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DISSERTATION FOR DOCTORAL (PHD) DEGREE

INTEGRATING TRADITIONAL WOODCARVING TECHNIQUES WITH CONTEMPORARY CONSTRUCTION: ENHANCING THE ENERGY EFFICIENCY OF TRADITIONAL MALAY HOUSES

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Abstract

This dissertation explores integrating traditional woodcarving designs into modern architecture, focusing on enhancing natural ventilation (NV) while preserving cultural heritage. The study examines the ventilation performance of Malay woodcarving panels, particularly those in Rumah Limas Hutan Bandar MBJB. It compares them with designs inspired by the Székely Gate motif, applied in contemporary houses in Johor, Malaysia and Szombathely, Hungary. Additionally, the study evaluates the role of houses with woodcarving ventilation panels, fully opened vents, no vents and mechanical ventilation featuring narrow diffuser-type inlets in optimising indoor airflow and thermal comfort.

The research employs a multi-faceted approach, combining wind analysis conducted in Johor Bahru, climatic analysis for Szombathely using Climate Consultant 6.0, and computational fluid dynamics (CFD) simulations to assess the impact of woodcarving ventilation panels, opened vents, closed vents and mechanical ventilation on indoor airflow. These situations are reinterpreted within a 10m x 6m x 3.5m building configuration to evaluate their effectiveness in facilitating airflow under extreme climatic conditions in both Johor and Szombathely. The relationship between practical ventilation and cultural aesthetics can be better understood by drawing comparisons with traditional Malay homes like Rumah Tok Su and Rumah Limas Hutan Bandar MBJB.

According to the results, woodcarving panels can help preserve culture while greatly improving natural airflow. This research promotes sustainable architecture practices by proposing an approach that combines contemporary technology with vernacular design. Building design becomes more sustainable and heritage conscious because of the basis it creates for future study into culturally inspired architectural solutions that address NV and climate adaptability.

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Chapter 1

1.1 Introduction

Approximately one-fifth of the planet's surface, characterised by hot and humid climates, is home to one-third of the world's population. As a result, the reliance on HVAC (heating, ventilation, and air conditioning) systems has surged to manage indoor comfort in these challenging climates, accounting for approximately 68% of the total energy consumption in residential and service sectors (Orme, 2001). Despite energy conservation efforts by industrialised nations, the increased use of HVAC systems often leads to higher energy consumption and negative environmental impacts. NV (natural ventilation), achieved through passive design strategies, is a viable alternative to artificial climate control. However, modern buildings depend heavily on mechanical ventilation (Chan et al., 2013).

Malay vernacular architecture offers a sustainable approach to NV, utilising multiple windows, building orientation, roof design, and multi-level floors to enhance thermal comfort (Rizal et al., 2021). With their intricate woodcarving, traditional Malay houses demonstrate an inherent understanding of NV and thermal comfort. Woodcarvings on fascia boards, door leaves, and ventilation panels contribute functionally and aesthetically, allowing for airflow and light penetration while creating visual interest through intricate patterns (Kamarudin & Said, 2008). In contemporary contexts, integrating traditional woodcarvings into modern architecture is often limited to symbolic uses rather than functional applications.

This research addresses the gap in integrating traditional woodcarving techniques to enhance energy efficiency in modern buildings. It will analyse wind patterns in traditional Malaysian houses, such as Rumah Limas Hutan Bandar and Rumah Tok Su (Wahab & Ismail, 2014b), focusing on how woodcarving ventilation panels influence airflow and indoor comfort. The study will evaluate ventilation performance using ASHRAE Standard 55. The research will also conduct a climatic analysis of Szombathely, Hungary, examining wind speed and temperature during the summer. Drawing inspiration from the Szekely Gate, the study will explore the integration of traditional Hungarian woodcarvings into contemporary architectural designs in Szombathely. The study will also compare the effects of these woodcarving ventilation panels with opened vents, closed vents, and mechanical ventilation. Fluid flow simulations will be employed to evaluate the impact of these woodcarvings on passive ventilation in a house model, considering Johor and Szombathely's unique climate conditions.

1.2 Problem Statement

Despite the potential of traditional woodcarving techniques to contribute to sustainable and energy-efficient building design, their integration into modern construction still needs to be improved. In traditional Malay houses, intricate woodcarvings are decorative and serve functional purposes, promoting NV and enhancing energy efficiency. Similarly, Hungarian architecture, notably the Székely Gate, incorporates woodcarvings with potential applications in contemporary design. However, modern construction practices often overlook these techniques, resulting in a disconnect between sustainable design approaches and the preservation of cultural heritage in both Malaysian and Hungarian contexts. Current research fails to adequately explore how these traditional woodcarvings can optimise energy performance in modern architecture, leaving their potential untapped. There is a pressing need for in-depth studies investigating how traditional woodcarving techniques from diverse cultural traditions can be effectively integrated into contemporary construction to improve energy efficiency while preserving cultural identity.

1.3 Research Objectives & Research Questions

Research Objective 1 (RO1): To investigate the critical architectural elements of Malay traditional houses that contribute to enhanced ventilation performance and to examine the impact of architectural woodcarvings on this performance.
Research Question 1 (RQ1): What architectural elements of Malay traditional houses significantly improve ventilation performance, and how do architectural woodcarvings influence this performance?
Research Objective 2 (RO2): To evaluate the impact of various environmental conditions and climates on the effectiveness of woodcarvings as passive ventilation devices using CFD simulation.
Research Question 2 (RQ2): How do different environmental conditions and climates affect the effectiveness of woodcarvings as passive ventilation devices?
Research Objective 3 (RO3): To compare the performance of woodcarving panels with fully open vents, closed vents, and mechanical ventilation using CFD simulations.
Research Question 3 (RQ3): How do woodcarving ventilation panels perform compared to fully open vents, closed vents, and mechanical ventilation systems based on CFD simulation results?
Research Objective 4 (RO4): To develop guidelines for integrating woodcarving into modern construction practices to achieve sustainable, energy-efficient, and culturally preserving building designs.
Research Question 4 (RQ4): What key considerations and best practices are essential for integrating woodcarving into modern construction to ensure sustainable, energy-efficient, and culturally preserving building designs?

1.4 Hypotheses

The strategic integration of traditional woodcarvings in contemporary architecture enhances ventilation performance by optimising natural airflow. This integration contributes to sustainable and energy-efficient building practices aligned with key design elements and environmental conditions.

1.5 Significance of Study

This study bridges the gap between traditional architectural practices and contemporary construction methods, offering innovative solutions for sustainable building design. Its significance lies in several key areas:

1. Preservation of Cultural Heritage:

   By investigating the role of traditional Malay and Hungarian woodcarving techniques in enhancing ventilation performance and energy efficiency, the study contributes to the preservation and appreciation of cultural heritage. Integrating these techniques into modern architecture helps maintain cultural continuity and fosters a deeper understanding of traditional craftsmanship in Malaysian and Hungarian contexts.

2. Advancement of Sustainable Design:

   This research addresses the need for sustainable building practices by exploring woodcarvings as a passive ventilation solution. Evaluating their potential to improve energy efficiency and natural airflow offers practical insights into reducing reliance on mechanical ventilation systems, thus lowering energy consumption.

3. Innovative Construction Practices:

   Developing guidelines for incorporating traditional woodcarvings into contemporary construction introduces a novel approach to architectural design. These guidelines provide architects, builders, and designers with strategies for harmoniously blending the aesthetic and functional elements of traditional craftsmanship with modern construction technologies.

4. Enhanced Building Performance:

   Using CFD simulations, the study quantitatively assesses how woodcarvings impact ventilation under varying environmental conditions. This scientific approach deepens understanding of passive ventilation techniques and provides evidence-based recommendations for optimising building performance across different climates.

5. Contribution to Academic Knowledge:

   The research fills a gap in the existing literature by comprehensively analysing woodcarving techniques in modern building design. It contributes to the academic discourse on architectural sustainability and heritage preservation as a foundation for future studies.

6. Practical Implications for Industry:

   The study has practical applications for the construction industry, particularly in regions with rich cultural traditions. By demonstrating how traditional techniques can be compared with and complement modern mechanical systems, it supports the development of environmentally responsible and culturally sensitive building solutions, encouraging the usage of passive design elements as a viable alternative to high-energy systems.

1.6 Scope and Delimitation

1.6.1 Scope

This study focuses on integrating traditional woodcarving techniques into modern construction practices, emphasising enhancing energy efficiency and maintaining cultural heritage. The research encompasses the following areas:

1. Architectural Elements of Malay Traditional Houses:

The study examines specific architectural features of traditional Malay houses that contribute to NV. This includes analysing the role of woodcarving in improving ventilation performance.

2. Impact of Woodcarvings on Ventilation:

   The research investigates how woodcarving influences the ventilation efficiency of traditional Malay architecture, highlighting its potential as a passive design element.

3. Environmental Conditions and CFD Simulations:

   The study evaluates the effectiveness of woodcarvings as passive ventilation devices under various environmental and climatic conditions. CFD simulations model and assess these impacts. It includes a comparative analysis of scenarios with fully opened vents, closed vents, and mechanical ventilation, offering a comprehensive understanding of airflow behaviour and ventilation performance.

4. Guidelines for Modern Integration:

   The research develops practical guidelines for integrating traditional woodcarving techniques into contemporary construction practices, focusing on achieving sustainable, energy-efficient, and culturally respectful designs.

1.6.2 Delimitations

To maintain focus and manage the scope of the research, the study includes the following delimitations:

1. Geographical Focus:

   The research is primarily concerned with traditional woodcarving techniques from Malaysia and Hungary. The findings may not directly apply to other cultural contexts or geographical locations with different architectural traditions.

2. Architectural Focus:

   The study centres on the impact of woodcarving panels on NV and energy efficiency in comparison to scenarios with fully opened vents, closed vents, and mechanical ventilation. Other architectural features, such as materials or structural configurations beyond woodcarving, are outside the scope.

3. Woodcarving Techniques:

   The research analyses selected traditional woodcarving patterns and techniques from Malay and Hungarian architectural heritage. It does not explore contemporary interpretations, modern styles, or variations that deviate from the traditional techniques under study.

4. Climatic Conditions:

   The CFD simulations are conducted based on specific environmental conditions relevant to the Malaysian (Johor) and Hungarian climate (Szombathely). The study does not include extreme or atypical climatic scenarios that may not represent the region's typical conditions.

5. Technological Constraints:

   The study employs CFD simulations to analyse ventilation performance across various design configurations. It does not incorporate physical prototypes or real-world testing of woodcarving designs beyond computational models.

6. Cultural Aspects:

   While the study emphasises preserving cultural heritage through traditional woodcarving, it does not address broader cultural or socio-economic factors influencing architectural practices in Malaysia and Hungary.

1.7 Research Structure

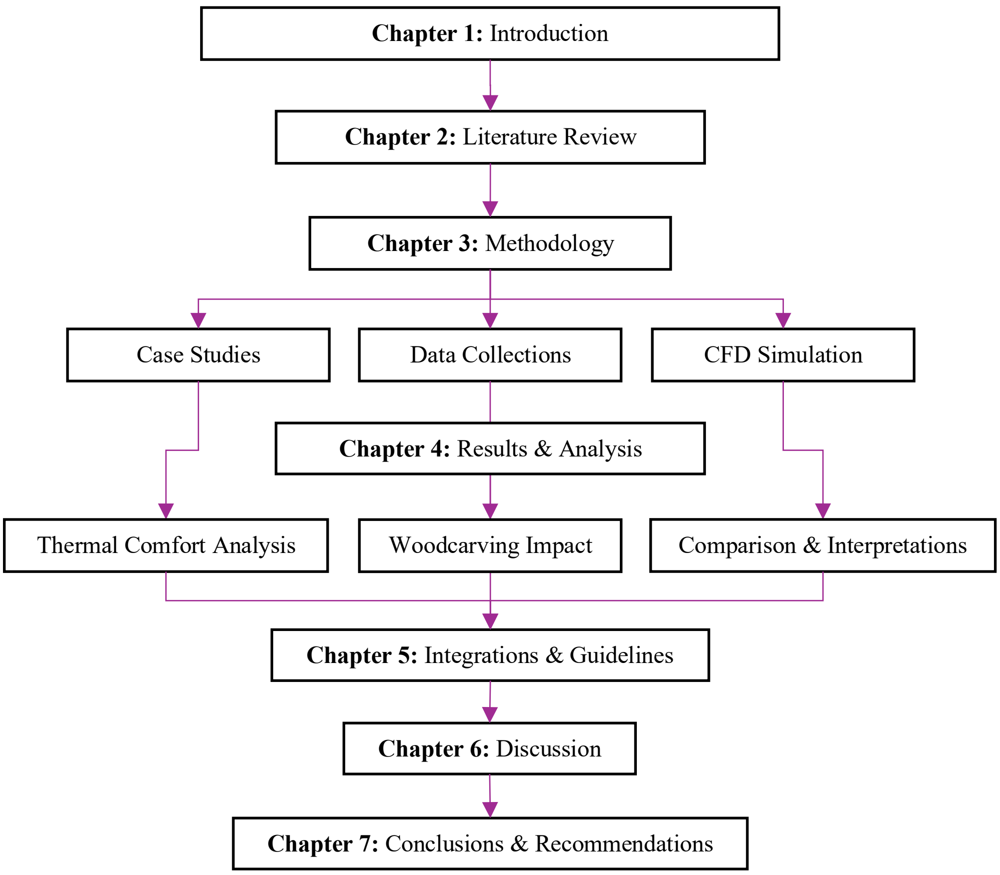


Figure 1: Structure of the research.

1.8 Conclusion

Chapter 1 introduces the foundational aspects of this research, outlining the critical need to address the integration of traditional woodcarving techniques into contemporary construction practices. The global reliance on HVAC systems due to challenging climates has increased energy consumption and environmental impacts. Traditional architectural approaches, particularly those from Malay vernacular architecture, offer valuable insights into NV and energy efficiency through passive design strategies. The research highlights the significance of traditional Malay woodcarving, which contributes to the cultural heritage and possesses inherent qualities that enhance ventilation performance. Despite its potential, modern construction practices often need to pay more attention to these traditional techniques, leading to missed opportunities for sustainable design.

This chapter also establishes the research's scope, focusing on how traditional woodcarving can be integrated with contemporary construction practices to balance cultural preservation and energy efficiency. The research explores how these techniques can be effectively employed in modern buildings, using case studies from traditional Malay houses and contemporary Hungarian architecture as key reference points. Additionally, the study compares the performance of woodcarvings with fully opened vents, closed vents, and mechanical ventilation, evaluating their impact on ventilation and thermal comfort. The problem statement underscores the gap in current research regarding optimising energy efficiency through traditional woodcarving techniques. By examining the effectiveness of these techniques in improving ventilation and integrating them with modern design practices, the study seeks to address this gap.

In summary, Chapter 1 lays the groundwork for the subsequent chapters by defining the research objectives, questions, and significance. It sets up a clear pathway for exploring the potential of traditional woodcarving in enhancing contemporary building design, aiming to contribute to more sustainable and culturally resonant architectural practices.

Chapter 2: Literature Review

2.1 Introduction

This chapter delves into the literature review, comprehensively examining existing research on integrating traditional design elements into contemporary architecture. This chapter also explores the historical and cultural significance of conventional architectural practices, focusing on woodcarvings on Malay traditional houses and Székely gates. It also evaluates their roles in building design's aesthetic and functional aspects. This review will contextualise these traditional elements within modern architectural practices by analysing various studies and theoretical frameworks.

The literature review begins with exploring the traditional techniques, patterns, and cultural meanings behind the woodcarvings. It examines how these carvings, deeply rooted in their respective cultural contexts, contribute to architectural beauty and functionality. The review then discusses modern ventilation practices and energy efficiency, highlighting how traditional design elements can be adapted to contemporary needs. Key findings from the literature are synthesised to identify how traditional techniques influence building performance, particularly in terms of ventilation and energy efficiency. Additionally, the review addresses gaps in existing research, such as the limited exploration of integrating traditional design elements into modern building systems and the need for a deeper understanding of their impact on contemporary architectural practices.

This chapter frames the discussion within the context of traditional craftsmanship and modern architectural requirements, setting the stage for the study's investigation into how traditional woodcarvings can be effectively incorporated into contemporary design to enhance functionality and cultural relevance.

2.2 Traditional Malay Architecture

Traditional Malay architecture boasts a rich history shaped by diverse cultural influences and historical developments. Its origins can be traced back to ancient Malay kingdoms, such as the Bujang Valley in Kedah, home to 87 early historic sites, including stone religious complexes. Chinese historical records from the 7th century also reference the walled city of Langkasuka, known for its intricately decorated gates (Baniyamin et al., 2022). One of the most celebrated achievements in Malay architecture is the grand wooden palace of Mansur Shah in 15th-century Malacca in Figure 2, as described in the Sejarah Melayu (Malay Annals). This palace featured an elevated seven-bay structure on wooden pillars and a distinctive seven-tiered roof, reflecting traditional Malay craftsmanship (Alsheikh Mahmoud et al., 2024). Traditional houses, such as the Rumah Limas Bumbung Perak, exemplify local adaptations to environmental conditions and cultural values, highlighting the importance of ongoing preservation efforts (Che et al., 2024; Kuswoyo et al., 2023).

Figure 2: Istana Melaka

The traditional Malay houses are designed for thermal comfort, utilising NV and materials suited for the tropical climate (Nik et al., 2023). Constructed predominantly from timber, these houses feature pitched roofs, porches, and high ceilings, often adorned with intricate wood carvings. Over time, regional variations emerged, influenced by the Acehnese, Minangkabau, and Javanese cultures. Introducing colonial materials like bricks, metal roofs, and stucco led to hybrid architectural forms, such as the Baba Nyonya shophouses, which blend Asian and European design elements (Yew & Jung, 2024). In the 1980s, a resurgence of "regional architecture" sought to integrate traditional Malay features with modern materials, particularly resort architecture (Alsheikh Mahmoud et al., 2024). This movement emphasised preserving traditional design principles while adapting to contemporary needs.

2.2.1 Vital Architectural Features of Traditional Malay Houses

Figure 3: Traditional Malay House

Several distinct characteristics define traditional Malay houses, shown in Figure 3:

1. **Raised on Stilts**: Malay houses are often raised on stilts made from hardwood, such as Cengal, to prevent flooding (Alsheikh Mahmoud et al., 2024) and allow air circulation (Prihatiningrum & Ramawangsa, 2022). The height of these stilts varies depending on whether the house is built in coastal or inland areas. This design also minimises the impact on the earth, respecting the natural environment.

2. **Modular Construction**: These houses' modular nature allows for expansion as families grow (Misnat et al., 2023). The primary structure, the Rumah Ibu, is the main living area. In contrast, additional units such as the kitchen (Rumah Dapur) and sleeping area (Rumah Tengah) can be added, like the design of Sarawak longhouses. Traditional designs incorporate flexible space planning, allowing for modifications without compromising structural integrity (Kuswoyo et al., 2023).

3. **Wooden Structure**: Traditional Malay houses utilise a post-and-lintel timber frame, with walls made from wood or bamboo. The joints are fastened using tree roots or rattan, avoiding using nails, which enhances the structure's flexibility and resilience, particularly in seismic areas. The use of wooden materials throughout the construction, including floors, walls, and roof trusses, is a hallmark of these houses, contributing to their durability and cultural significance (Kuswoyo et al., 2023).

4. **Ventilation**: High ceilings, large windows, grilles, and the elevated stilt design allow for excellent air circulation. The raised floors enable air to flow beneath the house, enhancing ventilation (Nik et al., 2023).

5. **Sloping Roofs**: Roofs are steeply pitched, typically in a gable or hip style. While thatch was traditionally used, many roofs today are made from metal or tiles (Kuswoyo et al., 2023). Gables on both sides are a common feature, enhancing the aesthetic and functional design of the house.

6. **Woodcarvings**: Elaborate woodcarvings are a hallmark of traditional Malay architecture, often adorning houses' exterior and interior. These carvings are decorative and indicative of the homeowner's social status and rank (Azman et al., 2022).

7. **Passive Design**: Traditional Malay houses incorporate passive design strategies to enhance natural cooling. Elements such as building orientation, window placement, and overhanging roofs provide shade and promote NV. Landscaping, which includes using trees and vegetation, further aids in cooling the house naturally (Nik et al., 2023).

Traditional Malay woodcarvings serve both aesthetic and functional purposes in architecture. Aesthetically, woodcarvings are a critical decorative element, enhancing the visual appeal of structures such as houses, palaces, and mosques. The intricate designs, often featuring motifs inspired by flora, fauna, geometry, calligraphy, and cosmic symbols, reflect the artistry and craftsmanship of Malay woodcarvers and are also influenced by Islamic principles (Yusof et al., 2022; Abu Bakar et al., 2022). These motifs beautify the buildings and embody the Malay people's cultural identity, beliefs, and traditions. Additionally, perforated carvings allow sunlight to filter into the interiors of buildings, casting striking silhouettes that further enhance the nighttime aesthetics of traditional architecture. The intricate designs of Malay woodcarvings are a testament to the high level of skill and precision involved in their creation. These carvings serve as a decorative element that enhances the visual appeal of buildings, making them functional works of art (Mohamad Ba'ai et al., 2022).

Functionally, woodcarvings contribute significantly to the ventilation and airflow of traditional Malay houses. Carved panels and screens, often found on walls, windows, doors, and gables, facilitate air circulation while simultaneously providing occupants with privacy. The perforations in these carvings ensure that airflow and daylight penetration are maximised without compromising the building's overall structural integrity (Zain et al., 2023). Furthermore, carved elements such as pillars, railings, fascia boards, and gables, though non-structural, contribute to the overall aesthetic and functionality of the building. These woodcarvings are precisely fitted to the specific shapes, sizes, and dimensions required by the timber frame structures, exemplifying the high level of skill and precision in their creation.

2.3 Woodcarving Techniques

2.3.1 Traditional Malay Woodcarving Techniques

Traditional Malay woodcarving is distinguished by two primary techniques: Ukiran kasar (rough carving) and Ukiran halus (intricate carving). Ukiran kasar in Figure 4 is typically used for more prominent architectural elements such as pillars, windows, roof eaves, gables, and furniture. This technique involves chiselling significant chunks of wood from planks to create bold and pronounced designs, reflecting the aesthetic values of Malay culture. In contrast, Ukiran halus is employed for more delicate and intricate carvings found on objects like keris hilts in Figure 5, bed head frames, and cupboard tops. This technique requires a high level of skill and precision, evident in the finely detailed carvings of traditional Malay jewellery, which often feature floral, fauna, and abstract designs (Mohamad Ba'ai et al., 2022).

Figure 4: Ukiran Kasar at Malay traditional house.

Figure 5: Ukiran halus on Keris, which is a traditional tool.

Malay woodcarvings are known for their diverse motifs. Floral patterns, including leaves, vines, and the Awan Larat pattern, dominate early Malay carvings, illustrating the close relationship between the Malay people and nature (Wahid et al., 2021). Animal motifs are also used, though less commonly, and animal motifs, although less common, are also present. Arabic calligraphy is a significant motif, especially in carvings influenced by Islam, marking a transition from earlier Hindu-Buddhist influences that featured mythical animal motifs (Abu Bakar et al., 2022). Geometric patterns add symmetry and complexity, reflecting similar cultural practices in other traditions, such as Chinese and Egyptian geometric patterns with rich cultural and historical significance (Hu, 2022; Mahmoud, 2017).

Patterns in Malay woodcarving are typically arranged in three ways: single, framed, and complete. Single patterns highlight individual motifs, such as floral or geometric designs, and are inspired by early Malay designs incorporating sinusoidal curves and symmetry (Mohamed et al., 2022). Framed patterns enclose motifs within a border, enhancing the visual impact and providing a structured aesthetic commonly seen on walls and ventilation panels of heritage houses (Abu Bakar et al., 2022). Complete patterns involve integrating multiple motifs into a unified design, covering larger surfaces, as seen in the intricate carvings on mosque pulpits that convey complex cultural narratives (Ismail et al., 2023). These carvings are executed on carefully selected hardwoods like Cengal and Merbau, using specialised tools to ensure durability and precision (Said, 2005). Woodcarving holds profound cultural significance in Malay society, serving as an ornamental and symbolic medium. Beyond simply beautifying buildings and objects, Malay woodcarving is a form of artistic expression that infuses structures with rich cultural motifs and symbolism. For instance, the minbar of the Ulul Albab Mosque in Terengganu incorporates nature-inspired motifs that embody the purity and craftsmanship of Malay culture (Ismail et al., 2024). The intricate designs represent the beauty of nature, calligraphy, cosmic mysteries, and geometric patterns, all of which convey traditional Malay cultural values.

Additionally, woodcarvings are often indicators of social status in Malay society, with more elaborate carvings signifying higher social rank, particularly in traditional Malay homes. Beyond their symbolic significance, woodcarvings in traditional Malay architecture also serve functional purposes. Carved elements, such as panels on pillars, windows, and roof eaves, though non-structural, play a vital role in improving ventilation and allowing daylight to penetrate buildings (Zain et al., 2023). The intricate patterns in these carvings enable air to pass through wooden screens and grilles, promoting airflow while simultaneously providing privacy for occupants. This dual-functional ventilation panel, which enhances ventilation while preserving privacy, illustrates traditional Malay woodcarving's practicality and cultural wisdom.

2.3.2 Szekely Gate Woodcarving and Its Relation to Hungarian Culture

Székely woodcarving, particularly exemplified in the iconic Székely gates shown in Figure 6, is a significant element of Hungarian folk art and a rich reflection of Székely's cultural heritage. The Székely people, a subgroup of Hungarians primarily residing in Transylvania, Romania, have preserved this unique craftsmanship for generations. Székely woodcarving is defined by techniques such as relief carving, where raised designs on wooden surfaces depict culturally significant motifs. These intricate patterns showcase the artistic skill and cultural narratives of the Székely people, reflecting their deep connection to nature and tradition (Bárth, 2023). One of the prominent features of Székely woodcarving is its geometric precision, which was created using tools like compasses and chisels. These patterns, deeply ingrained in Hungarian craftsmanship, echo the advanced carpentry skills of early Neolithic woodworking in Europe, where specialised tools were used to achieve high levels of detail (Muigg et al., 2023). Floral motifs in Székely woodcarving are deeply tied to the natural environment and cultural identity of the Székely people. These designs symbolise growth and life, serving as decorative elements and as symbols of continuity in Székely traditions. These motifs are often digitally preserved and applied to modern furniture, bridging past and present (Lungu et al., 2021). The use of plant motifs extends into Székely ethnomedicine, where specific plants are believed to offer protection and have predictive powers, reflecting a spiritual connection to the natural world(Papp, Birkás-Frendl, et al., 2014). For example, the floral motifs on wooden grave posts represent the "tree of life," symbolising the cycle of life and death, with tulips and stars often serving as anthropomorphic representations (László et al., 2019).

In addition to floral designs, animal motifs are common in Székely woodcarving, symbolising strength, resilience, and protection. These motifs highlight the Székely people's connection to their environment and their cultural ties to Hungarian traditions. Incorporating Celtic patterns further underscores the historical interactions within the region and the shared heritage of Central European cultures (Dani, 2016). These motifs enhance the gates' visual beauty and serve as a form of protection for the household, echoing traditional beliefs about the protective powers of animals (Preda et al., 2018). The cultural significance of Székely woodcarving extends beyond its aesthetic value. It is a vital part of the Székely people's identity and symbolises their heritage. The carvings often feature symbols and colours associated with Hungarian national identity, reinforcing the Székely people's connection to the broader Hungarian culture. These traditional motifs, including representations of plants and animals, embody Hungarian folk art's deep-rooted values, conveying cultural narratives through intricate designs (Sang, 2024). Furthermore, efforts to preserve traditional craftsmanship, such as those seen in Harta village, demonstrate the importance of these skills in maintaining Hungary's cultural identity for future generations(Ament-Kovács, 2024).

The Székely gates are primarily constructed using locally available wood species. This includes hardwoods that are known for their strength and ability to withstand the elements, which is crucial for outdoor structures like gates. The use of local wood not only ensures the durability of the gates but also reflects the traditional practices of utilizing readily available resources (Preda et al., 2018). Among the wood types used by the Székelys, Betula pendula, or silver birch, is noted for its use in various traditional applications. While the primary focus of its use is in ethnomedicine and household items, its presence in the region suggests it may also be used in gate construction, particularly for decorative elements or smaller structural components (Papp, Czégényi, et al., 2014).

Figure 6: Székely gate.

Székely gates are steeped in historical traditions and serve as cultural symbols within the community. Historically, the maintenance of these gates was a communal responsibility passed down through generations (Bárth, 2023). The gates represent more than just physical barriers; they are imbued with cultural narratives that reflect the Székely community's resilience in the face of historical challenges, such as redrawing borders after the Trianon treaties (Dani, 2016). Today, these gates play a crucial role in cultural tourism, with visitors drawn to their unique architectural style and rich heritage, incorporating traditional materials and forms into modern landscapes.

2.4 Modern Architectural Practices and HVAC Systems

Modern architectural practices and HVAC systems have evolved significantly, blending historical influences with advanced technology to shape contemporary design. Integrating intelligent systems and sustainable design principles defines today's architectural landscape, where energy efficiency and environmental impact are key priorities. Early modern architecture emphasised dynamic facades that responded to the climate, incorporating external shading systems like brise-soleil to manage thermal environments. This approach was central to the International Style, particularly in tropical regions like Brazil, where shading and NV were crucial for indoor comfort (Barber, 2020). Over time, architectural design shifted towards static facades, with a greater reliance on mechanical HVAC systems for climate control. This trend often led to a reduction in energy efficiency and environmental responsiveness (Barber, 2020). However, earlier architectural approaches in regions like Egypt, which relied on passive ventilation strategies, offer valuable lessons for contemporary sustainable design. These historical examples demonstrate how natural airflow can be harnessed to reduce energy consumption while maintaining indoor comfort (Elkady & Goubran, 2022).

In modern building design, intelligent HVAC systems enhance energy efficiency and occupant comfort. These systems utilise artificial intelligence, such as support vector machines, to optimise heating, ventilation, and air conditioning in real time, adjusting to environmental changes and user preferences (Ali & Aldaiyat, 2021). Direct digital control (DDC) technology has expanded HVAC system capabilities, enabling precise integration and improved energy management (Meckler, 1994). This shift towards smart buildings reflects the growing demand for efficiency and adaptability, where HVAC systems are more responsive to environmental conditions, reducing energy consumption while improving indoor air quality.

Mechanical ventilation, such as diffusers, plays a significant role in modern HVAC systems by controlling the distribution of airflow. They are designed to direct air from ventilation systems into specific areas of a room, promoting better air circulation and temperature control. While diffusers are effective in managing airflow and maintaining indoor comfort, they come with energy and maintenance costs, particularly when compared to the passive solutions like NV through woodcarvings. The use of diffusers typically requires mechanical power and can be less environmentally friendly due to the energy consumed by HVAC systems.

Despite these advancements, the widespread use of HVAC systems has influenced architectural design in ways that sometimes prioritise mechanical solutions over ecological considerations. This trend has led to criticism, particularly in modernist architecture, for its lack of sustainability (Elkady & Goubran, 2022). Budget constraints and subjective decision-making often affect the selection of HVAC systems, leading to inefficiencies and increased costs (Khodeir, 2015). However, the increasing focus on sustainability has prompted a revaluation of modernist principles, encouraging the integration of passive design strategies alongside intelligent systems to minimise environmental impact (Elkady & Goubran, 2022; Meckler, 1994). Architects and engineers can create energy-efficient and environmentally responsible structures by incorporating NV and external shading into building designs.

While modern architectural practices and HVAC systems have made substantial progress, challenges remain in balancing technological innovation with sustainability. Integrating intelligent systems offers promising solutions for improving energy efficiency and occupant comfort, yet the architectural community must continue prioritising ecological responsibility. The ongoing dialogue between tradition and innovation is crucial for the future of sustainable architecture, ensuring that design choices support both technological progress and environmental stewardship.

2.5 Climate and Ventilation

The role of climate in building design is critical, as it heavily influences a structure's performance, energy efficiency, and ventilation strategies. With the increasing effects of climate change, designs that rely on historical weather data need to be updated, necessitating the incorporation of future climate variability into building plans. A framework developed by Gholami Rostam and Abbasi highlights the importance of this adaptation, demonstrating that using synthesised weather files can reduce annual thermal loads by up to 31%, showcasing the potential of dynamic design upgrades to maintain energy efficiency in changing climates (Gholami et al., 2024).

In hot and humid regions like Malaysia, maximising NV and minimising heat gain are essential for achieving thermal comfort. Traditional architectural features such as high ceilings, large windows, and overhangs are commonly used to facilitate airflow and provide shade. Traditional Malay houses are a prime example of this approach, utilising occupant-controlled air ventilation systems to maintain optimal indoor temperatures, typically between 25.5°C and 29.5°C, which aligns with comfort standards (Hassin et al., 2023). In contrast, colder climates like Szombathely, Hungary, necessitate designs focused on heat retention, with smaller windows, insulated walls, and compact building forms to reduce energy loss and enhance thermal efficiency, as shown in Figure 7. The effectiveness of NV depends heavily on local climate conditions. In Hungary, where the temperate climate brings cold winters and warm summers, NV's potential varies significantly by season. The research underscores the importance of considering meteorological uncertainties and specific climate characteristics when evaluating NV (Li et al., 2024). Precipitation and wind patterns also dictate structural designs, particularly in tropical regions with heavy rainfall, where steeply pitched roofs help prevent water accumulation and leaks. Similarly, wind patterns play a pivotal role in ventilation strategies. Architectural features like wind catchers enhance NV in areas with high wind speeds, while more sheltered locations may require a greater reliance on mechanical systems.

Wind analysis is critical in understanding ventilation performance, as wind pressure and temperature differences can significantly affect NV rates. Key design elements like facade openings and window-to-wall ratios (WWR) boost NV. Larger facade openings have significantly improved thermal comfort, as demonstrated in numerical simulations conducted in Johor Bahru. Such design features improve air quality and reduce energy consumption by decreasing the need for mechanical ventilation systems (Al Rikabi et al., 2022). Advanced simulation models, including CFD, are frequently employed to predict airflow patterns and ventilation rates based on wind conditions. These models consider terrain roughness and building orientation, offering valuable insights into how design modifications can enhance ventilation efficiency.

Additionally, hybrid ventilation systems, combining wind-driven and buoyancy-driven ventilation, have increased airflow rates by 1.5 to 3.5 times, depending on outdoor wind speeds. This approach optimises ventilation performance across various climatic conditions. One of the critical challenges in implementing NV is the discrepancy between simulation outcomes and real-world scenarios, often due to model and parameter uncertainties (Li et al., 2024). The use of CFD tools can aid in predicting and optimising NV, ensuring buildings are designed to maximise airflow while maintaining indoor air quality (Gupta & Khare, 2021).

Figure 7: Traditional Hungarian House.

Comparative climate analysis between Szombathely and Malaysia further illustrates how climate shapes building design. Szombathely's temperate continental climate, characterised by cold winters and warm summers, necessitates designs focused on thermal insulation, with smaller windows and airtight construction to retain heat during the colder months. NV is often limited in the winter to conserve heat. On the other hand, Malaysia's tropical rainforest climate, marked by high humidity and stable temperatures year-round, emphasises NV. Traditional Malay architecture, with its high ceilings, large openings, and shaded areas, is designed to promote airflow and cooling, with materials chosen to withstand the region's high moisture levels. The evolution of shopping mall designs in Malaysia from enclosed, fully air-conditioned spaces to hybrid systems integrating NV is a response to improved air quality and energy efficiency. This trend reflects a broader shift towards bioclimatic design strategies that include NV and daylighting, which are effective in maintaining thermal comfort, particularly in residential college buildings in Malaysia's tropical climate (Norzelan et al., 2023) (Jamaludin et al., 2017).

2.6 Integration of Traditional Design in Contemporary Architecture

Integrating traditional architectural elements into contemporary design presents both challenges and opportunities. One primary challenge is balancing traditional architecture's cultural and aesthetic value with modern functionality and efficiency requirements. While rich in cultural significance, traditional construction techniques often need to be adapted to meet current building codes and safety standards, which can be both complex and costly. While valuable, these adaptations are necessary because many historic structures only sometimes align with modern grading systems like BREEAM or LEED (Ahmed et al., 2024). Additionally, sourcing traditional materials, which are often labour-intensive and expensive, poses another hurdle. Integrating these materials requires careful planning to ensure they go beyond superficial decoration and genuinely enhance the overall design (Ishika & Sangramsinh, 2023).

Despite these challenges, the integration of traditional design elements offers significant opportunities. By incorporating traditional techniques and aesthetics, contemporary architecture can preserve and celebrate cultural heritage while enhancing modern buildings' sustainability and energy efficiency. Traditional materials and craftsmanship bring rich textures, patterns, and a sense of place to modern spaces, fostering connections to local communities and cultural identity. For example, traditional furniture with unique artistic elements, such as carving and painting, can enhance modern interiors by linking them to cultural heritage (Madan, 2024).

Numerous case studies highlight the successful blending of traditional and modern design approaches, as illustrated in Figure 8. The Wooden House project, designed by architects András Varsányi, Péter Pozsár, and Norbert Vas, exemplifies this by thoughtfully merging traditional Hungarian architectural elements with modern conveniences and contemporary design aspects. Similarly, in Iran, integrating historical architecture into modern design reflects a productive relationship between past-oriented architecture and modern thought, adding new value to contemporary architectural practices (Kamali, 2024). The use of materials like bamboo in Thailand's Bamboo Sports Hall, shown in Figure 9, and rammed earth in Angola's Dyeji Building highlights these materials' ecological benefits and cultural significance. By honouring local building traditions, these projects promote sustainability while respecting heritage (Pan & Wang, 2023).

Additionally, incorporating passive design strategies, such as woodcarvings and mechanical ventilation, into modern architecture preserves cultural heritage and promotes energy efficiency. The use of carved panels, informed by biomimetic designs that draw inspiration from natural patterns like elephant skin, has been explored for its potential to enhance airflow and improve building thermal performance (Hays et al., 2024). These elements facilitate natural ventilation in hot climates, reducing reliance on mechanical systems and contributing to more sustainable design practices. For example, diffusers in traditional woodcarvings or strategically placed ventilation openings can improve air circulation, minimizing the need for energy-intensive air conditioning. By integrating such features, contemporary buildings can achieve a balance between energy efficiency and cultural significance.

Preserving cultural heritage through architecture is crucial in today's globalised world. Integrating traditional design elements into contemporary structures fosters continuity between past and present, strengthens community connections with the built environment, and promotes cultural diversity. Moreover, this integration inspires innovative solutions by combining traditional and modern practices, leading to more sustainable approaches rooted in time-tested building techniques.

Figure 8: The blend of traditional and modern Hungarian architecture.

Figure 9: Thailand's Bamboo Sports Hall.

2.7 Computational Fluid Dynamics (CFD) in Natural Ventilation (NV) Analysis

CFD has become an essential tool in analysing NV in buildings, providing detailed insights into airflow dynamics without relying on mechanical systems. Using NV, driven by wind and buoyancy, can significantly improve indoor air quality and reduce energy costs associated with mechanical ventilation. CFD offers a powerful method for simulating these airflow patterns, allowing architects and engineers to optimise building designs that fully harness the benefits of NV. CFD simulations enable a detailed evaluation of NV strategies by simulating various conditions, such as building geometry, wind exposure, and temperature gradients. These simulations can accurately predict ventilation rates and air distribution patterns, critical for ensuring occupant comfort and indoor air quality (Chen et al., 2023). By integrating CFD with parametric modelling, designers can explore multiple design configurations and assess their impact on ventilation efficiency. This iterative process supports more innovative building designs that enhance airflow, minimising or eliminating the need for mechanical ventilation (Guo et al., 2015). CFD offers a more efficient and cost-effective solution than traditional methods like physical testing and manual calculations.(Oliveira et al., 2023). CFD simulations also play a crucial role in assessing thermal comfort and indoor air quality. For instance, modifying the size and placement of openings in building facades can dramatically influence internal wind speeds, directly affecting thermal comfort and air quality (Oliveira et al., 2023). These detailed simulations help designers understand the impact of different design choices on the overall performance of the building's NV system.

A critical factor in producing reliable CFD simulations is the accurate modelling of boundary conditions. Elements such as window openings, surrounding structures, and local climatic conditions must accurately represent real-world conditions. Additionally, the choice of turbulence models, such as Reynolds-Averaged Navier-Stokes (RANS) or Large Eddy Simulation (LES), should align with the specific airflow characteristics being studied, whether the airflow is driven by wind or buoyancy (Sakiyama et al., 2021). Furthermore, validating CFD results against experimental data, such as wind tunnel tests or field studies, is critical to ensure the accuracy of the simulations (Jiru & Bitsuamlak, 2010).

2.8 Conclusion

Chapter 2 of the literature review comprehensively explores the intersection between traditional design elements and modern architectural practices. The review begins with an introduction to traditional Malay houses and their distinctive architectural features, particularly focusing on woodcarving's role in enhancing aesthetics and functionality. Traditional Malay woodcarvings are significant culturally and contribute to the house's performance by facilitating NV and daylighting. The discussion then transitions to the Szekely Gate, a prominent example of Hungarian woodcarving. This section delves into the cultural and functional aspects of the Szekely Gate, highlighting its integration into Hungarian heritage and its impact on architectural design. The comparison between Malay and Szekely woodcarvings underscores the universal importance of traditional craftsmanship in architecture, offering insights into their respective cultural contexts and functional roles. In examining modern architectural practices and HVAC systems, the review highlights the evolution of building design and the increasing reliance on intelligent HVAC systems. Integrating these systems with traditional design elements presents challenges and opportunities, particularly in achieving energy efficiency and maintaining cultural relevance.

The review further addresses climate and ventilation considerations, emphasising how different climatic conditions influence building design and ventilation strategies. Adapting traditional architectural features to modern climatic contexts is crucial for optimising indoor air quality and energy efficiency. Integrating traditional design into contemporary architecture reveals how traditional elements can enhance modern buildings' functionality, aesthetics, and cultural significance. Case studies illustrate successful examples of blending traditional craftsmanship with modern design principles, demonstrating the potential for preserving cultural heritage while advancing architectural practices.

Finally, the review covers the application of CFD in analysing NV. CFD simulations provide valuable insights into airflow patterns and ventilation performance, enabling architects to design buildings that maximise NV benefits. This technology helps validate and optimise ventilation strategies, addressing the challenges of integrating traditional designs with modern ventilation needs. This chapter underscores the importance of bridging traditional and modern architectural practices. It highlights the need for further research into the practical applications of traditional design elements in contemporary settings and their impact on building performance and cultural preservation. By integrating traditional craftsmanship with modern technological advancements, architects can create designs that honour cultural heritage while meeting contemporary demands for functionality and sustainability.

Chapter 3: Methodology

3.1 Introduction

The methodology chapter introduces the approaches used to explore the role of traditional woodcarvings in enhancing NV and thermal comfort within different climatic contexts. The research integrates several methods, including a literature review, site visits, wind analysis, microclimate analysis, and CFD simulations, all aimed at understanding the impact of woodcarving on architectural designs. The literature review focuses on Rumah Tok Su, providing historical insights into traditional Malay architecture. In contrast, the site visit to Rumah Limas Hutan Bandar MBJB, a traditional Malay house, offers practical observations on woodcarving ventilation in a contemporary setting. The research further incorporates wind analysis for Johor Bahru and a microclimate analysis for Szombathely, Hungary, using Climate Consultant 6.0 to assess environmental conditions such as wind speed and temperature.

Airflow analysis is conducted using Autodesk CFD to evaluate air circulation through the woodcarving ventilation panels, comparing their performance with fully opened vents, closed vents, and mechanical ventilation. This method investigates how traditional woodcarving designs, as well as opened vents and diffusers, influence airflow and thermal comfort within a basic room setup. By integrating these diverse methods, the research creates a comprehensive framework for incorporating traditional woodcarving into modern architectural designs, enhancing both functionality and cultural significance while considering modern ventilation solutions.

3.2 Literature Review and Case Study Analysis

Several traditional houses across Malaysia were considered for this study, as depicted in Figure 10. However, due to time constraints, the case study focused on two specific buildings: Rumah Tok Su in Kedah and Rumah Limas Hutan Bandar MBJB in Johor Bahru. The case study methodology was employed to investigate these examples thoroughly. A site visit to Rumah Limas Hutan Bandar MBJB allowed for direct observation and documentation of the traditional woodcarvings and their influence on NV; for Rumah Tok Su, a detailed literature review was conducted by referring to Wahab & Ismail (2014), exploring its architectural features and the role of traditional woodcarvings in improving airflow and aesthetics. These case studies comprehensively understand woodcarving's functional and cultural significance in traditional Malay architecture.

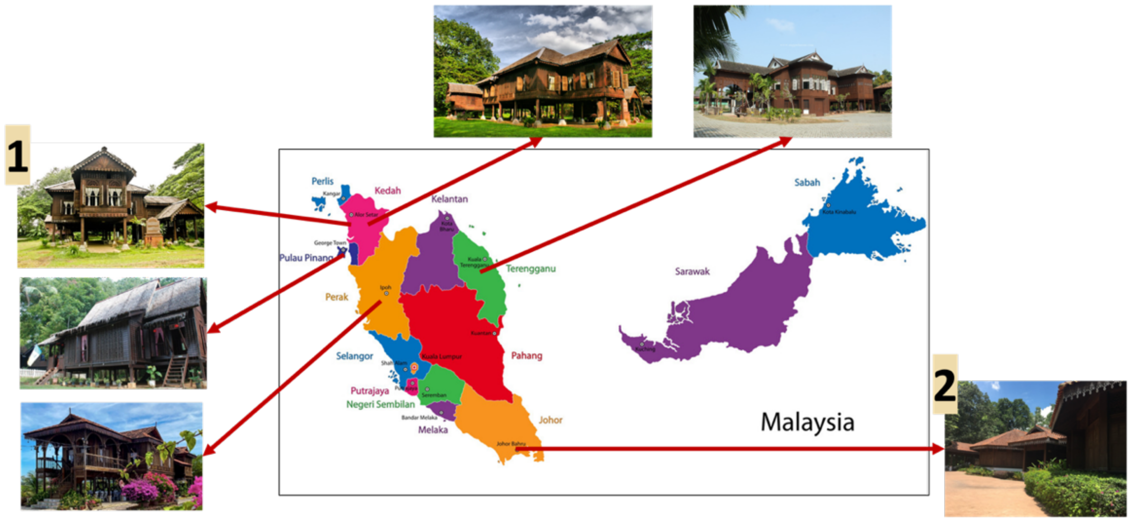


Figure 10: Site visit locations

Rumah Limas Hutan Bandar MBJB: Located in Johor Bahru, Johor, Rumah Limas Hutan Bandar MBJB is a traditional Malay house, also known as Rumah Limas Bugis or the Bugis Five-Roofed House, influenced by the Bugis people of Sulawesi, Indonesia. The house is oriented at the serambi (verandah) entrance, and the Anjung and Rumah Ibu are facing west, with the elongated wall aligned towards the southwest and northeast. This house is characterised by its extended, ridged roof (Perabung Panjang) with four outward-projecting ridges. Constructed from Cengal wood, Rumah Limas features carved wood panels on the lower sections of the walls and vertically arranged wooden planks on the upper sections. The house has numerous windows measuring 1150 mm x 1350 mm and 138 woodcarving ventilation panels positioned internally and externally. The roof is covered with clay tiles, contributing to the building’s thermal performance. The floor level is elevated to 1500 mm, which helps enhance NV by utilising the prevailing southern winds in Johor to maintain indoor comfort.

Tok Su House: Located in Kampung Warisan, Alor Setar, Kedah, Tok Su House exemplifies traditional Malay vernacular architecture. The house is oriented so that the entrance to the Serambi (veranda) and the Anjung Tamu (guest area) faces south, with its elongated walls aligned towards the east and west. The building envelope is entirely made of wood, featuring carved wood panels on the lower portions of the walls and vertically arranged wooden planks above. The house includes numerous windows, each positioned at floor level with wooden kerbs acting as window leaf stoppers, and most windows measure approximately 900 mm x 1800 mm. Ventilation openings are strategically placed above the windows and on the upper walls. The roof structure is a straightforward gabled design with ventilation openings, comprising a main gabled roof and smaller attached gabled roofs for additional spaces. The roofing is covered with ardec (corrugated roofing) and layered with dried leaves to maintain a cool interior. The floor level is about 1000 mm at the Serambi and approximately 1950 mm in other areas, with wooden floors with gaps between the planks to allow airflow from beneath the house.

3.3 Wind Analysis

Table 1: ASHRAE standard 55.

Parameter	Value	Unit
Summer Clothing Indoors	0.5	Clo
Activity Level Daytime	1.1	Met
Predicted Percent of People Satisfied	90.0	%
Comfort Highest Summer Temperature	26.7	°C
Maximum Humidity	84.6	%
Minimum Dry Bulb Temperature for Sun Shading	23.8	°C
Minimum Global Horizontal Radiation for Sun Shading	315.5	Wh/sq.m
Maximum Wet Bulb Temperature (Direct Evaporative Cooling)	20.0	°C
Minimum Indoor Air Velocity for Comfort	0.2	m/s
Maximum Comfortable Air Velocity	1.5	m/s
Maximum Mechanical Ventilation Velocity	0.8	m/s
Maximum Perceived Temperature Reduction (Fan-Forced Ventilation)	3	°C

Table 1 summarises thermal comfort parameters based on ASHRAE Standard 55, focusing on summer indoor conditions. It outlines critical factors influencing occupant comfort, including clothing insulation (0.5 Clo), metabolic activity levels (1.1 Met), and a predicted 90% occupant satisfaction rate. The table identifies a maximum comfortable indoor temperature of 26.7°C, with relative humidity reaching up to 84.6%, emphasising the importance of maintaining optimal indoor air conditions. Shading is recommended to manage solar heat gain when the dry bulb temperature exceeds 23.8°C or the global horizontal radiation reaches 315.5 Wh/m^2. Direct evaporative cooling is adequate for cooling strategies up to a wet-bulb temperature of 20.0°C. The table also highlights airflow considerations, requiring a minimum indoor air velocity of 0.2 m/s for comfort, with a maximum perceived cooling effect of 3°C from fan-forced ventilation. Comfortable air velocities range between 0.2 m/s and 1.5 m/s, while mechanical ventilation systems should not exceed 0.8 m/s to avoid discomfort.

3.3.1 Rumah Limas Hutan Bandar MBJB

Wind analysis is crucial for evaluating how traditional woodcarvings impact ventilation in both modern and traditional buildings. For Rumah Limas Hutan Bandar MBJB, wind analysis was conducted using on-site data collected from July 28th to 29th, 2022, between 6 AM and 18:00. This analysis focused on measuring outdoor wind speed and temperature, particularly in areas with woodcarving ventilation panels, to assess their effectiveness in achieving thermal comfort.

The measurement methodology for Rumah Limas Hutan Bandar MBJB differed from that used for Rumah Tok Su. Data was collected at eight designated points within and around the house, as shown in Figure 11. The measurement approach adhered to ASHRAE Standard 55, focusing on thermal environmental conditions for human occupancy. Wind speed (m/s) and temperature (C°) were measured at these points. The floor plan of Rumah Limas Hutan Bandar MBJB was drafted using AutoCAD to guide the selection of measurement locations. It is important to note that the Anjung and Dewan Rumah Ibu areas were excluded from the analysis due to their conversion into office spaces, where the ventilation panels were covered with acrylic to accommodate air conditioning systems.

Measurements were conducted in various building areas to assess ventilation performance, excluding the converted office spaces of Dewan Rumah Ibu and Anjung, where ventilation panels were covered with acrylic for air conditioning purposes.

1. Outdoor area (10m from the house): reference point for outdoor conditions
2. Serambi (2): Assessment of ventilation performance in Serambi
3. Plantar (3): Evaluation of ventilation performance in the plantar
4. Kelek Anak SW (4,5): Measurement of ventilation performance in Kelek Anak
5. Dewan Rumah Dapur (6,7,8): Assessment of ventilation performance in the kitchen area

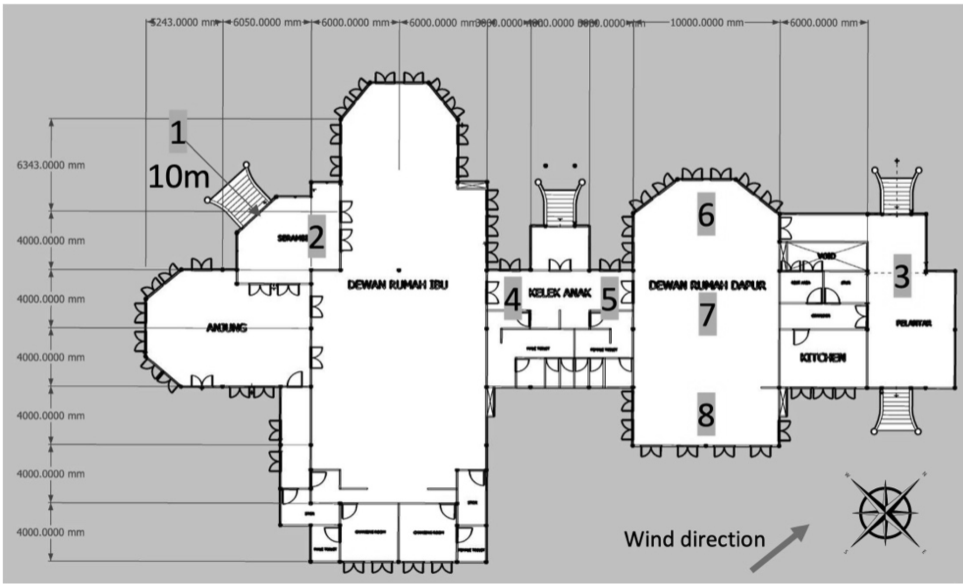


Figure 11: Floor plan of Rumah Limas Hutan Bandar MBJB Johor Bahru.

3.3.2 Rumah Tok Su

According to the findings presented in the literature review by Wahab & Ismail (2014), for Rumah Tok Su in Figure 12, measurements were taken at various points inside and twelve points outside, positioned at least 2.1 meters from the building walls. Data was collected hourly from 08:00 to 18:00 over three days, with a maximum 10-minute interval between data collection points within the same hour. This methodology was similarly applied in the Rumah Limas Hutan Bandar MBJB, focusing on points 1 to 8 to gather relevant wind and temperature variations data.

Measurements were conducted in various areas of the building to assess ventilation performance, as shown as follows:

1. Outdoor area (2.1m from the house): reference point for outdoor conditions
2. Serambi Tamu (2): Assessment of ventilation performance in this specific area
3. Ruang Tamu (3,4,5): Assessment of ventilation performance in the living area
4. Bilik Tidur (6): Assessment of ventilation performance in a room
5. Ruang Tengah (7,8): measurement of ventilation performance in the centre area of the house
6. Kelek Anak (9,10,11): Evaluation of Ventilation Performance in Kelek Anak

7. Ruang Dapur (12,13,14): Evaluation of ventilation performance in the kitchen area
8. Ruang Basahan (15): Evaluation of ventilation performance in the changing or bathroom

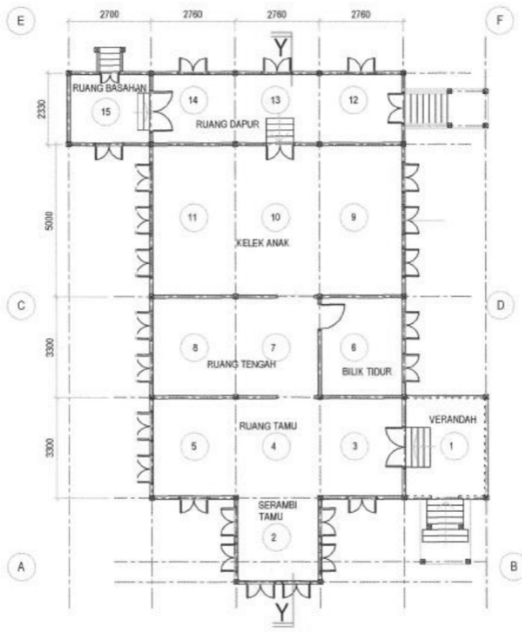
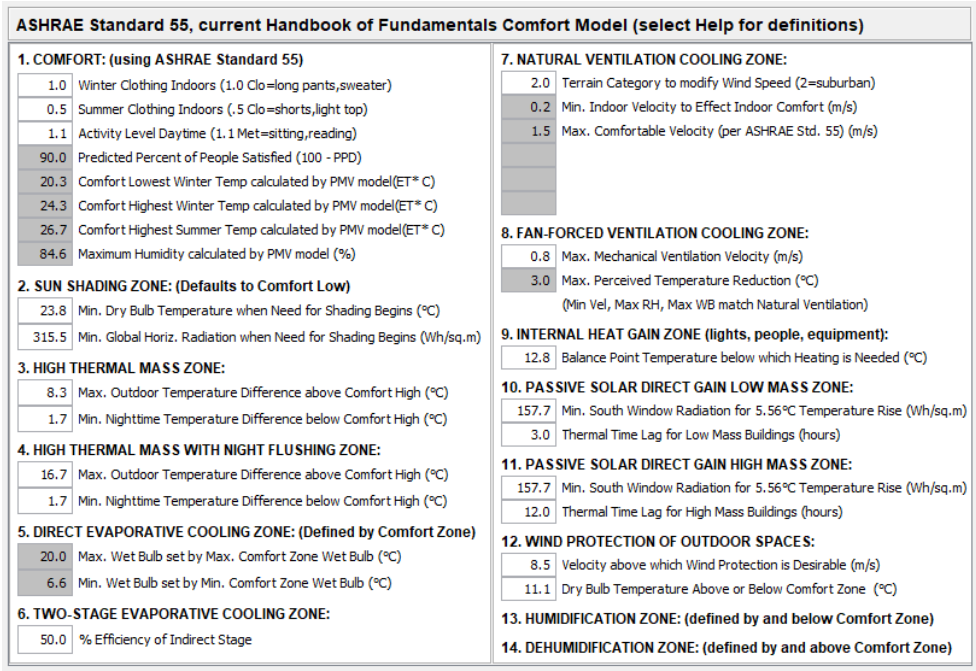


Figure 12: Floor plan Rumah Tok Su (Source:*Wahab & Ismail, 2014)*

3.4 Microclimate Analysis

For Szombathely, Hungary, wind analysis was conducted using Climate Consultant 6.0 to evaluate the environmental conditions specific to the region. This analysis is crucial for understanding airflow patterns and integrating traditional designs into a contemporary setting that experiences distinct climatic conditions.

Our methodology employs Climate Consultant 6.0 to uncover effective ventilation strategies, enriching our research's depth and comprehensiveness. Additionally, we incorporate the Adaptive Comfort Model from ASHRAE Standard 55 in Table 1 and Figure 13, which defines the thermal conditions deemed acceptable to occupants, particularly in spaces that rely on NV. This methodology is specifically tailored for scenarios where mechanical cooling systems are not utilised and does not apply when mechanical heating systems are in operation. Temperature and wind speed during the summer season were documented using Climate Consultant 6.0 to understand the temperature and wind velocity during the summer season in Szombathely.



ASHRAE Standard 55, current Handbook of Fundamentals Comfort Model (select Help for definitions)

1. COMFORT: (using ASHRAE Standard 55)
1.0 Winter Clothing Indoors (1.0 Clo=long pants,sweater)
0.5 Summer Clothing Indoors (.5 Clo=shorts,light top)
1.1 Activity Level Daytime (1.1 Met=sitting,reading)
90.0 Predicted Percent of People Satisfied (100 - PPD)
20.3 Comfort Lowest Winter Temp calculated by PMV model(ET* C)
24.3 Comfort Highest Winter Temp calculated by PMV model(ET* C)
26.7 Comfort Highest Summer Temp calculated by PMV model(ET* C)
84.6 Maximum Humidity calculated by PMV model (%)

2. SUN SHADING ZONE: (Defaults to Comfort Low)
23.8 Min. Dry Bulb Temperature when Need for Shading Begins (°C)
315.5 Min. Global Horiz. Radiation when Need for Shading Begins (Wh/sq.m)

3. HIGH THERMAL MASS ZONE:
8.3 Max. Outdoor Temperature Difference above Comfort High (°C)
1.7 Min. Nighttime Temperature Difference below Comfort High (°C)

4. HIGH THERMAL MASS WITH NIGHT FLUSHING ZONE:
16.7 Max. Outdoor Temperature Difference above Comfort High (°C)
1.7 Min. Nighttime Temperature Difference below Comfort High (°C)

5. DIRECT EVAPORATIVE COOLING ZONE: (Defined by Comfort Zone)
20.0 Max. Wet Bulb set by Max. Comfort Zone Wet Bulb (°C)
6.6 Min. Wet Bulb set by Min. Comfort Zone Wet Bulb (°C)

6. TWO-STAGE EVAPORATIVE COOLING ZONE:
50.0 % Efficiency of Indirect Stage

7. NATURAL VENTILATION COOLING ZONE:
2.0 Terrain Category to modify Wind Speed (2=suburban)
0.2 Min. Indoor Velocity to Effect Indoor Comfort (m/s)
1.5 Max. Comfortable Velocity (per ASHRAE Std. 55) (m/s)

8. FAN-FORCED VENTILATION COOLING ZONE:
0.8 Max. Mechanical Ventilation Velocity (m/s)
3.0 Max. Perceived Temperature Reduction (°C)
(Min Vel, Max RH, Max WB match Natural Ventilation)

9. INTERNAL HEAT GAIN ZONE (lights, people, equipment):
12.8 Balance Point Temperature below which Heating is Needed (°C)

10. PASSIVE SOLAR DIRECT GAIN LOW MASS ZONE:
157.7 Min. South Window Radiation for 5.56°C Temperature Rise (Wh/sq.m)
3.0 Thermal Time Lag for Low Mass Buildings (hours)

11. PASSIVE SOLAR DIRECT GAIN HIGH MASS ZONE:
157.7 Min. South Window Radiation for 5.56°C Temperature Rise (Wh/sq.m)
12.0 Thermal Time Lag for High Mass Buildings (hours)

12. WIND PROTECTION OF OUTDOOR SPACES:
8.5 Velocity above which Wind Protection is Desirable (m/s)
11.1 Dry Bulb Temperature Above or Below Comfort Zone (°C)

13. HUMIDIFICATION ZONE: (defined by and below Comfort Zone)

14. DEHUMIDIFICATION ZONE: (defined by and above Comfort Zone)

Figure 13: ASHRAE standard 55

3.5 Simulations

3.5.1 Geometry Setup

The floor plan depicted in Figure 14 illustrates the modelled structure used for analysing the integration of traditional woodcarving elements into modern architectural designs. The basic house layout measures 10m x 6m, with a ceiling height of 3.5m. The design incorporates multiple rooms with strategically positioned doors and windows to optimise NV and daylighting.

Traditional woodcarving elements are integrated into the openings to enhance airflow while preserving the cultural significance of the motifs. The structure features seven windows along the walls to facilitate cross-ventilation, and the doors enable air circulation between rooms. Additionally, ten woodcarving ventilation panels are installed above the windows, including one in the bathroom and one above the main entrance door on the exterior wall, as shown in Figure 15. The figure also highlights a simplified model designed for CFD analysis, focusing on airflow patterns and thermal comfort within the building.

To further enhance the realism of the simulation, two human figures were included in the scenario to evaluate thermal comfort under the given conditions shown in Figure 16. The first human figure is placed between the living area and the kitchen, and other human figures are placed in the bedroom. This addition allows for a more accurate assessment of how airflow and temperature distributions impact occupants within the space. The layout plays a crucial role in examining the influence of woodcarving elements on ventilation efficiency, particularly under summer conditions. To simulate realistic airflow, Figure 17 shows two interior doors that are left open, mimicking actual usage scenarios where doors remain open for improved air circulation.

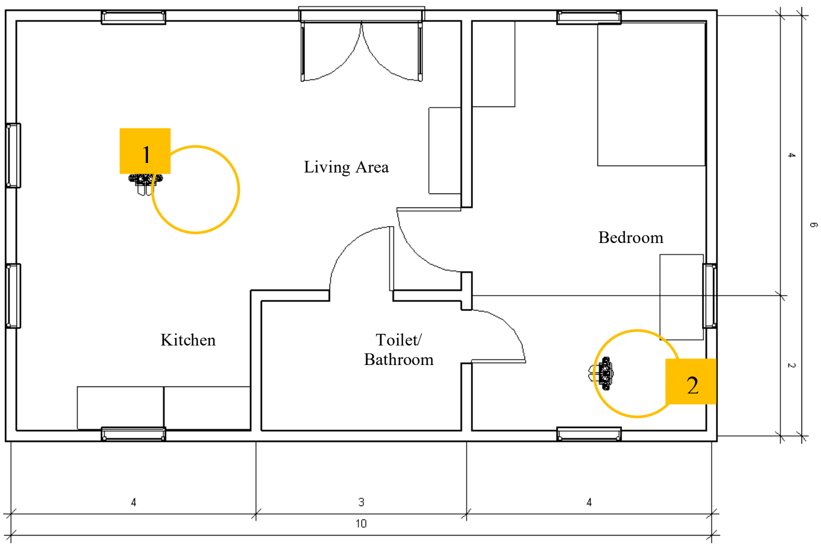


Figure 14: Floor Plan.

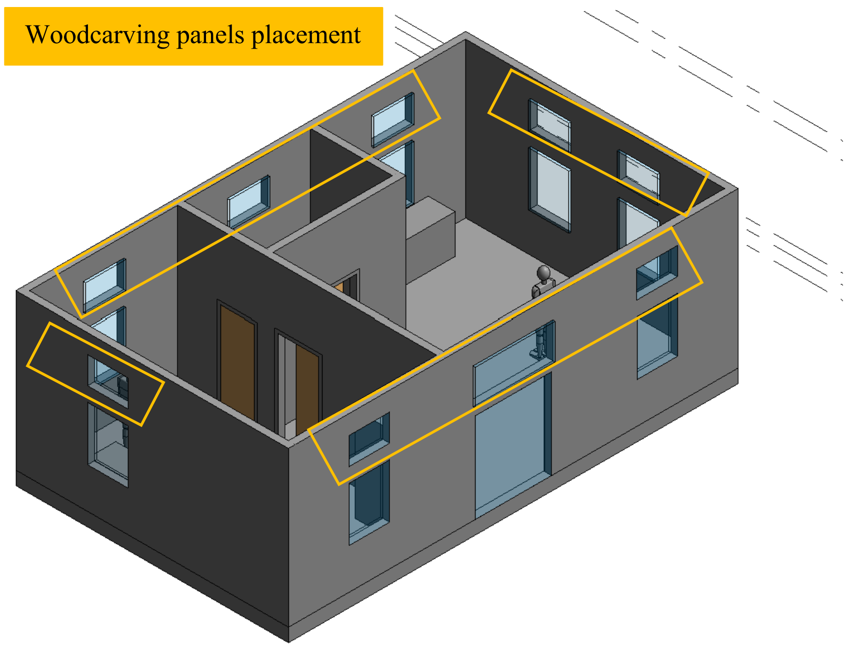


Figure 15: Woodcarving panels placement.

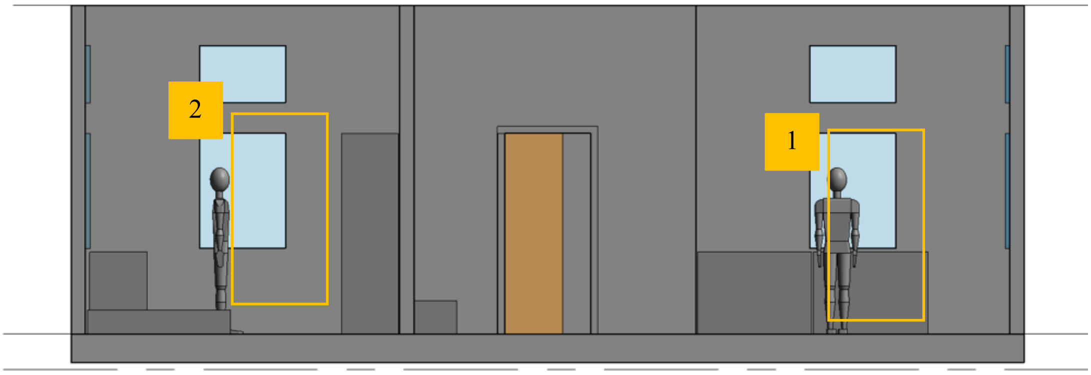


Figure 16: Human figure placement.

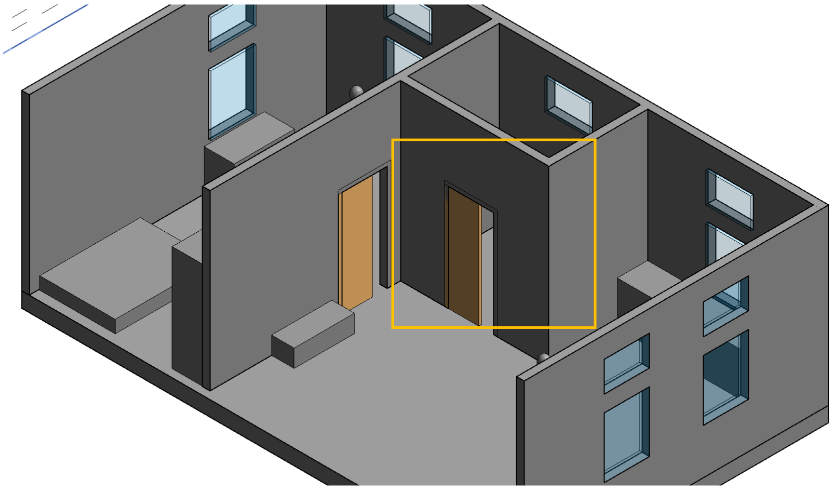


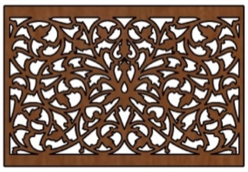
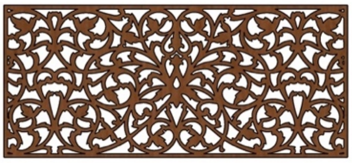
Figure 17: Interior door condition.

To enhance the analysis of airflow and thermal comfort, the model incorporates fully opened vents, no vents, and mechanical ventilation as alternative ventilation strategies. These elements are integrated into the simulation to compare their effectiveness with traditional woodcarving ventilation panels. Hollow openings strategically placed along the walls where the woodcarving panels are located allow for unobstructed airflow, mimicking a more straightforward ventilation method.

In addition, modern diffusers are included in the setup to simulate mechanical ventilation solutions. These diffusers are used to regulate airflow by directing and distributing air more uniformly across the space. This allows for a comparison between the traditional NV strategies offered by the woodcarving panels and the more controlled ventilation provided by the diffusers. The fully opened vents, no vents, and mechanical ventilation are set up to simulate airflow under varying internal and external temperature and wind speed scenarios by following Johor and Szombathely's extreme conditions. The CFD model will analyse how each method impacts the temperature distribution, air velocity, and occupant comfort within the house. By comparing these ventilation methods, the research aims to identify the relative advantages and limitations of natural versus mechanical ventilation systems in enhancing indoor environmental quality.

3.5.2 Woodcarving Panel Design Analysis Johor

Table 2: Woodcarving type for Johor situation.

Location	Code	Panel	Description
Above the windows & toilet wall	WC1		• QTY: 8 Nos • 609.6 mm x 914.4 mm
Above the main entrance	WC2		• QTY: 1Nos • 800 mm x 1800 mm

The woodcarving designs documented in Rumah Limas Hutan Bandar MBJB, depicted in Figure 18, were implemented as ventilation panels within these models for Johor simulation. This 3d modelling approach facilitates the visualisation of how traditional designs can be integrated into contemporary architectural layouts and assesses their potential impact on building performance. The carving found in Rumah Limas Hutan Bandar MBJB includes the ukiran kerawang tebuk tembus (rata or tidak bersilat) and the ketumbit flower motif. The ukiran kerawang tebuk tembus carving exhibits intricate patterns and designs, while the Ketumbit flower motif depicts the graceful beauty of the torch ginger flower, commonly found in Southeast Asia. The woodcarvings in Rumah Limas Hutan Bandar MBJB were carefully categorised based on their specific location and type. Each carving was meticulously assessed to determine the ratio of solid (opaque) material to void (cut-out) space, expressed as a percentage or ratio. Regarding the woodcarvings in Rumah Limas Hutan Bandar MBJB, the solid-to-void ratios ranged from 1:1.56 for C1, 1:3.7 for C2, to 1:1.68 for C3. The chosen panels were C1 to be implemented in the model. The size was adjusted based on the opening in the newly constructed geometry using Autodesk Revit. This ensures that the comparison results will use similar models with the same panel size. The sizes of woodcarving panels used in the Johor situation are shown in Table 2.

The table provides an overview of the placement and specifications of woodcarving panels used in the modelled structure. These panels, labelled with distinct codes, are strategically positioned to enhance ventilation and airflow while contributing to the cultural aesthetic of the design. The panels labelled WC1 are placed above the windows and the toilet wall. Eight panels are installed, each measuring 609.6 mm x 914.4 mm, ensuring uniformity in size and design across the specified locations. These panels facilitate NV while preserving privacy in the respective spaces. The panel labelled WC2 is positioned above the main entrance. This location features a single, larger panel measuring 800 mm x 1800 mm, making it a prominent decorative and functional element. Its size and placement emphasise its role in allowing air circulation at the building's main access point while maintaining a visually striking feature that reflects traditional design motifs.

Figure 18: Woodcarving ventilation panel from Rumah Limas.

3.5.3 Woodcarving Panel Design Analysis Szombathely

The woodcarving designs inspired by the *Székely* Gate motifs, depicted in Figure 19, were traced and implemented as ventilation panels within these models for the Szombathely simulation. This 3D modelling approach facilitates visualising how traditional designs can be integrated into contemporary architectural layouts and assesses their potential impact on building performance.

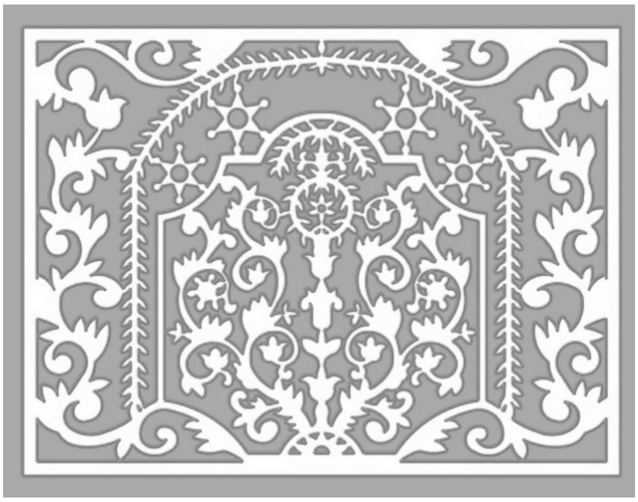


Figure 19: woodcarving inspired by Kaputükör motif on Székely gate.

The kaputükör, or gate mirror shown in Figure 20, is a prominent decorative element of Székely gates, characterised by intricate patterns that vary in style and complexity. Common patterns found in kaputükör designs include:

1. **Floral Arrangements**: These designs often feature elaborate, stylised flowers, ranging from single large blooms to dense clusters of smaller flowers surrounded by leaves and vines.
2. **Fruit and Vegetables**: Some patterns incorporate depictions of fruits or vegetables, symbolising abundance and fertility.
3. **Birds**: Birds, such as doves or other symbolic or mythical species, are frequently featured, often perched on or near floral arrangements.

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4. **Sun and Stars**: Celestial symbols like the sun and stars may be included, representing light and guidance in a stylised form.
5. **Geometric Patterns**: Intricate geometric shapes and repeating patterns reflect mathematical precision and aesthetic balance.
6. **Mythical Figures**: Some designs incorporate figures from folklore or mythology, adding cultural narrative to the gate.
7. **Nature Motifs**: Stylized leaves, vines, and other natural elements create a flowing, organic appearance.

Figure 20: Kaputükör minták. (Source: Kovács, 2005)

These patterns are not merely decorative; they embody cultural and symbolic meanings, reflecting the values and beliefs of the Székely people. The meticulous craftsmanship of the kaputükör significantly enhances the aesthetic and cultural value of Székely gates.

The design takes inspiration from traditional kaputükör patterns, which are intricately adapted to reflect the rich cultural heritage of the Hungarian region. These patterns incorporate a harmonious blend of floral motifs, celestial elements such as the sun and stars, and designs inspired by nature. The floral engagement symbolises growth and vitality, while the sun and star motifs evoke timelessness and a connection to the cosmos. Including nature-based motifs further underscores a deep appreciation for the natural world, seamlessly blending cultural symbolism with aesthetic appeal. This integration not only preserves Hungarian traditions but also enhances the visual and functional value of the woodcarving elements.

Table 3: Woodcarving panel type for Szombathely.

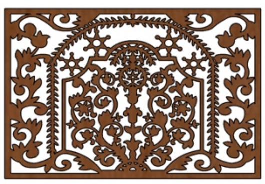
Location	**Code**	**Panel**	**Description**
Above the windows & toilet wall	WC3		• QTY: 8 Nos • Size: 609.6 mm x 914.4 mm
Above the main entrance	WC4		• QTY: 1 Nos • Size: 800 mm x 1800 mm

Table 3 shows that the panels were installed at two critical locations within the building: above the windows, the toilet wall, and the main entrance. The panels installed above the windows and toilet wall are labelled as WC3. Eight units were placed in this location, each with 609.6 mm x 914.4 mm dimensions, ensuring consistent design and functionality across these openings. These panels support cross-ventilation within the structure while enhancing its aesthetic appeal. In contrast, the panel above the main entrance is labelled WC4 and features a larger single unit with 800 mm x 1800 mm dimensions. Positioned prominently, this panel serves as both a functional ventilation feature and a decorative element that highlights the traditional woodcarving motifs integrated into the design.

3.5.4 Parameters Set Up

The external air volume for the CFD simulations shown in Figure 21 was carefully defined to reflect realistic environmental conditions. Its dimensions were 1289.112 mm in height, 3412.6 mm in width, and 6700.589 mm in depth, adhering to the proportional guidelines outlined in the Autodesk tutorial. These proportions ensured that the air volume extended sufficiently beyond the building geometry to model airflow interactions without boundary interference accurately. The height of the air volume was determined to be three times the height of the building geometry, while the width and depth were set at five and six times the respective dimensions of the geometry. Materials were assigned to the geometry after defining the external air volume, as specified in Figure 22. This setup, combined with positioning the external air volume at an angle of -22.5 degrees, simulated the natural wind flow conditions, which are rarely perpendicular to building facades. The wind direction for Johor and Szombathely is shown in Figure 23. This comprehensive setup enabled detailed analyses of how traditional woodcarving panels, inspired by kaputükör motifs and adapted from Rumah Limas Hutan Bandar MBJB, influence airflow patterns and thermal comfort in contemporary architectural designs.

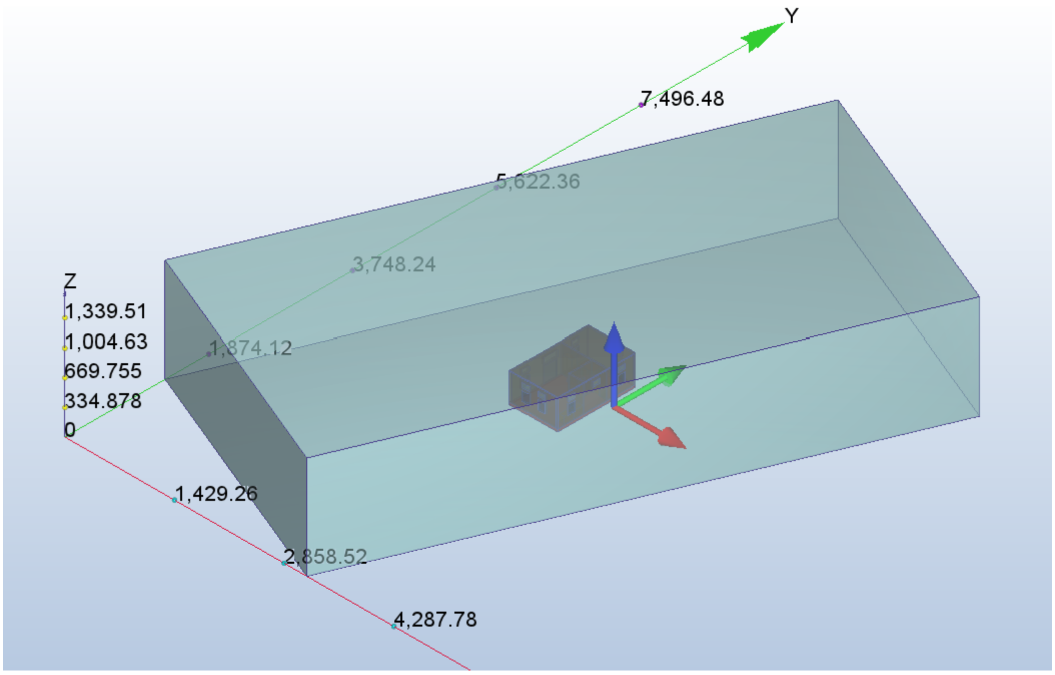


Figure 21: Geometry set-up

Figure 22: Materials assigned to the geometry.

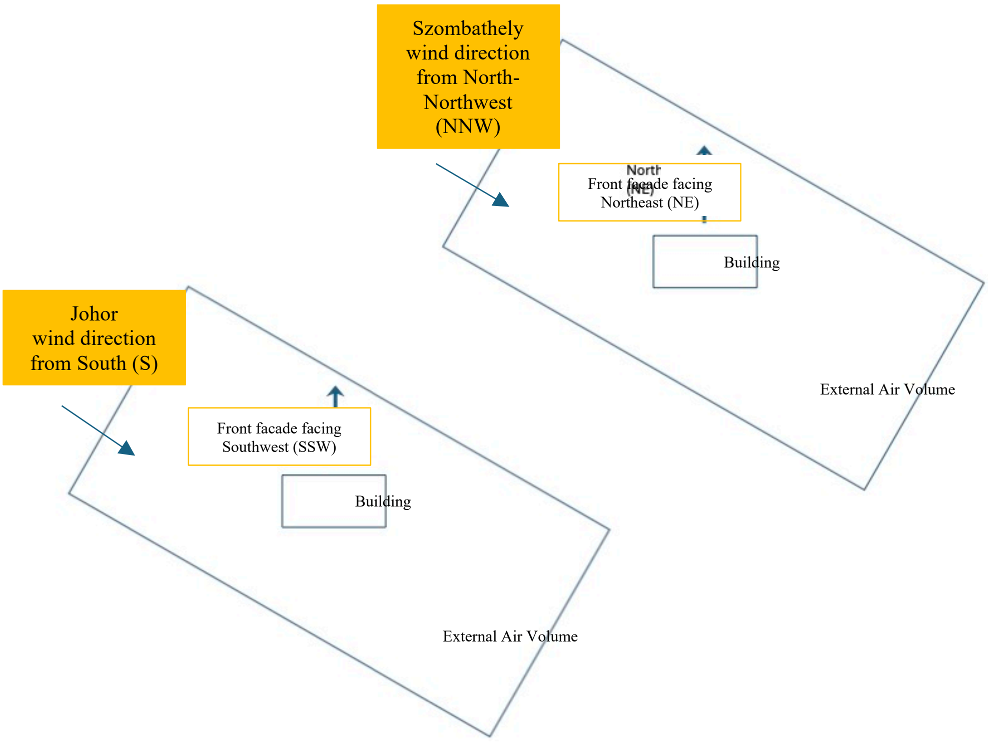


Figure 23: Wind directions for Johor and Szombathely.

After setting up the external air volume, the next step was to define the parameters for fully opened vents, no vents, and mechanical ventilation within the simulation. To ensure a fair comparison of airflow performance, fully opened vents, closed vents, and mechanical ventilation were modelled to be the same size as the woodcarving ventilation panels. This approach ensured that the airflow paths remained consistent across all scenarios, allowing for an accurate evaluation of how these different ventilation strategies influenced airflow and thermal comfort.

With the external air volume and parameters for the ventilation systems established, the simulation was divided into two scenarios to analyse the airflow and thermal conditions based on distinct temperatures and wind speeds. The boundary conditions applied are summarised in the table below:

Table 4: Boundary conditions for Johor and Szombathely.

Boundary condition	**Value (Johor)**	**Value (Szombathely)**	**Surface/Volume**
Temperature	32°C	34°C	South (Johor) & North-Northwest facing (Szombathely) external air volume
Velocity	7 m/s	14m/s	South (Johor) & North-Northwest facing (Szombathely) external air volume to simulate wind flow
Pressure	0 Pa	0 Pa	North (Johor) & South-Southeast facing (Szombathely) external air volume, acting as the outlet.
Film coefficient	20 W/m^2K	20 W/m^2K	Entire outer surface of the building
Human	60 W/m^2K	60 W/m^2K	Two human figures positioned within the building to assess thermal comfort

To account for the influence of preceding cooler conditions before daily temperature peaks, heat abstraction by floors and outer walls was incorporated into the models with an intensity of -12 W/m^2K. Additionally, to simulate the real-world scenario of imperfect window and door closures, a free area ratio (FAR) of 0.005 was applied for the Johor building. In contrast, a ratio of 0.004 was used for the Szombathely building.

Material Edits for the Johor Building:

1. Walls:
   - Material: Hardwood
   - Thermal conductivity: 1.2 W/mK
   - Other properties: Remain unchanged. This material is saved as Wall 2.

The wall material represents typical brick-plastered walls commonly used in modern Malaysian buildings with a standard thickness of 150 mm (6 inches). This material was saved as Wall1, allowing it to be applied to other parts of the simulation for accurate thermal performance modelling under different boundary conditions.

Material Edits for the Szombathely Building:

2. Walls:
   - Material: Hardwood
   - Thermal conductivity: 0.065 W/mK (0.00065 W/cmK)
   - Other properties: Remain unchanged. This material is saved as Wall 1.
3. Windows:
   - Material: Window (solar)
   - Thermal conductivity: 0.2 W/mK (0.002 W/cmK)
   - Other properties: Remain unchanged. This material is saved as Window 1.
4. Entrance Door:
   - Material: Window (solar)
   - Thermal conductivity: 0.23 W/mK (0.0023 W/cmK)
   - Other properties: Remain unchanged. This material is saved as Door 1.

These material updates ensure that the building components, such as walls, windows, and doors, are accurately represented with their respective thermal properties. This approach enables a more realistic simulation of thermal performance and airflow within the building, considering the climate conditions of both Johor and Szombathely. The framework provided allows for evaluating how architectural features and materials influence ventilation and thermal comfort in the modelled environments.

A significant challenge encountered during the study was the complex geometry of the woodcarving panels, which rendered them unsuitable for direct import into Autodesk CFD for simulation purposes. FAR was employed to quantify the airflow resistance of the panels to overcome this. This metric facilitated the representation of the woodcarvings as resistive boundaries in the CFD simulation. By defining the resistance based on the calculated ratio of solid material to open spaces, the airflow through the woodcarving panels was effectively restricted in line with their design characteristics. This approach enabled the accurate modelling of airflow dynamics without the need for detailed simulation of each void in the carvings, thereby streamlining the computational process. The resistive boundary condition was applied in Autodesk CFD, allowing the woodcarving panels' influence on NV and airflow efficiency within the room to be analysed.

Documenting the overall and solid areas of the woodcarving panels, derived from SketchUp models, was a crucial step in determining the FAR. This methodology ensured that the panels' cultural and functional significance was preserved while maintaining the practicality of the simulation process.

The formula for calculating the FAR is as follows:

$$\text{FAR} = \frac{\text{Total Area}}{\text{Solid Area}} \text{ x } 100$$

To simplify the simulation process, the complex geometry of the woodcarvings was replaced with a resistance boundary condition based on FAR. The FAR results are shown in the table below:

Table 5: Woodcarving panel free area ratio

Woodcarving Panel	**FAR**
WC1	0.4314 or 43.14%
WC2	0.3773 or 37.73%
WC3	0.4657 or 46.57%
WC4	0.4485 or 44.85%

The FAR analysis highlights the proportion of void areas in the panels, reflecting their potential for ventilation and structural integrity. Among the four panels evaluated, the first panel, with dimensions of 1800 mm x 800 mm, has a FAR of 43.14%. This indicates a moderate balance between solid and void areas, suitable for maintaining ventilation while ensuring structural stability. The second panel, measuring 609.6 mm x 914.4 mm, shows a FAR of 37.73%, reflecting a design that leans more towards solidity than ventilation, making it ideal for areas requiring higher coverage. The third panel, also sized at 1800 mm x 800 mm, achieves the highest FAR of 46.57%. This makes it highly effective for maximising airflow while retaining sufficient material for support, making it optimal for enhancing NV. The fourth panel, measuring 609.6 mm x 914.4 mm, has a FAR of 44.85%, balancing ventilation and decorative appeal.

In summary, the FAR values demonstrate a range of designs tailored for different applications. Panels with higher FAR, such as the third and fourth, are better suited for improving NV, while those with lower FAR, like the first and second, are more appropriate for areas prioritising structural solidity and coverage.

The CFD simulation was conducted as a steady-state analysis to evaluate airflow patterns and NV efficiency within the modelled room, focusing on how traditional woodcarvings influence ventilation. The simulation began by configuring boundary conditions, with airflow entering through the woodcarving panels, replicating Johor and Szombathely's climate conditions. An unstructured grid mesh was employed, with finer elements around the woodcarving panels to ensure accurate airflow capture. Validation was achieved by comparing the simulated results with Johor and Szombathely's simulation results.

3.5.5 Transient Analysis Set Up

In this study, a transient analysis was performed in Szombathely on July 29th to evaluate the dynamic behaviour of airflow and thermal conditions over time in a house with woodcarving ventilation panels, under varying external and internal conditions. This analysis allows us to simulate how air velocity, temperature, and ventilation efficiency fluctuate throughout the day, reflecting the real-time impact of environmental factors such as outdoor temperature and wind speed.

The transient analysis spans 12 hours, from 07:00 to 19:00, simulating variations in temperature and wind velocity that correspond to diurnal conditions specific to the locations of Johor and Szombathely. This time-dependent simulation will provide insights into the thermal comfort and airflow distribution within the building under changing climatic conditions.

Table 6: Estimated Solar Irradiation on Building Surfaces in Szombathely (29 July).

Time (o'clock)	NE (W/m²)	SE (W/m²)	SW (W/m²)	NW (W/m²)
07:00	425.37	361.76	425.37	361.76
07:30	374.09	384.95	374.09	384.95
08:00	318.02	399.95	318.02	399.95
08:30	258.04	406.60	258.04	406.60
09:00	195.20	404.69	195.20	404.69
09:30	130.60	394.21	130.60	394.21
10:00	65.34	375.52	65.34	375.52
10:30	0.55	348.76	0.55	348.76
11:00	62.73	314.50	62.73	314.50
11:30	123.38	273.26	123.38	273.26
12:00	180.32	225.80	180.32	225.80
12:30	232.58	172.86	232.58	172.86
13:00	279.36	115.43	279.36	115.43
13:30	319.72	54.42	319.72	54.42
14:00	353.15	9.06	353.15	9.06
14:30	378.92	74.00	378.92	74.00
15:00	396.60	139.20	396.60	139.20
15:30	405.95	203.55	405.95	203.55
16:00	406.83	266.02	406.83	266.02
16:30	399.14	325.53	399.14	325.53

17:00	3834	381.04	3834	381.04
17:30	358.92	431.55	358.92	431.55
18:00	326.98	476.29	326.98	476.29
18:30	287.96	514.39	287.96	514.39
19:00	242.35	545.34	242.35	545.34

Table 6 shows the hourly solar irradiation values on different facades of the case study house in Szombathely on 29th July, derived from sun path diagrams and adjusted based on building orientation. This data was used to estimate solar heat gain and supports the thermal boundary conditions set in the CFD simulation.

3.6 Conclusion

Chapter 3 summarises the methodology to explore how traditional woodcarving ventilation panels, fully opened vents, closed vents, and mechanical ventilation can enhance NV and thermal comfort in various climatic contexts. The research employs a combination of qualitative and quantitative approaches, including literature review, site visits, wind analysis, microclimate analysis, airflow analysis, and CFD simulations. Reviewing Rumah Tok Su and site visits to Rumah Limas Hutan Bandar MBJB provide historical and practical insights into traditional Malay architecture and woodcarving ventilation systems. Wind and microclimate analysis, conducted using Climate Consultant 6.0 for the Johor Bahru and Szombathely sites, respectively, offer a detailed assessment of environmental conditions. Airflow analysis using CFD simulations in a standardised house setup further investigates how woodcarving ventilation panels, opened vents, closed vents, and mechanical ventilation impact air circulation and contribute to thermal comfort. The CFD simulations also employed a transient analysis for the woodcarving ventilation panel, examining how airflow and thermal comfort evolve in response to changing environmental factors throughout the day on 29th July in Szombathely.

Altogether, this methodological framework not only supports the integration of traditional elements into modern architectural design but also offers valuable insights into sustainable and culturally resonant ventilation strategies.

Chapter 4: Findings and Analysis

4.1 Introduction

Chapter 4 comprehensively explores the findings and analyses regarding ventilation performance and airflow dynamics in traditional Malay houses, specifically focusing on Rumah Limas Hutan Bandar MBJB in Johor Bahru and its comparative counterpart, Rumah Tok Su. The importance of NV in enhancing indoor comfort, energy efficiency, and overall occupant well-being is underscored, particularly in tropical climates where humidity and temperature fluctuations can significantly impact living conditions. The chapter is structured into distinct sections that systematically dissect various aspects of the case studies. Beginning with a case study, by doing the wind analysis for temperature and wind speed. The data was then compared with Rumah Tok Su, gathered from a literature review, and evaluated against established benchmarks such as the ASHRAE comfort zone.

Furthermore, the chapter incorporates microclimate analysis data collected from Szombathely, Hungary, to contextualise the findings within a broader climatic framework. The influence of environmental factors on NV design is emphasised, highlighting the necessity for adaptive strategies that consider local conditions. While field surveys were conducted at the Malaysian sites to collect real-world data, the analysis for Szombathely relied on Climate Consultant 6.0. This difference in approach is attributed to the availability of reliable climate datasets for Szombathely and the constraints of conducting site surveys in Hungary, including language barriers and the challenge of conducting a site visit without local accompaniment. Consequently, the use of Climate Consultant 6.0 was deemed appropriate for understanding the Szombathely climate, particularly for summer conditions, where reliable data for wind and temperature variations were available.

CFD simulations further deepen the investigation by modelling airflow patterns and assessing how different architectural elements affect ventilation performance. Through this multi-faceted analysis, Chapter 4 aims to bridge the gap between traditional architectural practices and contemporary sustainability goals, offering valuable insights for future design applications in similar climates.

4.2 Case Study Analysis

4.2.1 Rumah Limas Hutan Bandar MBJB, Johor Bahru

During the site visit to Rumah Limas Hutan Bandar MBJB in Johor Bahru, several architectural features were observed that contributed to the house's NV, particularly the role of traditional woodcarving ventilation panels. The house, designed in the Bugis architectural style, is known for its extended ridged roof and multiple woodcarving ventilation panels, which significantly enhance airflow throughout the building. 138 woodcarving ventilation panels were identified and placed on the interior and exterior walls to facilitate air movement.

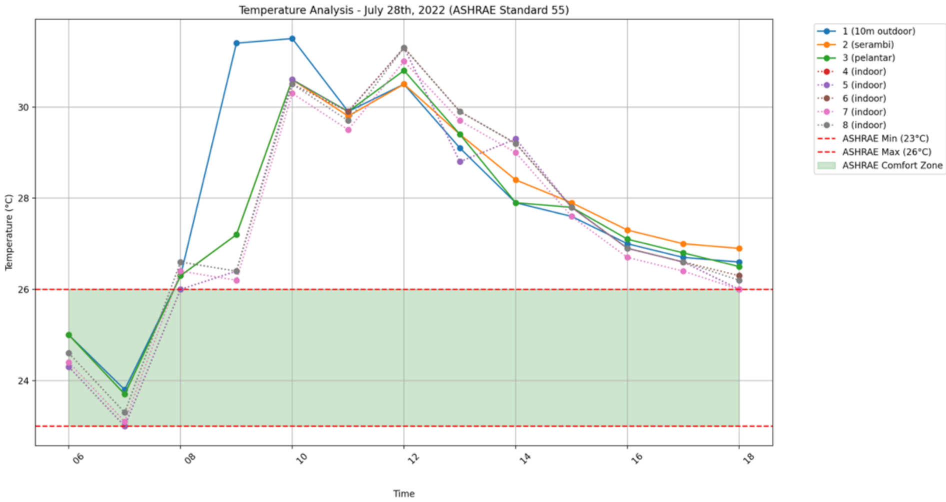


Figure 24: Temperature performance points 1-8 on the 28th of July 2022.

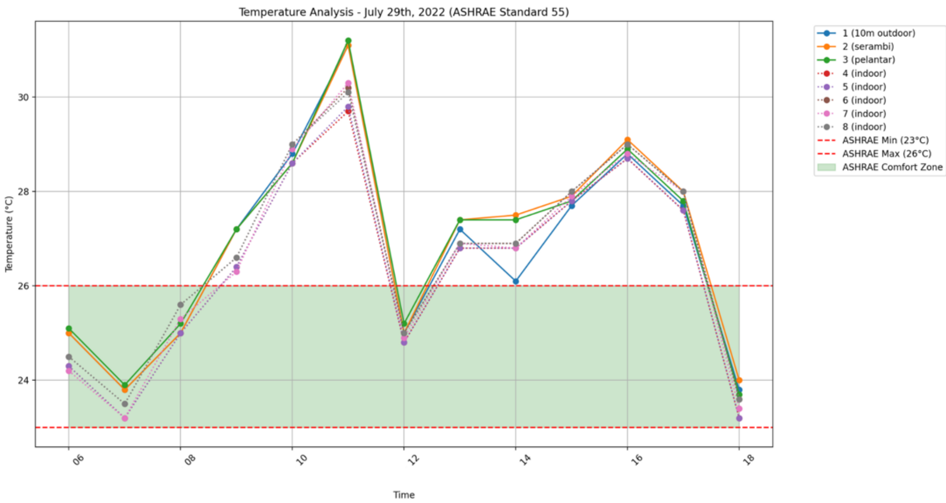


Figure 25: Temperature performance points 1-8 on the 29th of July 2022.

Both graphs in Figure 24 and Figure 25 depict temperature variations over time outdoors (points 1, 2, and 3) and indoors (points 4,5, 6,7, and 8). The y-axis represents temperature in degrees Celsius, and the x-axis shows the time from 6 a.m. to 18:00 on the same day. Both graphs include the ASHRAE standard 55 (highlighted in green), with minimum and maximum lines set at 23°C and 26°C, respectively.

For July 28th, temperatures start within the comfort zone but rise significantly above it before gradually declining. Point 1 outdoor temperature (represented by the blue line) shows the most substantial increase, reaching a peak of around 31°C. Indoor temperatures remain more stable but still exceed the comfort zone for much of the day, with temperatures beginning to return to the comfort zone towards the end of the period. In contrast, the July 29th graph reveals more fluctuations in temperature throughout the day. Temperatures begin within the comfort zone but rise sharply above it, drop dramatically at one point, and then rise again. The peak temperature is slightly higher, reaching about 32°C for both outdoor and some indoor locations. There is a noticeable dip in all temperatures around noon, briefly bringing them back into the comfort zone, with the graph ending in a sharp temperature decline. When comparing the two graphs, July 29th demonstrates greater temperature extremes and variability, with higher peak temperatures and more pronounced rises and falls. Despite the peak temperatures on July 29th, the readings spend more time near or within the ASHRAE comfort zone. Additionally, July 28th displays a more consistent difference between outdoor and indoor temperatures, whereas July 29th shows closer tracking between these two settings, particularly during the temperature shifts. Overall, July 29th reflects more dynamic weather conditions, potentially indicating a day with intermittent cloud cover or rain, while July 28th suggests a more stable but hot day.

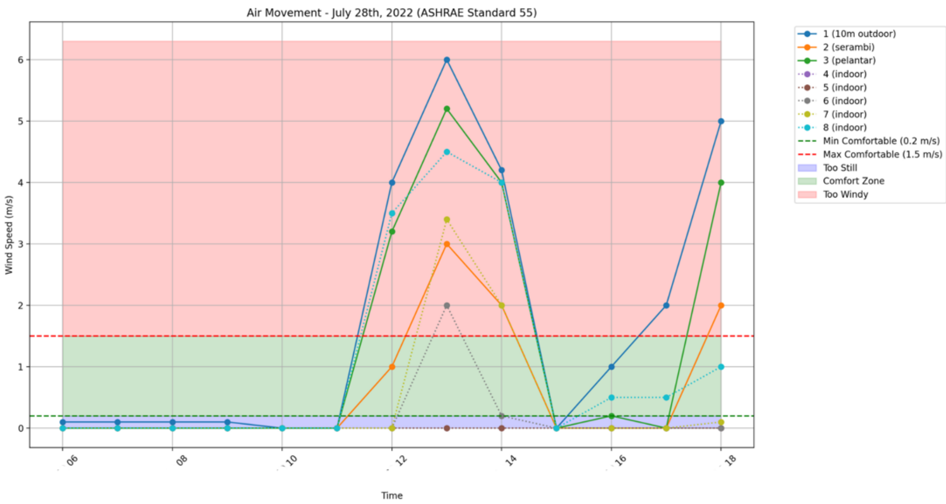


Figure 26: Air movement on 28th July 2022.

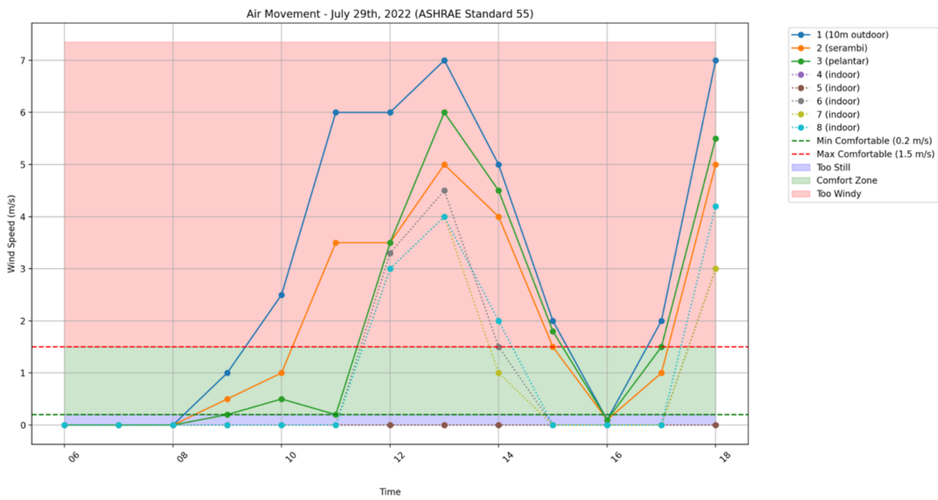


Figure 27: Air movement on 29th July 2022.

The graphs in Figure 26 and Figure 27 illustrate air movement at all eight points (both outdoor and indoor) while incorporating the ASHRAE Standard 55 comfort zone for NV. The comfort zones are represented as follows: a blue zone for air speeds between 0 and 0.2 m/s (considered "Too Still"), a green zone for air speeds between 0.2 and 1.5 m/s (the "Comfort Zone"), and a red zone for air speeds above 1.5 m/s (considered "Too Windy").

The expanded comfort zone for the outdoor points (1, 2, and 3) means these locations now spend more time within the "Comfort Zone." On July 29th, outdoor points still show more periods in the "Too Windy" zone compared to July 28th, but overall, there are fewer instances of discomfort. Point 1, located at 10 meters outside, shows the highest wind speeds, with a maximum of 7m/s, occasionally exceeding the comfort zone. Regarding the indoor points (4, 5, 6, 7, and 8), points 4 and 5 remain in the "Too Still" zone throughout both days, as previously observed. However, points 6, 7, and 8 display improved comfort conditions. On July 28th, these points are within the "Comfort Zone" for a larger part of the day, and on July 29th, they are mostly within the "Comfort Zone," with fewer instances of excessive wind. A comparison of both days still shows that July 29th demonstrates better overall compliance with ASHRAE Standard 55.

The diurnal pattern of increased air movement in the afternoon remains consistent across both days. In contrast, mornings are still characterised by "Too Still" conditions, especially for the indoor points. Concerning ASHRAE Standard 55 compliance, outdoor points are now more frequently within the comfort zone, with fewer instances of being too windy. Points 4 and 5, however, never reach the comfort zone and remain in the "Too Still" zone. Indoor points 6, 7, and 8 show significant improvement, with a large portion of the day spent within the comfort zone, particularly on July 29th.

4.2.2 Comparison of Ventilation Performance: Rumah Limas Hutan Bandar MBJB and Rumah Tok Su

Table 7: Temperature and wind speed comparison of Rumah Tok Su and Rumah Limas Hutan Bandar MBJB

Aspect	**Rumah Tok Su**	**Rumah Limas Hutan Bandar MBJB**
Temperature Performance	Mirrors outdoor temperature	Better temperature regulation
Thermal Comfort Zones	Brief comfort periods in early morning and late afternoon	Longer comfort periods (8-9am, 3-6pm)
Wind Speed Analysis	Max indoor speed: 0.6 m/s	Max indoor speed: 4.6 m/s
Ventilation Effectiveness	Air speeds mostly falling between 0.1 and 0.6 m/s , comfortably within the ASHRAE comfort zone of 0.2 to 1.5 m/s	Air speeds mostly exceed the ASHRAE comfort zone of 0.2 to 1.5 m/s
Comfort vs Discomfort	Passive cooling through structural gaps	Comfort achieved with higher wind speeds

The comparison between Rumah Tok Su and Rumah Limas Hutan Bandar MBJB highlights significant differences in ventilation performance and comfort levels in Table 7, based on outdoor and indoor air movement data. Rumah Tok Su experiences more moderate outdoor air speeds, ranging from 0.1 to 0.85 m/s, suggesting that it is situated in a calmer environment with less exposure to strong winds. In contrast, Rumah Limas Hutan Bandar MBJB faces more extreme outdoor conditions, with air speeds ranging from 0 to 7.0 m/s, indicating higher wind variability and greater exposure to environmental factors.

Indoors, Rumah Tok Su demonstrates better control over air movement, with air speeds mostly falling between 0.1 and 0.6 m/s, comfortably within the ASHRAE comfort zone of 0.2 to 1.5 m/s. This indicates that Rumah Tok Su’s architectural features, such as its carved hollow panels and strategic window placements, effectively moderate airflow and maintain comfortable conditions throughout the day. On the other hand, Rumah Limas Hutan Bandar MBJB has much more variable indoor air speeds, ranging from 0 to 4.0 m/s, frequently exceeding the ASHRAE comfort zone. This suggests that the house may suffer from over-ventilation, leading to discomfort, especially during high outdoor wind speeds. Rumah Tok Su's limited data points make it difficult to establish a full daily trend when examining the diurnal patterns. Still, the available data suggests relatively stable air movement throughout the day, even during peak outdoor wind conditions. In contrast, Rumah Limas Hutan Bandar MBJB exhibits a clear diurnal pattern, with indoor air speeds peaking in the afternoon, mirroring outdoor wind fluctuations. This indicates a less controlled ventilation system, with indoor air speeds directly influenced by external conditions, which may cause discomfort during peak hours.

Regarding overall comfort and compliance with the ASHRAE standard, Rumah Tok Su performs better, maintaining indoor air speeds that consistently fall within the comfort zone, making it a more stable and comfortable environment for its occupants. In contrast, Rumah Limas Hutan Bandar MBJB frequently experiences indoor air speeds exceeding the comfort zone, particularly on afternoons, potentially causing drafts or discomfort. However, despite the higher recorded temperatures, the higher wind speeds contributed to achieving thermal comfort. This suggests that the climate conditions, rather than ventilation control alone, significantly influence comfort levels. The differences in ventilation control and comfort levels between the two houses may be attributed to architectural design choices, such as the placement of ventilation panels and modifications like acrylic coverings in Rumah Limas Hutan Bandar MBJB, which appear to affect natural airflow and ventilation effectiveness.

4.3 Site Analysis Data Collection Results

4.3.1 Szombathely, Hungary

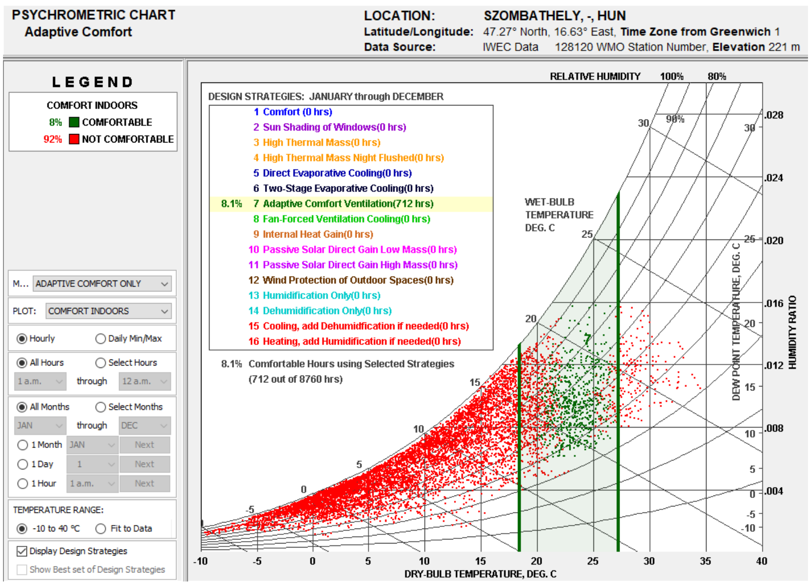


Figure 28: Psychometric chart.

The psychrometric chart analysis for Szombathely, Hungary, focuses on the summer months, which are June, July, and August, to assess conditions conducive to NV. The

"Adaptive Comfort Ventilation" zone, highlighted in green on the chart, represents the ideal temperature and humidity conditions for effective NV. Key observations indicate that the adaptive comfort zone generally encompasses temperatures ranging from 20°C to 27°C. Correspondingly, the relative humidity within this zone typically falls between 30% and 70%. To optimise NV strategies during the summer months, it is essential to maintain indoor conditions within this green zone.

Figure 28 shows that 8.1% (or 712 hours) indicates the proportion of the year during which the outdoor climate conditions naturally fall within this adaptive comfort zone, allowing effective use of NV to maintain indoor comfort. This percentage is derived by comparing the number of hours within the zone during the year to the total hours that can be used to create a thermally comfortable indoor environment for about 712 hours annually, primarily during the summer months.

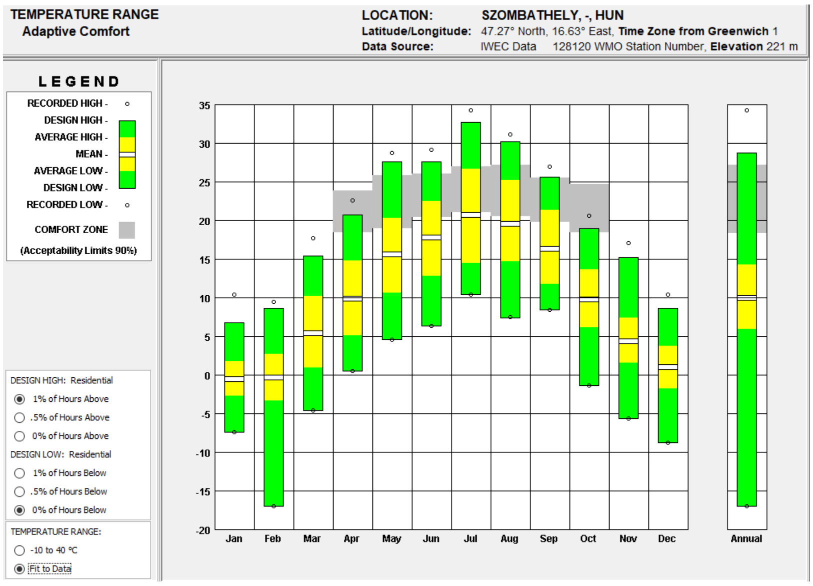


Figure 29: Whole year temperature in Szombathely.

Szombathely's temperature and humidity data were collected and analysed with Climate Consultant 6.0. During the summer, the temperature typically ranges from early morning lows of around 18°C to afternoon highs of 30°C. A series of charts illustrates the daily fluctuations in temperature and humidity levels over a typical summer day in Szombathely, as depicted in Figure 29. The temperature range chart for Szombathely provides a detailed overview of the area's climatic conditions, showcasing monthly temperature variations throughout the year and an annual summary. Located at 221 meters and coordinates 47.27° North and 16.63° East, Szombathely's data is sourced from IWEC Data, specifically from WMO Station Number 128120. The region operates within a time zone one hour ahead of Greenwich Mean Time.

Distinct temperature trends are evident, indicating that the warmest months are July and August, during which peak temperatures frequently exceed 30°C. Conversely, in the coldest months, typically December, January, and February, minimum temperatures drop below- 15 °C. April, May, September, and October are the most comfortable, with temperatures generally falling within the acceptable comfort range. The annual temperature range for Szombathely spans from approximately -17°C to 34°C. The chart employs a colour-coding system to enhance clarity and represent various temperature metrics. The green colour denotes the design's high and low temperatures, while yellow indicates the average high and low temperatures. The red line represents the mean temperature, and the grey area denotes the comfort zone, defined as the Acceptability Limit at 80%. Additionally, recorded high and low monthly temperatures are depicted as small circles above and below the coloured bars.

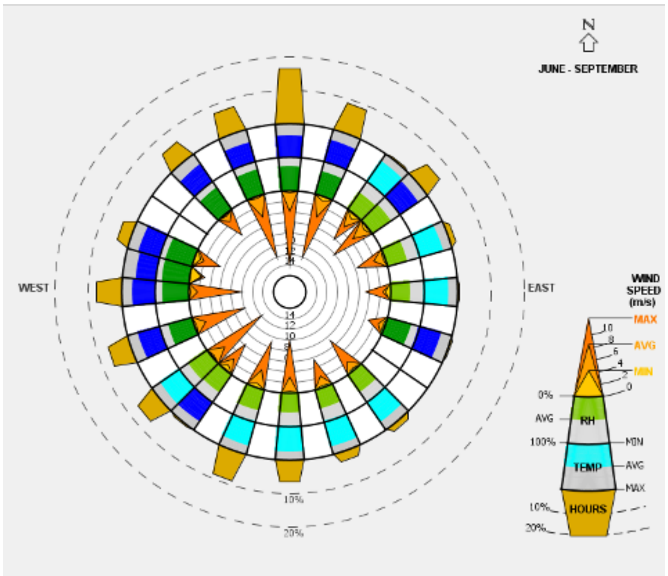


Figure 30: Wind rose diagram.

The circular wind rose diagram in Figure 30 for Szombathely illustrates the wind patterns observed from June to September, providing valuable insights into local climatic conditions. The analysis reveals several key features regarding wind direction, speed, and overall patterns. In terms of wind direction, the predominant flow comes from the North-Northwest (NNW), with significant contributions from the North (N) and Northwest (NW). Conversely, winds originating from the South and Southeast directions are notably less active, indicating a regional preference for northerly winds during summer. Wind speed is represented through a colour-coded system on the chart, ranging from calm conditions (white) to speeds exceeding 19 km/h (orange). The data indicates that the most frequent wind speeds fall within the lower to moderate range, as seen in the green and blue segments. Higher wind speeds, represented by the orange segments, are less common but still noticeable, particularly from the northern directions.

The length of each spoke in the wind rose correlates with the frequency of winds emanating from that direction. The NNW direction boasts the longest spokes, signifying it as the most frequently observed wind direction during this period. Concentric circles around the wheel display percentages (5%, 10%, 15%), illustrating the relative frequency of winds from each direction. Calm periods, characterised by wind speeds below 2 km/h, are located at the centre of the wheel. While the exact percentage of these quiet periods is not explicitly detailed, it appears relatively low, suggesting that breezy conditions are more common.

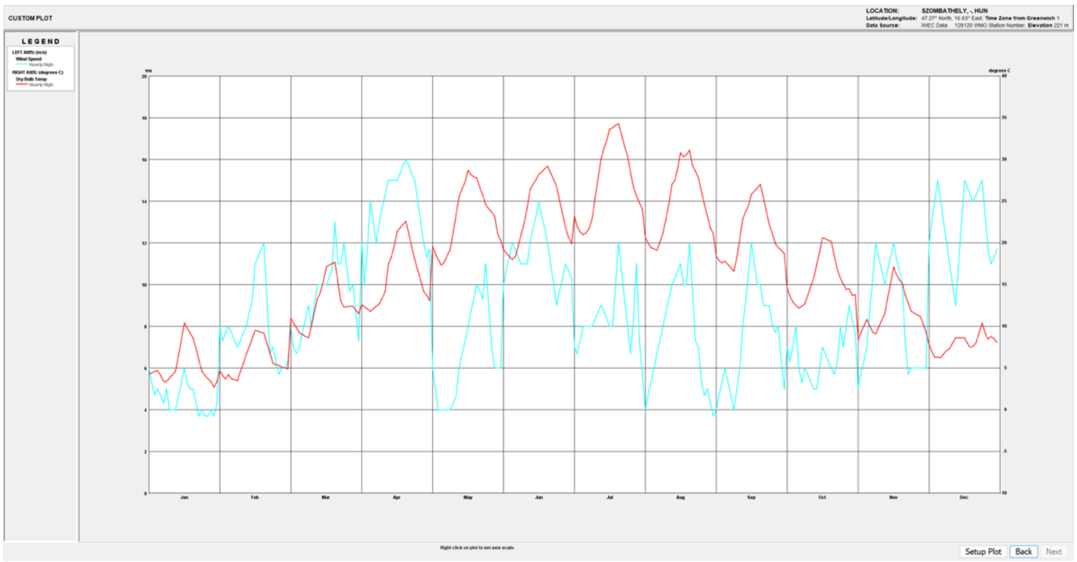


Figure 31: Course of temperature (red line) and wind SPEED (blue line) in Szombathely, hourly high data.

During the summer months of June to September, Szombathely experiences its warmest period, characterised by distinct temperature and wind velocity patterns. Temperatures peak in July, reaching approximately 34°C, with August showing similar highs around 31°C. June and September are comparatively cooler, with peaks of 29°C and 27°C respectively. A noticeable diurnal pattern emerges during these months, with higher temperatures during the day and cooler conditions at night, reflecting the typical daily heating and cooling cycle shown in Figure 31.

Wind velocity remains relatively steady during this period, averaging 2 to 4 m/s. While there are minor fluctuations, the overall trend is stable, with wind speeds slightly lower compared to the winter months. These stable wind conditions, combined with the pronounced diurnal temperature variations, provide important insights into the summer climatic behaviour in Szombathely, which is critical for understanding NV potential and thermal comfort during this season.

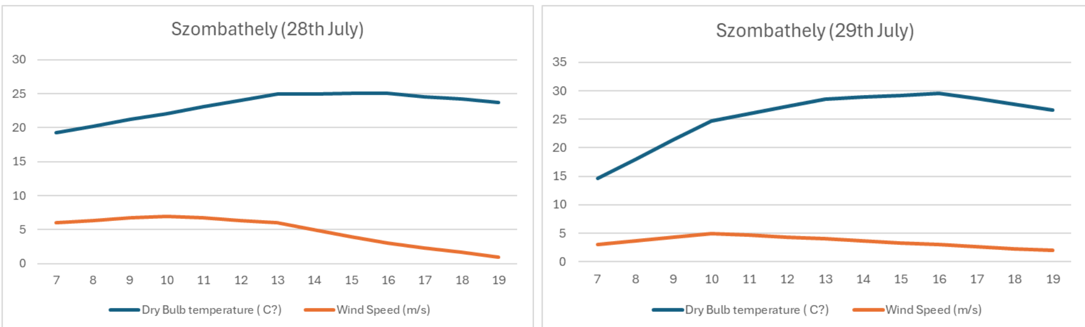


Figure 32: 28th and 29th diurnal pattern in Szombathely.

To identify the pattern for a specific day in Szombathely, the diurnal course of dry bulb temperature (°C) and wind speed (m/s) in Szombathely for two consecutive days, 28th and 29th July, is extracted and illustrated through the following analysis shown in Figure 32.

On 28th July, the dry bulb temperature gradually rises from early morning, starting at 7:00 AM. It peaks between 1:00 PM and 3:00 PM, where it remains relatively steady. After 3:00 PM, the temperature begins to decrease, reflecting the cooling effect of the evening. The wind speed is initially low in the morning, then increases to a peak around mid-morning to noon. Following this peak, the wind speed steadily declines in the afternoon and evening, suggesting calmer conditions as the day progresses. On 29th July, the temperature follows a similar pattern to 28th July, starting low in the morning and peaking between noon and 2:00 PM before declining in the evening. However, the peak temperature on 29th July is slightly higher than the previous day. Wind speeds on 29th July are generally lower compared to 28th July. While there are minor fluctuations, the wind speed increases slightly during the late morning before steadily decreasing throughout the afternoon and evening.

In comparison, both days exhibit typical summer diurnal temperature variations, with the temperature peaking in the early afternoon and declining in the evening. However, the maximum temperature on 29th July is slightly higher than on 28th July. Wind speeds on 29th July are consistently lower than those on 28th July. This reduction in wind speed may contribute to a higher perception of thermal discomfort on 29th July, as reduced air movement limits the cooling effects of the wind.

4.3.2 Natural Ventilation (NV) Design Guidelines by Climate Consultant 6.0

Table 8: Design guideline for NV by climate consultant 6.0.

Guideline category	Design guideline	Description	Figure reference
Ventilation and air movement	Window orientation	Shades windows and face them toward breezes to reduce AC use.	Figure 33
	Stack ventilation	Increase vertical space between air inlets and outlets.	Figure 34
	Cross ventilation	place windows and doors on opposite sides for airflow	Figure 35
	Ceiling fans	use fans to enhance cooling and lower AC needs.	Figure 36
Outdoor and transitional spaces	Shaded area	Create shaded outdoor areas aligned with breezes.	Figure 37
	Screened spaces	use screens for cooling and insect protection.	Figure 38
	Ventilated attics	Use pitched roof to manage rain and protect areas.	Figure 39
Building layout	Elevated design	Raise the building to improve airflow and reduce dampness.	Figure 40
	Open interiors	Design open layouts for better air movement.	Figure 41
	High ceilings	Incorporate high ceiling and tall windows for ventilation.	Figure 42
Heat management	Landscaping	Plant trees on the west side to block heat gain.	Figure 43
	Roof overhangs	Use wide overhangs on roofs to manage heat.	Figure 44
	Window overhangs	Design shades to limit heat gain and reduce AC use.	Figure 45
Daylight and glazing	Minimize west glazing	Reduce west facing windows to limit afternoon heat gain.	Figure 46

In architectural design, optimising NV is essential for creating sustainable and energy-efficient buildings, especially in regions like Szombathely that experience four distinct seasons. NV utilises the movement of outdoor air to regulate indoor temperatures, improve air quality, and reduce reliance on mechanical cooling and heating systems. The guidelines in Table 8 are tailored specifically to Szombathely's climate conditions, derived from an analysis of the EPW data for Szombathely. This data provides detailed information on temperature, humidity, wind patterns, and other climatic factors. Climate Consultant 6.0 processes this data to create recommendations that align with Szombathely's seasonal variations, particularly addressing the extreme summer conditions. These tailored guidelines help architects and designers develop strategies to optimise NV, such as determining the ideal placement of openings, selecting suitable materials and integrating shading devices to maintain indoor comfort effectively.

Figures 33 to 46, generated using Climate Consultant 6.0, illustrate Szombathely's climatic conditions and corresponding NV strategies. These figures visually support the guidelines derived from the analysis, offering actionable insights that ensure the architectural design aligns with Szombathely's unique climate profile.

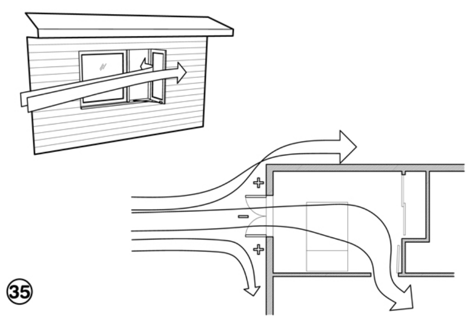


Figure 33: Design guideline 35.

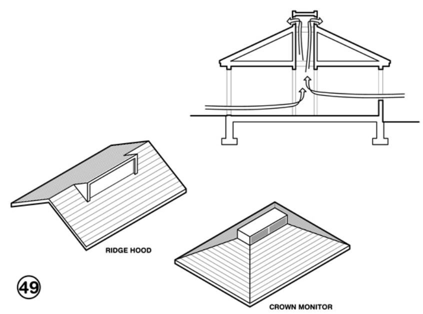


Figure 34: Design guideline 49.

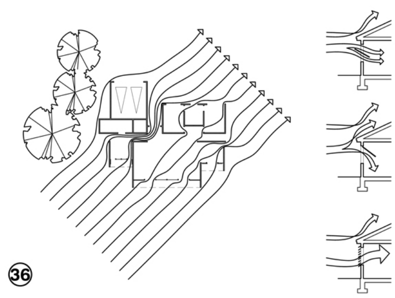


Figure 35: Design guideline 36.

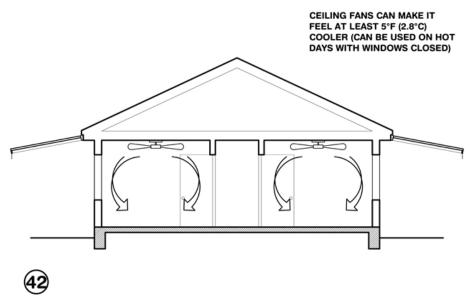


Figure 36: Design guideline 42.

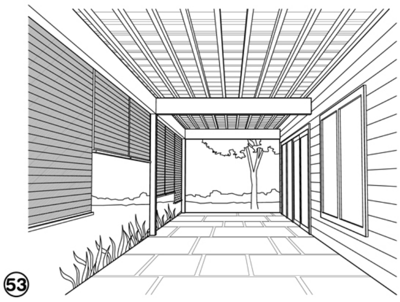


Figure 37: Design guideline 53.

Figure 38: Design guideline 56.

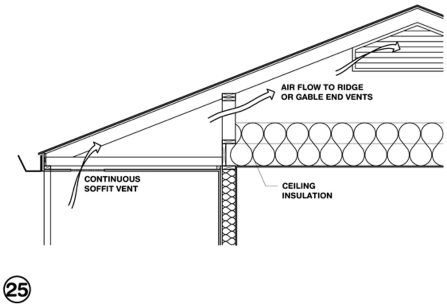


Figure 39: Design guideline 25.

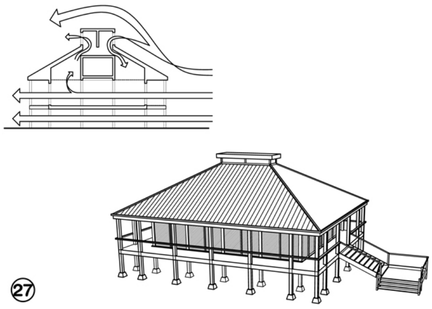


Figure 40: Design guideline 27.

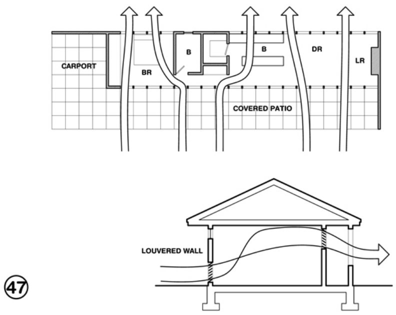


Figure 41: Design guideline 47.

Figure 42: Design guideline 65.

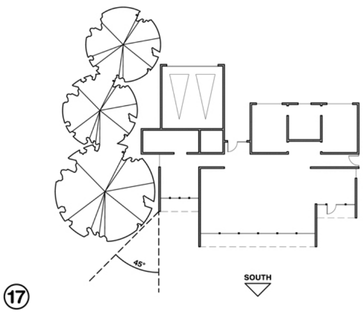


Figure 43: Design guideline 17.

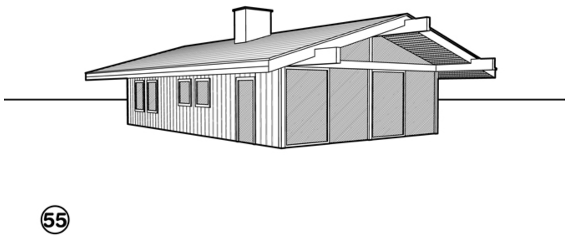


Figure 44: Design guideline 55.

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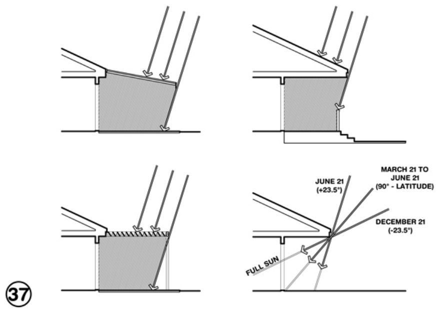


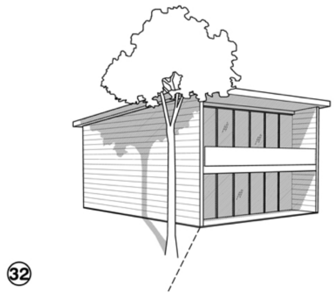


Figure 45: Design guideline 37.

Figure 46: Design guideline 32.

4.4 CFD Simulations Results

This section on CFD simulation results provides a detailed analysis of airflow and temperature distribution in two different climates, Johor and Szombathely, through simulations designed to test the effectiveness of woodcarving ventilation panels, fully opened vents, closed vents and mechanical ventilation under extreme conditions. The two models are identical in structure to ensure a consistent basis for comparison.

Figure 47 provides a side view of the models, detailing the dimensions of the external air volume: height (z) is 1289.112, width (x) is 3412.6, and depth (y) is 6700.589. This configuration accurately represents the air volume interacting with the models. Figure 48 illustrates the positioning of the external air volume, which is slanted at an angle of -22.5 degrees from the z-axis. This specific orientation is designed to represent that air is typically not perpendicular in real-world conditions, offering insights into how angled airflow dynamics influence the models in both climates.

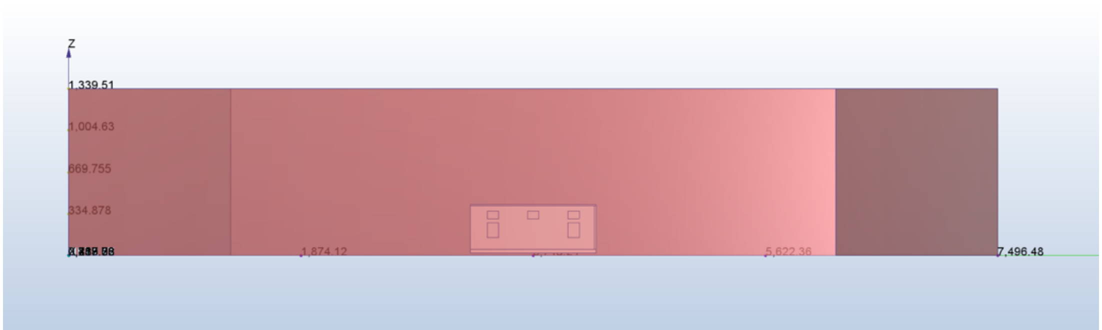


Figure 47: Side view of the model in CFD Autodesk.

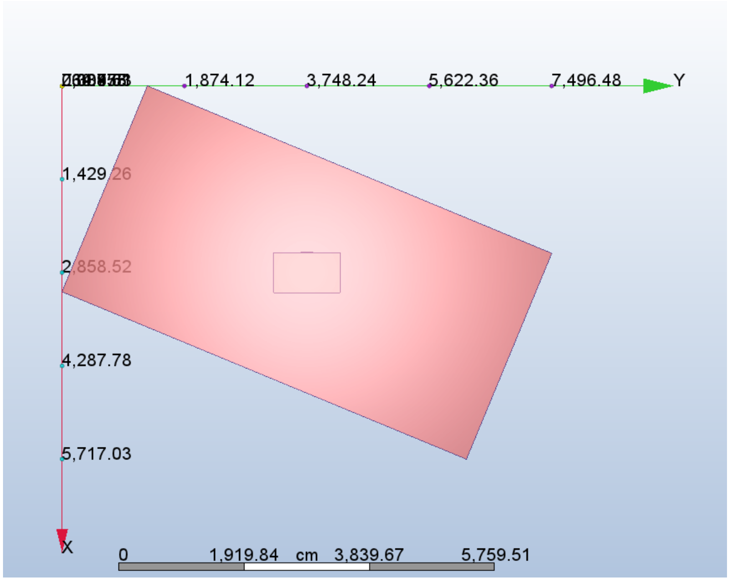


Figure 48: Top view with the external air volume.

Boundary conditions for the geometry were carefully configured to simulate realistic environmental conditions. Figure 49 and Figure 50 show that the highest conditions for both scenarios were set: 7 m/s windspeed and 32 °C temperature for Johor and 14 m/s for 34 °C Szombathely. The steady-state CFD simulations were designed to assess worst-case scenarios using extreme temperature and wind conditions for Szombathely. These conditions represent prolonged environmental effects, ensuring the analysis identifies potential limitations in ventilation performance under adverse weather. The pressure boundary condition was set to 0, represented by the colour orange in Figure 49. To account for heat transfer, the film coefficient of 20 W/m2/K was applied to all external surfaces of the building, marked in green. In Figure 50, a total heat generation of 60W was assigned to the human figures in both scenarios, as indicated by brown. These boundary settings ensure that the simulations accurately reflect the interaction between environmental factors and the models, providing insights into their thermal and airflow performances.

The steady-state fluid flow and thermal analyses provide conditions that represent equilibrium states achieved after an extended period under prescribed boundary conditions. However, the boundary conditions used in the simulation models for both Szombathely and Johor sites represent extreme scenarios that occur only for a few hours, following prolonged cooler conditions before daily temperature peaks, and heat abstraction by floors and outer walls was incorporated.

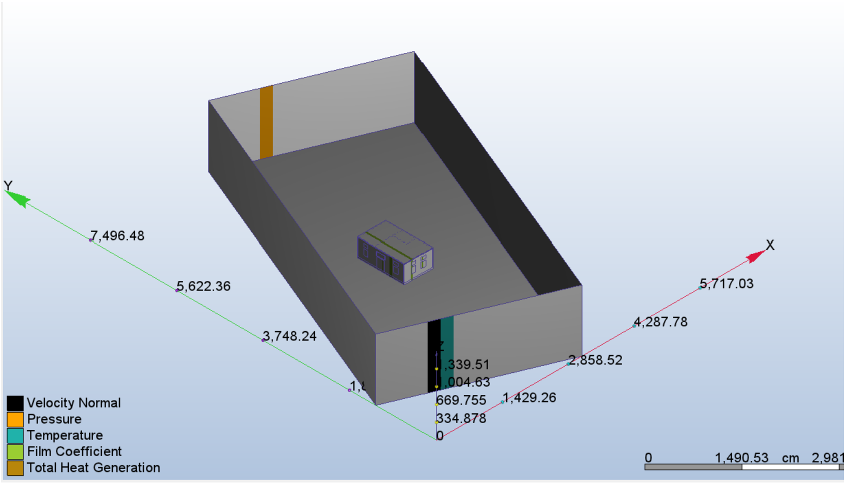


Figure 49: Boundary conditions.

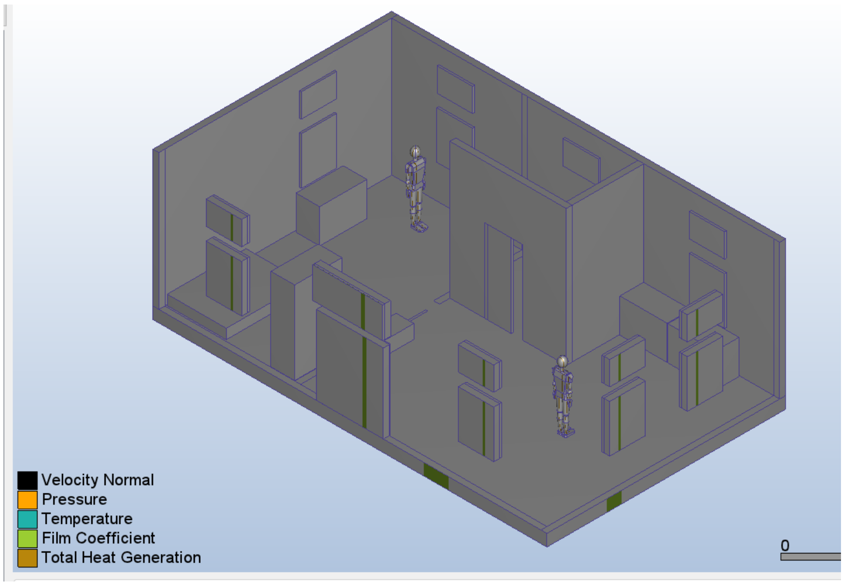


Figure 50: Human figures.

4.4.1 Flow and Temperature Distribution

This section presents a comparative analysis of airflow and temperature distribution patterns in Johor and Szombathely. These simulations provide insights into how local climatic conditions impact airflow dynamics and thermal comfort within buildings. The analysis focuses on how varying wind speeds, directions, and ambient temperatures influence airflow distribution and the resulting temperature gradients inside the buildings.

Table 9 compares the different ventilation strategies, including woodcarving ventilation panels, open vents, closed vents, and mechanical ventilation, in terms of their influence on airflow and temperature distribution.

Table 9: Comparison of indoor environmental conditions under different ventilation strategies.

Building type/ Location	Temp (°C) Near Humans	Velocity (m/s) Near Human 1	Velocity (m/s) Near Human 2
Woodcarving Panels – Johor	28 – 29.7	0-0.656	0-0.375
Woodcarving Panels – Szombathely	32-32.75	0-0.9375	0-0.46875
Open Vents – Johor	31-32.1	0-0.9375	0-0.375
Open Vents – Szombathely	32-33.1	0-2	0-0.6
Closed vents – Johor	34.2-37	0-0.2	0-0.18
Closed vents – Szombathely	30-34.8	0-0.1	0-0.15
Mechanical Ventilation – Johor	28-31.1	0-0.3	0-0.3
Mechanical ventilation – Szombathely	29.5-33.3	0.1-0.28	0.1-0.28

In the house featuring woodcarving ventilation panels, the airflow around human figures in Johor, as seen in Figure 52 and Figure 52, exhibits a moderate temperature range of 24.8–29.7°C, with air velocities of 0–0.656 m/s near human 1 and 0–0.375 m/s near human 2. The air velocities are within the ASHRAE comfort range for airflow, yet the elevated temperature suggests a degree of discomfort. Szombathely's performance in Figure 54 and Figure 55 exhibits a comparable trend of elevated temperatures (32-32.75 °C) and augmented air velocities (up to 0.9375 m/s). The airflow is slightly more than in Johor; yet, the temperature remains elevated, suggesting that despite the augmented airflow, thermal comfort is inadequate. The inside temperature ranges from 31.4°C to 33.1°C, as depicted in Figure 53 in Johor and 32 to 34.25°C in Figure 56.

a)
b)

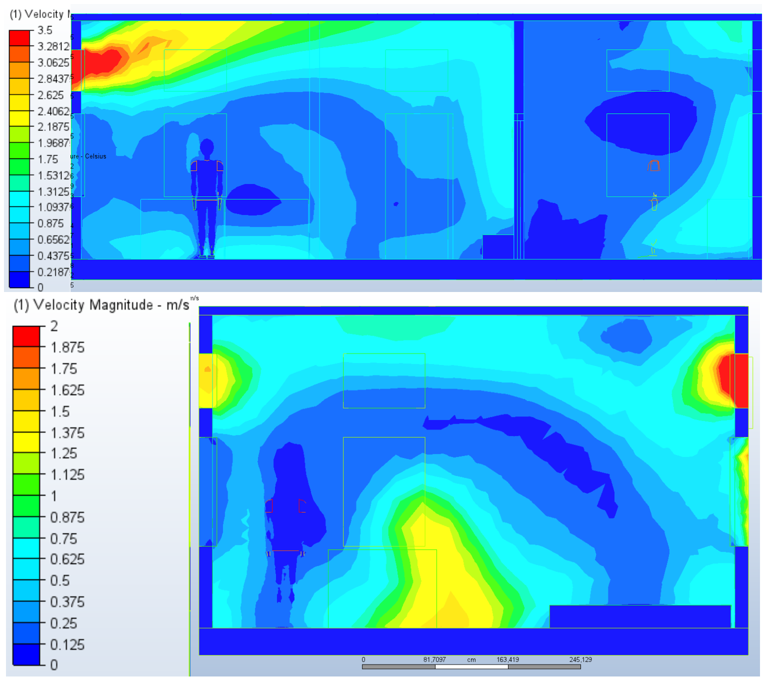


Figure 51: Flow velocity distribution for the house with woodcarving ventilation panels (Johor).

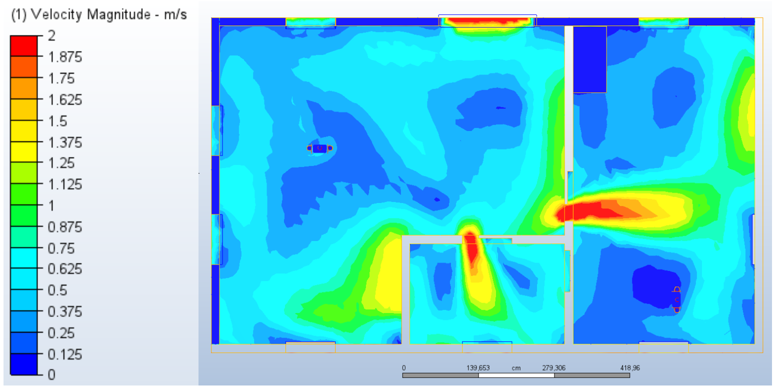


Figure 52: Flow velocity distribution for the house with woodcarving ventilation panels at the level of human height (Johor).

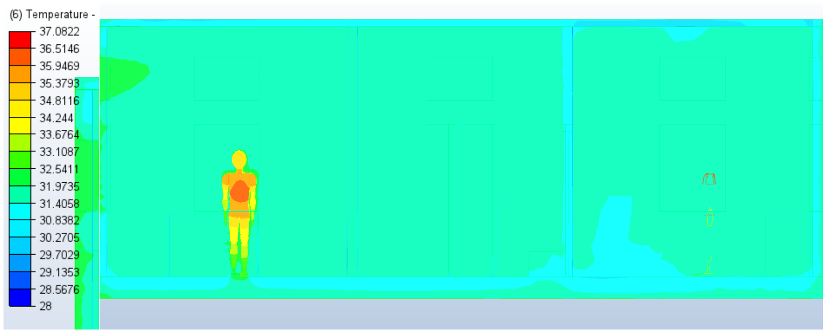
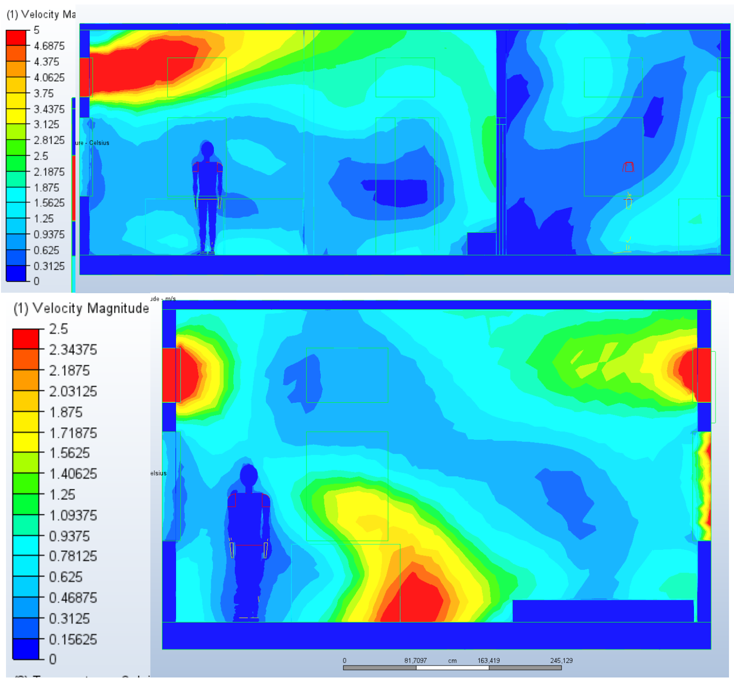


Figure 53: Temperature distribution for the house with woodcarving ventilation panels (Johor).

a)



b)

Figure 54: Flow velocity distribution for the house with woodcarving ventilation panels (Szombathely).

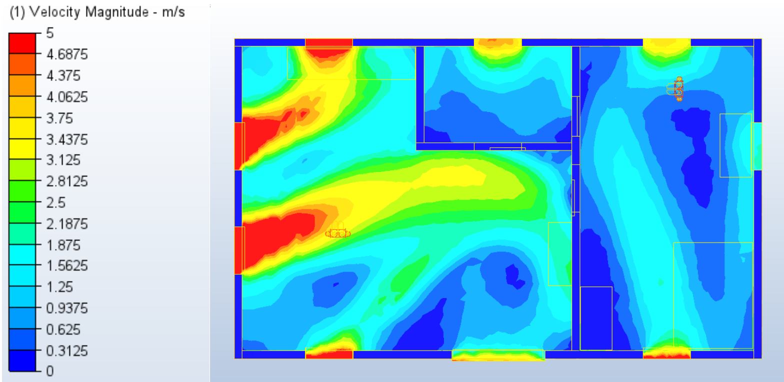


Figure 55: Flow velocity distribution for the house with woodcarving ventilation panels at the level of human height (Szombathely).

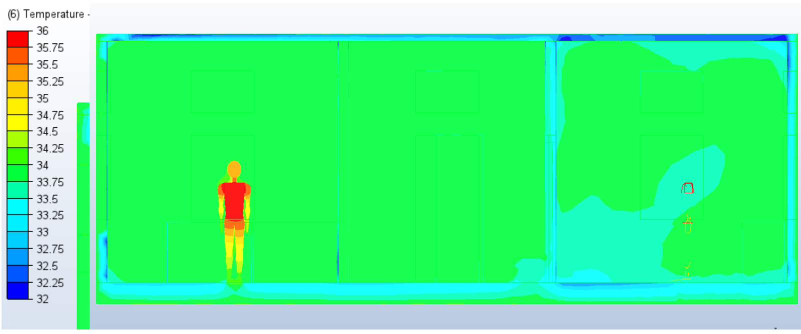


Figure 56: Temperature distribution for the house with woodcarving ventilation panels (Szombathely).

Open vents, while a common passive ventilation method, demonstrated inconsistent outcomes. In Johor, temperatures varied from 31 to 32.1°C, with airflow velocities ranging from 0 to 0.9375 m/s near Human 1 and from 0 to 0.375 m/s near Human 2, as shown in Figure 57 and Figure 58. This indicates that although the air exchange was efficient, it may cause localised pain due to inconsistent airflow. The interior temperature range in Johor is 31 to 32.4°C. Szombathely, however, recorded slightly elevated temperatures (32°C to 33.1°C) and markedly increased airflow velocities, reaching 2 m/s near Human 1 and 0.6 m/s near Human 2, as shown in Figure 60 and Figure 61. The increased velocity enhances ventilation but may exceed comfortable airspeed limits, leading to drafts and discomfort, especially in cooler temperate regions. The interior temperature range is from 32 to 34.7°C.

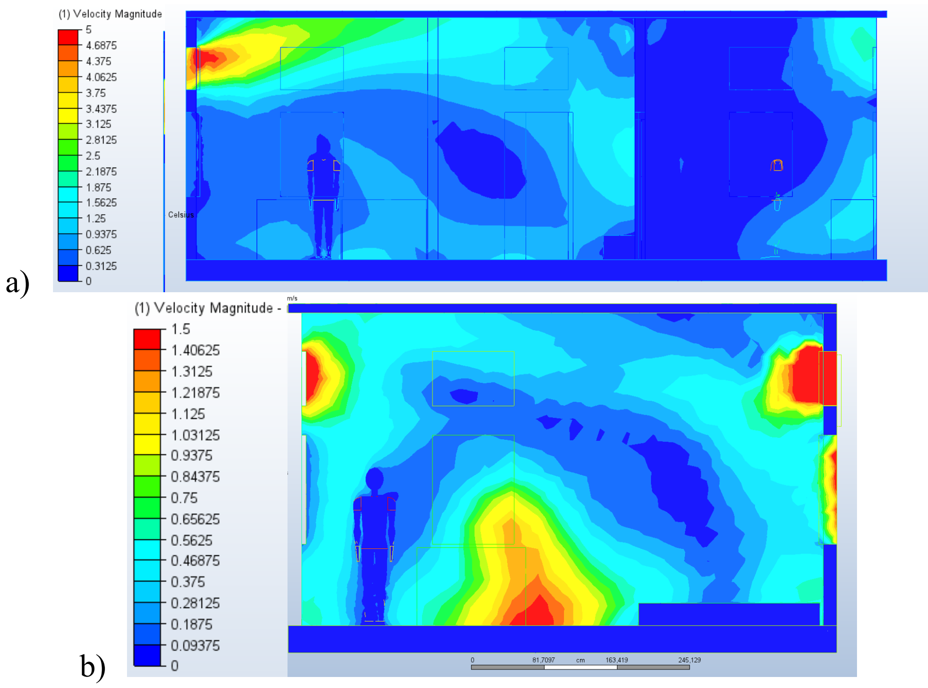


Figure 57: Flow velocity distribution for the house with opened vents (Johor).

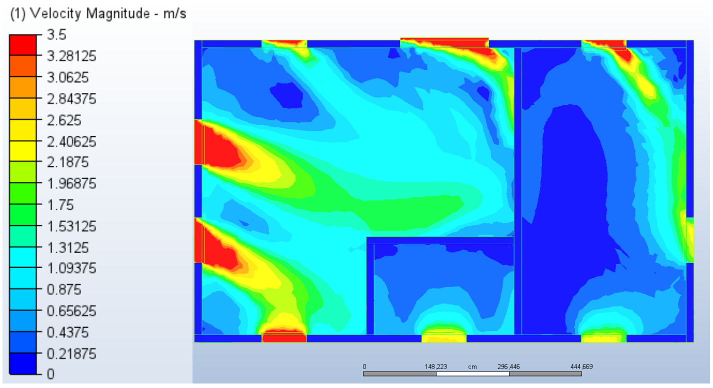


Figure 58: Flow velocity distribution for the house with open vents at the level of human height (Johor).

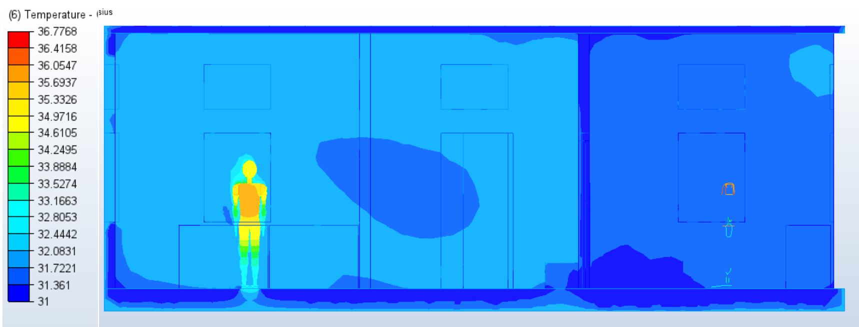


Figure 59: Temperature distribution for the house with opened vents (Johor).

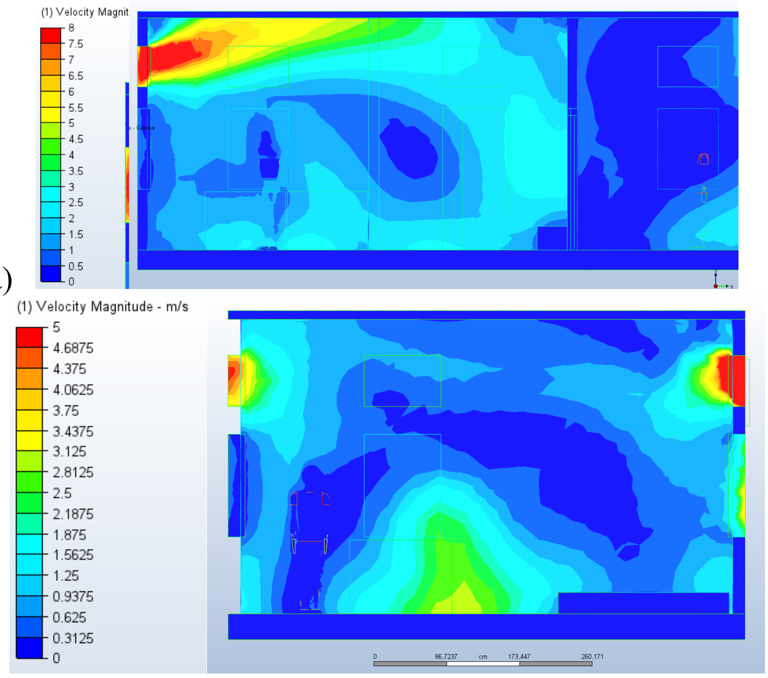
a)
b)


Figure 60: Flow velocity distribution for the house with opened vents (Szombathely).

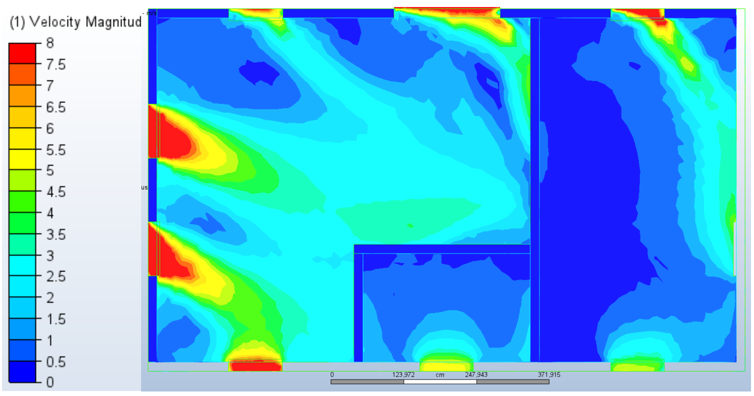


Figure 61: Flow velocity distribution for the house with open vents at the level of human height (Szombathely).

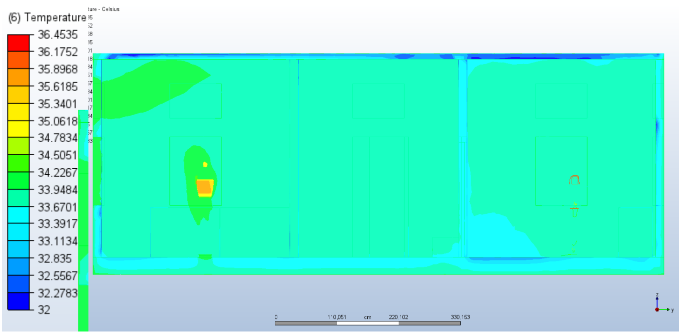


Figure 62: Temperature distribution for the house with open vents (Szombathely).

Conversely, closed vents significantly restricted ventilation in both places. Johor registered the highest indoor temperatures in this context (34.2°C to 37°C), accompanied by minimal air velocities of 0 to 0.2 m/s and 0 to 0.18 m/s shown in Figure 63 and Figure 64. Temperature ranges from 28-31.9°C in Johor's interior shown in

Figure 65. Szombathely in Figure 66 and Figure 67 exhibited comparably inadequate airflow, with temperatures ranging from 30°C to 34.8°C and negligible air movement (0 to 0.1 m/s near Human 1 and 0 to 0.15 m/s near Human 2). The data unequivocally demonstrate that closed vents obstruct natural ventilation, leading to heat accumulation and discomfort, especially during warm intervals. The interior temperature ranges from 30 to 34.3 °C in Figure 68.

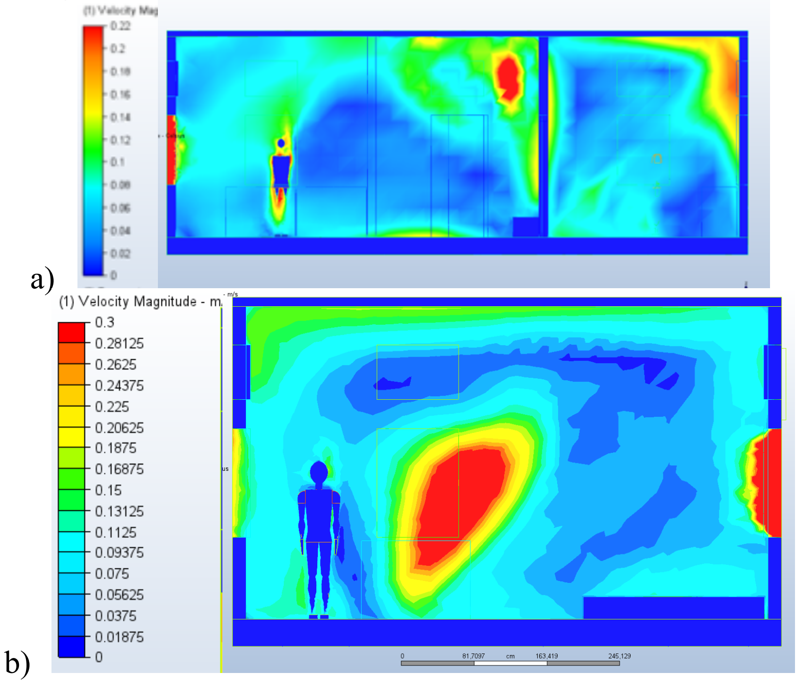


Figure 63: Flow velocity distribution for the house with closed vents (Johor).

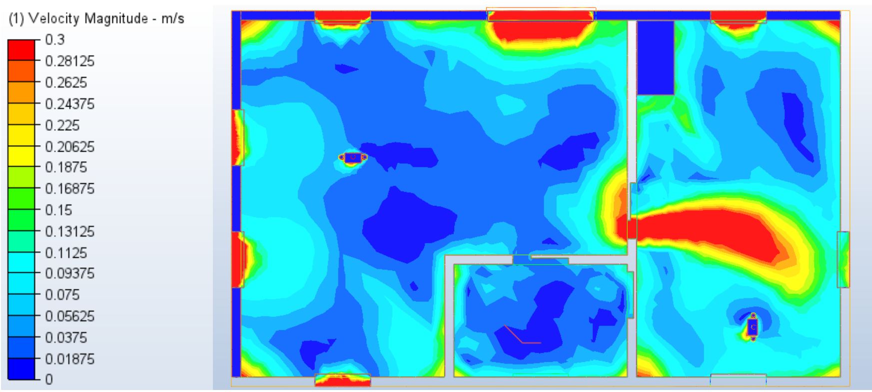


Figure 64: Flow velocity distribution with closed vents at the level of human height (Johor).

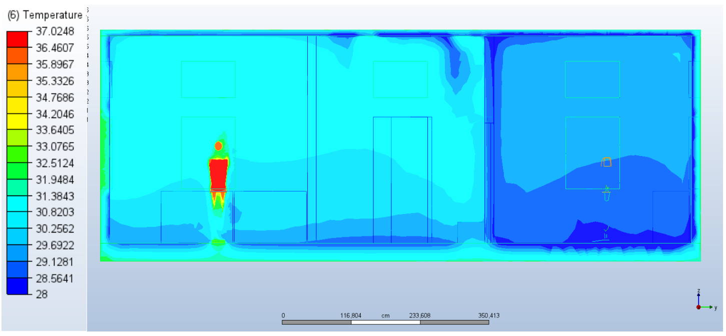


Figure 65: Temperature distribution for the house with closed vents (Johor).

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a)

b)

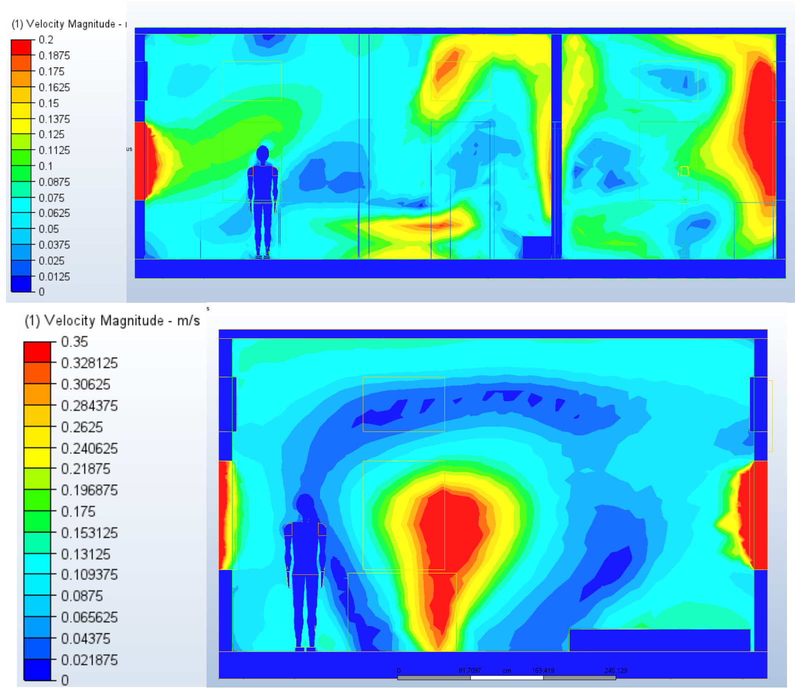

Figure 66: Flow velocity distribution for the house with closed vents (Szombathely).

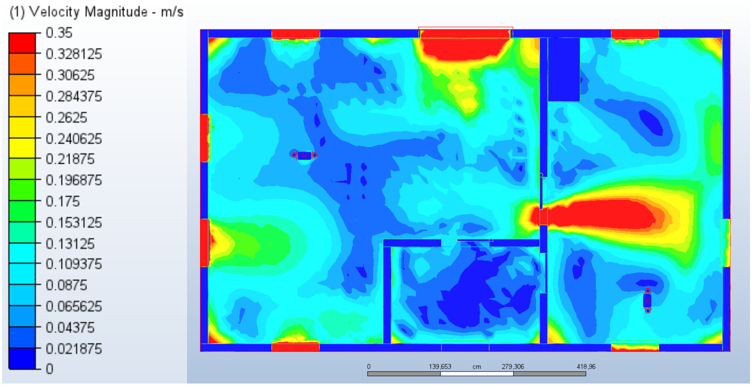

Figure 67: Flow velocity distribution for the house with closed vents at the level of human height (Szombathely).

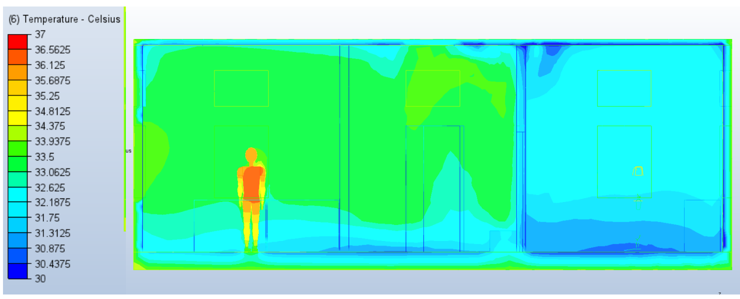

Figure 68: Temperature distribution for the house with closed vents (Szombathely).

Mechanical ventilation, frequently employed as a regulated alternative, exhibited mild heat conditions. In Johor, indoor temperatures were sustained between 28°C and 31.1°C, with airflow velocities limited to 0.3 m/s for both monitored occupants shown in Figure 69 and Figure 70 which is sufficient for ensuring satisfactory comfort but lacking the dynamic cooling effect characteristic of natural systems. The interior temperature is 30 °C in Figure 71. In Szombathely, mechanical systems produced indoor temperatures ranging from 29.5°C to 33.3°C, accompanied by a consistent airflow of 0.1 to 0.28 m/s in proximity to individuals shown in Figure 72 and Figure 73. Although these settings satisfy comfort criteria, mechanical ventilation does not possess the cultural and artistic integration characteristic of passive systems such as woodcarving panels.

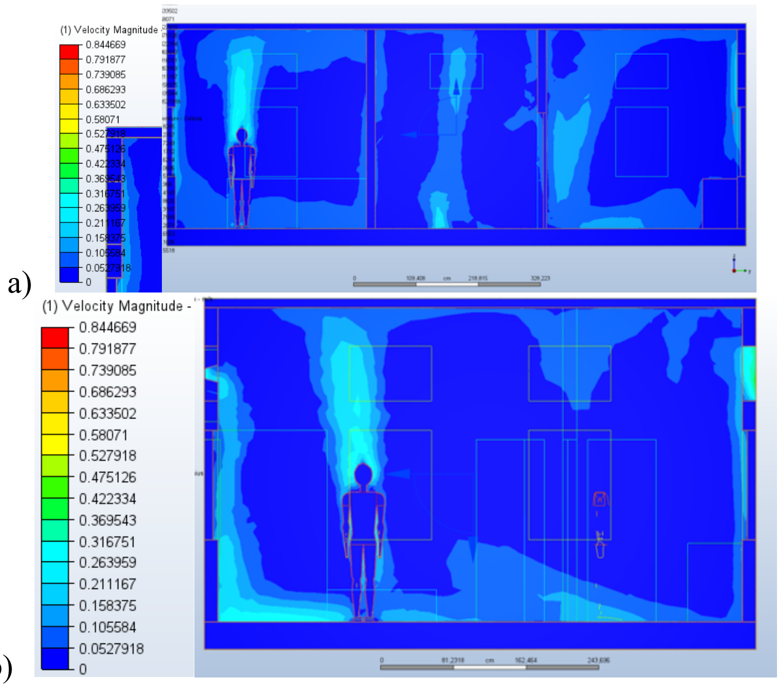

Figure 69: Flow velocity distribution with mechanical ventilation (Johor).

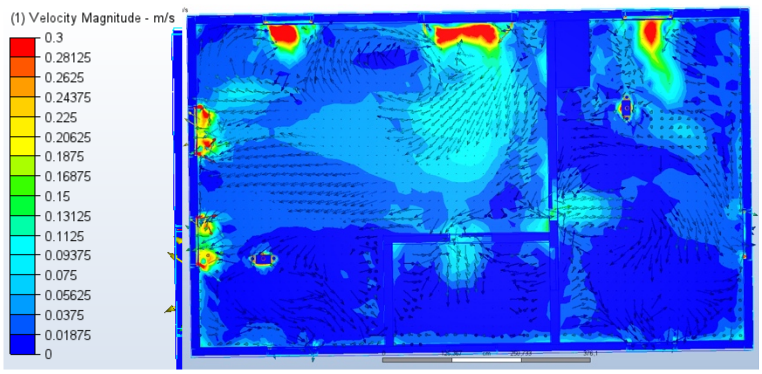

Figure 70: Flow velocity distribution for the house with mechanical ventilation (Johor).

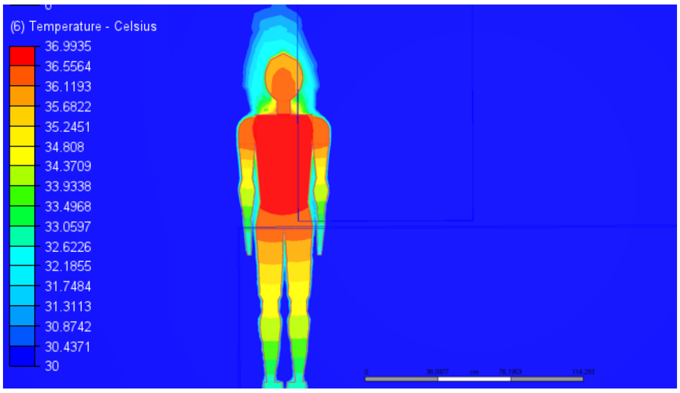

Figure 71: Temperature distribution for the house with mechanical ventilation (Johor).

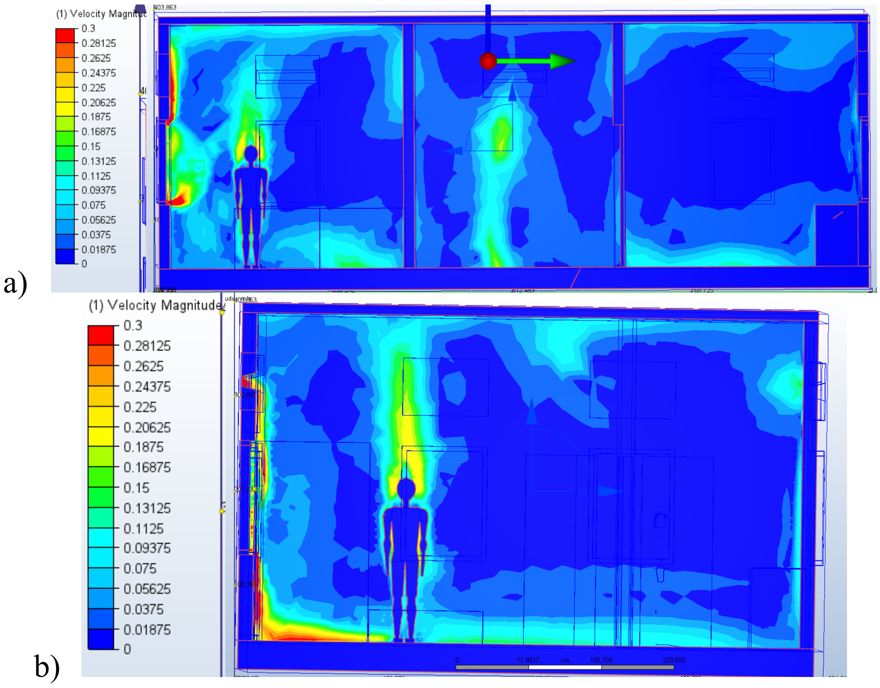

Figure 72: Flow velocity distribution for the house with mechanical ventilation (Szombathely).

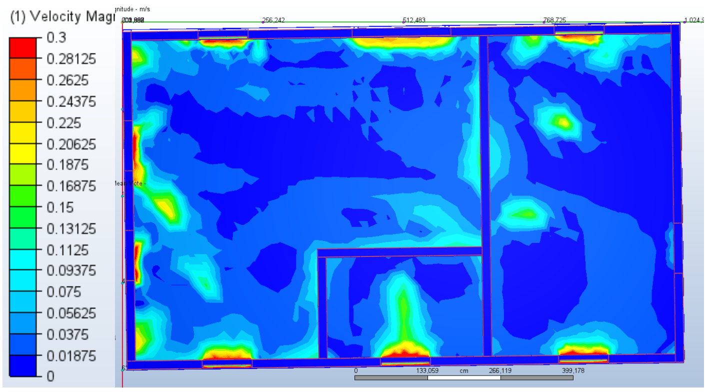

Figure 73: Flow velocity distribution for the house with mechanical ventilation (Szombathely).

While mechanical ventilation provides steady results, the research remains focused on understanding the potential of natural ventilation systems, particularly through

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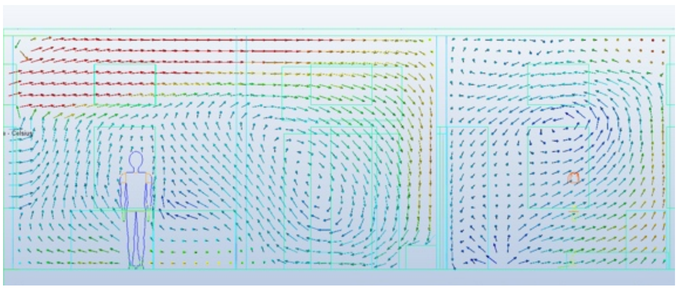
integrating woodcarving panels. As noted, the natural ventilation performance in both sites often reflect external climate variations, and although mechanical systems offer improved control, natural ventilation has the added benefit of reduced energy consumption and greater cultural benefits.

4.4.4 Flow dynamics and Air circulation

The airflow patterns between Johor and Szombathely, analysed with the presence of woodcarving ventilation panels, reveal several similarities but also notable differences influenced by the distinct climatic conditions of each location. In both locations, the wind enters through the ventilation panels situated near the ceiling, creating horizontal airflow that moves across the upper portion of the rooms shown in a) and b) in Figure 74. This strong wind path beneath the ceiling ensures that airflow is effectively channelled at higher altitudes in both settings. As the air enters, it disperses downward, leading to the formation of circular vortexes in the central areas of the rooms, particularly around the occupants. However, the key difference between the two locations is the size and intensity of these airflow features. Figure 75 shows the airflow velocity vectors on a horizontal plane at approximately human height. Air enters through the openings in the walls, particularly the intricately carved panels, creating multiple zones of air circulation within the interior. The airflow disperses across the rooms, forming several distinct vortex patterns that demonstrate effective natural ventilation. In the central space, a pronounced circular air movement is observed, facilitating even distribution of air across the room. Adjacent rooms also exhibit swirling flow patterns, though with variations in speed and circulation intensity. These vortex formations suggest the presence of a well-mixed indoor environment that promotes thermal comfort through air movement.

In Szombathely, the arrows representing airflow are closer together, indicating a more focused and concentrated wind flow. This could be attributed to higher wind speeds or the design of the ventilation panels, which might have smaller openings, creating a more concentrated wind path. Additionally, the circular vortexes in Szombathely are smaller compared to those in Johor. This could result from lower wind speeds or more compact room configurations in Szombathely, leading to a more constrained recirculation of air. While Johor experiences larger vortices with broader circulation patterns, Szombathely's airflow is more concentrated in both a) and b) Figure *76* as well as in Figure *77*, contributing to smaller recirculation zones. Both regions show higher wind velocities near the upper left inlet. Still, in Szombathely, the velocity decrease toward the central and right sections of the room is more gradual and less pronounced. In contrast, Johor experiences more noticeable reductions in airflow near the floor, possibly due to physical obstructions or thermal stratification.

a)



b)

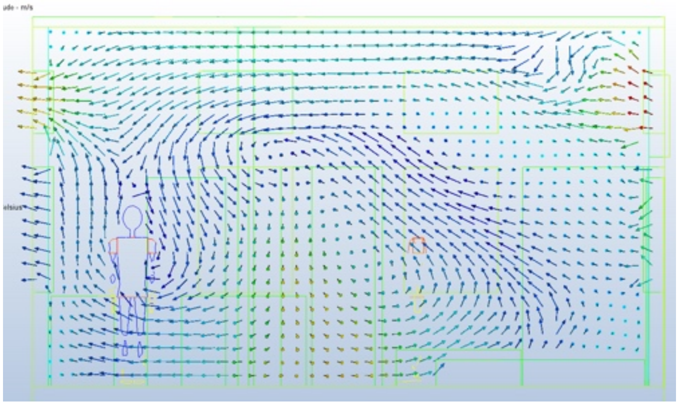


Figure 74: Vertical airflow and circulation patterns in the house with woodcarving ventilation panels (Johor).

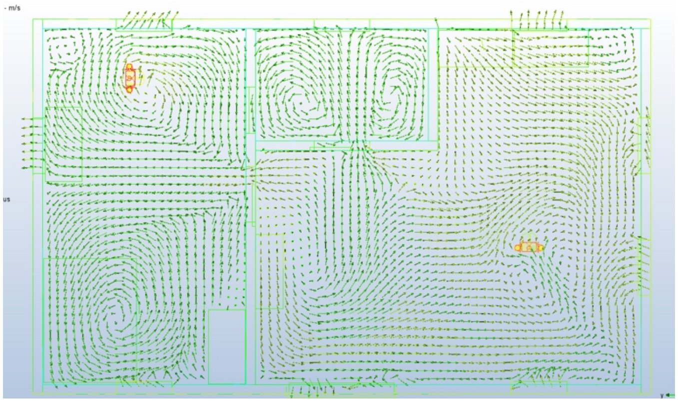
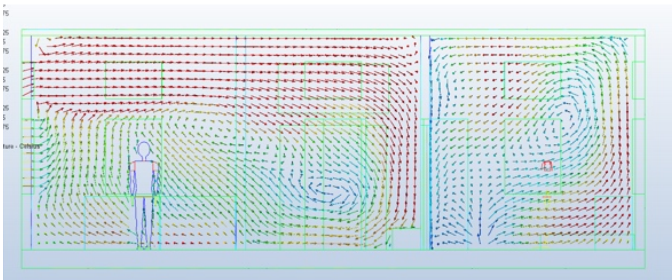


Figure 75: Horizontal airflow and circulation patterns in the house with woodcarving ventilation panels at the level of human height (Johor).

a)



b)

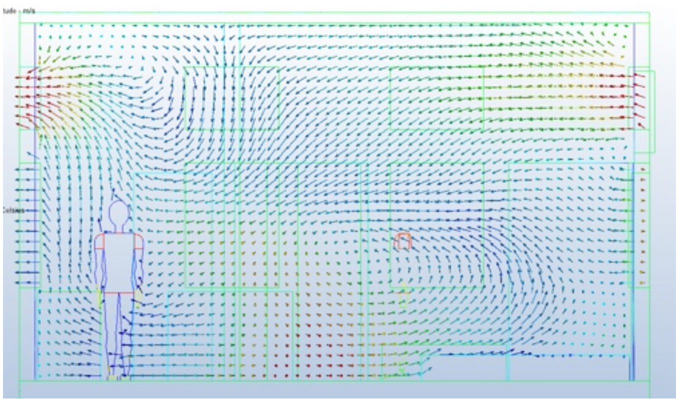


Figure 76: Vertical airflow and circulation patterns in the house with woodcarving ventilation panels (Szombathely).

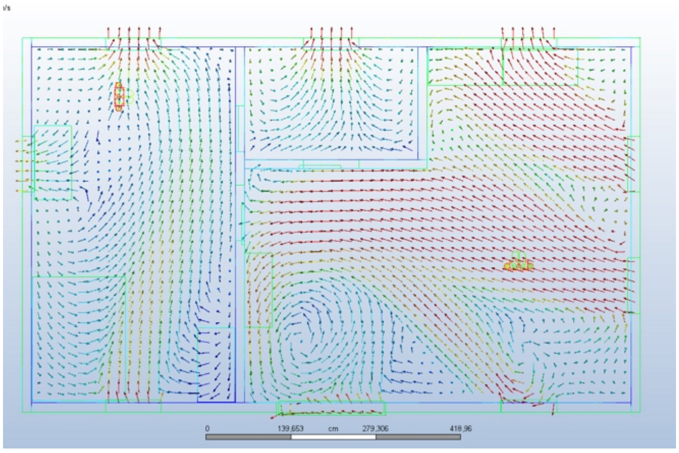
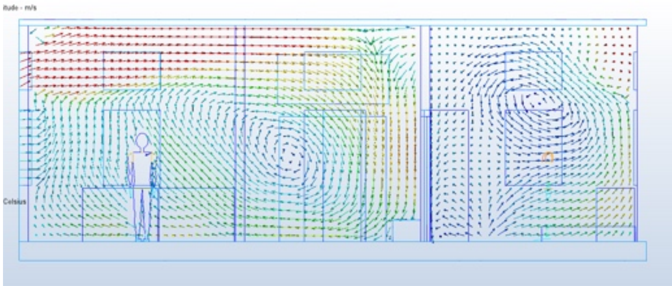
c) 

Figure 77: Horizontal airflow and circulation patterns in the house with woodcarving ventilation panels at the level of human height (Szombathely).

In buildings with open ventilation panels, both Johor and Szombathely exhibit a similar wind entry pattern, where air flows through the carved vents, creating distinct entry points for cross-ventilation. In both cases, the primary airflow moves horizontally across the upper section of the room, as shown in a) and b) Figure 78, driven by external wind entering through the upper wall openings. However, the intensity and distribution of this airflow differ between the two locations.

In Johor, the airflow appears more diffuse, with velocity vectors spread across the upper part of the room. While the wind is relatively strong, it is mostly concentrated at higher altitudes and gradually weakens as it moves further into the interior. This results in limited penetration of airflow toward the lower regions of the space. The horizontal plane visualisation in Figure 79 confirms that airflow is well-distributed throughout the house, with no obvious stagnant areas.

Conversely, in Szombathely, shown in a) and b) Figure 80, demonstrates a more concentrated and focused wind flow. The airflow vectors appear thicker and more densely packed, indicating stronger and more directed air movement. In this case, the airflow reaches down to floor level, allowing for more uniform distribution of air throughout the entire interior volume, including the occupied zones near the ground. This may be attributed to Szombathely’s cooler, temperate climate, which enables more forceful and sustained airflow. The tighter spacing of the vectors near the entry points also suggests that wind in Szombathely is more concentrated upon entry, contributing to a more effective and consistent air circulation pattern. However, the horizontal plane in Figure 81, like Johor, reveals that the wind velocity is relatively high, which could lead to excessive air movement and potential discomfort for occupants.

a)


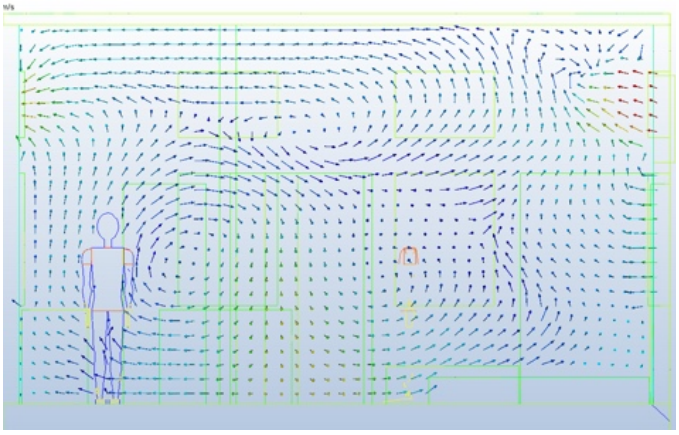
b)


Figure 78: Vertical airflow and circulation patterns in the house with open vents (Johor).

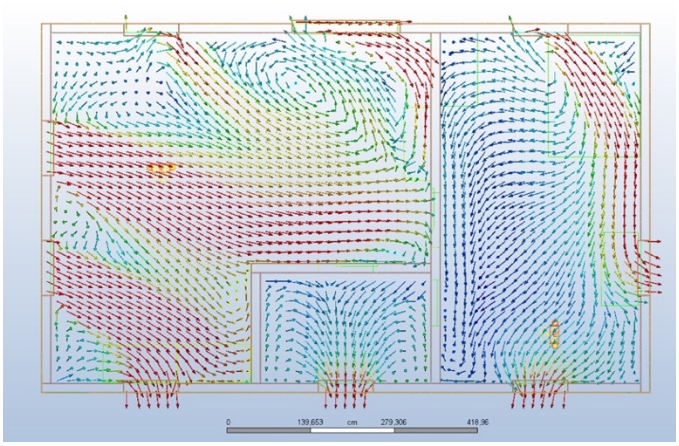


Figure 79: Horizontal airflow and circulation patterns in the house with open vents at the level of human height (Johor).

a)

b)

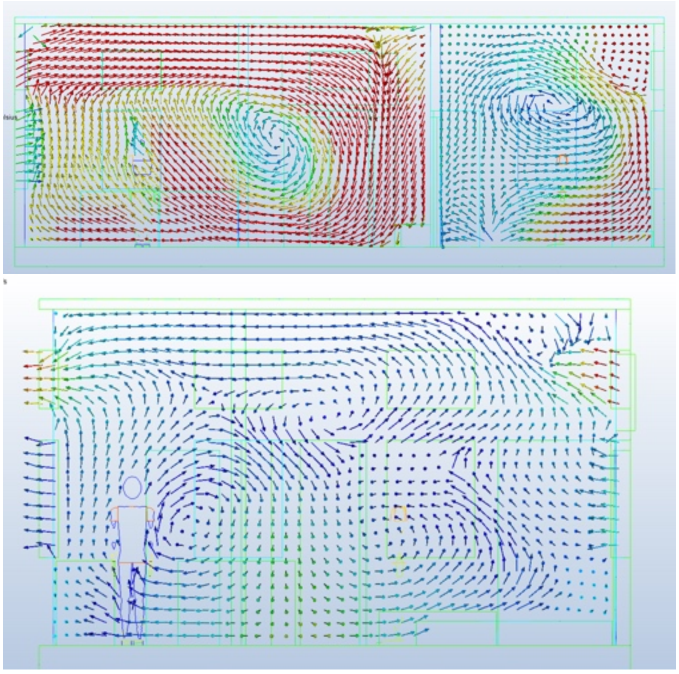


Figure 80: Vertical airflow and circulation patterns in the house with open vents (Szombathely).

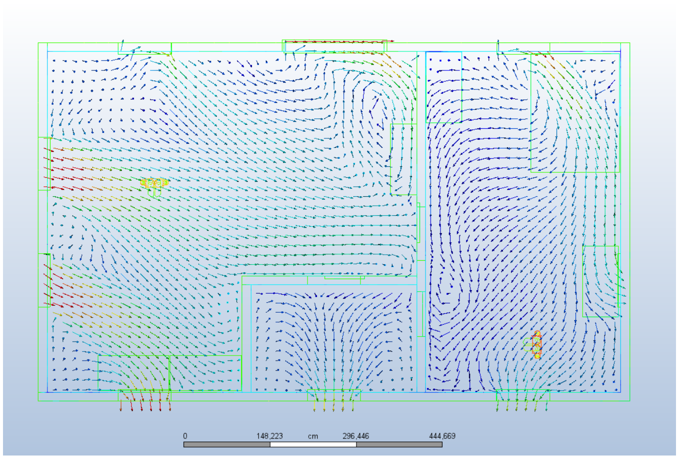
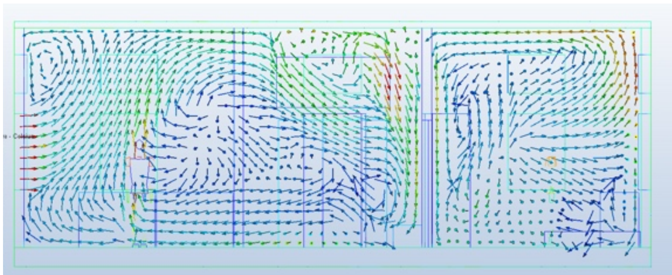


Figure 81: Horizontal airflow and circulation patterns in the house with open vents at the level of human height (Szombathely).

In buildings with closed vents, both Johor and Szombathely exhibit similar internal air circulation patterns; however, the airflow dynamics are influenced by the distinct climatic conditions of each location. In Johor, the closed-vent configuration results in prominent recirculation zones within each room, a) and b) in Figure 82. Major vortices are observed in isolated areas, with wind entering primarily through gaps in the windows, producing concentrated airflow at these localised entry points. In the upper regions of the room, where ventilation panels would typically be located, the airflow remains minimal. The highest airflow velocity occurs at the narrow openings between compartments, indicating that air is being funnelled through these transitional spaces. Conversely, low-velocity regions develop at the centres of the vortices, resulting in stagnation points where opposing flows converge, thus limiting effective air exchange between rooms.

Similarly, in Szombathely Figure 84 a) and b), the closed vents lead to airflow concentration near the available window gaps. However, as in Johor, the air struggles to move deeper into the interior spaces. The limited penetration of airflow, coupled with the formation of confined circulation loops, highlights the reduced effectiveness of natural ventilation in the absence of upper ventilation openings. The horizontal plane view for both locations in Figure 83 and Figure 85 further illustrates the limitations in airflow distribution. In both Johor and Szombathely, the airflow vectors appear sparse and stagnant, particularly at the central zones of the house. The arrows are relatively straight and aligned through the middle, indicating minimal turbulence or circulation. This linear and undisturbed flow suggests a lack of effective mixing, with limited air movement reaching the interior areas away from the windows. Consequently, extensive areas of the rooms remain inadequately ventilated, confirming the presence of stagnant air pockets and insufficient natural ventilation when vents are sealed.

a)



b)

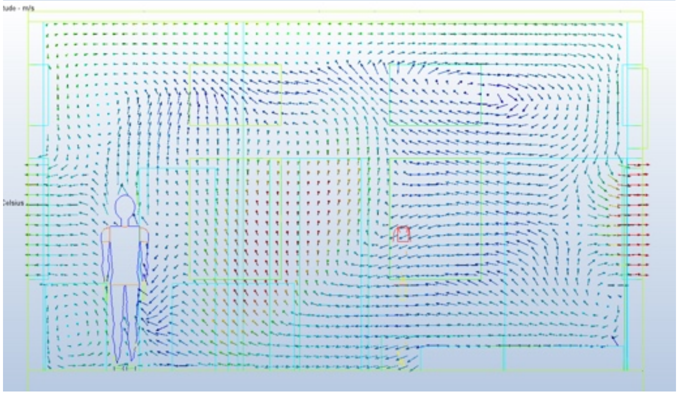


Figure 82: Vertical airflow and circulation patterns in the house with closed vents (Johor).

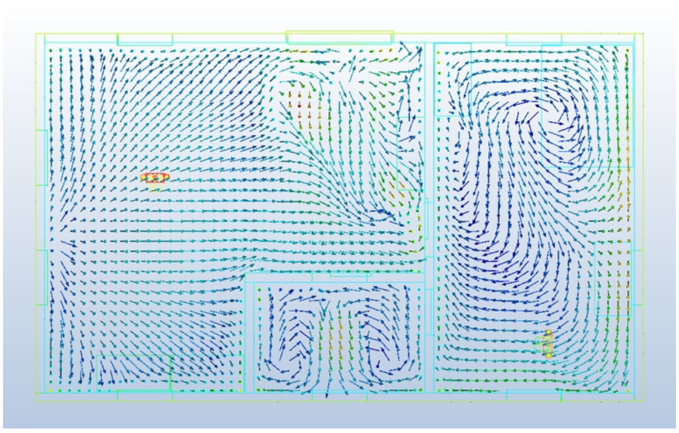


Figure 83: Horizontal airflow and circulation patterns in the house with closed vents at the level of human height (Johor).

a)

b)

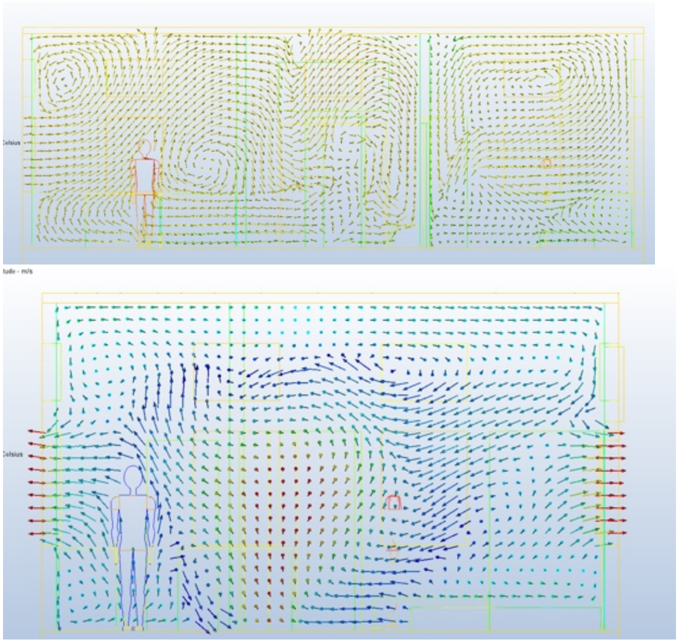


Figure 84: Vertical airflow and circulation patterns in the house with closed vents (Szombathely).

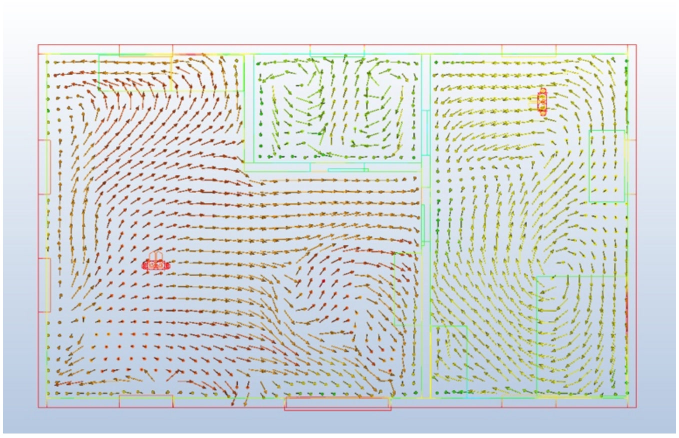
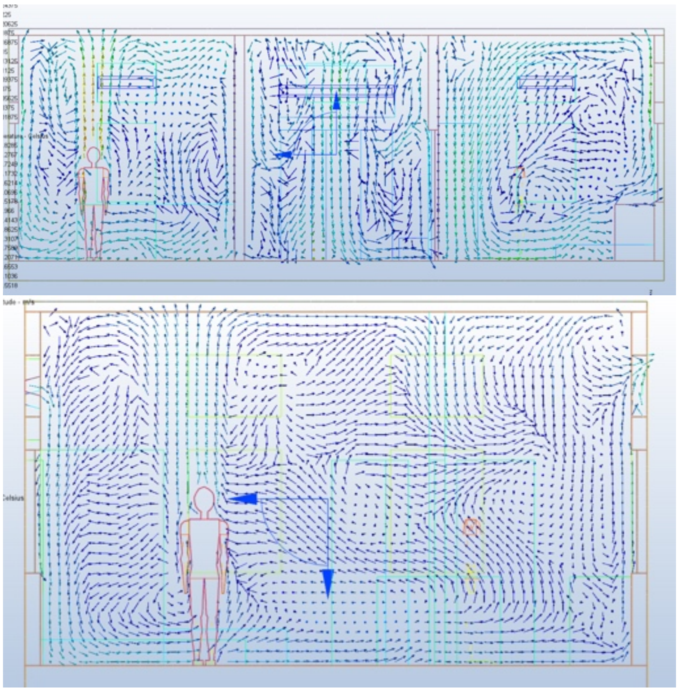


Figure 85: Horizontal airflow and circulation patterns in the house with closed vents at the level of human height (Szombathely).

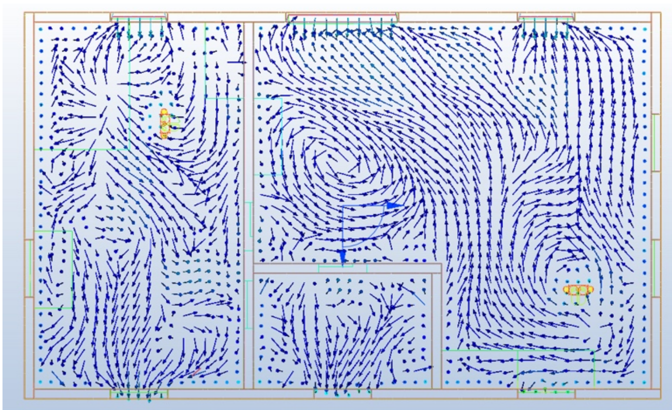
In both Johor and Szombathely, the mechanical ventilation systems facilitate excellent air mixing, as shown in the vertical a) and b) in Figure 86 and Figure 88, as well as in the horizontal planes in Figure 87 and Figure 89, near human-occupied areas. These systems enhance airflow dynamics, leading to more uniform air distribution throughout the space. The effective air mixing helps minimise stagnation zones and ensures consistent circulation across the entire interior. Consequently, ventilation efficiency is significantly improved in both locations, contributing to a more comfortable indoor environment.



a)

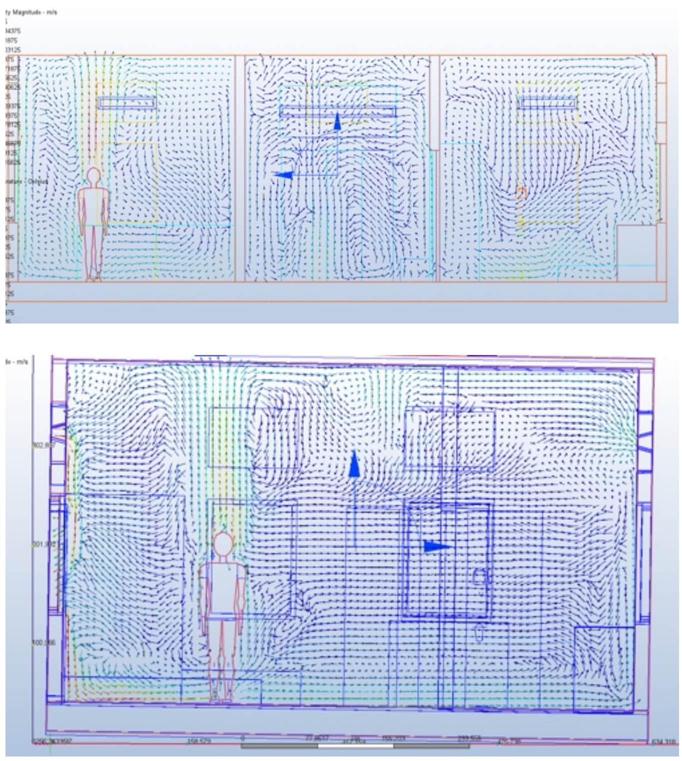
b)

Figure 86: Vertical airflow and circulation patterns in the house with mechanical ventilation (Johor).



c)

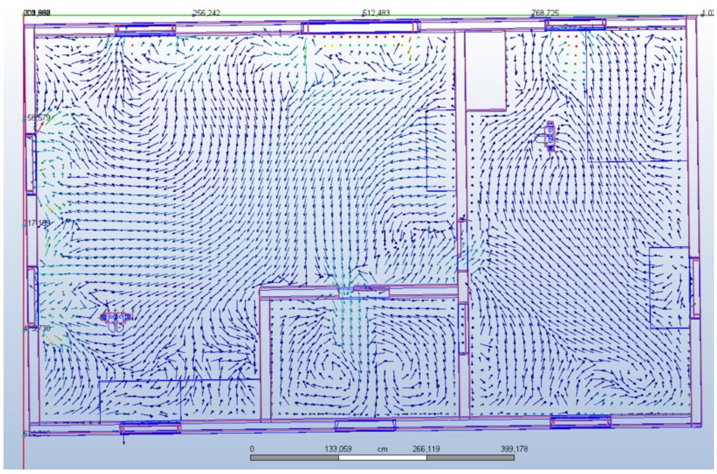
Figure 87: Horizontal airflow and circulation patterns in the house with mechanical ventilation at the level of human height (Johor).



a)

b)

Figure 88: Vertical airflow and circulation patterns in the house with mechanical ventilation (Szombathely).



c)

Figure 89: Horizontal airflow and circulation patterns in the house with mechanical ventilation at the level of human height (Szombathely).

4.4.3 Predicted Mean Vote (PMV)

The Predicted Mean Vote (PMV) is a widely recognised index used to evaluate thermal comfort based on the average thermal sensation of a group of people. This index uses a seven-point scale ranging from -3 (cold) to 3 (hot), where values closer to 0 represent thermal neutrality, and higher values indicate increased discomfort. Table 10 outlines the PMV values and their corresponding thermal sensations.

Table 10: Predicted Mean Vote (PMV) for thermal sensation.

Value	Sensation
-3	Cold
-2	Cool
-1	Slightly cool
0	Neutral
1	Slightly warm
2	Warm
3	hot

The PMV index is used to assess the thermal comfort level of building occupants. Table 11 provides a summary of PMV values for various scenarios across building types and locations.

Table 11: PMV in all scenarios.

Ventilation Type	Region	Human	Feet–Knee	Knee–Waist	Waist–Shoulder	Shoulder–Head
Woodcarving Panel	Johor	Human 1	2 – 2.8	2 – 3	2 – 3	2 – 2.8
		Human 2	2 – 2.8	2 – 3	2 – 3	2 – 3
	Szombathely	Human 1	2.9 – 3	2.9 – 3	2.9 – 3	2.9 – 3
		Human 2	3	3	3	3
Open Vents	Johor	Human 1	2.25 – 2.53	2.25 – 2.9	2.25 – 2.9	2.25 – 2.9
		Human 2	2.25 – 2.53	2.3 – 2.9	2.25 – 2.9	2.4 – 2.9
	Szombathely	Human 1	3	3	3	3
		Human 2	2.9 – 3	3	2.9 – 3	3
Closed Vents	Johor	Human 1	1.75 – 2.5	2.1 – 3	2.1 – 3	2.1 – 3
		Human 2	1.3 – 2	1.3 – 2.6	1.3 – 3	1.75 – 2.8
	Szombathely	Human 1	2.55 – 3	2.7 – 3	2.55 – 3	2.85 – 3
		Human 2	2.25 – 2.55	2.4 – 3	2.25 – 3	2.25 – 3
Mechanical Ventilation	Johor	Human 1	1.4 – 2.3	2 – 3	2.3 – 3	2.1 – 2.9
		Human 2	1.4 – 2.1	1.4 – 3	1.9 – 3	1.9 – 2.9
	Szombathely	Human 1	1.8 – 2.5	2.1 – 3	2.3 – 3	2.3 – 3
		Human 2	2.1 – 2.5	2.1 – 3	2.3 – 3	2.5 – 3

In Johor (Figure 90), the use of woodcarving ventilation panels resulted in PMV values ranging from 2 to 3, indicating a sensation of warm to slightly hot conditions throughout the body. Both Human 1 and Human 2 exhibited similar thermal profiles, with slightly higher PMV values recorded around the torso area (waist to shoulder), where readings reached up to 3. Despite these elevated values, woodcarving panels provided a more consistent thermal distribution compared to open vents.

In contrast, in Szombathely (Figure 91), the PMV values for both human models consistently ranged between 2.9 and 3 across all body parts. These values indicate hot thermal conditions, suggesting that woodcarving ventilation panels were less effective in mitigating indoor heat during the hot summer period in Szombathely. The lack of variation also reflects limited air movement, which contributes to reduced thermal comfort.

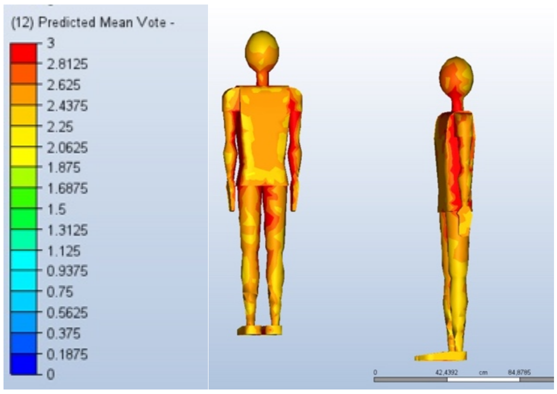


Figure 90: PMV value of human figure in the building with woodcarving ventilation panels (Johor).

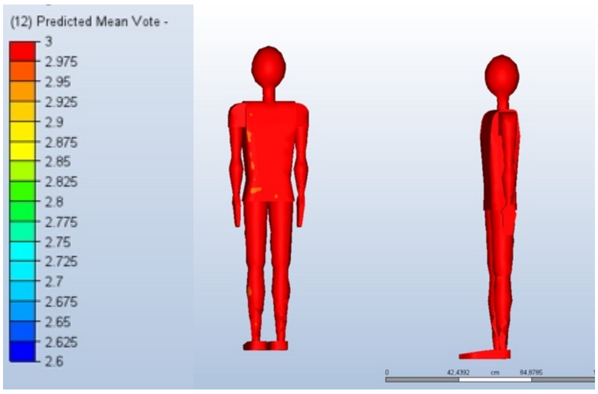


Figure 91: PMV of the human figure in the building with woodcarving ventilation panels (Szombathely).

The open vent configuration in Johor (Figure 92) yielded PMV values slightly lower than the woodcarving panel, ranging from 2.25 to 2.9. These results still fall within the category of warm thermal sensation, with a slight tendency for discomfort, particularly in the upper body regions. The airflow introduced through open vents contributed to a more varied temperature distribution but failed to deliver significant cooling, especially during peak external temperatures.

In Szombathely (Figure 93), the open vent scenario produced consistently high PMV values between 2.9 and 3 for both Human 1 and Human 2, across all body levels. This configuration proved to be the least effective in reducing indoor heat, as it allowed the warm outdoor air to flow in with minimal modulation, leading to thermal discomfort throughout the space.

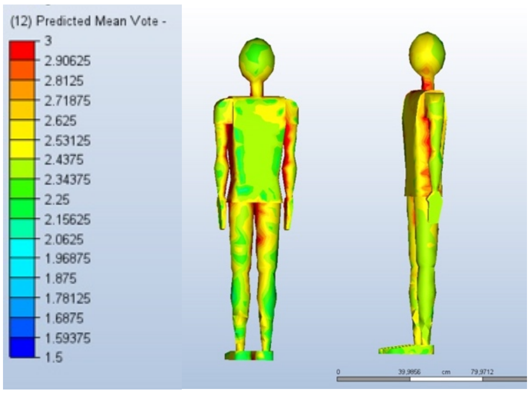


Figure 92: PMV of the human figure in a building with open vents (Johor).

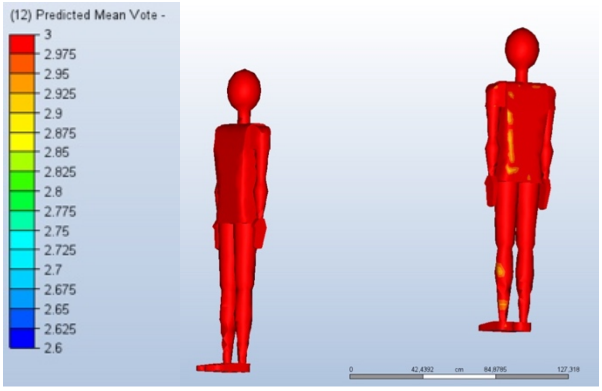


Figure 93: PMV of the human figure in a building with open vents (Szombathely).

When vents were completely closed, PMV values in Johor (Figure 94) varied more significantly, with readings ranging from 1.3 to 3, depending on body height and user. Human 2 showed cooler values in the lower body (as low as 1.3), suggesting some thermal stratification within the room. However, the values increased to 3 at the torso and head level, indicating uneven thermal conditions and discomfort due to insufficient ventilation.

In Szombathely (Figure 95), closed vents generated PMV values between 2.25 and 3. Although slightly better than the open vent scenario, thermal comfort remained poor, especially around the upper body. The limited air exchange restricted cooling and caused heat to accumulate, particularly in the head and torso areas.

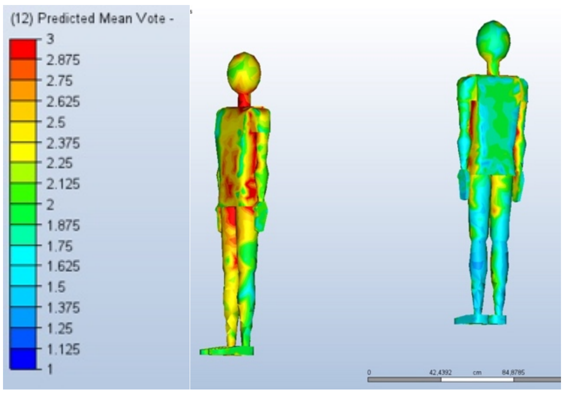


Figure 94: PMV of the human figure in a building with closed vents (Johor).

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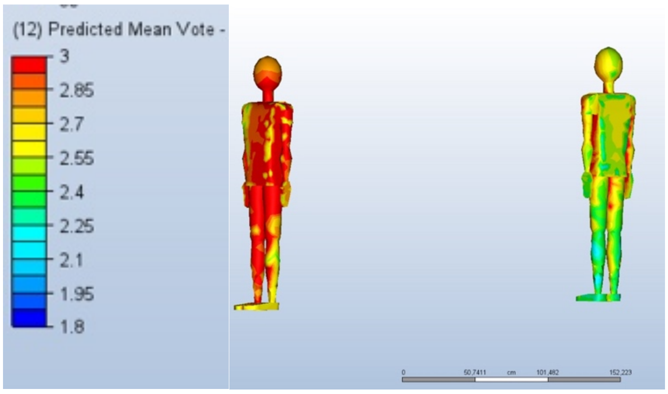

Figure 95: PMV of the human figure in a building with closed vents (Szombathely).

Mechanical ventilation proved to be the most effective strategy in maintaining acceptable thermal comfort in both locations. In Johor (Figure 96), PMV values for Human 1 and Human 2 ranged from 1.4 to 3, with lower readings observed in the lower body and slightly higher readings at the torso and head. Most values hovered around 2 to 2.5, which indicates a moderately warm but acceptable thermal environment.

In Szombathely (Figure 97), mechanical ventilation significantly improved indoor comfort, with PMV values between 1.8 and 3. The thermal sensation was generally less intense compared to natural ventilation strategies. Human 1 recorded lower PMV at the feet (1.8–2.5), while Human 2 experienced slightly higher but stable values across the body. This steady airflow helped regulate temperature distribution, resulting in more balanced and comfortable indoor conditions, especially during the summer season.

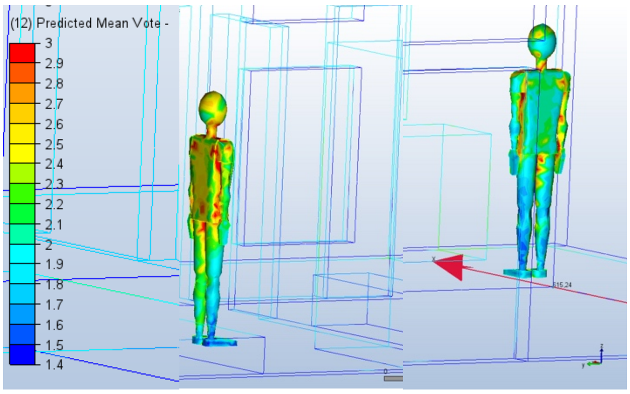

Figure 96: PMV of the human figure in a building with mechanical ventilation (Johor).

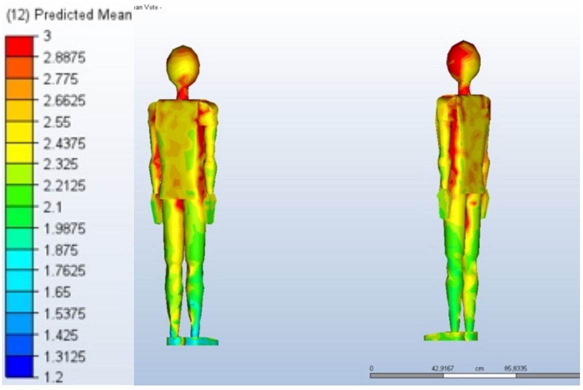

Figure 97: PMV of the human figure in a building with mechanical ventilation (Szombathely).

4.4.4 Transient Thermal Comfort Analysis in Szombathely (29 July)

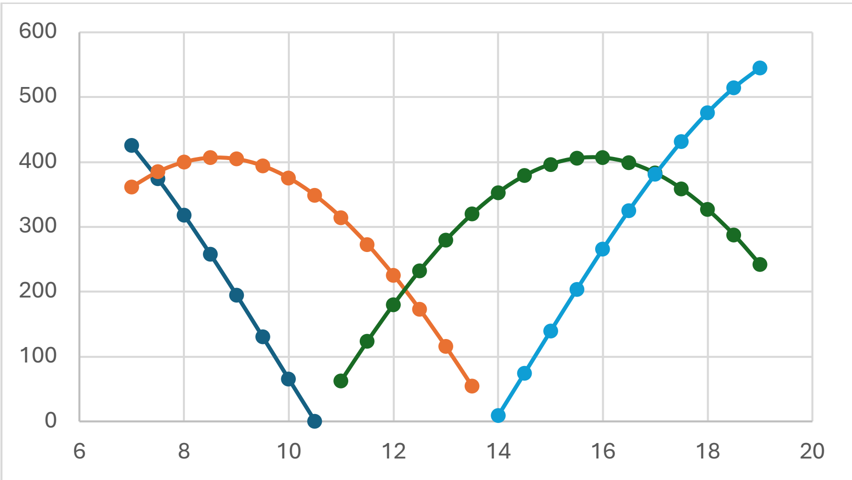

Figure 98: Diurnal variation in solar irradiation on the building facade on 29th July.

Figure 98 illustrates the diurnal variation in solar irradiation on the building facades throughout 29 July, revealing distinct trends in solar exposure. The blue line, representing the northeast (NE) facade, shows the highest irradiation at 07:00, peaking at 425.37 W/m², but gradually declines as the sun shifts, dropping to 195.20 W/m² by 09:00 and nearly zero by 10:30. In contrast, the orange line, indicating the southeast (SE) facade, experiences a gradual increase in irradiation, reaching its peak at 406.60 W/m² by 08:30, before decreasing to 54.42 W/m² by 13:30, reflecting the SE facade's role in contributing to heat gain during the mid-morning period. The grey line, showing the southwest (SW) facade, demonstrates a steady increase from 62.73 W/m² at 11:00, peaking at 406.83 W/m² at 16:00, with the highest solar exposure occurring between 14:00 and 16:00. The yellow line, depicting the northwest (NW) facade, indicates a gradual rise from 9.06 W/m² at 14:00, peaking at 476.29 W/m² at 18:00, and reaching its maximum at 545.34 W/m² by 19:00, reflecting the late afternoon and evening solar exposure. These varying irradiation patterns across the facades highlight the dynamic influence of solar exposure throughout the day, impacting indoor thermal loads and potentially contributing to fluctuating thermal comfort levels within the building.

To assess the diurnal variation of thermal comfort in Szombathely, a transient CFD simulation was conducted for 29 July, one of the hottest days during the summer period. This analysis aimed to understand how hourly fluctuations in solar irradiation influence indoor thermal conditions and occupant comfort throughout the day. The evaluation integrates hourly solar irradiation data applied to building facades with PMV distribution results on two human models placed inside the space.

At 09:00 in Figure 99, the SE facade absorbed 404.69 W/m², contributing to early discomfort. PMV results for Human 1 ranged from -1.5 to 1.5, transitioning from slightly cool in the lower legs to slightly warm conditions from the waist upwards. Human 2 showed similar patterns, with the head area being slightly more neutral (-0.75 to 0.75), likely due to airflow near the ventilation panel.

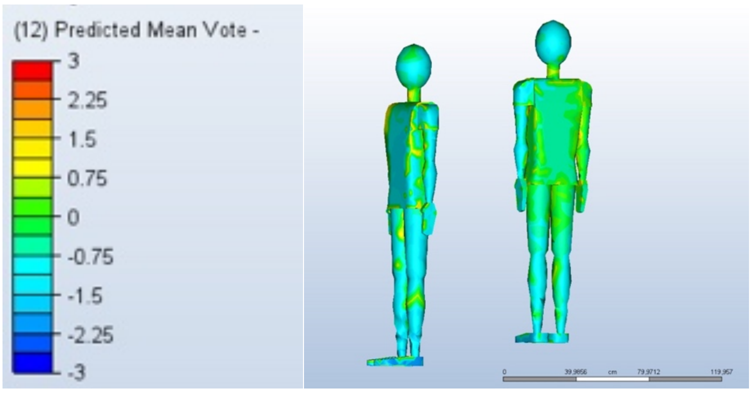

Figure 99: PMV at 09:00.

By noon in Figure 100, internal heat buildup increased, particularly in zones exposed to consistent solar gains. Human 1 displayed a PMV range from 0 to 1.5 across all body zones, while Human 2 still recorded a slightly cooler lower leg zone (-0.75 to 0.75), with the rest of the body trending toward slight warmth. These values reflect increasing indoor temperature as solar exposure intensified.

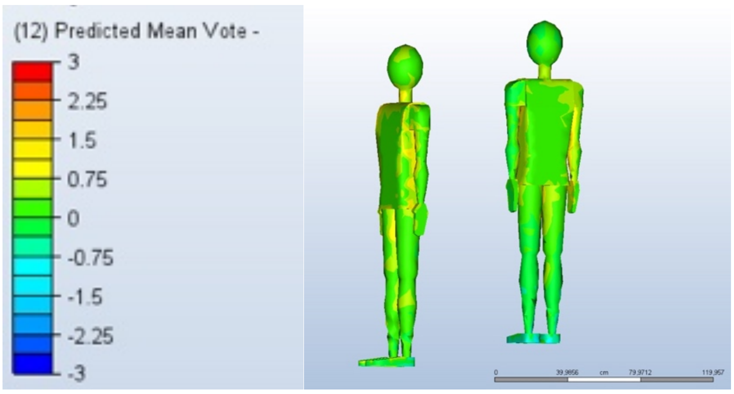

Figure 100: PMV at 12:00.

At 14:00 in Figure 101, PMV values became more uniformly warm. Human 1 recorded consistent PMV levels between 0 to 1.5 across the body, suggesting a more homogeneous thermal sensation. Human 2 maintained slightly cooler legs (-0.75 to 0.75), but the mid and upper body reached 1.55, approaching the warm discomfort threshold.

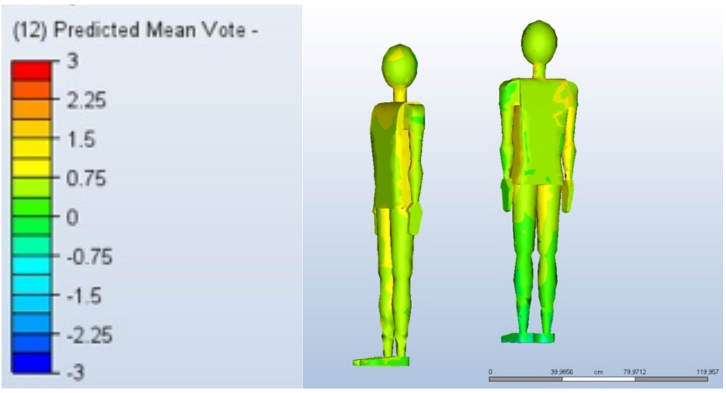

Figure 101: PMV at 14:00.

Thermal discomfort peaked at 16:00 in Figure 102, as solar irradiation from the SW facade (406.83 W/m²) contributed to elevated internal temperatures. Human 1 experienced a sharp rise in PMV values, with the upper body showing levels as high as 2.25 and the head stabilising at 1.5, which is well into the "warm" range. Human 2 also exhibited increased values, ranging from 0 to 1.5 in the lower body and reaching 1.5 at the upper torso and head. These findings indicate significant heat stress in the late afternoon, particularly for occupants near sun-exposed walls.

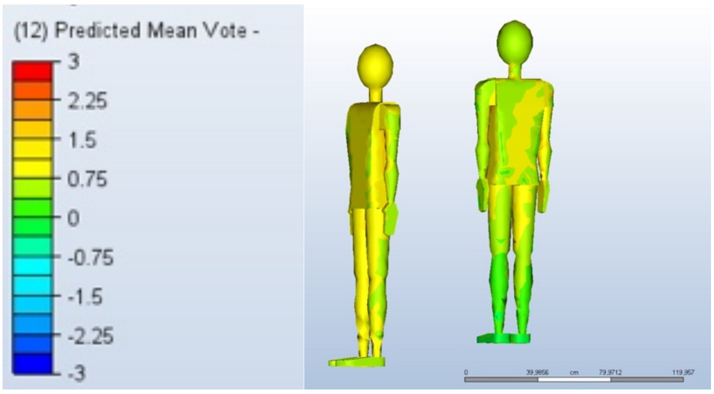

Figure 102: PMV at 16:00.

By 18:00 in Figure 103, thermal conditions remained elevated despite reduced solar angles. Human 1 retained high PMV values (0.75 to 2.25) from the waist to head, suggesting thermal discomfort due to accumulated heat. Human 2 showed similar trends, with the upper body reaching 2.25, indicating a lag in cooling down the interior space even after peaking solar hours.

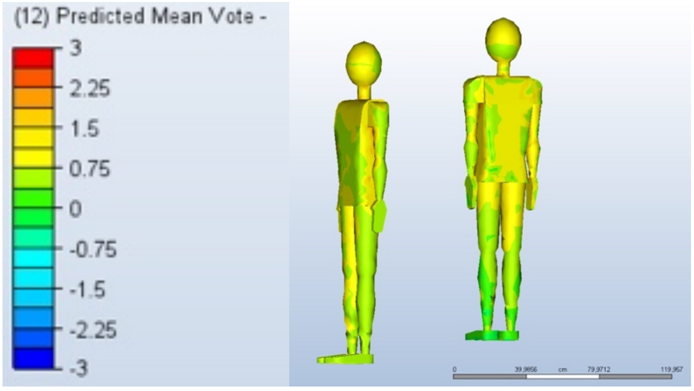

Figure 103: PMV at 18:00.

To evaluate the role of air movement in thermal comfort, Figure 104 presents the velocity distribution at 16:00. Air velocity around Human 1 ranged between 0.25 to 0.375 m/s, while Human 2 experienced notably lower airflow, from 0 to 0.1875 m/s. These low velocities, especially around Human 2, contributed to limited convective cooling and higher thermal discomfort. The data suggest that despite some airflow entering the space, it was unevenly distributed and insufficient to counteract the heat accumulated indoors during peak solar hours.

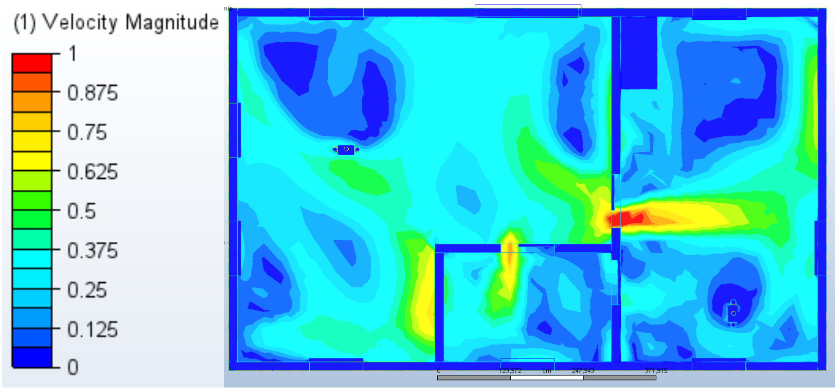

Figure 104: Air velocity distribution at 16:00.

4.4.5 Estimation of Cooling Energy Consumption for Mechanical Ventilation

Based on a temperature reduction of 5 °C and an air exchange rate of 1.5 air changes per hour (ACH) used in the mechanical ventilation simulation, a cooling energy consumption estimation was carried out for a typical summer scenario. The calculated cooling system power requirement is approximately 1 kW. With an operating schedule of 8 hours per day, the monthly energy consumption amounts to 240 kWh. At a residential electricity rate of HUF 36/kWh, this leads to a monthly cost of HUF 8,640.

The detailed calculation is presented below:

Density of dry air:1.169 kg/m3

Specific heat: 1.013 kJ/kg K (physical tables)

$$1.169 \times 1.013 = 1.184 \frac{kJ}{m^3} K$$

Vapour content of air at 29 °C 60% RH:

$$6 \times 50 = 30g/m^3 \text{ (physical tables)}$$

Specific heat of water at 29 °C: 4.182 J/g K (physical tables)

$$4.182 \times 30 = 125.46\frac{J}{m^3}K = 0.125\frac{kJ}{m^3}K$$

For the air of 60% RH:

$$1.184 + 0.125 = \frac{1.31kJ}{m^3}K$$

With an average outside temperature of 29 °C, we want to cool it to 24°C the cooling energy:

$$1.31 \times 5 = \frac{6.55kJ}{m^3}$$

We want to cool 0.1 m3 of air per second, the cooling performance will be:

$$0.1 \times 6.55 = \frac{0.655kJ}{s} = 0.655kW$$

Let us suppose an efficiency of the cooling equipment of 65%, the needed performance is:

$$\frac{0.655}{0.65} \approx 1.00kW$$

Daily consumption 10:00 to 18:00 (8 hours):

$$8 \times 1.00 = 8kWh$$

Monthly consumption (30 days):

$$30 \times 8 = 240kWh$$

The price of electricity for private consumption in Hungary is HUF 36/kWh (homepage of the supplier)

Cost of cooling energy in a month:

$$240 \times 36 = HUF\ 8\ 640$$

This estimation highlights the energy and cost implications of operating mechanical ventilation systems with active cooling during hot summer periods, serving as a baseline for evaluating alternative or passive ventilation strategies.

4.5 Conclusion

Chapter 4 presents a comprehensive analysis of ventilation performance and airflow dynamics in traditional Malay houses, focusing on the Rumah Limas Hutan Bandar MBJB in Johor Bahru and comparing it to Rumah Tok Su. The chapter begins by emphasising the importance of NV in improving indoor comfort and energy efficiency in traditional architecture. A detailed case study of Rumah Limas Hutan Bandar MBJB reveals that although the house incorporates various design features to enhance airflow, it often experiences elevated indoor air speeds that may exceed comfort levels during peak periods. In comparison, Rumah Tok Su provides more effective cross-ventilation, maintaining indoor air speeds within the ASHRAE comfort zone, demonstrating a more balanced approach to ventilation design. This contrast highlights how architectural differences influence ventilation effectiveness.

The chapter also includes an analysis of the climate factors affecting NV in Szombathely, Hungary, offering insights into how local environmental conditions impact the performance of traditional ventilation systems. This comparison underscores the importance of adaptable ventilation strategies that consider local climate. Drawing on Climate Consultant 6.0, the chapter discusses NV design guidelines, stressing the need for tailored designs to optimise airflow management. Additionally, the role of woodcarving patterns in enhancing ventilation is explored, showing how these intricate designs can facilitate air circulation.

Additionally, the intricate woodcarving patterns featured in traditional Malay architecture were explored regarding their role in enhancing airflow. The findings show that these decorative designs can actively facilitate air circulation by creating complex airflow pathways, which contribute to more effective ventilation and improved indoor comfort.

The comparative performance of different ventilation strategies, which include fully opened vents, closed vents, and mechanical ventilation, was also examined. Results indicated that fully opened vents significantly increase airflow but can lead to discomfort during peak wind conditions, as observed in Rumah Limas Hutan Bandar MBJB. On the other hand, closed vents, while offering a more stable and comfortable indoor environment, can restrict overall airflow, leading to a PMV of 3 (hot conditions), which may compromise comfort. Mechanical ventilation systems provide a controlled airflow alternative but may disrupt the passive design intentions, depending on the system’s integration and design.

Furthermore, transient thermal comfort analysis conducted for the Szombathely model on 29 July adds temporal depth to the ventilation study. Using hourly solar irradiation data and PMV results, the simulation revealed how thermal comfort varied significantly throughout the day due to facade-specific solar exposure and air movement patterns. The analysis showed that occupants experienced increasing discomfort during peak solar hours, especially in the late afternoon when internal heat buildup and uneven airflow distribution contributed to higher PMV values. This emphasises the need for integrating both spatial and temporal considerations when designing for thermal comfort in naturally ventilated spaces. By combining architectural features such as woodcarving panels with climate-responsive design, improved comfort can be achieved without relying solely on mechanical systems.

The chapter concludes by thoroughly exploring traditional ventilation systems, highlighting the interaction between architectural design, climate, and airflow dynamics, and the importance of adapting designs to local environmental conditions.

Chapter 5: Discussion

5.1 Introduction

This chapter presents the findings of the study, combining CFD simulations, climatic analysis, and architectural evaluations to explore the role of traditional woodcarving ventilation panels in enhancing NV and thermal comfort. By examining two case studies, this research uncovers how traditional Malay architecture incorporates carved ventilation panels not only for aesthetic and cultural expression but also as a passive cooling strategy.

The comparative analysis highlights the performance of these traditional systems in regulating indoor temperature and airflow, with specific attention to their alignment with ASHRAE thermal comfort standards. This study also extends its scope to include climatic adaptation in Szombathely, Hungary, testing the applicability of Malaysian woodcarving principles in a temperate climate using Climate Consultant 6.0 and CFS simulations.

This chapter also explores the airflow dynamics generated by different ventilation methods by assessing their impact on energy efficiency and indoor thermal comfort. Transient analysis is employed to understand how these systems respond to diurnal changes in weather conditions, offering a more realistic portrayal of ventilation performance over time.

In integrating traditional design with modern standards, this chapter also reflects on the cultural significance of woodcarving in sustainable architecture and its cross-cultural potential. The chapter concludes by addressing key limitations and proposing future research.

5.2 Comparative Analysis of Traditional Malay Houses

5.2.1 Rumah Limas Hutan Bandar MBJB

The analysis of Rumah Limas Hutan Bandar MBJB uncovers the complex relationship between traditional architectural elements and modern comfort standards. The house employs a sophisticated woodcarving ventilation system consisting of 138 panels, serving as an innovative NV approach. However, the effectiveness of this system is nuanced:

- **Temperature Regulation:** The house maintains indoor temperatures within the ASHRAE 80% acceptability range for most of the day, particularly on July 28th. This suggests that the woodcarving panels play an essential role in passive cooling, demonstrating the potential of traditional designs in regulating indoor temperatures effectively.

- **Air Movement Challenges:** Despite successful temperature regulation, the air movement data reveal that indoor air speeds often fall outside the ASHRAE comfort zone (0.2-1.5 m/s). This inconsistency, alternating between stagnant air and excessive air movement, indicates that while the woodcarving panels contribute to airflow, further refinement of the ventilation strategy is needed to ensure a more consistent comfort level.

5.2.2 Rumah Tok Su

In contrast, Rumah Tok Su demonstrates superior performance in air movement control:

- **Consistent Comfort:** Rumah Tok Su's indoor air speeds consistently fall within the ASHRAE comfort zone, indicating more effective airflow regulation and a more stable indoor climate.
- **Architectural Features:** The carved hollow panels and strategic window placements in Rumah Tok Su contribute to a more balanced ventilation system. This suggests that specific architectural elements, rather than simply the presence of woodcarvings, are key to ensuring optimal ventilation effectiveness.

5.3 Integration of Traditional Design with Modern Standards

The comparison between Rumah Limas Hutan Bandar MBJB and Rumah Tok Su highlights the potential for integrating traditional Malay architectural elements with modern comfort requirements:

1. **Adaptive Design:** The success of Rumah Tok Su in maintaining comfort suggests that traditional designs can be adapted to meet modern standards without compromising their cultural significance.

2. **Precision in Ventilation Design:** The challenges faced by Rumah Limas Hutan Bandar MBJB highlight the need for more precise engineering in ventilation systems, even when using traditional design elements.

3. **Holistic Approach:** Effective NV depends not only on individual elements like woodcarvings but also on the overall architectural composition, including the placement of openings and the internal layout.

5.4 Climatic Considerations and Adaptive Strategies

The inclusion of microclimate analysis for Szombathely, Hungary, provides valuable insights into adapting traditional ventilation strategies to different climatic contexts:

1. **Adaptive Comfort Ventilation:** Identifying an "Adaptive Comfort Ventilation" zone for Szombathely underscores the importance of designing climate-specific solutions to optimise indoor comfort.

2. **Wind Patterns:** The predominant north-northwest wind direction in Szombathely contrasts with tropical wind patterns, highlighting the need for location-specific adaptations of traditional ventilation methods.

3. **Design Guidelines:** Using Climate Consultant 6.0 to develop tailored ventilation strategies shows how modern tools can enhance the practical application of traditional design principles in different climatic conditions.

5.5 CFD Simulations and Airflow Dynamics

The CFD simulations offer crucial insights into the performance of woodcarving ventilation panels, open vents, closed vents, and mechanical ventilation, highlighting their distinct contributions to airflow dynamics and indoor comfort.

1. **Woodcarving Ventilation Panel vs. Open Vents:** Both allow for NV, but their impacts on airflow differ. The intricate patterns in woodcarving ventilation panels create multiple pathways for air movement, enhancing mixing and diffusion. This results in a more uniform distribution of air, reducing temperature stratification and improving thermal comfort. In contrast, open vents typically provide a more direct, less controlled airflow, which may lead to drafts in some areas, especially when wind speeds are high. While open vents allow for greater air exchange, the air distribution is often less balanced, with potential stagnation zones in areas further from the vents or openings.

2. **Woodcarving Ventilation Panels vs. Closed Vents:** When vents are closed, NV is significantly reduced, and the airflow is more restricted. In this scenario, woodcarving panels provide a significant advantage due to their ability to promote air movement through their designs, even when conventional vents are not in use. CFD simulations show these panels help maintain some circulation, creating micro-pathways for air and mitigating thermal stratification. Without them, confined air movement leads to recirculation and discomfort.

3. **Woodcarving Ventilation panels vs. Mechanical Ventilation:** Mechanical ventilation systems ensure consistent ventilation using fans. However, it relies on energy consumption. Woodcarving panels, while less controlled, offer an energy-efficient alternative. CFD simulations suggest that airflow through these panels is adaptive to external conditions, reducing reliance on mechanical systems in favourable climates. However, during low wind or extreme heat, mechanical support may still be needed to maintain comfort.

4. **Energy efficiency and Thermal Comfort:** Woodcarving panels offer passive thermal comfort without energy use. They enhance air circulation even in minimal wind conditions, so rendering interior climate regulation more sustainable. Mechanical systems ensure uniform airflow; however, they consume greater energy. Simulations indicate that mechanical ventilation during summer, requiring 1 kW of cooling, consumes 240 kWh and incurs a monthly cost of HUF 8,640 for private users. This financial element underscores the enduring advantages of passive systems. The integration of woodcarving panels with mechanical ventilation can enhance energy efficiency and thermal comfort. This technique enables mechanical systems to generate airflow just when necessary, thereby reducing operational costs and enhancing indoor comfort during high temperatures or low wind conditions. Woodcarving ventilation panels integrate historical significance with contemporary environmental efficiency, enhancing cultural identity and aesthetic appeal in indoor environments.

5. **Transient Analysis**: Transient analysis in CFD models clarifies the variations in airflow and thermal comfort throughout the day, particularly under real external environmental circumstances. The analysis mimics daily variations in temperature and wind speed, similar to those observed in Szombathely on July 29, to illustrate the temporal dynamics of NV systems. The temporal element is essential for evaluating real-world performance, as static models may fail to adequately represent occupant comfort in various environments. The preliminary findings indicate when NV suffices and when mechanical or hybrid assistance is required to maintain indoor conditions. This approach enhances

passive cooling design by forecasting thermal lag in building materials and the delayed response of air temperature. Transient simulations assess adaptive ventilation strategies to guarantee system efficiency despite fluctuating environmental demands.

5.6 Cultural Significance and Cross-Cultural Applications

The comparison between various ventilation methods, such as woodcarving panels, open vents, closed vents, and mechanical ventilation, provides further insights into how traditional and modern systems can coexist in sustainable architecture. In this context, integrating Malaysian and Székely Gate motifs into the woodcarving designs offers both functional and cultural benefits:

1. **Functionality Meets Culture:** Woodcarving patterns in ventilation panels not only improve airflow dynamics but also preserve cultural heritage. While mechanical and open vents may provide efficient ventilation, they lack the cultural richness that woodcarving patterns offer. By incorporating these intricate designs, ventilation systems can reflect the values and aesthetic principles of their respective cultures while ensuring that air circulation remains optimal, aligning with the goals of sustainable architecture.

2. **Cultural Dialogue and Design Innovation:** The integration of traditional motifs from Malaysia and Hungarian cultures offers an opportunity for cross-cultural dialogue. This fusion demonstrates how architectural elements from different traditions can be combined to address modern challenges like energy efficiency and sustainable building design. The woodcarving panels, which serve as both decorative and functional elements, exemplify how cultural preservation can be achieved through innovative, hybrid designs that meet contemporary needs.

3. **Adaptability and Scalability:** the woodcarving ventilation panels' adaptability across different climates (as observed in Johor and Szombathely) emphasises the potential for these designs to be scaled and customised for various environmental conditions. This adaptability not only contributes to improved airflow but also reflects the flexibility of traditional motifs in modern architectural contexts. As a result, these designs can be applied in a wide range of buildings, bridging the gap between sustainability, functionality, and cultural heritage.

5.7 Implications for Sustainable Architecture

The bibliometric analysis conducted in this study highlights a significant research gap in integrating traditional woodcarving designs with modern ventilation systems. While extensive literature exists on NV and vernacular architecture, few studies focus on enhancing thermal comfort while preserving cultural identity. As shown in Figure 105, a search for "natural ventilation, traditional, vernacular house, windcatcher, woodcarving, mashrabiya, latticework, or Kumiko" yielded 53 documents in Scopus. However, when narrowed to "woodcarving" alone, the search returned no results. This striking gap underscores the need for research on culturally informed sustainable architecture. By incorporating Hungarian and Malay motifs into woodcarving ventilation panels, this study aims to bridge this gap, contributing to theoretical and practical advancements in bioclimatic design and cultural sustainability.

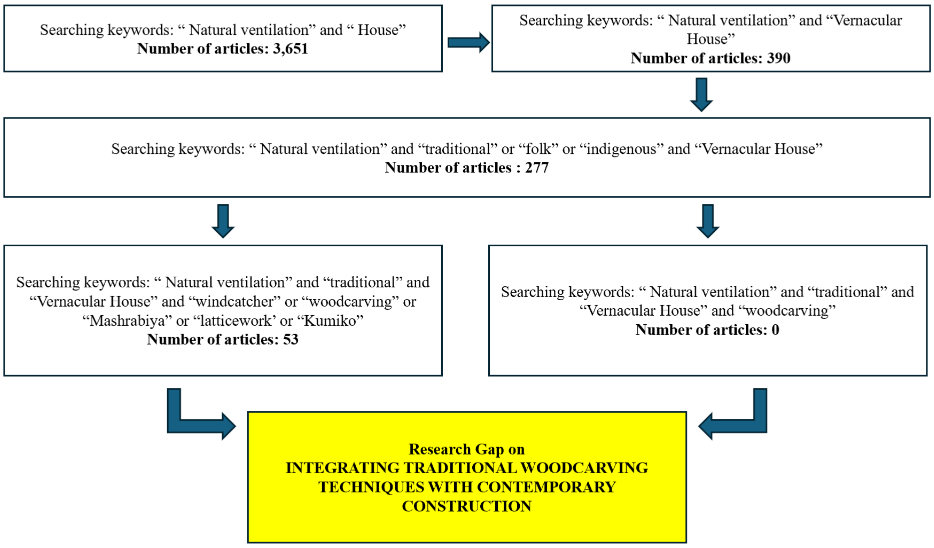

Figure 105: Research gap.

5.8 Limitations

This study presents a detailed analysis of traditional woodcarving ventilation panels, focusing on two case studies: Rumah Limas Hutan Bandar MBJB and Rumah Tok Su. However, several methodological limitations must be acknowledged:

5.8.1 Limited Sample Size

The study primarily focuses on two traditional Malay houses due to their unique woodcarving ventilation panels. While these case studies provide valuable insights, the limited sample size restricts the ability to generalise the findings to other traditional or contemporary buildings. A larger sample size would enhance the robustness and generalizability of the conclusions. Future research could expand the analysis to include a broader range of buildings, particularly other traditional houses with varying woodcarving patterns, or explore similar techniques from different cultural contexts. Such studies could provide more comprehensive insights into the role of woodcarving ventilation systems across various architectural and climatic settings.

5.8.2 Lack of Experimental Validation

While CFD simulations offer valuable insights into airflow dynamics and NV performance, the study lacks experimental validation. Physical measurements, field studies, and occupant surveys are necessary to verify the simulated results. Unfortunately, due to logistical and resource constraints, on-site experiments were not feasible within the scope of this research. Incorporating in-situ measurements from different seasons, including the temperature and humidity variations, would strengthen the verification of CFD simulations and improve the robustness of the results. Future studies could integrate these methods to enhance the reliability and accuracy of the findings.

5.8.3 Steady-State vs. Transient Analysis

This study encompasses a transient analysis conducted on July 29th, chosen for its exceptional summer conditions in Szombathely, indicative of one of the largest thermal stress times; nonetheless, it is important to highlight that most CFD simulations were executed under steady-state conditions. The steady-state approach presumes continuous excessive summer heat, yielding valuable baseline insights on ventilation efficacy. A comprehensive transient analysis conducted over an extended duration, accounting for variable weather patterns, would provide a deeper insight into the performance of ventilation systems throughout time. Supplementary transient analysis across several days, seasons, or locations, bolstered by enhanced computer resources, could provide a more comprehensive understanding of real-world ventilation dynamics.

5.9 Future Research Directions

This study opens several avenues for future research:

1. **Optimisation Studies:** Further research could focus on optimising the design of woodcarving panels to maximise ventilation effectiveness across different climatic zones. By studying the impact of different woodcarving patterns, sizes, and materials, researchers could identify the most efficient configurations for improving airflow and thermal comfort. This would contribute to developing more adaptable and context-specific solutions for traditional ventilation systems.

2. **Long-Term Performance:** Longitudinal studies on woodcarving ventilation systems' durability and maintenance requirements would offer valuable insights into their practical implementation. Understanding how these systems perform over extended periods, considering factors such as material degradation, wear, and maintenance needs, would be crucial for assessing their long-term viability in contemporary buildings.

3. **Occupant Comfort Studies:** In-depth studies on occupant perception and comfort in buildings utilising these traditional ventilation systems would complement the technical findings of this research. These studies could involve surveys, interviews, and environmental monitoring to assess factors such as air movement, temperature, humidity, and perceived comfort. By integrating both objective measurements and subjective occupant feedback, future research could provide a deeper understanding of how traditional ventilation systems impact human well-being and overall building performance.

4. **Integration with Smart Building Technologies:** Exploring the integration of traditional ventilation systems with smart building management systems could lead to innovative hybrid solutions for sustainable architecture. Integrating these passive systems with modern HVAC or building management systems could provide optimal performance, maximizing energy efficiency and comfort while maintaining cultural and architectural significance.

5. **Experimental Validation and Real-World Studies**: As highlighted in this study's limitations, incorporating experimental validation alongside CFD simulations would significantly enhance the reliability and applicability of the

findings. Future studies should aim to conduct field experiments with physical measurements, occupant surveys, and in-situ data collection to verify the simulated results and ensure a more accurate representation of real-world performance.

6. **Broader Geographic and Cultural Scope**: Expanding research to include a wider range of traditional and contemporary buildings from different geographic and cultural contexts would improve the generalizability of the findings. By comparing woodcarving ventilation systems across various climates and architectural traditions, researchers could uncover valuable insights into the universal and context-specific benefits of these systems.

7. **Seasonal and Diurnal Variability**: Future studies should explore the performance of woodcarving ventilation panels over a full year, considering the seasonal and diurnal fluctuations in temperature, wind speed, and humidity. A comprehensive understanding of the panels' effectiveness in different seasons would provide a more holistic view of their performance and adaptability to various weather conditions.

By pursuing these research directions, future studies could further enhance our understanding of traditional woodcarving ventilation systems and their potential in sustainable building design. This would not only preserve and promote cultural heritage but also offer practical solutions for modern architecture in an era of increasing environmental and energy efficiency concerns.

5.10 Conclusion

The analysis of traditional Malay houses reveals the sophisticated understanding of environmental design principles embedded in vernacular architecture. While these conventional designs are highly effective in temperature regulation, the challenges in maintaining consistent air movement highlight areas for potential improvement. Integrating traditional design elements with modern comfort standards and simulation techniques offers a promising path for sustainable architecture in tropical climates. By adapting these principles to contemporary needs, architects can create culturally resonant, environmentally responsive, and comfortable buildings for occupants. Contemporary Malaysian architecture can benefit from these principles by integrating NV and local materials, reducing energy consumption, and enhancing cultural identity. This approach fosters a sense of community and continuity with heritage while addressing modern sustainability goals (Xuan & Abd Manan, 2024).

As climate change and urbanisation present increasing challenges, traditional Malay architecture's lessons provide valuable insights for creating resilient, energy-efficient, and comfortable living spaces. Future research and design innovations in this area have the potential to significantly contribute to sustainable urban development in tropical regions and beyond.

Chapter 6: Conclusion

6.1 Introduction

This final chapter synthesises the findings from the study and explores their broader implications in the context of traditional and modern architectural practices. The research focused on the effectiveness of traditional Malay woodcarving ventilation systems in enhancing NV and thermal comfort while exploring their potential for integration into contemporary architecture. By combining empirical data with computational analysis, this study provides valuable insights into how traditional designs can contribute to sustainable building practices. Additionally, the chapter discusses the significance of these findings for cultural preservation, sustainability, and future research. Ultimately, it aims to demonstrate how traditional architectural knowledge can be adapted and applied in modern contexts, addressing environmental challenges and cultural heritage.

6.2 Summary of Key Findings

The research examined the role of traditional Malay woodcarving ventilation systems in enhancing NV and thermal comfort and their integration with contemporary building practices. The key findings are summarised as follows:

1. **Effectiveness of Traditional Design:** Traditional Malay houses, particularly Rumah Tok Su and Rumah Limas Hutan Bandar MBJB, showcase the functional benefits of woodcarving ventilation systems. These designs significantly improve air movement control, contributing to indoor thermal comfort within the ASHRAE comfort zone. The woodcarving panels prove effective in regulating temperature and promoting even airflow distribution throughout the building, reflecting the potential of traditional designs in achieving passive cooling.

2. **Airflow Dynamics:** CFD simulations revealed that the intricate woodcarving patterns create multiple airflow pathways, promoting effective air mixing and turbulence. When compared to opened and closed vents, the woodcarving panels exhibit a more balanced air distribution, ensuring that air velocity is moderate enough to maintain comfortable indoor conditions. These simulations also showed that woodcarving ventilation systems contribute to even temperature regulation across the building, further enhancing comfort levels. Mechanical ventilation systems, while providing more control over airflow, can disrupt the intended passive ventilation patterns created by the woodcarving panels.

3. **Integration with Modern Standards:** The research demonstrates that traditional woodcarving ventilation systems can be successfully adapted to meet modern comfort requirements. Combining traditional design principles and contemporary building standards shows promising potential for integration into modern architectural practices, especially in climates that demand natural cooling strategies.

4. **Cross-Cultural Applicability:** The principles derived from Malay woodcarving ventilation systems have broader applicability across diverse cultural and climatic contexts. The study also explored cross-cultural design

integration by incorporating traditional Hungarian motifs into modern structures in Szombathely, Hungary, showcasing the global potential of this approach to NV. This cross-cultural exploration underscores the relevance of traditional design principles in diverse architectural contexts worldwide.

6.3 Implications for Sustainable Architecture

The findings of this study carry important implications for the development of sustainable architecture:

1. **Energy Efficiency:** Woodcarving panels' effectiveness in enhancing NV suggests a significant reduction in reliance on mechanical cooling systems, thereby improving building energy efficiency. By harnessing passive design strategies, buildings can maintain comfortable indoor environments with reduced energy consumption, making them more sustainable.

2. **Bioclimatic Design:** The success of woodcarving systems reinforces the importance of bioclimatic design in creating buildings that respond effectively to local climatic conditions. By aligning building features with the local climate, traditional design elements provide a sustainable solution to maintaining thermal comfort without compromising energy efficiency.

3. **Cultural Sustainability:** Integrating traditional design elements, such as woodcarving panels, into modern buildings offers an opportunity to preserve cultural heritage within the architectural context. This approach promotes cultural sustainability by embedding historical and regional identities into contemporary architectural practices.

4. **Innovative Hybrid Solutions:** This research paves the way for developing hybrid ventilation systems that combine traditional passive cooling methods with modern technological advancements. Such systems could offer a sustainable solution by leveraging traditional knowledge and modern technology, addressing the growing demand for energy-efficient and comfort-oriented buildings.

6.4 Recommendations for Future Research

Based on the findings and limitations of this study, several avenues for future research can be identified to explore further and enhance the application of woodcarving ventilation systems:

1. **Optimization Studies:** Further research should explore how the design of woodcarving panels can be optimized for various climatic conditions to improve ventilation performance. Specifically, it would be valuable to study the effectiveness of woodcarving ventilation systems during winter and explore how wind patterns and indoor air quality influence system performance.

2. **Long-Term Performance:** Longitudinal studies on the durability, maintenance, and long-term performance of woodcarving ventilation systems across different climates would provide practical insights into their real-world application and potential for integration into modern architecture.

3. **Occupant Comfort:** In-depth investigations into occupant perceptions of comfort in buildings utilizing traditional ventilation systems would complement the technical findings of this research. Understanding how occupants experience airflow, temperature, and overall comfort will help refine these designs for broader application.

4. **Smart Integration:** Integrating woodcarving ventilation systems with smart building management technologies could lead to innovative solutions that dynamically respond to indoor and outdoor environmental changes. This would enhance both energy efficiency and occupant comfort.

5. **Experimental Validation and Real-World Measurements:** Incorporating experimental validation, such as physical measurements and field data, alongside CFD simulations would significantly strengthen the reliability and applicability of the findings. Real-world data would also help assess the practical effectiveness of woodcarving systems.

6. **Broader Geographical Application:** Further research is needed to adapt the principles of woodcarving ventilation systems to diverse cultural and climatic contexts. Exploring similarities in traditional architectural practices across regions with comparable climatic conditions could help extend the applicability of woodcarving ventilation techniques to various global contexts, enriching our understanding of sustainable building practices worldwide.

7. **Seasonal and Diurnal Variability:** Future studies should also consider the seasonal and diurnal variations in performance, assessing how woodcarving ventilation systems function throughout the year. This would provide a more comprehensive understanding of their effectiveness in different weather conditions.

6.5 Theses and Related Publications

Thesis 1 (Functional Benefits of Woodcarving Ventilation Systems in Traditional Malay Houses): Traditional Malay houses, particularly Rumah Tok Su and Rumah Limas Hutan Bandar MBJB, showcase the functional benefits of woodcarving ventilation systems. These designs significantly improve air movement control, contributing to indoor thermal comfort within the ASHRAE comfort zone. The woodcarving panels prove effective in regulating temperature and promoting even airflow distribution throughout the building, reflecting the potential of traditional designs in achieving passive cooling.

Related Publications:

Abdul Rahim, N. R. B., & Kovács, Z. (2024). Cultural Preservation Meets Modern Design: Investigating the Impact of Traditional Woodcarvings on Natural Ventilation in Johor, Malaysia. In Wood 4 Sustainability (pp. 131–149). https://doi.org/10.35511/978-963-334-541-2-14

Abdul Rahim, N. R. B., & Szabó, P. (2023). THE ROLE OF WOODCARVING AS A NATURAL VENTILATION IN PASSIVE COOLING STRATEGIES OF TRADITIONAL MALAY ARCHITECTURE: A CASE STUDY OF RUMAH LIMAS

HUTAN BANDAR, JOHOR BAHRU. XXVI. Tavaszi Szél Konferencia 2023, 540–554. https://m2.mtmt.hu/api/publication/36096188

Abdul Rahim, N. R. B., & Szabó, P. (2025). Woodcarving in Malay Architecture: Patterns, Structures and Cultural Significant. Built Environment Journal (BEJ). https://m2.mtmt.hu/api/publication/36057971

Thesis 2 (CFD Simulations and Airflow Analysis of Woodcarving Panels): CFD simulations revealed that the intricate woodcarving patterns create multiple airflow pathways, promoting effective air mixing and turbulence. The panels' high FAR allows substantial airflow while moderating air velocity to ensure comfortable indoor conditions. This capability highlights the effectiveness of traditional carvings in facilitating natural ventilation without the need for mechanical cooling.

Related Publications:

Abdul Rahim, N. R. B., & Kovács, Z. (2025). Comparative Air Flow Analysis Between Johor and Szombathely: Evaluating Woodcarving Ventilation Panels. ACTA SILVATICA ET LIGNARIA HUNGARICA: AN INTERNATIONAL JOURNAL IN FOREST, WOOD AND ENVIRONMENTAL SCIENCES. https://m2.mtmt.hu/api/publication/35930307

Seidu, H., Brougui, M., Abdul Rahim, N. R. B., & Németh, R. (2024). EVALUATION OF DYNAMIC AND STATIC MODULI OF ELASTICITY OF HYBRID EUCALYPTUS WOOD FROM DIFFERENT LOCATIONS IN GHANA. WOOD RESEARCH, 69, 132–142. https://doi.org/10.37763/wr.1336-4561/69.1.132142

Thesis 3 (Adapting Traditional Woodcarving Ventilation Systems for Modern Comfort Standards): The research demonstrates that traditional woodcarving ventilation systems can be successfully adapted to meet modern comfort requirements. Combining traditional design principles and contemporary building standards shows promising potential for integration into modern architectural practices, especially in climates that demand natural cooling strategies.

Related Publications:

Abdul Rahim, N. R. B., & Szabó, P. (2023). THE ROLE OF WOODCARVING AS A NATURAL VENTILATION IN PASSIVE COOLING STRATEGIES OF TRADITIONAL MALAY ARCHITECTURE: A CASE STUDY OF RUMAH LIMAS HUTAN BANDAR, JOHOR BAHRU. XXVI. Tavaszi Szél Konferencia 2023, 540–554. https://m2.mtmt.hu/api/publication/36096188

Abdul Rahim, N. R. B., & Szabó, P. (2025). Woodcarving in Malay Architecture: Patterns, Structures and Cultural Significant. Built Environment Journal (BEJ). https://m2.mtmt.hu/api/publication/36057971

Thesis 4 (Cross-Cultural Integration of Woodcarving Ventilation Systems in Hungary): The principles derived from Malay woodcarving ventilation systems have broader applicability across diverse cultural and climatic contexts. The study also explored cross-cultural design integration by incorporating traditional Hungarian motifs into modern structures in Szombathely, Hungary, showcasing the global potential of this approach to natural ventilation.

Related Publications:

Abdul Rahim, N. R. B., & Kovács, Z. (2024). Cultural Preservation Meets Modern Design: Investigating the Impact of Traditional Woodcarvings on Natural Ventilation in Johor, Malaysia. In Wood 4 Sustainability (pp. 131–149). https://doi.org/10.35511/978-963-334-541-2-14

Abdul Rahim, N. R. B., & Kovács, Z. (2025). Comparative Air Flow Analysis Between Johor and Szombathely: Evaluating Woodcarving Ventilation Panels. ACTA SILVATICA ET LIGNARIA HUNGARICA: AN INTERNATIONAL JOURNAL IN FOREST, WOOD AND ENVIRONMENTAL SCIENCES. https://m2.mtmt.hu/api/publication/35930307

Thesis 5 (Hybrid Ventilation Systems Combining Traditional and Modern Approaches): This research paves the way for developing hybrid ventilation systems that combine traditional passive cooling methods with modern technological advancements. Such systems could offer a sustainable solution by leveraging traditional knowledge and modern technology, addressing the growing demand for energy-efficient and comfort-oriented buildings.

Related Publications:

Abdul Rahim, N. R. B., Julaila, A. R., & Rajabi, A. R. (2019). A STUDY ON THE SIGNAGE SYSTEM IN MELAKA, THE UNESCO HERITAGE SITES. Journal of Architecture, Planning and Construction Management, 1, 22. https://m2.mtmt.hu/api/publication/35896748

Abdul Rahim, N. R. B., Szabó, P., & Kovács, Z. (2024a). Natural Ventilation Technique in Traditional Dwellings: A bibliometric Analysis of Research Trends. EVERGREEN. https://m2.mtmt.hu/api/publication/35444866

Abdul Rahim, N. R. B., Szabó, P., & Kovács, Z. (2024b). OPTIMIZING NATURAL VENTILATION FOR SUSTAINABLE ARCHITECTURE: A COMPREHENSIVE STUDY ON WIND-DRIVEN HOUSE ORIENTATION STRATEGIES IN SZOMBATHELY, HUNGARY. XXVII. Tavaszi Szél Konferencia 2024 - Absztraktkötet, 383. https://m2.mtmt.hu/api/publication/35896212

6.6 Concluding Remarks

This research highlights the significant potential of traditional architectural elements, particularly woodcarving ventilation systems, in contributing to contemporary sustainable building practices. By bridging the gap between cultural heritage and modern performance standards, these designs offer valuable insights for addressing today’s architectural challenges, particularly energy efficiency and thermal comfort.

As the world faces increasingly complex environmental challenges, the wisdom embedded in traditional architecture provides a rich source of inspiration for developing sustainable, comfortable, and culturally resonant built environments. Integrating traditional woodcarving techniques with modern technology preserves cultural identity and paves the way for innovative architectural solutions that respond to environmental concerns and cultural heritage.

The findings of this study demonstrate that traditional designs, such as woodcarving ventilation systems, are not only relevant but also essential in shaping resilient and energy-efficient buildings for the future. These systems hold the potential to support sustainable urban development, particularly in tropical regions, where NV plays a crucial role in maintaining thermal comfort. By combining traditional knowledge with modern advancements, we can create living spaces that are not only more energy-efficient but also more attuned to the cultural and environmental contexts in which they are situated.

The lessons learned from this study offer valuable contributions to the ongoing dialogue on sustainable architecture, providing a framework for future research and practical applications in building design. Ultimately, the integration of traditional architectural principles with contemporary practices can contribute significantly to creating built environments that are both culturally enriching and environmentally responsible.

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