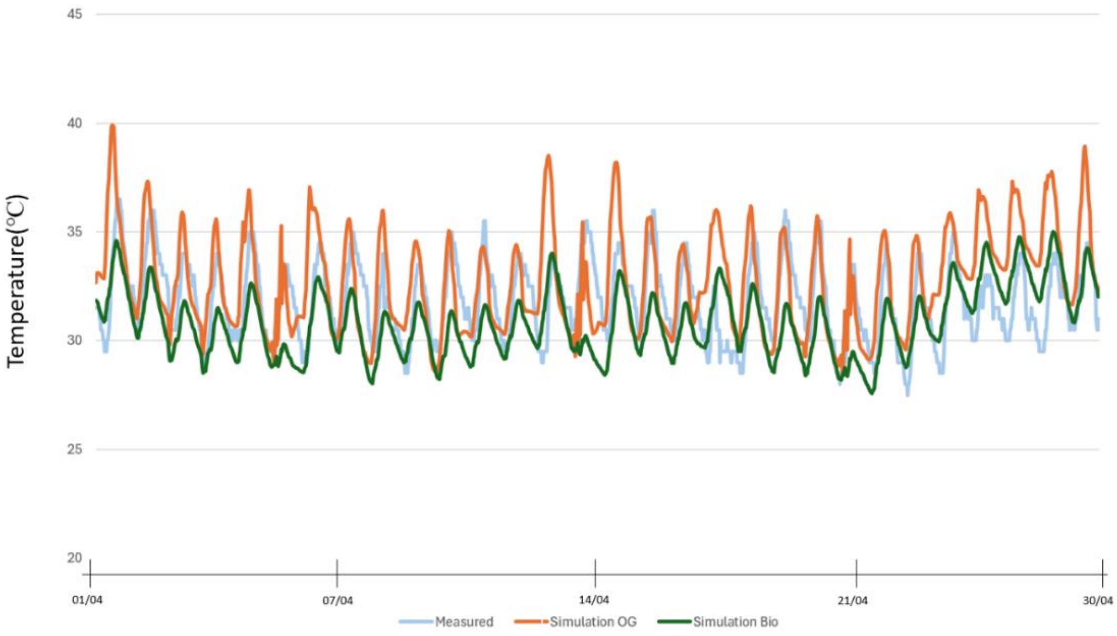


Figure 7-29: Temperature of the apartment with the integration of bioclimatic design compared to measure and simulation data.

We receive a lower temperature in the bioclimatic building even though the temperature is still higher than the acceptable comfort temperature. The bioclimatic building seems to have smaller temperature variation between day and night compared to the original building which comes from the effect of roof material. In the original house where zinc is the material for the roof, the temperature during the day is much more elevated than the night. Since the original building is already in good orientation and a good stack ventilation, the lower temperature seen in the new design comes from the effect of the courtyard, the positioning of the openings, the shading from the cut-out corner, and the horizontal shading. The temperature in the bioclimatic building would be lower if we could model the effect of the green roof and green façade in the simulation.

7.4 Strength and Limitations of the BDGC

BDGC aims to support informed decision-making in building design to maximize indoor thermal comfort. As demonstrated through usability tests and scenario simulations, BDGC effectively achieves this goal. It is the first design guideline introduced in Cambodia to help architects create comfortable residential spaces. Rather than imposing strict design regulations, the guideline seeks to guide architects toward best-practice solutions. BDGC helps designers feel confident and provides a structured approach to achieving bioclimatic goals in their buildings. Cooperating with both Esad and BDGC during the design process will help architects and designers make informed design choices from the early stages of the design process. The guideline is user-friendly, featuring schemas and descriptive explanations of each element, organized according to design phases. BDGC is intended to be simple so architects or students at any level can use it. The usability test proves that this intention is met as we see students with less experience use the guidelines more than those with more experience. The usability tests indicate that, due to its simplicity, this guideline is particularly suitable for young architects with limited experience and for designers who are not familiar with working on Cambodian projects.

The scope of the BDGC is confined to the architectural design of residential structures, specifically addressing the climatic and living conditions unique to Cambodia. Presently, as these guidelines emphasize passive and bioclimatic design strategies, therefore several critical aspects of building design, including construction material selection, active systems, and the incorporation of contemporary building technologies can’t be included. This limited the usage of BDGC for broader design aspects. It is anticipated that the guidelines may be expanded in the future to encompass a wide range of design elements, integrating both passive and active strategies to enhance thermal comfort in buildings.

7.5 Esad and BDGC

Based on the bioclimatic building scenarios derived from the usability test, we evaluated the performance of Esad in analyzing building thermal performance and providing decision support for architects. Figure 7-30 and Figure 7-32 illustrate the comparison of indoor temperature and PMV between building D1 and bioclimatic building scenarios 1 and 2. The analysis using Esad reveals that the indoor temperature in bioclimatic building scenario 1 is lower than in scenario 2 and the baseline building. This finding is similar to the result from simulations conducted using DesignBuilder.

When comparing the outputs from Esad (Figure 7-30) and DesignBuilder (Figure 7-31) for the bioclimatic scenarios, it is evident that both tools indicate scenario 1 as the most suitable design for achieving optimal thermal comfort. These results validate the effectiveness and reliability of Esad as a decision support tool for architects in assessing building thermal performance across different design strategies. Furthermore, this outcome demonstrates that Esad can effectively analyze designs incorporating BDGC elements.

The PMV-adaptive results (Figure 7-32) provide additional insights by evaluating different design strategies, specifically focusing on the effectiveness of window placement for ventilation, which temperature-based results alone may not capture adequately.

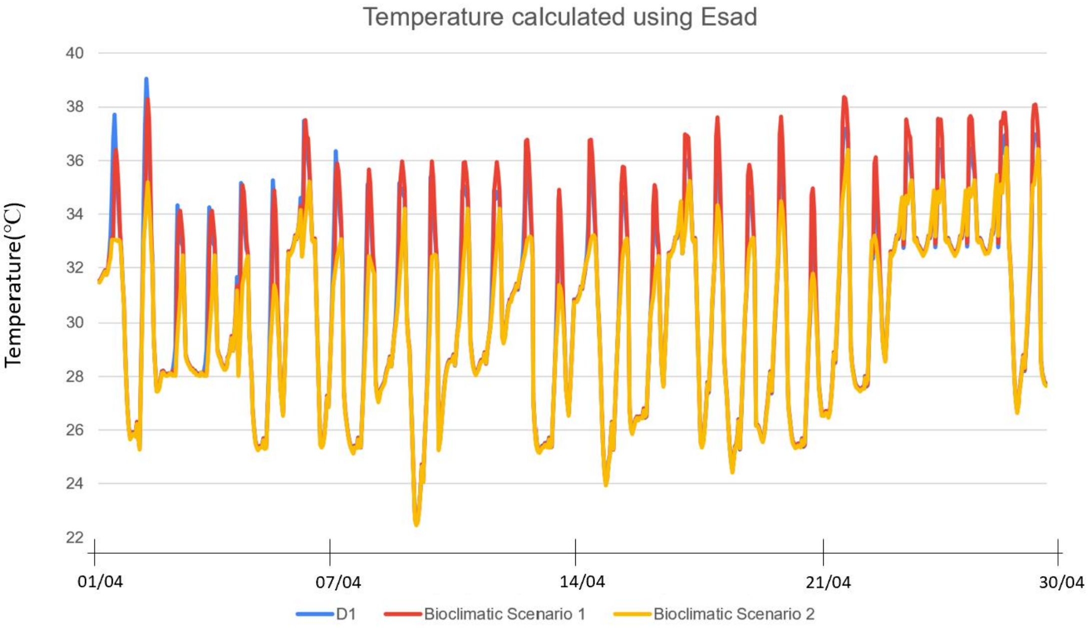


Figure 7-30: Indoor temperature of D1 compared to bioclimatic building scenarios 1 and 2 calculated using Esad.

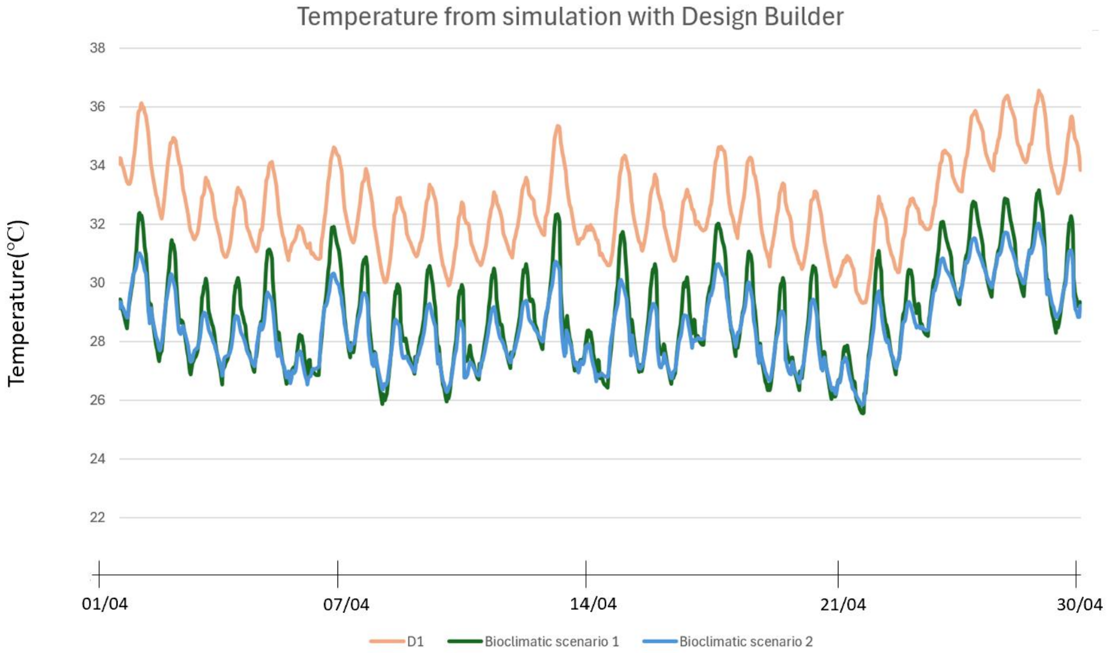


Figure 7-31: Indoor temperature of D1 compared to bioclimatic building scenarios 1 and 2 simulated with DesignBuilder.

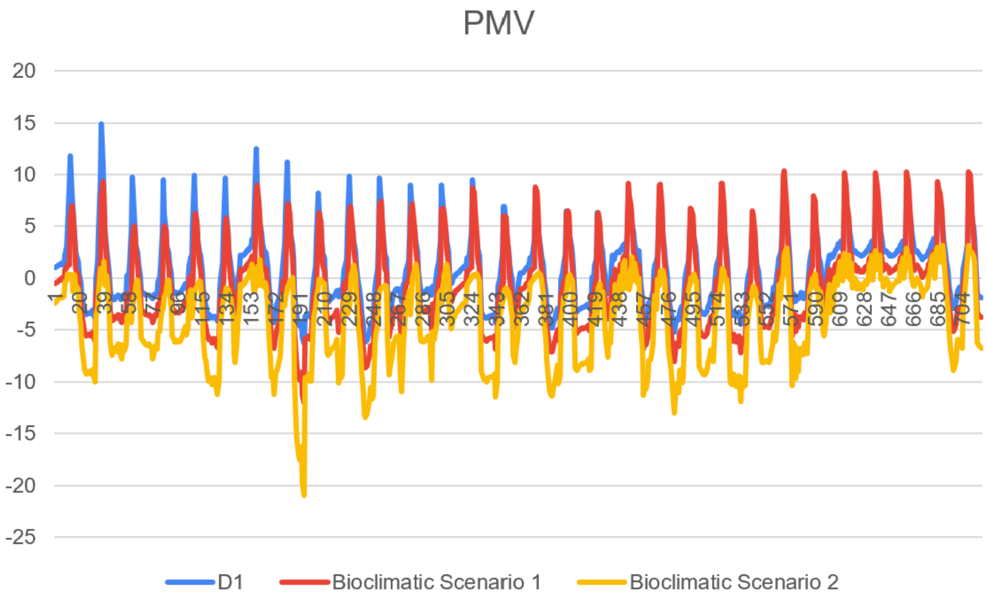


Figure 7-32: PMV of D1 compared to bioclimatic building scenarios 1 and 2 calculated using Esad.

On the other hand, for the link house, the temperature calculations derived from Esad indicate an insignificant difference between the base case and the bioclimatic scenario, which contrasts with the results generated by the DesignBuilder simulation (see Figure 7-33 and Figure 7-34. However, a more noticeable difference is observed in the calculation of PMV in Esad as seen in Figure 7-35. This is due to the result of the temperature of Esad primarily emphasizes on solar gain, while the PMV focuses on airflow. It is crucial to note that the differences in design between the base case and the bioclimatic scenarios are minimal in terms of building geometry, orientation, and solar gain through opening factors that significantly influence temperature calculations in Esad. The main difference lies in the wind well created by the staircase, a feature that cannot be accounted for in Esad. However, the inclusion of louvers in both bioclimatic scenarios is reflected in the PMV calculations. The design variations across each bioclimatic scenario remain minimal in terms of the previously mentioned parameters that influence the calculations in Esad. Nonetheless, these subtle differences effectively yield comparable results between Esad and DesignBuilder. Notably, Scenario 2 demonstrates a lower temperature than Scenario 1, aligning with the simulation result generated in DesignBuilder. This alignment suggests that even small design adjustments can effectively present in Esad.

The comparison between Esad and DesignBuilder for both house types demonstrates that Esad can be effectively utilized to evaluate different design strategies and provide decision support for architects. However, it is crucial to analyze both temperature and PMV results, as each metric may be influenced by different design strategies. Design strategies that affect solar gain are more likely to be reflected in the temperature results, while those impacting airflow will be more apparent in the PMV results.

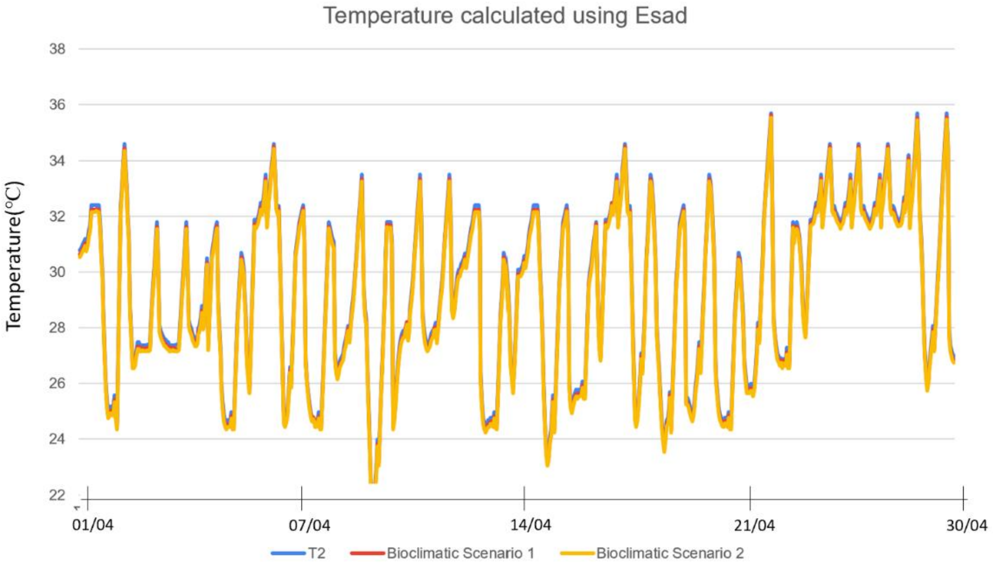


Figure 7-33: Indoor temperature of T2 compared to bioclimatic building scenarios 1 and 2 calculated using Esad.

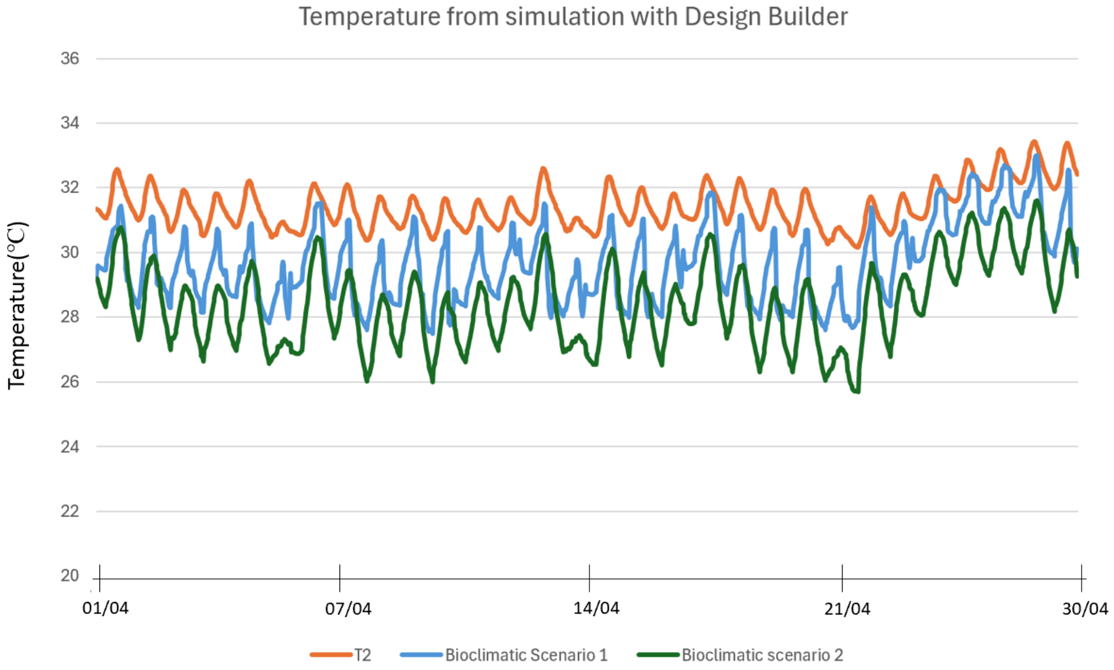


Figure 7-34: Indoor temperature of T2 compared to bioclimatic building scenarios 1 and 2 simulated with DesignBuilder.

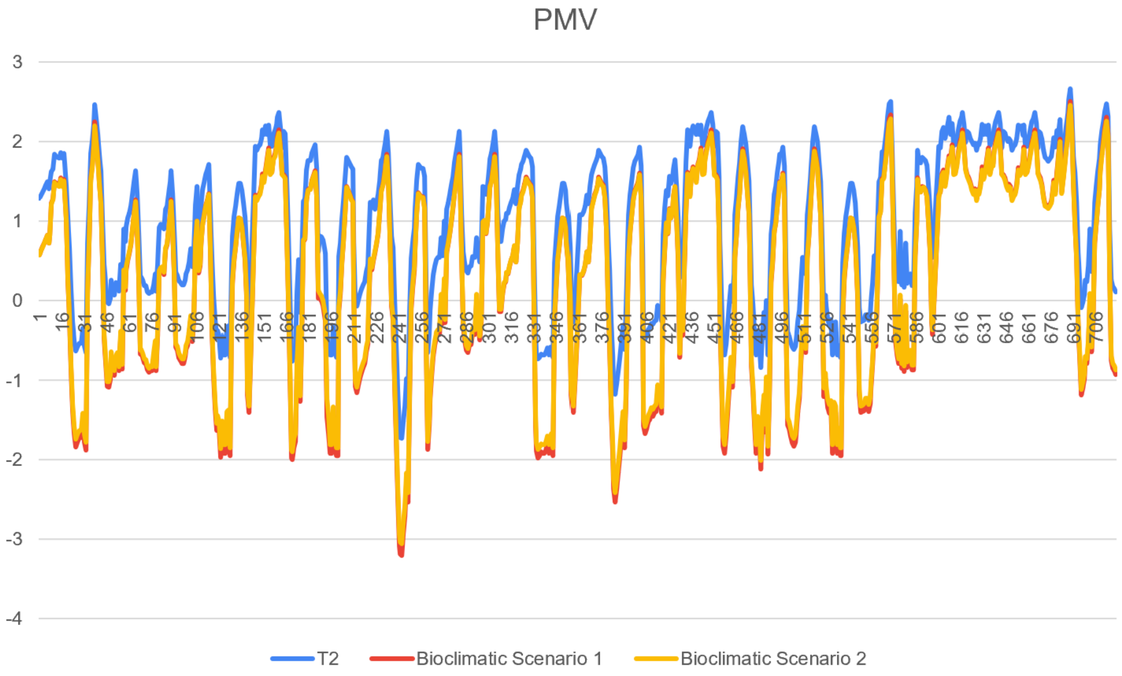


Figure 7-35: PMV of T2 compared to bioclimatic building scenarios 1 and 2 calculated using Esad.

7.6 Architectural Design Process for Bioclimatic Building

From the observations during the usability tests, we were able to identify differences in architectural design processes between students and professionals and assess how BDGC influences architects' decision-making, the evolution of their conceptual phases, and its integration into the design process. The design process across all usability tests follows a consistent pattern (see Figure 7-36), progressing from the assessment of provided documents to programming and master plan design, then to floor plan design, façade design, and finally roof design. This indicates that *Phase Design* is prominently practiced throughout these stages, suggesting that the BDGC card is suitable for both educational and professional environments. Utilizing the BDGC helps architects clarify their goals and facilitates problem-solving aligned with specific design intentions across all phases of the design process. The integration of the BDGC is evident from the early stages of the design process and continues to be utilized throughout. At the first design stage, architects establish clear design goals using the BDGC, which serves as a guide to keep them focused on their objectives. As the design phases evolve and concepts develop, participants frequently return to the BDGC for consultation when uncertainties arise. Certain cards selected at the beginning may be adjusted to reflect the evolving concepts. Having the cards provides insights into the potential direction of the next design iteration, thereby helping to eliminate unnecessary correction loops during the design process. The integration of BDGC into the design process highlights its importance and demonstrates when tools like Esad are necessary as decision support aids for architects.

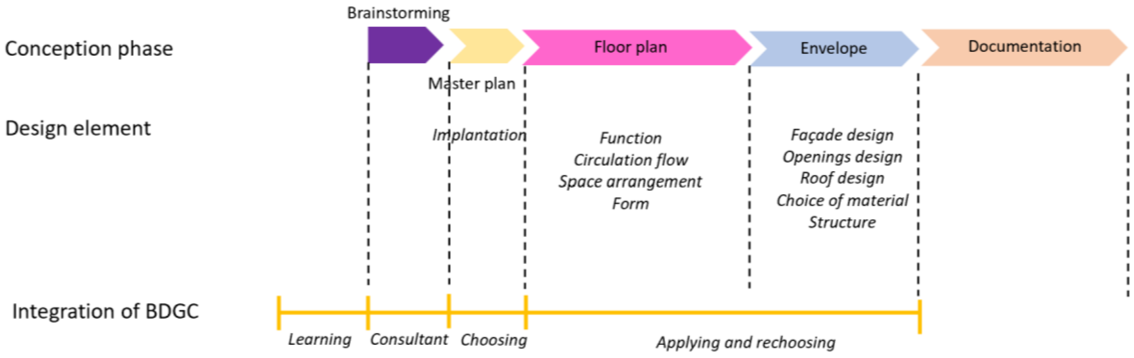


Figure 7-36: Integration of BDGC in the design process during the usability test.

To achieve designing a bioclimatic building, we propose an architectural design process where all of the findings from Chapter 6 and this chapter can be integrated to make the design process go smoothly, avoid correction loops at the later design stage, and effectively achieve optimum thermal performance.

In the proposed bioclimatic design process as illustrated in Figure 7-37, BDGC is recommended for implementation from the pre-design phase and can be practiced throughout the design process. This allows architects to establish clear goals and define certain aspects of their building design based on location analysis and the design recommendations provided by the guideline. More than that, at each design loop solving each issue, architects can go back to BDGC for more clarification, particularly after testing the design with Esad. Esad should be introduced at the end of the pre-design phase, when design elements are still flexible, to assist in identifying and refining these elements. The use of Esad at every design loop helps minimize the risk of the correction loop happening if the BPS is conducted in the design development phase. CAD can be employed for detailed design, and if BIM integration is required, it should commence starting at the schematic design phase. Utilizing BIM or CAD ensures that the data input for Esad remains clear and precise. BPS can be initiated at the beginning of the design development phase for detailed simulation or to verify the requirement for the green building certificate if needed.

The proposed design process is intended for architects to successfully design a bioclimatic building with the help of BDGC and Esad to provide informed decision support at every design loop. With this application correction loop from one design phase to another could be avoided.

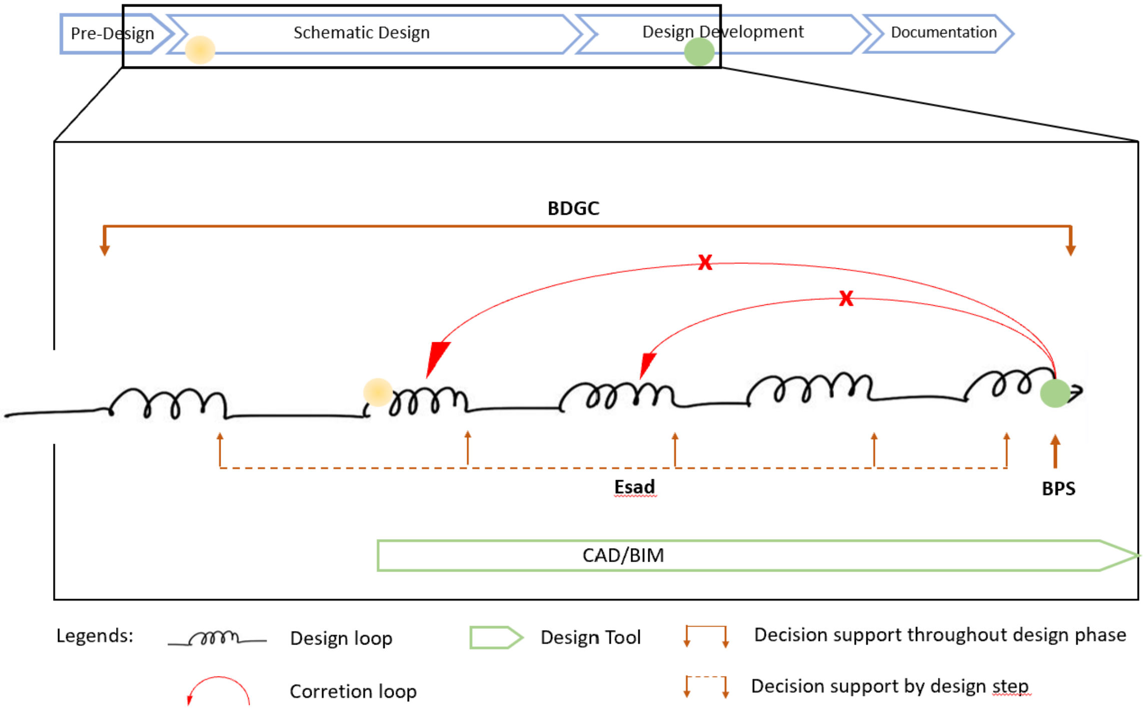


Figure 7-37: Architectural design process integrated decision support to achieve bioclimatic building.

7.7 Chapter Conclusion

BDGC is proposed as a design strategy aid for architect decision-making in the early design process. BDGC offers architects and designers a valuable framework to improve thermal comfort and energy efficiency within interior spaces. While each designer brings a distinct vision and focus to their projects, these guidelines function as a supportive tool rather than a restrictive mandate. They facilitate informed decision-making by providing best practices and recommendations, ensuring that key aspects of thermal comfort are considered. However, designers maintain the creative freedom to pursue their artistic vision, adapting and interpreting the guidelines as necessary. This approach enables them to create spaces that are not only comfortable and functional but also innovative and reflective of their individual style and intent.

From the validation using simulation, we can see the improvement of thermal performance in all 3 house typologies. By adjusting some design features following BDGC, we can lower the temperature by 2 to 4 ℃. The test with Esad further validated the effect of BDGC and Esad as decision support material to achieve bioclimatic building. Even if the design following the guidelines can’t provide 100% comfort to the occupant, the improved thermal performance would still benefit when adding the use of fans for less energy consumption.

The applicability of BDGC and Esad in helping architects improve building thermal performance allows us to propose an architectural design process where these two decision support materials can be integrated from the early design phase to avoid correction loops at the end of the design process.

CHAPTER 8

DISCUSSION

In this chapter, we present the discussion on the various results that we received from the 5-phase research methodology and answer the 4 research questions developed in Chapter 2.

8.1 Answer to Research Questions

Before entering into the response to the research questions, we would like to remind you that this thesis aims to answer 4 research questions revolving around the improvement of the quality of residential buildings in terms of thermal comfort in Cambodia:

> Q1. How is the thermal performance of current residential buildings in Cambodia?
>
> Q2. What are the effective bioclimatic design strategies to achieve thermal comfort in buildings in Cambodia to fit with climate transition and change of socio-cultural?
>
> Q3. Can BIM and BPS assist designers in achieving maximum thermal comfort in buildings during the design process in the context of Cambodia?
>
> Q4. What method can be implemented to facilitate the analysis of thermal comfort to achieve bioclimatic buildings in the early design phase?

8.1.1 How is the thermal performance of current residential buildings in Cambodia?

The global survey shows that current residential buildings in urban areas such as Phnom Penh don’t provide enough thermal comfort for their occupants. Upon in-depth monitoring of 5 buildings in Phnom Penh within 3 common house typologies, it shows that the temperature in the 3 house types during both rainy and dry seasons usually have a temperature 1 to 3℃ higher than the standard of comfort temperature for tropical regions and 5 to 6 ℃ higher than the international standard as ASHRAE. In contrast, the air velocity seems to be lower than the standard. The house type doesn’t have a lot of impact on the temperature difference but more on the airflow. It is noticed that the detached house has the best thermal performance despite having a relatively high temperature compared to other house types due to its elevated air velocity. It turns out air velocity is the most important factor that influences on thermal performance of Cambodians. This resulted in them using pedestal fans as their main solution for thermal comfort throughout the year.

The variation of temperature between day and night in both link house and detached house isn’t high (Figure 4-26). It suggests that the house wasn’t well refreshed during the nighttime which is the most important factor for thermal comfort for houses in hot climate regions. The cooling nocturnal effect during the nighttime could keep the house cool until noon. The lack of this effect results in a rapid temperature increase as soon as the sun rises. This is due to the house design, which does not incorporate louvers for nighttime ventilation, an alternative that could allow airflow when opening windows may feel unsafe for occupants during the night.

The design of the link house doesn’t favor natural ventilation while the design of the detached house doesn’t pay much attention to shading devices and recreation of the microclimate to surround the building. The house design is more focused on aesthetics with the cooperation of glass panels for all openings and the lack of louvers for natural ventilation safely and securely. This concept alters the occupant's behavior to seek fans and air conditioners for comfort.

8.1.2 What are the effective bioclimatic design strategies to achieve thermal comfort in Cambodia?

Bioclimatic design strategies that have been applied in traditional houses and other best practices in other countries with similar climate conditions are effective sustainable design strategies for thermal comfort. Many of these strategies are examined, chosen, and combined to create a design guideline that is optimally suited to the context of Cambodia.

A bioclimatic design guideline for Cambodia is proposed which includes 18 bioclimatic design elements focusing on creating a microclimate, increasing shading and airflow inside the building. The strategies include:

- Building orientation with the long side of the building along the north-south axis or 45° toward the east.
- Application of water bodies and trees to create a microclimate surrounding the building.
- Space arrangement and composition.
- Opening design and position for cross ventilation and stack effect with the cooperation of wind well.
- Shading through horizontal shading devices, vegetation, and vertical landscape.
- Roof design with double slop roof, double ventilated roof, and green roof.
- U-value of the material (high U-value material to north and east and low U-value material to south and west).

After applying the bioclimatic design elements, the redesign of the case study building shows a better thermal performance compared to the original design. It turns out that using solar protection (shading devices and the design with minimal solar gain) combined with stack effect or wind well could lower temperature from 2 to 3 ℃. For maximum building thermal performance, as many bioclimatic strategies as possible should be integrated into the building design. The integration however needs to be aligned with the essence of the architectural design of the building and other requirements of the project. From the simulation of the bioclimatic building scenario, it is noticed that building scenarios that have more louvers seem to have a lower temperature and better building nocturnal cooling effect.

8.1.3 Can BIM and BPS assist architects in designing a building for optimum thermal comfort in Cambodia?

BIM and BPS can assist architects in designing a building for optimum thermal comfort. The use of BIM as a BIM model can speed up the modeling of the BEM model and the simulation process. However, the complications of BIM modeling, the issues of interoperability between BIM and BEM models, and the required data needed to conduct the simulation, make the whole process require a lot of time which doesn’t make it an efficient method in decision-making for architects since the early design phase. As evidenced in Chapter 7, sustainable design is applied since the preliminary design phase, and choosing design strategies at this stage is crucial which requires a suitable and convenient approach as a decision support for the architect in terms of analyzing building thermal performance.

The current practice of BIM and BPS in Cambodia is still limited. More than that, it turns out BPS isn’t practiced directly by the architects during the design process. As of now, for Cambodia, the use of BIM and BPS is more like an add-up approach rather than a primary practice, especially for residential buildings where sustainability can be easily integrated. Even if architects are open to the practice of BIM and BPS in the future, these two methods don’t seem to work as decision support tools for architects but more as modeling tools, collaboration, and verification methods for certain requirements by the project and client (i.eg green building certificate).

If the architect were to practice BIM during their design process, BIM protocol should be integrated from the early design phase and BIM modeling can start when the first preliminary design with sketch is done to smooth the entirety of the design process. For BPS, however, it can only be feasibly conducted during the intermediate stages of the design process due to its complications, the data, and time requirements. Employing BPS at this phase, however, may introduce correction loops if simulation outcomes deviate from expectations, potentially delaying the overall design process.

8.1.4 What method can be implemented to assist architects since the early design process to achieve designing a bioclimatic building?

The initial design phase exerts a more significant influence on the final outcomes of a building's design than later phases. However, findings from the previous question show that BPS cannot be easily applied during the early design stage due to its complexity and time-consuming nature. Consequently, we propose a new tool called Esad that is more simple, user-friendly, has minimal data requirements, and is time-efficient for conducting building thermal performance. The proposed method to support architects in achieving bioclimatic building design from the early stages involves providing resources for informed decision-making, including a design guideline (BDGC) offering various bioclimatic strategies, and an evaluation tool (Esad) for identifying optimal strategies tailored to specific projects.

BDGC is intended to guide architects in establishing clear goals and targets for bioclimatic design from the pre-design phase, while also supporting adherence to these goals throughout the entire design process. Using Esad, architects can evaluate the performance of bioclimatic strategies integrated at each design loop, allowing them to select the most effective strategies that optimize thermal comfort with minimal energy consumption, thereby achieving bioclimatic building while aligning with other project requirements.

8.2 General Discussion

This section opens the discussion on decision support material in the architectural design process to ensure thermal comfort and the sustainability of the building.

We first started the study by analyzing the thermal performance of the current housing design. Like other studies in this climate, the current building design doesn't provide enough thermal comfort to its occupants. The main reason for this discomfort is of course due to global warming which made the traditional design to not be able to handle the harsh weather conditions anymore. Another main reason is due to the mal design of the current house, which doesn't accommodate the weather conditions naturally and sustainably which results in the change of occupant behavior toward the improvement of their comfort (i.e., increasing use of AC).

We believe that action and decision-making during the design process play an important role in ensuring the comfort and sustainability of buildings. We examine various tools and methods that can act and help architects to have informed decision-making during their design process. BIM model and BPS are tested as decision support tools in terms of building analysis. It turns of the BIM model contribute to facilitating the process of BPS which leads it to be considered as a tool in decision support as well. However, the limitation of interoperability between the BIM and BEM models and the complication of the BPS process make it a suitable decision-support tool in the later design phase. This finding is also found in a study by Han et al. (2018) In a similar context of the application.

The architectural design processes, particularly those focused on building comfort and sustainability currently practiced in Cambodia, have been identified through extensive interviews and observations conducted in both professional and educational contexts. Notable similarities exist in these design processes, particularly regarding the development phases and tools utilized. In terms of decision support tools applied within these processes, BPS is perceived as inadequate and may lead to correction loops during the final design phase. While correction loops are anticipated during the design process, they ideally occur in the early phases, where necessary adjustments are less intensive than in the later stages.

In both professional and educational settings, these correction loops frequently arise due to a lack of decision support tools in the early design phase, at each design loop, or the late application of such tools in the final design phase. Moreover, in educational environments, the absence of effective decision support has resulted in varying collaborative methods, culminating in the establishment of three distinct actor profiles, with one actor serving as the decision support for design validation. These findings underscore the necessity for decision support tools that can be employed from the early design phase to assist architects in achieving bioclimatic buildings.

Our proposed tool, Esad, has been demonstrated in our study to effectively provide decision support for architects from the early design phase, facilitating the selection of various design strategies for optimizing building comfort. More than that, utilizing BDGC has been shown to enhance architects' confidence and minimize corrective loops in the later design phase. Furthermore, integrating Esad with BDGC could furnish adequate decision support material at each design loop, promoting the development of bioclimatic buildings while mitigating the risk of corrective loops associated with the implementation of BPS in the later stages of design.

8.3 Supplementary Discussion

- **Methodology**

The observation method during the student review session with the professor doesn’t collect enough data for analyzing the design process. In the long-term design process, especially in an educational environment where students work separately according to their available time, observing their design process during the actual process is very challenging. The method of observation through questionnaires or progression sheets turns out to be more effective. It is important to note that, observing the architectural design process within a professional environment, where architects predominantly collaborate in shared spaces, the observation method during the conception period might be more suitable. This approach could involve, for example, tracing tool usage throughout the design process. The doctoral thesis by Calixte (2021) explores and discusses this topic.

- **Thermal comfort**

The result of the first methodology phase gives insight into the thermal performance of current Cambodian houses and the adaptation of Cambodians to the hot climate. We see their higher acceptable temperature than the international standard but similar to other findings of acceptable temperature value in tropical regions. In terms of important influential parameters, our findings indicate that in naturally ventilated environments, air velocity exerts the greatest influence. This finding is similar to a study in Indonesia (Feriadi & Wong, 2004). However, this contrasts with another study in Benin and Malaysia which lies under similar climate conditions where relative humidity was identified as the most significant factor (Olissan et al., 2016; Shafizal MAAROF, 2009). The difference in this finding is likely attributable to the adaptation of the Cambodian population to wearing conservative clothing, which minimizes the impact of humidity on skin evaporation. Additionally, the widespread use of electric fans to enhance comfort may further mitigate the effects of humidity. A study in Singapore has shown a similar finding where elevated air velocity can maintain comfort level at a high temperature (Cen et al., 2023). This results in adaptive comfort models develop for each region to accommodate the impact of the most critical influence parameter.

- **BIM and CAD**

Despite the considerable advantages offered by BIM, it is apparent that CAD remains an indispensable tool within the design process. In developing countries, while BIM is anticipated to become increasingly prevalent over the long term, CAD currently continues to serve as the primary design instrument. As seen from the observation and the interview, even with the integration of BIM, the architect has to go back to CAD at the end of their design process for documentation as other stakeholders can’t work with the BIM model. The 100% use of BIM during the design process would happen only if all stakeholders have adapted to BIM, which is a very small possibility for developing countries in the foreseeable future.

- **BDGC**

During the usability test, it was observed that certain BDGC elements were integrated into the final designs more frequently than others. Six recommended elements were consistently incorporated into the building designs: orientation, vegetation shading, stack effect, wind well, horizontal shading, and the design of openings. Some cards from the roof design and shading design categories were used more selectively, which is understandable, as these factors may depend on site constraints and the aesthetic preferences of the participants. Interestingly, two recommended elements, double-ventilated roofs, and U-value considerations, were not used at all. The lack of focus on U-value may be attributed to the widespread use of brick in Cambodian construction, which is already regarded as a suitable option for thermal comfort due to its heat resistance. As a result, architects may not have felt the need to prioritize this factor. However, despite the popularity of double-ventilated roofs in Cambodia, especially for flat roof designs, this element was also not integrated during the test. Instead, participants favored the incorporation of green roofs to create green spaces, potentially indicating an emerging design trend for flat roofs in Cambodia.

8.4 Chapter Conclusion

In this chapter, we discuss various points that were found in the application of the methodology for data collection, the results, and some comparisons with similar studies:

- In our assessment, BPS and BIM are considered decision support tools, however, aren’t suitable for application in the early design phase, especially in the context of Cambodia
- The absence of a robust decision support framework leads to fluctuations in the design process, resulting in a cyclical correction loop. This uncertainty in collaborative design work manifests in the emergence of three distinct actor profiles, with one actor potentially assuming a decision support role.
- Implementing design strategy guidelines combined with Esad as decision support materials can enhance the confidence of architects in achieving bioclimatic building and avoid the correct loop in the design process. Through observation methods, such as using cards to track design development, it becomes evident that these guidelines provide consistent support to architects throughout the entire design proces

CONCLUSION

The final chapter of this manuscript synthesizes the study's findings, highlighting the innovative aspects and original contributions of the research. This section will also address the limitations identified throughout the study. Additionally, the author will provide a reflective discussion on their perspectives concerning the research and propose directions for future research that could further advance the field. Finally, the chapter will offer several recommendations for implementing the research findings in practical contexts.

9.1 Synthesis

The challenges related to thermal comfort in Cambodian housing are increasingly pressing, and current solutions in practice fail to adequately address environmental concerns (see page 36). This underscores the critical importance of interventions during the design process to enhance building comfort while simultaneously upholding principles of sustainability.

This thesis aims to create a decision support material for architects and designers that could assist them in achieving a bioclimatic building with maximum comfort and minimum energy consumption for the context of Cambodia. Four research questions were developed to aim to address this objective (section 2.3):

> Q1: What is the thermal performance of current houses in Cambodia?
>
> Q2: What are the effective bioclimatic design strategies to achieve thermal comfort in buildings in Cambodia?
>
> Q3: How do BIM and BPS assist the designer in achieving maximum thermal comfort in the building during the design process in the context of Cambodia?
>
> Q4: What method can be implemented to facilitate the analysis of thermal comfort to achieve bioclimatic buildings in the early design phase?

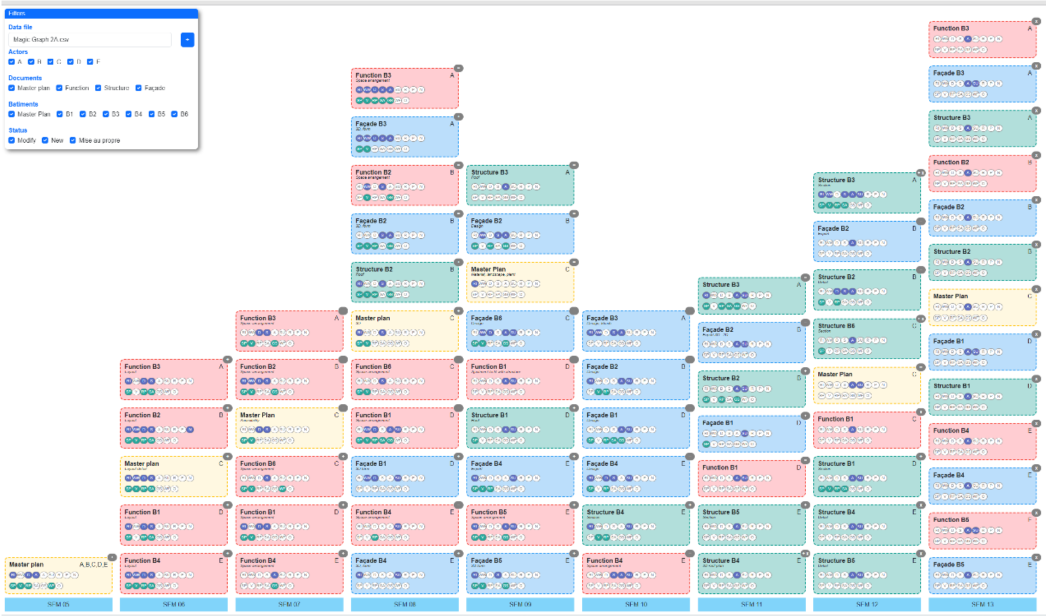
A five-phase research methodology (sections 3.2 and 3.3) is employed to address our objectives, incorporating qualitative, quantitative, and modeling approaches. First, we examine the thermal performance of the most common housing typology in urban Phnom Penh, highlighting the significance of air velocity and proposing an adaptive comfort model. Subsequently, we investigated the application of BIM and BPS as decision support tools during the early design phase to assist architects in optimizing building comfort. Evaluating on our experience (sections 5.3 and 5.4), BIM and BPS aren’t suitable to apply as decision support tools in the early design phase due to time-consuming of the simulation process.

Based on interviews with architects and student observation, we explore the feasibility and challenges of implementing these approaches in Cambodia (sections 6.2 and 6.3). Our findings reveal that the traditional architectural design process (sections 6.2.1 and 6.3.3), alongside basic design tools, remains the primary method in practice (sections 6.2.2 and 6.3.4). We identify the limitations of current BIM and BPS practices and the challenges associated with integrating these approaches in a developing country, particularly given the constraints of limited resources and expertise. To address these challenges, we propose two approaches as decision support material to assist architects in achieving bioclimatic building designs: a tool for evaluating design strategies based on their thermal performance (section 6.5), and a bioclimatic design guideline tailored specifically to the Cambodian context (section 7.1). The two materials are intended to be applied in the design process from the early design phase to facilitate informed decision-making in the selection of design strategies, ultimately contributing to the creation of comfortable and sustainable buildings.

9.2 Original Contributions

9.2.1 Methodology

A part of the contribution of this thesis lies in the methodology used for the collection and analysis of data. First, a platform called Vireli (see Section 6.3) is developed to visualize the collected data from student observations. Vireli utilizes a production bubble timeline, which facilitates the analysis of various elements within the architectural design process, as illustrated in Figure 9-1. This approach enables a more structured and comprehensive examination of design activities.



Filters

Data file: Magic Graph 2A.csv

Actors: ☑ A ☑ B ☑ C ☑ D ☑ E

Documents: ☑ Master plan ☑ Function ☑ Structure ☑ Façade

Batiments: ☑ Master Plan ☑ B1 ☑ B2 ☑ B3 ☑ B4 ☑ B5 ☑ B6

Status: ☑ Modify ☑ New ☑ Mise au propre

Figure 9-1: Vireli, the original method used for visualization of data of architectural design process observation.

The second contribution in methodology lies in the approach employed to collect data during the usability test, which involved a game-like manner of the BDGC cards. This interactive process between participants and the cards enabled a detailed observation of how each design element was integrated into the overall framework and decision-making process. The BDGC cards played a critical role in guiding participants toward finalizing their building redesign, offering insights into their cognitive and design strategies.

Figure 9-2: BDGC card, original method used for collection of data during the usability test.

9.2.2 Thermal Performance and Design Issues of House in Cambodia

The first contribution of this thesis is the investigation into the thermal performance of residential buildings, where we were able to identify common house typologies in urban areas of Cambodia, as well as the thermal performance of the most common house types: link houses, detached houses, and apartments. Even though all three house typologies have a high discomfort level compared to the standard in tropical regions and international standards, it appears that the detached house provides the most comfort compared to the other two house types. Several house design issues are identified upon in-situ visits, house monitoring, and interviews with occupants. Link house turns out to have the most issues for its lack of attention in designing for natural ventilation and forcing occupants to use fans and air conditioners.

9.2.3 Acceptable temperature value and adaptive comfort model

From the occupant survey, we identify an acceptable value of temperature of 29-30 °C for comfort which is similar to other studies in neighboring countries. The most influential parameter for thermal comfort in Cambodia is identified to be air velocity through PMV with occupants from the link house. The linear regression of PMV vote by the occupants allows us to identify a correction coefficient for PMV to be adapted to the context of Cambodia (see section 4.8). Even though a higher number of samples is needed, this finding is still imposed as a reference and methodology for future research. The adaptive PMV for Cambodia can be written as below:

$$PMVadaptive = PMVcalculated - (0.018Ta + 0.39AV)$$

9.2.4 Decision Support Materials

An architect aid in the form of decision support material is proposed to help architects in decision-making to achieve designing bioclimatic buildings. The decision support materials are proposed with a design guideline (BDGC) of bioclimatic strategies (section 7.1) and a tool (Esad) for thermal performance analysis (section 6.5), designed specifically for the context of Cambodia.

The BGDC consists of 18 bioclimatic design elements. Even though the design elements already exist in traditional houses and have been proposed by other studies in similar climates, the proposed elements take into consideration the living conditions and the possible design strategies that can be easily implemented in the context of Cambodia. More than that, combining all the elements and categorizing them following the design process could help architects apply them more efficiently throughout their different design phases (section 7.1).

Similarly, for Esad, even though the equation used for the calculation of the influence parameter isn’t invented in this study, the proposed tool, designed as spreadsheets, is simple to use and requires minimal data input and less time to obtain building performance results compared to BPS. More than that, the equation used for the calculation of PMV is based on the finding from our study, making Esad to be suitable for usage in Cambodia.

9.2.5 Architectural Design Process in Cambodia

The architectural design process that is currently practiced in Cambodia for both professional and educational environments is identified (sections 6.2.1 and 6.3.3). The traditional 4 phases design process is still practical for residential projects with the use of CAD tools. The integration of BIM and BPS during the design process is still limited and the use of BPS normally happens at the end of the design phase.

Three types of design collaboration are found in the design process in educational environments along with three profiles of actors (section 6.3.6). Due to the lack of decision support material, the correction loop happens at the third stage of the design process.

An architectural design process is proposed (section 7.6) for smoothly integrating new decision support material from this thesis such as BDGC and Esad and the application of BIM and BPS to avoid correction loops and assist architects in achieving designing a bioclimatic building.

9.3 Limitations

The limitations present in this study are mostly caused by the boundaries of the research, the lack of resources and materials, and the fact that the start of the research happened during the pandemic which restrained some data collection.

A minor limitation is present in the second phase of the research, which focuses on the investigation of building thermal comfort (sections 4.6 and 4.7). The COVID pandemic led us to conduct global surveys online through social media outlets which people of all ages couldn’t participate due to the lack of access to this technology. More than that, this phase of the study selected only five case studies, all located in the same city and subject to similar design constraints. However, the selected buildings represent different residential types and are situated in various locations within Phnom Penh, providing diverse insights into building design issues related to discomfort and occupant behavior. Additionally, a global survey has been conducted to offer a broader perspective on other buildings that were not measured directly.

Another limit is regarding the number of samples from the case study building survey and PMV interview. The lack of data on gender allows us to identify an acceptable comfort range only for women.

The limited number of architectural firms practicing sustainability and their reluctance to share their experiences restricted the number of interviews and observations regarding the integration of BIM and BPS in the design process (sections 6.2 and 6.3). Although 10 companies would be considered a sufficient sample for this study, in-depth observations within these firms would have provided a deeper understanding of the design timeline, interactions between stakeholders, and the application of these methods with a focus on sustainability in a professional environment.

Due to the time needed for each test and the availability of participants, only seven usability tests were conducted. Additionally, the backgrounds of participants lacked diversity, as they all graduated from the same university. However, many participants have extensive experience working in the design field with colleagues from various backgrounds, allowing us to distinguish differences in design actions between each test.

The main limitation of this study is the accuracy of input weather data for the simulation. Even though the building was calibrated following the standard of ASHRAE before the simulation of bioclimatic building scenarios, the building could be calibrated better with more accurate weather data to give higher reliability to the simulation result.

Other main limitations arise on the proposed decision support material, the Esad, and BDGC. The design of Esad is to be used for quick analysis of building design for both experts and non-experts with simple requirements of input data, limit its usage for analysis of building thermal performance in real-time and complex design parameters such as green façades, double façades, or roof designs as outlined in BDGC. Consequently, Esad is suitable only for noncomplex buildings, such as single-family homes, and cannot effectively analyze buildings with high complexity in function, program, and geometry. Conducting usability tests with Esad would be valuable in assessing its impact and reliability in supporting architects and designers.

The final limitation pertains to BDGC, where the proposed elements were not subjected to a sensitivity analysis. However, numerous studies as mentioned in section 7.1.3 have already demonstrated the effectiveness of these proposed elements, and the simulations of bioclimatic design scenarios further validate the efficiency of these strategies.

9.4 Perspectives

In this section, we reflect on the limitations encountered and explore potential strategies to mitigate these challenges. Additionally, we identify valuable topics for future research that could enhance our understanding and address these issues.

For the study of thermal comfort that relies on simulation, an outdoor weather measurement needs to be conducted at the same time as the indoor measurements. For developing countries such as Cambodia where there is lacking resources and information isn’t easily accessible, having a precise outdoor climate for the case study location would provide a better and more accurate result and gain some time to conduct the calibration. This is one of the reasons why our study couldn’t analyze the whole year's building thermal performance based on the simulation but more from the interview with the occupants.

For the adaptive thermal comfort model (PMV adaptive), a larger number of samples could be done through survey and monitoring in a space such as an office or classroom where a lot of people can stay together for a long period, wearing the same cloth, and doing similar things. Creating an adaptive comfort model based on residential buildings consumes a lot of time and could result in inaccuracy due to age differences and various occupant behaviors.

The monitoring should also be done with vernacular houses that still exist in the urban area to understand why it is starting to disappear and see if the traditional strategies still withstand the harsh weather conditions nowadays.

The usability test could be expanded by incorporating a group that does not utilize the guidelines. This addition would offer deeper insights into the architectural design process by allowing a comparative analysis of design development with and without the use of the guidelines, as well as an evaluation of the differences in thermal performance simulations of all design scenarios created. Furthermore, the usability test could also be conducted for Esad to assess its effectiveness as a decision support tool during the design phase and to identify potential improvements in its performance. The participants for these tests should include individuals from diverse academic disciplines and professional backgrounds to ensure a comprehensive evaluation.

For future research, 3 main research topics can continue from the findings of this thesis:

- **Bioclimatic design strategies for nonresidential buildings**

Nonresidential buildings are as important as residential buildings. The energy consumption in non-residential buildings is shown to be higher than the residential buildings for maximum productivity of the staff or students. Even though BDGC wasn’t developed specifically for residential buildings and can be practiced for industrial buildings, office, and commercial spaces, the design element of the guidelines is more lightweight and more suitable for non-complicated buildings without HVAC systems such as single-family homes.

A bioclimatic design solution for non-residential buildings such as public buildings would be interesting to conduct. The study could focus on strategies to improve thermal comfort which results in improving the productivity of workers and minimizing the energy consumption for cooling and lightning. The efficiency of the current proposed bioclimatic guidelines can also be tested to see its performance for such building functions.

- **Tool that can link the BIM model directly to the BEM model**

It can be seen in this study and others (refer to section 1.3.3) that BIM and BEM are very powerful tools in terms of analyzing building thermal performance. The interoperability between the BIM model and the BEM model presents a high obstacle to linking the model. Even though some studies have developed an interoperability tool between the gbXML file and the BEM model, the file still needs to be exported multiple times when the BIM model is modified (Xu et al., 2019).

A tool that can link directly the BIM model to the BEM model would be very useful. If the BIM model modification can directly change the BEM model without export, it would save so much time and facilitate the simulation process and could have the potential of practicing these two methods since the early design phase. The topic could be interesting for many researchers in engineering domains including architecture, mechanical, and computer science. Currently, a collaborative project called JUMENGI is being undertaken by LUCID, CENAERO, and Thomas et Piron Bâtiment with one of its objectives is how to prepare the BIM model to provide enough building data for exploitation in the BEM model (M. Calixte et al., 2024).

- **Decision support tool based on simulation for Cambodia**

The Esad can work as a good decision support tool for now. However, as mentioned in the section above, it still has a lot of limits. Therefore, a decision support tool whether from the existing Esad and made into a more complete simulation or another tool that could provide more options for data input in terms of application of green façade, double skin façade, green roof, or water body influence on building thermal performance would be a valuable research.

A study was already done 30 years ago, where a tool was developed to link drawing on a tablet and a simulation machine where the tool can directly analyze the building thermal performance from the sketch as soon as the drawing is finished (Leclercq, 1996). The result from this tool simulation is far from accurate and it is also in the context of Belgium. However, as a decision support tool, this is very suitable for early design process application. This finding could be interpreted with nowadays advanced technology and make it suitable for the context of Cambodia.

Many more valuable research topics can be conducted from this thesis finding in terms of comfort, including the adoptive comfort model for controlled climate conditions, the study of local material impact on thermal performance, assessment of thermal performance of buildings in the countryside, urban heat issues, etc. In terms of decision support, other research topics would be intriguing such as tools or platforms that provide necessary data for building sustainability evaluation, decision support tools for green building certificate assessment, usage of tools to achieve sustainable buildings, etc.

9.5 Recommendations

This thesis produces a valuable finding that can be applied directly to architectural schools and professional fields as well as a reference for policymakers related to architecture and construction in Cambodia.

The BDGC and Esad are highly valuable resources that can be integrated into architectural education to enhance students' conceptual delivery. The BDGC card method employed during usability testing is anticipated to be adopted in an architectural class of 'Architectural Studio 2' for engineering degree students at the Institute of Technology of Cambodia and 'Architectural project methodology: bioclimatic' for bachelor students at the University of Liege. The BDGC framework should be incorporated into the design process of all residential buildings and could be developed into a dedicated course for architecture students. This would raise their awareness of designing buildings that prioritize occupant well-being, contribute to mitigating environmental impacts, and enhance overall building quality for thermal comfort. Both BDGC and Esad are ready to be integrated into professional practice and educational settings.

BDGC can serve as a useful reference for policymakers, providing essential guidelines to ensure that building construction adheres to high standards for comfort. This framework can help prevent developers and architects from designing and constructing low-quality buildings while emphasizing the importance of thermal comfort and the overall well-being of occupants.

Finally, as a developing country that still has limited resources and research findings in architecture, I hope that the result from numerous experiments, observations, interviews, and the architect decision support proposed in this thesis will activate the first step toward advancing architectural research, promoting sustainability in the construction sector of Cambodia and improving the living quality of all Cambodians.

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TABLE OF FIGURES

TABLE OF TABLES

ANNEXES

The annexes for manuscript is available online. Please access through the link or the QR code below for annexes.

Annex 1 – Questionnaire for the surveys

Annex 2 – Questionnaire for the interviews and usability test

Annex 3 – Encoding of architectural design process

Annex 4 – Usability test

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