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Passive Design Strategies in *Bolon* House through Activity Pattern and Wind Environment

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Abstract

In the *Bolon* house, a traditional *Toba Batak* vernacular architecture, the spatial layout is organized according to cultural meanings assigned to each zone, reflecting the social structure and adapting to the regional climate through passive strategies. Since scientific verification of such a principle remains limited, this research evaluates the thermal comfort within the *Bolon* house, focusing on the relationship between wind environment and local activity patterns. Firstly, the routine activities of residents were recorded and categorized into the activity pattern. Secondly, the thermal comfort range was calculated using the CBE Tool for two representative seasonal dates, while wind environments were analyzed through CFD simulations. Findings show that wind speeds are generally low, with a slight increase in the western rear zone due to the prevailing East wind. Nevertheless, indoor comfort is maintained during most activities, particularly in the central communal zone, which consistently provides the most suitable conditions for daily life.

INTRODUCTION

Traditional architecture in Indonesia reflects immense environmental knowledge in tropical regions where high humidity, heavy precipitation, and solar intensity challenge human comfort. The *Bolon* house of the *Toba Batak* tribe in North Sumatra exemplifies this feature with raised floors, steep roofs, and porous envelope elements that promote airflow and thermal comfort. As Burhany et al. (2022) mentioned, An architectural feature in Indonesian vernacular architecture, identically using a stilt floor to maintain the comfort of their house by wind flow. Beyond passive design, the *Bolon* house retains its symbolic importance, embodying kinship, ancestral values, and identity.

Fig. 1. *Bolon House* Location on *Samosir*, North Sumatera, Indonesia
(Source: author)

Unlike many other vernacular architectures shown mainly as tourist attractions, some *Bolon* houses are still occupied and used for daily routines and ritual gatherings. In villages such as *Huta Raja* and *Lumban Suhi-suhi*, these houses are occupied and function as spaces for ethnic ceremonies and intergenerational residents' cultural activities.

This ongoing use emphasizes the dynamic function of *Bolon* houses in maintaining social and cultural activities, also sustaining living heritage. Rather than being artefacts of the past symbol, these structures facilitate the continuity of customary traditions within a changing socio-environmental context (Simanjuntak et al., 2020).

The environmental features in traditional houses are closely linked to the cultural values, and it also greatly influences the space organization and architecture within them. Recent studies on the *Bolon house* have demonstrated its architectural logic, typology, and function in cultural preservation, particularly in relation to traditional houses. Tarigan et al. (2020) explained the tectonic expression of the *Bolon* house, emphasizing how its timber structure and saddle roof present indigenous construction knowledge and symbolic meanings in *Toba Batak* cosmology. Murphy (2008) analyzed spatial organization in relation to kinship systems, showing how interior zoning supports communal and ritual functions. In line with Yusran & Dirgantara (2021), in his findings regarding visual and spatial transformation due to the *Toba Batak* culture, which is no longer as strict as before, he discusses the addition of spaces such as kitchens and bathrooms outside the *Bolon* house structure and the use of new materials to replace old materials due to durability factors.

Beyond their physical form, the spatial organization and collective layout of *Bolon house*s within villages reflect environmental adaptation and communal living. Buildings are typically arranged to consider prevailing winds and solar conditions, maximizing shade and minimizing direct sun exposure. Furthermore, the houses are often located with open space areas in between, which supports air circulation and reduces heat build-up in dense settlements. Indoor thermal comfort thresholds in tropical vernacular houses are closely aligned with adaptive comfort models, where wind speed influences perceived comfort more than temperature factors. Studies by Tantasavasdi et al. (2001) Thai vernacular houses demonstrate that controlled wind flow through architectural features such as raised openings and steep roofs improves indoor comfort across the day, especially in uninsulated structures. In Central Java, the *Joglo* house typology features an open-plan interior with high ceilings and a central ventilation shaft, which together reduce indoor heat and promote air movement (Idham, 2018). Also, research on vernacular houses in Penang revealed that they exhibit excellent performance in regulating temperature and humidity through effective cross-ventilation and limited stack effect (Hassan & Ramli, 2010).

Although vernacular architecture in tropical regions has been analysed for its environmentally responsive design, specific investigations into the *Bolon house,* a traditional *Toba Batak* dwelling, remain limited, especially in relation to how its design supports comfort in daily living. The architectural form of the *Bolon* house, typically built near water bodies (Lake *Toba*) and located in the highlands of *Samosir*, represents intergenerational adaptation to climatic conditions such as wind and temperature patterns. However, previous research usually treats stilted or open-plan houses as a single category and rarely analyzes the specific distribution of wind within individual zones. This study addresses that gap by investigating how wind environments interact with spatial activity zones inside the *Bolon* house, and how those dynamics influence occupants' comfort throughout the day. By connecting environmental data with spatial patterns, the research provides a more grounded understanding of how vernacular architecture supports sustainable living in a tropical highland context.

The study also offers a comfort performance evaluation of the *Bolon* house layout by correlating wind environment with spatial activity patterns of residents. The spatial organization and architectural elements of the traditional *Bolon* house contribute to maintaining indoor thermal comfort by regulating wind flow across activity zones. Furthermore, it supports the restoration of the *Bolon* house as a traditional *Toba Batak* architecture and pursues design ideas for incorporating vernacular strategies into restoration planning or even contemporary projects.

LITERATURE REVIEW

The vernacular architecture of Indonesia visualizes sustainable adaptation to the climatic and cultural situation of each region. One of the most representative examples in the *Toba Batak* tribe's region is the *Bolon* house, found primarily on *Samosir* Island in Lake *Toba*, *North Sumatra* Province. These timber structures, built without nail joints and lifted above ground on stilts, have evolved in direct response to environmental, social, and spiritual needs. To situate the present study, this section reviews the climate of *Samosir*, the main adaptive features of the *Bolon* house*,* and previous work on spatial use in similar traditional houses.

Climatic Conditions in *Samosir*

Bolon houses are found in many villages across the *Samosir* Region, where *Samosir* Island is located. *Samosir* itself is located between 2°24'–2°25'N latitude and 98°21'–99°55'E longitude, spanning the mainland of *North Sumatra* and *Samosir* Island in the middle of Lake *Toba*, and experiences a tropical climate marked by the equatorial type that has relatively stable temperatures throughout the year. Also, with consistent sunlight and moderate wind speeds, the average daily temperature ranges from 17 to 29 °C, and high humidity averaging 85% (Haryadi et al., 2019). The persistent humidity levels remain high throughout the year, while wind speeds are generally low to moderate. This combination of environmental conditions shapes the architectural response of the region, where ventilation, moisture control, and protection from precipitation are central concerns.

Islam & Ahmed (2021) highlighted that traditional timber stilt houses located near water bodies benefit from optimized natural airflow, facilitated by multiple operable louvered openings positioned at the occupancy level. These features allow effective use of prevailing winds, enabling indoor spaces to be used primarily at night when temperatures are lower, while shaded outdoor areas provide comfort during daytime overheating. A comparable environmental condition exists in the *Bolon* houses of *Hutaraja* traditional village near Lake *Toba*, where the proximity to the water body and elevated topography enhance air movement and support natural ventilation. These conditions contribute to operative ventilation speeds that facilitate thermal comfort in highland tropical climates, consistent with findings in similar vernacular contexts (Fitriaty et al., 2023; Nguyen et al., 2019). Despite the continuous use of interior spaces for daily activities, the design allows for sufficient airflow to maintain comfort throughout the house.

Adaptive Architectural Features in the Tropical Climate Zone of the *Bolon House*

What makes the *Bolon* house's raised floor so distinctive? Studies of other traditional houses point out similar stilt designs used for livestock and service areas raised between 1.5 m and 3 m above ground. The stilt system serves multiple functions: it protects the interior from surface runoff and flooding during the rainy season, deters pests and wild animals, and enables underfloor airflow (Alsheikh Mahmoud & Bin Hashim, 2025). This airflow reduces heat conduction from the ground and lowers moisture accumulation, which is critical in a humid climate. Cross ventilation is achieved through the lower part of the building, where the elevated stilt system allows airflow beneath the floor, reducing ground heat transmission and promoting thermal comfort. Research in similar equatorial highland environments, such as in parts of Malaysia and Thailand, shows that elevated floors significantly lower indoor humidity and promote air circulation beneath the structure (Yuan & Ng, 2012). These layered ventilation mechanisms support indoor thermal regulation despite tropical climatic conditions. Such architectural strategies are consistent with findings by Angkasa & M. Kamil (2024). Furthermore, the stilted floor system, a common adaptation in humid equatorial regions, promotes subfloor ventilation by enabling airflow beneath the living area, thus mitigating ground heat and moisture transfer to interior spaces (Pan et al., 2024).

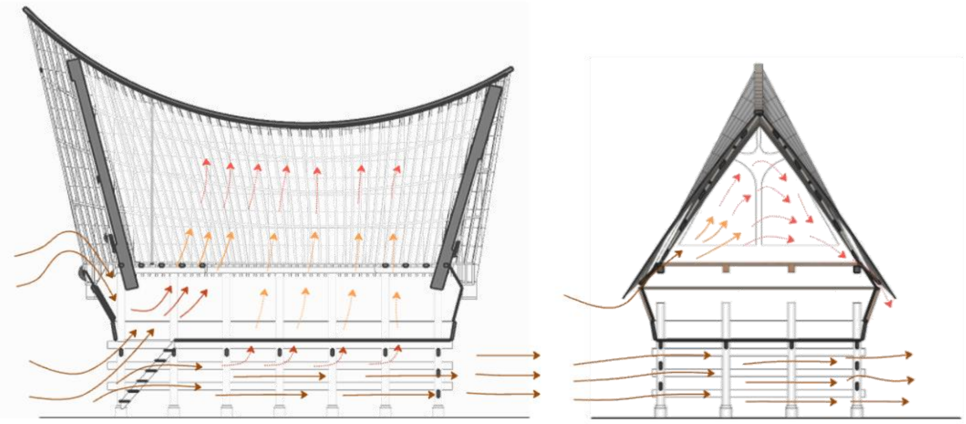


Fig. 2. Wind Flow Plan at *Bolon* house
(Source: author)

The steeply pitched roof, often rising well above ceiling height, is another important feature of the climate response system. In the *Bolon* house, the roof slopes are designed to shed heavy rainfall quickly and minimize heat on the roof surface, with ceiling heights ranging from 4 to 5 meters (Novrial et al., 2023). The design also encourages warm air to rise and exit through ridge vents or small openings at the apex. Meanwhile, the upper zone of the house exploits the stack effect, in which warm air rises and escapes through gaps in the high-pitched roof structure, thereby enhancing upward airflow and improving indoor ventilation. This creates a passive mechanism that draws cooler air into the occupied space below. Studied by Muqoffa et al. (2025), demonstrate that the method significantly improves indoor thermal comfort, particularly when cross-ventilation is limited by surrounding structures or vegetation.

Perforated walls on Fig.3, often constructed by woven bamboo or wood panels, allow for consistent airflow even under low wind environments (Jeger, 1970). These materials filter solar heat and reduce glare while ensuring the building envelope remains breathable. The shape of the *gevel*, or gable, and roof-wall also help guide wind flow into the house. The gable at the front of the house is built in two layers. While the outer layer often carries symbolic meaning and serves a visual purpose (Adeputera Yusran & Suryasari, 2016), it also helps to soften strong winds before they reach the interior. Behind this, the actual gable is made of wooden boards with narrow gaps between them. These small openings allow air to flow into the house slowly and gently, supporting ventilation without allowing strong gusts or too much sunlight. In high-humidity regions such as Samosir, these design choices are critical for preventing the accumulation of heat and condensation. Similar configurations in Southeast Asian vernacular housing have been shown to maintain more stable indoor temperatures and air quality throughout the day (Harun & Kassim, 2025).These design strategies are consistent with those identified in other tropical vernacular architectures, where passive cooling mechanisms are integrated into spatial organization and material selection to reduce reliance on mechanical systems (Murtyas et al., 2024). Furthermore, the stilted floor system, a common adaptation in humid equatorial regions, promotes subfloor ventilation by enabling airflow beneath the living area, thus mitigating ground heat and moisture transfer to interior spaces (Pan et al., 2024).


(a) (b)

Fig. 3. Vernacular house, bamboo woven and wooden wall (a) *Gadang house* (b) *Bale Mangina*
(Source: Anthony S. Rares, 2025; Saptaningtyas et al., 2025)

Spatial Use

Vernacular architecture, as the *Bolon* house evolved around socio-cultural norms rather than fixed architectural programs. This fluidity is aligned with the argument made by Amos Rapoport (2006), who noted that in many vernacular traditions, spatial usage is guided more by usage rather than by formal designations. As emphasized by Lang (1987), designing human comfort involves more than responding to climatic parameters; it is an understanding of spatial organization that determines social customs and daily routines. For instance, sitting and sleeping occur at floor level, which in turn determines the vertical zones where thermal comfort must be evaluated. This aligns with observations in *Cham Muslim* houses in the *Mekong Delta*, where multifunction spaces like living areas that also function as sleeping quarters are configured to accommodate cultural norms of seating, interaction, and privacy (Nguyen-Tran & Huynh, 2025). Recognizing these activity-based spatial patterns is important for accurately assessing the performance of passive design strategies, such as natural ventilation and thermal conditions.

If we look at the general division of space in the *Bolon* house, it will reveal the reasons for the placement of each activity zone. As expressed by Pardede (2017), women in *Batak* culture are honored by their nature task as mothers, but significantly not to have any influence in *Batak* social living, unlike men, who are honored based on their task in the position of making decisions, even for their firstborn son, who is most honored like a father. It is common for these women to be assigned the task of taking care of household needs only, which then leads to the arrangement of spaces in the house, placing service areas at the back, and their firstborn son is placed in the front area of the house. Women commonly prepare a meal and later continue weaving under the sheltered lower zone of the house. In fact, inside the *Bolon* house, the guest continues to be treated with high respect because the guest may symbolize blessings and social connections. The presence of a guest inside the house activates relational roles (Bobby Saragih, 2021). Guests are seated in the front-right corner, known as *Jabu Tampar Piring*. This position is closest to the entrance and slightly elevated in status. It is not just convenient, it is ritual significant, as it places the guests in the zone where they can be seen, heard, and served first (Nabila & Harnum, 2024). Concerning the arrangement of space within the *Bolon house, it* is determined by the cultural structure and norms that prevail in the *Toba Batak* tribal customs.

METHODS

This study investigates the relationship between environmental assessment of *Bolon* traditional house performance and residents' activity patterns within a structured process (Fig. 4), located in Hutaraja Village on *Samosir* Island, North Sumatra, Indonesia. Among the various North Sumatra traditional architectures, such as the *Siwaluh Jabu* (Karo community) and the *Bagas Godang* (Mandailing community), the *Bolon house* in Hutaraja Village remains actively inhabited while also functioning as a cultural tourism site. The research begins by identifying the structural elements of the *Bolon* house, focusing on features that promote natural airflow, such as elevated floors, roof openings, and wall perforations. Climate data from the Samosir region are then used to identify thermal comfort ranges across different months; since natural ventilation is important for indoor comfort, wind behaviour is examined as the main environmental variable in this study. Simultaneously, the observation stage is conducted to document and classify residents' activity patterns, which will be organized into an activity map, with particular attention to time-specific patterns such as food preparation in the morning, communal gatherings in the evening, and rest at midday. To examine wind environment patterns and evaluate their influence, a 3D model of the *Bolon house* is developed for wind flow simulations. The simulation results will be analyzed through visual interpretation of color-coded airflow patterns, presented as a percentage-based visual format. The analysis examines the correlations among thermal comfort, airflow, and activity zones on selected days, offering insight into how spatial and environmental design supports the timing and intensity of daily life within the *Bolon* house. Accordingly, the analysis proceeds in three stages: deriving adaptive comfort ranges, simulating the indoor wind environment, and then overlaying these with observed activity patterns in zones A–H.

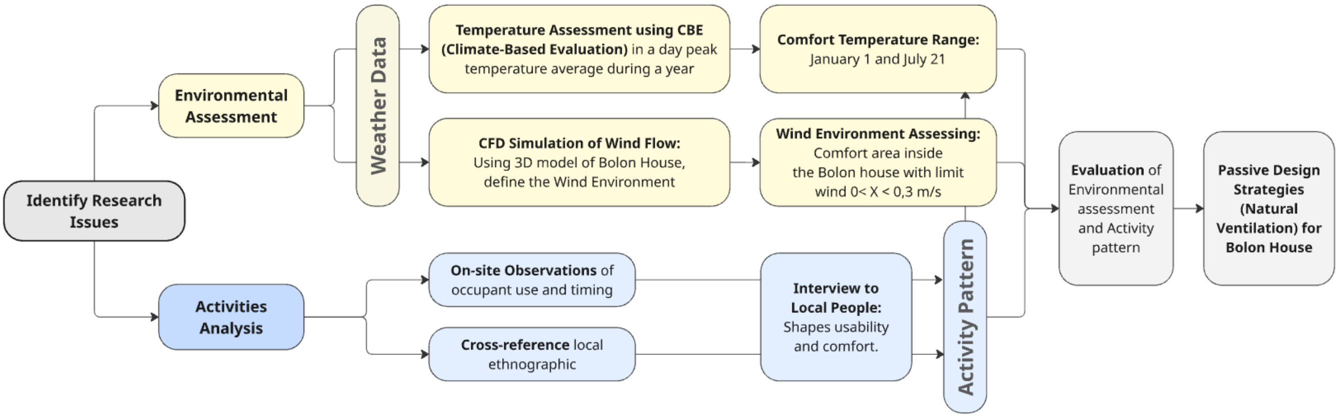


Fig. 4. Research Structure
(Source: author)

Activities Pattern from Field Observation

The *Bolon* house setting is within the *Toba* caldera, characterized by steep valleys and complex wind flow patterns under tropical highland conditions. From a passive design perspective, the *Bolon* house exhibits several architectural features that contribute to thermal regulation. The steeply pitched roof, integrated with gable-end ventilators, facilitates buoyant ventilation, allowing warm air to escape from the upper interior spaces. Additionally, the low thermal mass walls and the ventilated eaves gap between the wide overhanging roof and the vertical enclosure encourage cross-ventilation and air flushing, particularly during daytime heating periods.

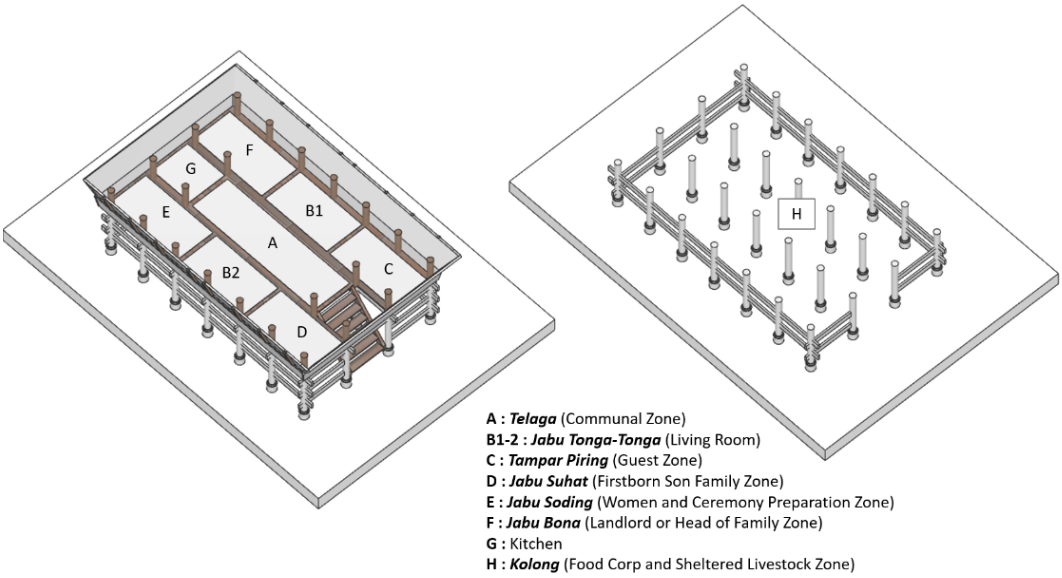


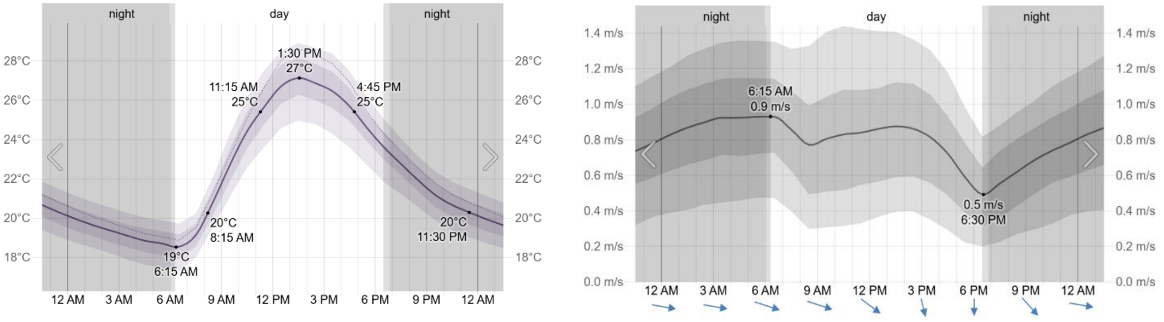
Fig. 5. Zone Division in Main Living Area (A-G) and Lower Floor (H)
(Source: Siahaan, 2019)

Field observation is essential in assessing building usage, particularly in traditional architecture, where thermal performance cannot be separated from daily spatial practices. For example, living areas often serve multiple purposes: men's sleeping quarters, guest reception, and communal gathering spaces where people typically sit and sleep directly on the floor. These spatial customs affect the relevant zones of thermal comfort to be assessed, particularly at low heights close to the ground. Such practices are also observed in the *Bolon houses* of North Sumatra, where residents engage in floor-level activities like weaving, social interaction, and food preparation.

To identify activity patterns, the observation focuses on how local people use different parts of the house in their daily routines, with particular attention to the types of activities performed, their spatial location, and the environmental context in which they occur. The daily routines of local people consistently involve movement across three spatial zones of the *Bolon* house: the indoor space (*Jabu*), the semi-indoor area beneath the stilted floor (*Kolong*), and the outdoor space (*Alaman*). Instead of the 3 main zones, any zones cover human activities inside of *Jabu* as shown in Fig. 4. The middle zone (*Telaga*) coded A is the communal area for tribes gathering for inter-family, B1 and B2 zone occupies for living room, C zone for guest room, D zone for firstborn son room and his family, E zone for women and ceremony preparation room, F for landlord room and G zone for kitchen.

Wind Environment Simulation

The *Bolon* houses in *Hutaraja* Village, located within a mountainous landscape and near Lake *Toba*, experience a distinctive microclimate shaped by both topography and the presence of a large water body. The lake moderates daytime temperatures, particularly during the dry season, by absorbing and releasing heat, thereby stabilizing local thermal conditions. As shown in Fig. 6(a), the heat pattern is lowest in the morning (06:15 AM), peaks at 1:30 PM, and then decreases until the following morning, with this cycle remaining nearly similar across the year. Demonstrate modest speed variations in Fig. 6(b), typically ranging between 0.5 m/s and 0.9 m/s, with higher velocities occurring in the early morning. However, the wind's directional pattern is more complex. On different days, wind flows show variation between Northeast (NE) and Southeast (SE) orientations, indicating that local topographical channels and daily thermal cycles can influence flow direction. Despite these variations, the predominant wind direction across the observed period is from west to east, meaning that the East wind (winds moving eastward) is the most consistent.



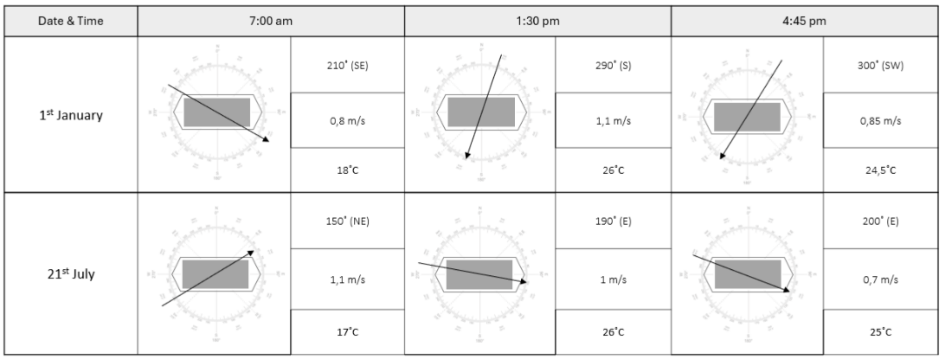
(a) (b)

Fig. 6. The Environmental Conditions, (a) Temperature and (b) Wind Behavior on a Selected Day in *Tomok Bolon*, Indonesia (Source: weatherspark.com)

To analyse the microclimatic conditions surrounding the *Bolon* houses, weather data must be collected and interpreted using the *Center for the Built Environment (CBE) Thermal Comfort Tool (comfort.cbe.berkeley.edu)*. This tool allows for the calculation of thermal comfort conditions. While the tool can also estimate thermal comfort in indoor environments using the Predicted Mean Vote (PMV) index defined by ASHRAE, this study focuses on semi-outdoor conditions and therefore employs the *Adaptive Thermal Comfort* assessment. It evaluates indoor environmental quality based on outdoor mean temperature and operative temperature thresholds that assess thermal comfort responses in naturally ventilated buildings (Al horr et al., 2016; Tartarini et al., 2020).

The selected methodology involves identifying the most difference of wind speed and wind direction, as well as temperature conditions of the year, which, based on regional climate records, typically occur around 1st January and 21st July (Fig. 7). These dates are used as a reference point for assessing thermal performance during the significantly different temperature and wind environment (speed and direction). Average wind speed data for this date are integrated into the *CBE* tool to determine the operative temperature and prevailing mean outdoor temperature. These values help to define the adaptive comfort range, identifying both the minimum (lowest acceptable temperature) and maximum (highest acceptable temperature) thresholds for human thermal comfort in a tropical climate. We calculate adaptive thermal comfort using CBE, as shown in Table 1, which indicates that the range of wind speeds (0 to 0.3

m/s and higher) is related to temperature according to the selected date and time, with the range mostly constant and slightly lower in the morning.



Date & Time	7:00 am		1:30 pm		4:45 pm	
1st January		210˚ (SE) 0,8 m/s 18˚C		290˚ (S) 1,1 m/s 26˚C		300˚ (SW) 0,85 m/s 24,5˚C
21st July		150˚ (NE) 1,1 m/s 17˚C		190˚ (E) 1 m/s 26˚C		200˚ (E) 0,7 m/s 25˚C

Fig. 7. Wind Direction and Speed on Extreme Temperature Day
(Source: weatherspark.com)

Table 1. *Samosir* Regional Thermal Assessment based on Adaptive Thermal Comfort Range (*CBE*)

Selected Time and Temperature	<0,3m/s		0,3-0,6m/s		0,6-0,9m/s		0,9-1,2m/s		>1,2m/s	
	Min˚C	Max˚C	Min˚C	Max˚C	Min˚C	Max˚C	Min˚C	Max˚C	Min˚C	Max˚C
Jan 01/7 AM (18˚C)	20	26,5	20	26,5	20	28	20	28,5	20	29
Jan 01/1.30 PM (26˚C)	22,5	29	22,5	29	22,5	30,5	22,5	31	22,5	31,5
Jan 01/4.45 PM (24,5˚C)	22	28,5	22	28,5	22	30	22	30,5	22	31
July 21/7.00 AM (17˚C)	20	26,5	20	26,5	20	27,5	20	28	20	28,5
July 21/1.30 PM (26˚C)	22,5	29	22,5	29	22,5	30,5	22,5	31	22,5	31,5
July 21/4.45 PM (25˚C)	22,5	29	22,5	29	22,5	30	22,5	30,5	22,5	31

A quantitative investigation of the wind environment inside the Bolon house was carried out using *Computational Fluid Dynamics* (*CFD*). Previous studies have demonstrated the application of *CFD* to model airflow in vernacular Indonesian houses, confirming that traditional roof and floor systems contribute to effective passive strategies in tropical climates (Suhendri & Koerniawan, 2017). Following this methodology, the 3D model was tested under selected dates above with similar environmental conditions, as ambient temperature and solar radiation level but differing in wind speed and direction. Additionally, to examine the wind environment at different heights relevant to human use, the model was divided horizontally into three sectional planes:

- H1 (1.0 m above ground level) to evaluate airflow beneath the house and under the stilted floor (important for understanding cooling by subfloor ventilation).
- H2 (0.5 m above the interior floor) corresponding to the level of seated or floor based on activities (e.g., resting, eating).
- H3 (1.5 m above the interior floor) corresponds to the average standing head height of occupants.

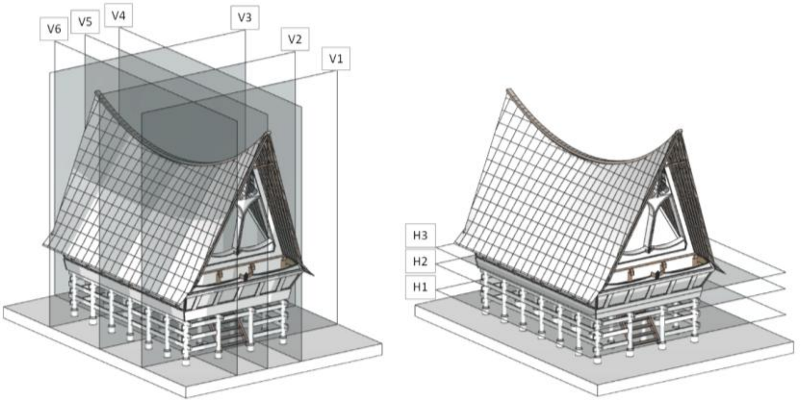


Fig. 8. Section Plan for Wind Environment Simulation
(Source: author)

The interior of the house is also divided into six vertical sections to facilitate tracking of wind environments in each room zone in the *Bolon house*. The enumeration will be given the code V1 to V6, as shown in Fig. 8.

RESULTS AND DISCUSSION

Activity Pattern

Typically, a *Bolon* house is home to several families, most of whom are related by blood or marriage. This form of cohabitation reinforces a spatial logic rooted not in individual privacy but in shared social and functional practices. As confirmed by (Napitupulu et al., 2020), communal living based on kinship remains common among *Toba Batak* households, with extended families organizing domestic life around shared spaces and inherited architectural typologies. Activities are classified based on their timing, frequency, and spatial distribution. This method enables a structured understanding of how different parts of the house serve multiple functions throughout the day. For instance, the same platform may function as a sleeping area at night and a communal gathering or food preparation space during the day. Certain areas may serve different purposes across the day, guided by informal understandings within the community. This flexible, time-responsive organization of space creates what scholars have referred to as *imaginary zoning* functional boundaries that exist through shared custom rather than walls or furniture. Research on Indonesian traditional housing supports this, noting how spaces shift in role depending on climate, social interaction, and time of day (Wiryomartono, 2020). As detailed in Table 2, the local people's activities typically correlated with time, and the house zones that are named (alphabetically) indicate the zone function. For example, men leave the house early to tend to agricultural fields or livestock, while women engage in weaving or domestic tasks, often outdoors or in communal areas. Children, meanwhile, spend the daytime at school or in courtyard areas and return home in the evening.

Table 2. Activities Based on Time and Age-Gender Classification

Time	Men (M)	Zone	Women (W)	Zone	Children (C)	Zone
05:00–07:00	Animal care (feeding, cleaning beneath the house)	H	Morning food preparation	G	Assisting parents/morning routines	A, B1, G
07:00–10:00	Farming / attending clan meetings in *Alaman*	-	Rice pounding, food prep, weaving	B1, E, G	Playing in the courtyard (*alaman*) & school	-
10:00–12:00	Wood gathering / minor house repairs	H	Water fetching/household tasks	-	Learning from elders / informal play	-
12:00–14:00	Rest / informal meetings	A	Cooking/eating with family	B1, G	Rest/eating/play	B1, D, E
14:00–16:00	Preparing ritual items or structural tasks	A	Sewing / weaving / preparing offerings	I	Cultural games/music practice	-
16:00–18:00	Returning livestock under house	H	Evening meal prep	B1, G	Bathing/helping parents	B1, G
18:00–20:00	Clan storytelling, singing, dancing with family	A	Participation in communal rituals / talking with elders	A, E	Listening to stories / joining family events	A
20:00–22:00	Rest or final livestock check	A, H	Cleaning up the house and weaving equipment	A, B, C, D, E, F, G	Sleeping/ storytelling with elders	A, D, E
After 22:00	Sleep	D, F	Sleep	D, E	Sleep	D, E

Inspired by Gómez et al. (2014), we observed residents' activity within the *Bolon* house by tracking how long residents spent in both the upper and lower parts of the house. Based on our fieldwork in *Hutaraja* Village, we visualized three scenarios of daily use mirroring the "activity pattern" method by mapping time spent at each location to reveal patterns of occupancy and movement. This representation enabled us to identify daily rhythms of local life within the *Bolon* house, distinguishing how cultural and functional use emerges in different areas over time. By giving the group based on color, it helps to identify in which zones each of them uses in the morning until night, based on their daily activities. From the acquisition of colored circle plotting, it will be known whether these zones are used by 1 group or can accommodate 2-3 gender groups in one day, so the circles will appear to overlap.

The pattern shows how different parts of the *Bolon house* are used by M (men), W (women), and C (children) throughout the day. In general, men engage in more outdoor activities during the daytime, resulting in limited interaction within the house, and are present in the lower area of the house only twice. Meanwhile, women use the spaces within the house primarily for cooking and cleaning. Children are outside during school hours and in the afternoon to play in the yard, and they are indoors during the day and at night to rest. Waterson (1990). Explain an ethnographic comparison of traditional Southeast Asian houses, including the Batak tribe's rules on layout and spatial use, which affect social relationships. It discusses how spatial divisions serve cultural roles: public areas welcome outsiders and affirm social ties; semi-private areas support communal daily life; and private areas reflect notions of modesty, seniority, or gender roles. This classification is shown in Table 3 in traditional houses, such as the *Bolon* house, that rely on passive design strategies. Activity patterns are important because they influence when and where spaces are used to maintain thermal comfort. These residents' locations within the house indirectly affect their exposure to airflow. As airflow is one of the environmental factors that contribute to thermal comfort in tropical climates, the relationship between spatial use and wind behaviour is further examined through wind environment simulation in the following section.

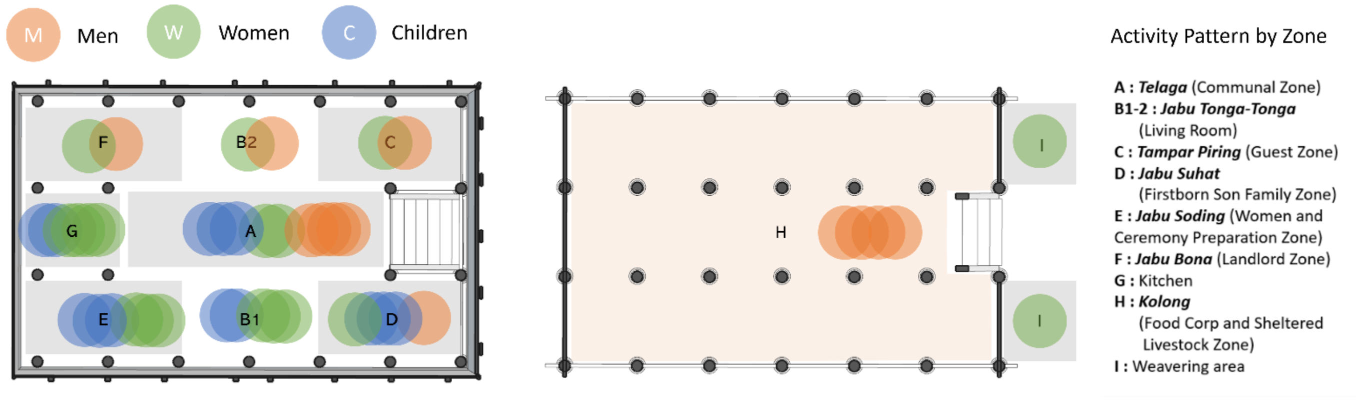


Fig. 8. Activity Pattern in *Bolon* house
(Source: author)

Table 3. Spatial Division Classification

Activity Pattern by zone	Men - Women - Children	Women - Children	Men - Women	Men	Reasons
A	•				Shared space for both family and guests (public area)
B1		•			Living room for guests (public area)
B2			•		Living room for family (semi-private area)
C			•		Space for a guest bedroom, no children's activity (public area)
D	•				Private room for family sons, including children (private area)
E		•			Women's room, also children help with chores (semi-private room)
F			•		Landlord's room (private room)
G		•			Kitchen (semi-private room)
H				•	Livestock area (semi-private room)

Wind Environment Assessment

For environmental CFD simulations, we identify the peak temperature range (cf. Table 1) and the different wind environment patterns recorded at the *Tomok-Bolon* weather station (cf. Fig. 6) for two dates: the 1st of January and the 21st of July. As shown in Fig. 9, each zone is assessed by the percentage of area experiencing "No Wind" and "Weak Wind" conditions. The study Shaeri et al. (2018), found that indoor wind speeds in traditional tropical houses were low, starting at calm levels (<0.3 m/s) in the early morning and reaching only light breeze levels (1.6–3.4 m/s) later in the day. These values remained below the gentle breeze range (3.4–5.4 m/s), which is generally considered more effective for natural ventilation and thermal comfort. Zone H is constantly windy, unlike the other zones. This relates to the Bolon house structure, in which the livestock area is located beneath the elevated floor. The open underfloor space allows wind to pass more freely, resulting in continuous airflow in this zone.

Zones C, B2, A, B1, and D experience slightly more airflow. In July, wind exposure improves in some areas, notably in zones C, B2, A, B1, and D, where Weak Wind percentages rise, reaching up to 30%. While zones G, E, and F have constant Weak Wind both in January and July. Despite these internal variations, the entire range of indoor airflow remains within the under 0.3 m/s threshold, which is consistent with the CBE adaptive comfort range. Generally, low wind velocities suggest that the layout and building envelopes of the *Bolon house* limit direct wind penetration. Interior partitions, the elevated floor, and the roof structure help regulate airflow, allowing the house to maintain relatively stable indoor conditions despite seasonal changes in wind direction.

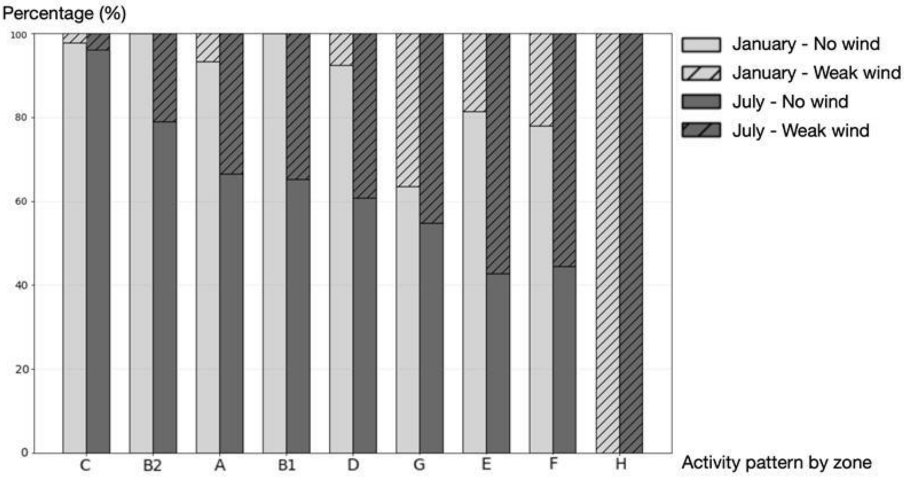


Fig. 9. Overview of Wind Environment Across All Zones in *Bolon* House
(Source: author)

Comfort Zone based on Wind Environment

Based on consistent activity patterns, three key time intervals were identified: morning (around 7.00 AM), midday (12.00 AM – 2.00 PM), and late afternoon (4.00 – 6.00 PM). These periods reflect moments when interior spaces are most actively used, allowing the study to assess the interaction between thermal conditions and spatial behavior. As shown in Table 3, group divisions are based on age-gender activities within each zone; 3 significant groups are identified. Group of Men-Women-Children using the zone, even for the guests and other families when they come to the house. Group of Women-Children indicates the service zone, household support zone, and living room for the family. A group of Men-Women consists of a private room for the landlord, a zone for welcoming guests, and a bedroom for guests. Thus, separated groups help explain the division in wind simulation results (Fig. 10). The chosen group, although it varies by activity, time, and age-gender, also reflects the cultural values of the Toba Batak tribe that place importance on serving guests. Then, the divided chart in Fig. 10 shows wind conditions separated by the guest activity zones (F, B2, C, A) and the family zone (E, B1, D, G, A), compared with the most stable zone A.

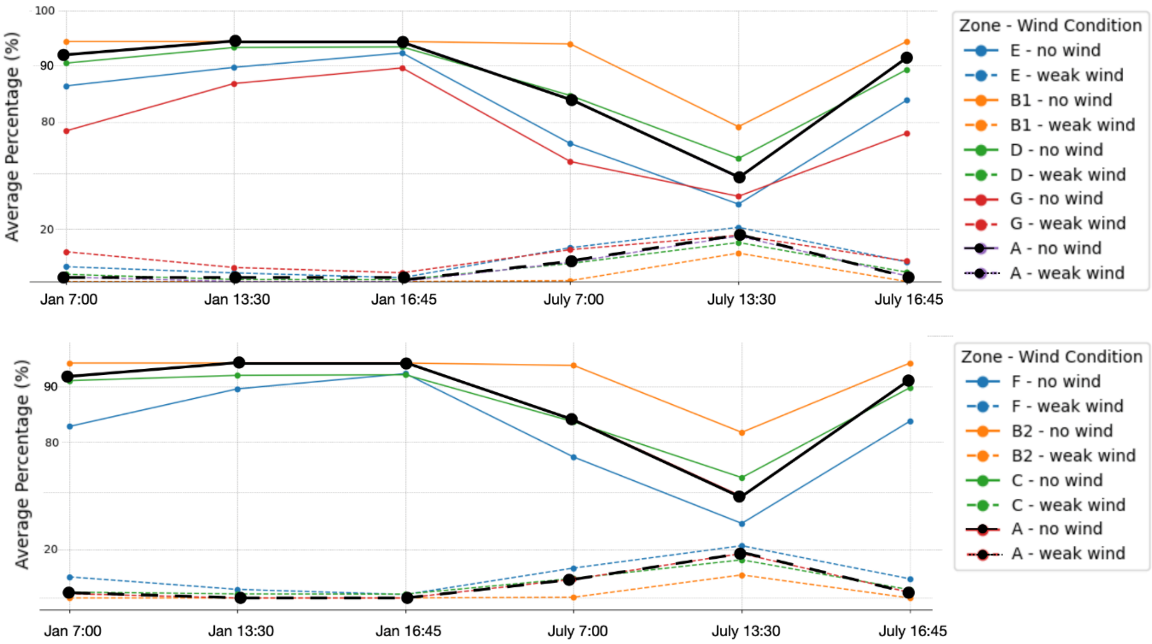


Fig.10. Tendency of Wind Flow at Defined Time Intervals of January and July in Each Zone
(Source: author)

Based on the wind environment in the *Bolon* house simulation, functional zones have been identified, each associated with specific patterns of occupant activity (cf. Fig. 8) and two specific wind patterns of indoor zones, characterized as no wind zone and weak wind zone (cf. Fig. 9).

Seasonal variations in the indoor climate of the *Bolon* house are particularly influenced by the East wind, which is most pronounced during the dry season, especially in July. This wind direction significantly affects peripheral west zones, notably zone E (rear-left), traditionally associated with female family members, and the kitchen area (zone G), where airflow levels increase modestly. This wind direction affects peripheral zones such as zone E and zone G, where airflow tends to increase slightly due to fewer structural enclosures on the eastern and southeastern sides. Based on all zones, a weak wind slightly increases during the afternoon hours in July, indicating a consistent pattern of airflow later in the day. Zone A is considered the best median to separate 2 parts of the wind environment. Zones B1, B2, C, D, and E are rather stable and comfortable throughout the day. However, zones F and G show more fluctuation, tending to experience partial weak wind in the morning of January and from morning until afternoon in July.

Zone G shows less thermal stability compared to the core areas of the house. However, this fluctuation aligns with the nature of the activities conducted there, primarily cooking and food preparation, which generate additional metabolic heat. The higher body heat output during these activities raises the occupant's thermal tolerance, meaning that even with increased air movement or temperature shifts, comfort levels can still be maintained. In this case, the modest increase in airflow during east wind periods helps excess heat disappear, creating a microclimate that remains functionally comfortable despite greater thermal variability. For zone G, this increase aligns with the timing of cooking activities and may be considered to support thermal comfort. The increase in weak wind in July in zone G could be beneficial for comfort.

In contrast, zone D, the firstborn living room area located toward the front and often aligned eastward, remains better protected from direct wind penetration due to the position being quite far from the peripheral East wind affected. Zone F for the landlord's area, positioned at the rear-right, shows relatively higher wind exposure compared to the core zones, possibly due to its placement near cross-ventilation paths between roof gaps and elevated floor slits. Despite the overall low airflow velocity within the house, these variations allow each spatial zone to support specific daily activities. The layout accommodates communal functions, food preparation, and private rest in a way that aligns with both thermal comfort expectations and culturally defined spatial use, demonstrating the *Bolon house*'s adaptive responses to seasonal and directional wind influences. Despite zone F during the January morning, no wind exposure could result in discomfort.

CONCLUSION

Environmental adaptation in the *Bolon house* reveals a relationship between cultural values and spatial layout through the viewpoint of the environment, where cultural considerations shape the indoor zones. The analysis focused on the indoor wind environment and its effect on indoor comfort in the *Bolon* house. It is calculated by the CBE Comfort Tool and simulated by CFD during activity timeframes. Weather data collected during occupied hours ranged from 18–26 °C, staying within the comfort zone of 20–31,5 °C and 0,3-1,2 m/s for wind speed as defined by the *Adaptive Thermal Comfort* tool. The horizontal sections of the *Bolon* house (H1–H3) reveal airflow behavior at human heights, from underfloor movement to sitting and standing levels. In contrast, the vertical sections of the *Bolon* house (V1–V6) capture both longitudinal and transverse airflow patterns, highlighting the stack effect that drives air upward and out through the roof, offering a natural ventilation performance. Simulation results show no wind in the protected core and weak wind in peripheral service zones, suggesting that cross-ventilation happens without producing discomfort, while being effective on a stilted floor, where the absence of walls promotes airflow. Inside the house, the breathable wall and high roof structures enable a stacked effect that drives vertical air movement upward due to lower density and escapes through openings at higher levels. This upward movement reduces indoor heat accumulation and simultaneously draws in cooler air from lower openings.

Concerning activities by zone, the analysis of wind flow helps demonstrate that the vernacular architecture of the *Bolon* house reflects an understanding of environmental conditions. The correlation between activity patterns and wind environments appears to support the way occupants achieve thermal comfort. The findings show that airflow tends to affect the service zones, while the bedroom and gathering areas remain consistently protected throughout the year. To improve comfort, zones such as the landlord's or women's spaces may be more suitably placed nearer to the central communal area. However, given the symmetrical layout of *Bolon* houses, such as those in *Hutaraja* village, reversing the orientation of the house does not significantly alter the comfort in each zone.

On a bigger scope, the vernacular architecture incorporates passive design principles, considering cultural customs. Vernacular houses are not merely historical artefacts that overlook the local wisdom; they can inspire design ideas for modern architecture, which too often pursues appearance and technology while neglecting contextual issues. From a practical perspective, the findings can give insight for architects and designers working on projects that involve traditional cultures or indigenous communities, especially in the planning of activity zones, where decisions face challenges regarding customs and environmental issues. By demonstrating how traditional houses like the *Bolon* house respond to environmental conditions, the study provides scientific support for incorporating vernacular strategies into restoration efforts. It also offers insight into empowering local communities to recognize and advocate for their traditional dwellings with greater comfort and harmony with nature than modern houses.

Finally, since this research focused on wind behavior and its relationship to activity patterns, using CFD simulations and adaptive comfort ranges from outdoor temperature. Humidity and mean radiant temperature (MRT) were not directly analyzed due to the scope limitation and lack of indoor measurements; however, the consistently high regional humidity (85% in Samosir) and shading from deep eaves are likely to support the low wind speeds found comfortable within adaptive bands. Future work should measure these parameters onsite to validate that architectural features moderate radiant heat and moisture alongside airflow. In addition, ethnographic methods, including deep interviews and spatial observations, are needed to explore how residents perceive and adapt to indoor comfort conditions. Combining physical data with lived experience will provide a comprehensive correlation between environmental and cultural factors in the spatial use and performance of vernacular architecture.

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