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An investigation on climate responsive design strategies of vernacular housing in Vietnam

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ABSTRACT

Energy conservation issues and environmental problems in recent years have increased interest in traditional architecture which is well known for its energy saving designs. This paper thoroughly investigates vernacular housing designs and evaluates on the aspect of building physics. A new research methodology which is adapted to the natural and social context of Vietnam was proposed and applied. The process was carried out step by step, including: climate zoning, systematic analysis, in-situ survey and building simulations. The results of this study indicate that vernacular housing in Vietnam is creatively adapted to the local natural conditions and uses various climate responsive strategies. Through this study, the most frequently used strategies and their effectiveness were derived. The authors also found that under extreme weather conditions, traditional designs might not be sufficient to maintain indoor thermal comfort.

Keywords : Vernacular housing ; Climatic design strategies ; CFD ; Solar shading ; Thermal simulation

1. Introduction

In recent years, facing the risk of global warming and of the depletion of fossil fuels, reduction in energy consumption along with sustainable development is a priority for many countries, including Vietnam. Today, we generally acknowledge that the building sector consumes about one-third of the total energy consumption worldwide and this figure may vary according to building type and location. In 2010, the building sector in Vietnam occupied between 20% and 24% of the total national energy consumption and this portion is expected to increase significantly [1]. Reducing energy use, especially energy used by occupants of buildings, is an important issue in Vietnam as the country is constantly in the state of energy crisis. Research to reduce energy consumption in the building sector through climate responsive strategies without compromising human comfort is essential. Vernacular architecture is widely recognised as a practical, effective and popular solution.

Vernacular architecture is a term used to categorise methods of construction which use locally available resources to address the local needs [2]. Vernacular architecture results from long-term growth and is part of traditional popular culture; therefore vernacular architecture is considered well adapted to the natural and social conditions of a specific location in which it exists.

In Vietnam, many detailed studies have shown that Vietnamese vernacular architecture is multiform and valuable. Unfortunately, due to many fierce wars, the impact of state policies (for example the land reform from 1953 to 1956) and natural disasters, much vernacular architecture in Vietnam has been destroyed or has disappeared altogether. Today, those remaining are very modest in scale and form, but the architectural and environmental lessons that they provide are still considerable.

The principal purposes of this study were to: (1) search and discover the underlying climate responsive strategies conceived in vernacular architecture; (2) transform and recommend appropriate solutions for current design and construction, aiming towards sustainable development and (3) assess the importance of preserving the vernacular housing remaining in Vietnam.

Six old houses in rural and urban areas spread over the 3 regions of Vietnam, representing vernacular architecture, traditional architecture and old architecture, were thoroughly investigated to understand the climatic design strategies employed and their effectiveness in maintaining human comfort and health.

2. Materials and methods

To comprehensively and systematically review architectural strategies in Vietnam, both scientific methods and respect for the natural and social context was essential. Various approaches were employed in the literature. Dili et al. [3] used *long-term in-situ measurement method* to evaluate the thermal environment in a traditional building in Kerala, India. Cañas and Martín [4] employed *statistical method* to gather data about vernacular Spanish buildings and categorised them into different bioclimatic strategies based on their locations. By doing so, they found the most frequently used strategies which correspondenced to the building locations and local climate. Vissilia [5] conducted a study to evaluate a sustainable Greek vernacular settlement by using *subsequent analysis*, based on two major steps: (1) a study concerning the evolution of the built environment (typological analysis, site planning, construction materials and techniques), and (2) an evaluation of specific vernacular dwelling types and their response to climate, based on passive design principles. She has made it clear that the vernacular settlement demonstrates an economical use of local building resources, adapting to climatic conditions without using much energy and providing human comfort.

Manioğlu and Yılmaz [6] studied energy saving design strategies employed in ancient housing in Mardin, Turkey. They made a simplified thermal evaluation and *comparison of a traditional house with a contemporary house* by using *in-situ measurement method and questionnaires* which were carried out for 100 buildings. They found traditional houses performed better than their counterparts in providing human comfort and energy saving.

In an intensive study in Japan, Hiroshi et al. [7] researched four traditional farmhouses using both *in-situ measurement and computer simulation* on a model house. Their findings revealed that cooling technologies of traditional buildings, such as solar shading by thatched roof, earthen floor and natural ventilation et cetera are effective for interior cooling.

The territory of Vietnam stretches from the North to the South and along the country the complex social background differs. Based on these geographical and social characteristics and referring to all the above-mentioned methods (in-situ measurement, statistical method, comparative study and computer simulation), this study proposes a new approach for analysing and evaluating vernacular dwellings in Vietnam in terms of building physics. This approach includes six subsequent steps as clearly described in Fig. 1. It is expected that both qualitative and quantitative analysis included in this method will reinforce the findings from this study.

Fig. 1. *New approaches and steps proposed and applied in this research.*

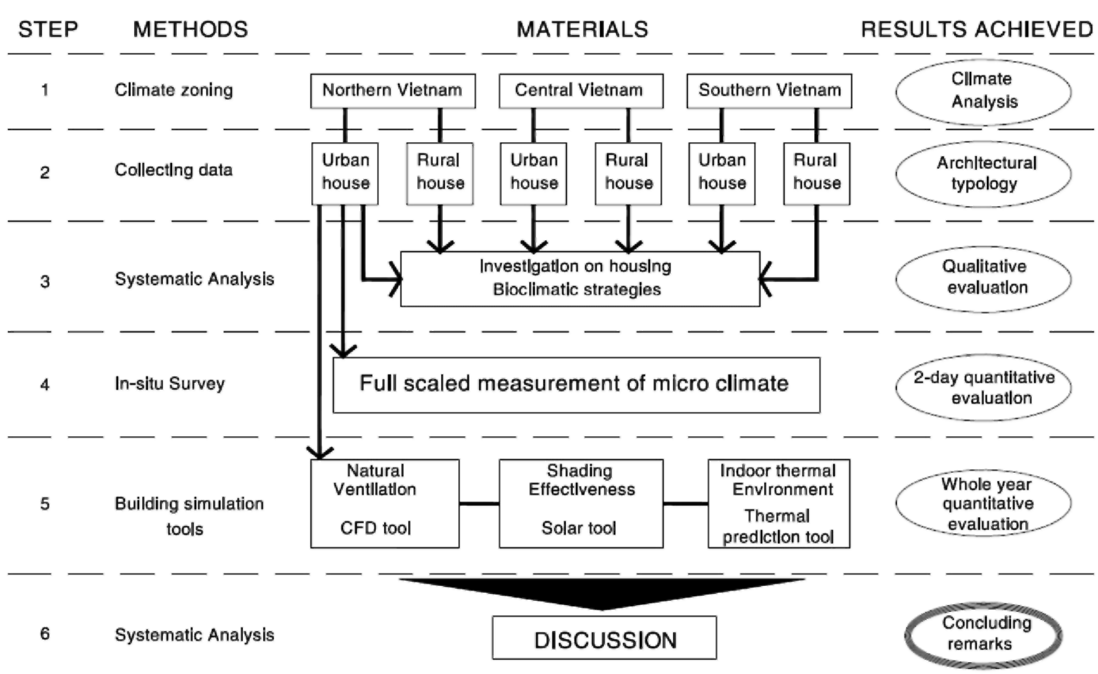

Fig. 2. *The map of Vietnam which shows the selected sites of the present study.*

Fig. 3. *Sun paths and climate data of three selected sites.*

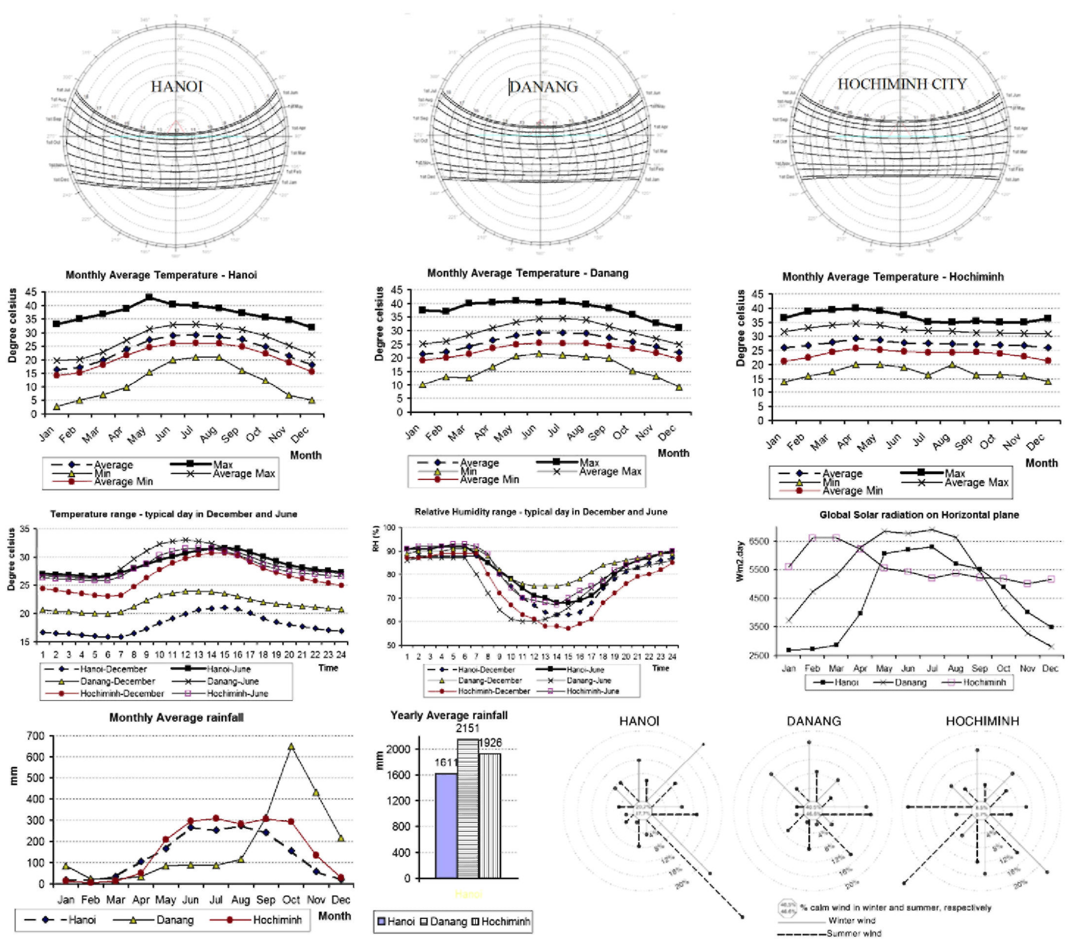

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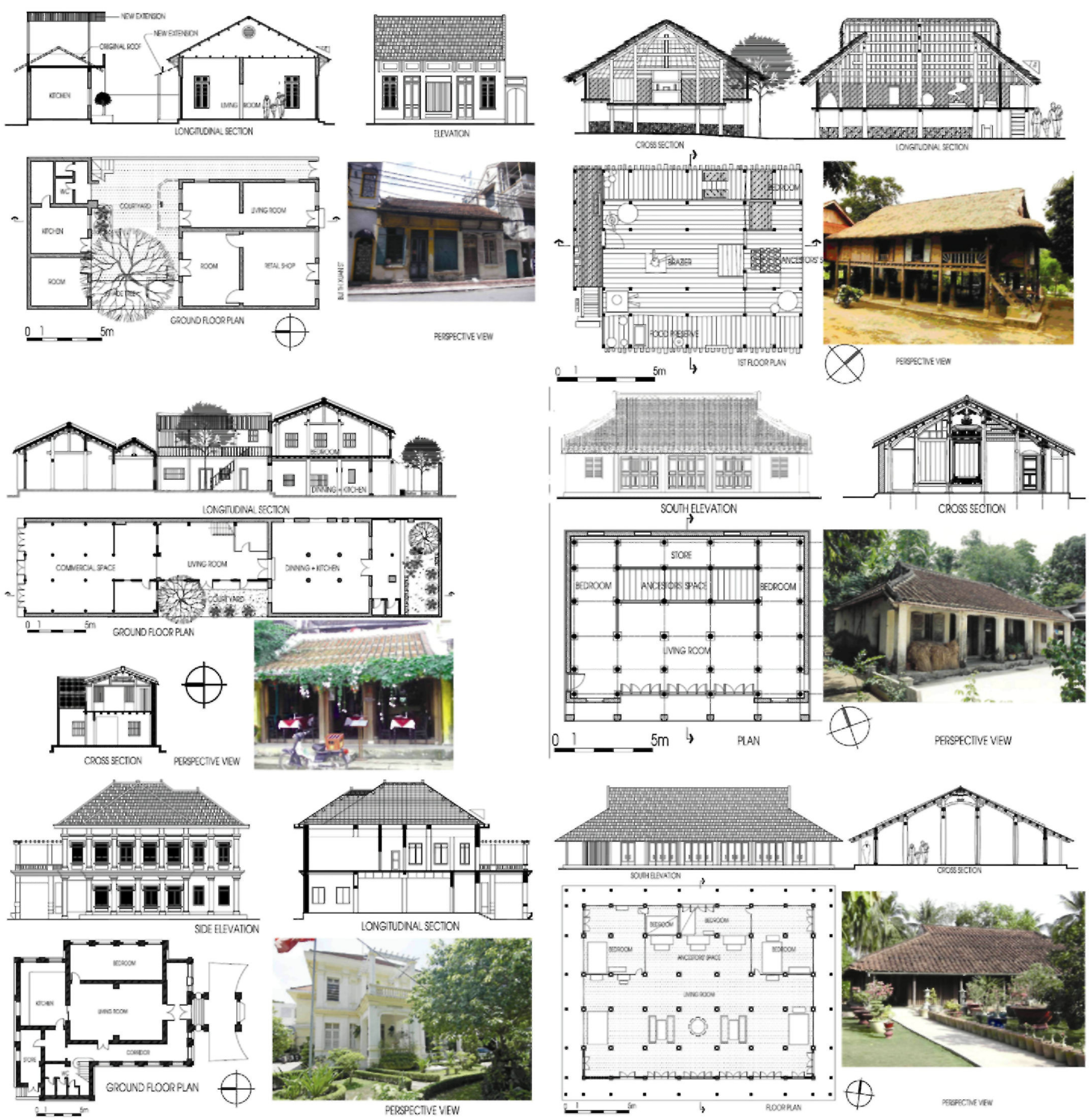
Fig. 4. *Traditional life on boats affected the housing style of Viet people: (a) ancient boat and (b) ancient house found on Dong Son bronze drum 6th century BC; (c) current Viet communal house.*

Fig. 5. *Architectural details of selected houses: house A; house B; house C; House D; house E; house F (from left to right and upper to lower, respectively).*



3. Theory, measurement, calculation and results

3.1. Step 1: climate zoning and selected sites of the survey

All the climatic data used in this analysis were gathered from Vietnam Building Code 2009 [8]. Data in the Code is based on monitoring data over several years from Meteorological stations of the Vietnam General department of Hydrometeorology. In this analysis, three typical sites, including Hanoi (*latitude*: 21° N), Danang (*latitude*: 16° N) and Hochiminh city (latitude: 11° N), which represent the three climatic regions in the North, Centre and South of Vietnam, were selected (see Fig. 2). Weather conditions in December and June, representing the winter and summer periods, were chosen for analysis and comparison.

Fig. 3 shows all climatic data of three selected sites in the diagrams and charts. It is clear that the Sun mainly moves on the South sky of the observation points; and the three sites have very high solar radiation, relative humidity and average yearly rainfall. We also emphasise the following points on the climatic features of each site:

- Hanoi has a short cold winter, but the lowest temperature hardly falls below 5 °C. The highest temperature can reach 40 °C. Temperature and humidity are generally moderate. Rainfall as well as rain intensity are more significant. Protection from the cold winds is required in winter. Generally, Hanoi is not affected by tropical storms.

- In Danang, the climate is tropical with monsoons. The winter is not cold and the lowest temperatures are often well above 10 °C. The highest temperatures can exceed 40 °C. Because of the impact of the sea, daily and yearly temperature ranges are quite small. Protection from the cold is not required. Coastal parts are directly influenced by strong tropical storms and rainfall often peaks during the month of October making appropriate roofing essential.

- Hochiminh city has a hot and humid climate with monsoons all year round. There are only two annual contrasting seasons; dry and wet, both consistent with two inhomogeneous monsoons in the region. Rainfall is quite high. Air temperature and solar radiation are quite high all year which indicate that cooling is in demand. Wind is abundant all year round and this resource can be exploited for passive cooling strategies, especially when the hot weather is uncomfortable.

3.2. Step 2: collecting data

Vietnam is a country of rivers. Its origins can be traced from two big deltas established by the Hong river in the North and the Cuu Long river in the South. In ancient times, Viet people travelled on boats, and then lived in stilt houses which have influenced current communal houses (see Fig. 4). Today, in many parts of Vietnam, people still live in stilt houses like their ancestors did.

Most traditional houses in Vietnam have been destroyed or have completely disappeared due to damage caused by wars, natural disasters and even the policies of both feudalism and the government. Those remaining, among which the most ancient house (property of the Nguyen Thac family) was built in 1734 [9], are modest in size and age.

This study investigated six typical houses in three climatic regions mentioned in Section 3.1. Each region is represented by two houses: one in an urban area and the other in a rural area, since many significant differences between these two housing styles exist. Urban houses are typically large, multi-functional, and influenced by foreign architectural styles whereas rural houses are smaller, purely vernacular and are only used for living purposes. All six houses are typical in terms of style and size and are in good state of repair. The purpose of this selection is to find the climate responsive designs corresponding to all climate types in Vietnam. Architectural details of these selected houses are presented in Fig. 5 and their specific data is listed in Table 1.

It is well-known that vernacular housing all over the world makes use of materials found locally which reduces energy consumption and environmental impact and also encourages local characteristics which is also the case of the houses studied (see Table 2).

Among the above mentioned materials, some types were widely used in housing construction in Vietnam, especially in rural areas, until the end of the 20th century. These materials have certain advantages and positive characteristics as described in Table 3.

Table 1 *General information about the houses in question.*

Code	Location	Climatic region	Year of cons.	Architectural style	Function	Construction method
House A	102 Bui Thi Xuan st, Hanoi city	North	1920	Traditional urban style	Commercial and living space	Traditional methods - workers were employed from adjacent trade villages of Hanoi
House B	Hoabinh province	North	NA[b]	Vernacular style	Living space	Mainly by owners with unwritten experience from their ancestors.
House C	75 Tran Phu, Hoian city	Central	1860	Traditional - Japanese influence	Commercial and living space	By local skilled workers of traditional carpenter bands, e.g. Kimbong or Vanha
House D	Tien Canh ward, Tienphuoc district, Quangnam province	Central	1890	Vernacular style	Living space	Traditional methods - by local skilled workers of traditional carpenter bands
House E	32 Tran Quoc Thao st, Hochiminh city	South	1920[a]	Colonial style	Living space	By French design and local builders
House F	Tan LyTay ward, Chauthanh district, Tiengiang province	South	1901-1904	Traditional style	Living space	By local skilled workers of traditional carpenter bands from Central Vietnam

[a] Year of construction estimated.
[b] Not available (housing style has existed for centuries, but the life span of each house is not very long).

Table 2 *Types of materials used in the houses investigated.*

Code	Foundation	Wall	Structure	Roof	Floor	Openings
House A	Normal solid fired clay brick	Solid brick wall with plaster on both sides	Load bearing wall and timber	Fired clay tile on timber frame	Cement tiled floor	Timber and glass
House B	No foundation	Bamboo lattice or wooden panel	Bamboo and wooden frame	Thatch (rice straw, thatch, reeds, palm leaves...)	Broken neohouzeaua[c]	Bamboo lattice
House C	Stone or burned clay brick	Fired - clay bricks with plaster on both sides	Hard timber	Fired clay tile on timber frame	Fired clay brick - wooden floor	Wooden panel
House D	Laterite stone[a]	Mixture of clay and straw on bamboo lattice[b]	Hard Timber	Two layers: Thatch roof (upper) and ramped earth (lower)[d]	Ramped earth	Wooden panel
House E	Stone	Fired - clay brick with plaster on both sides	Load bearing wall	Fired clay tile on timber frame	Reinforced concrete + cement tiles	Wooden panel
House F	No foundation	Wooden panel - vertical bars	Hard timber	Fired clay tile on timber frame	Fired clay brick	Wooden panel

[a] A special porous stone naturally formed from laterite soil (in Vietnamese: "dâ ong"), exploited by a local inhabitant. Laterite blocks connect together with mortar made from lime, resin of "boi loi" tree and molasses (treacle).
[b] It was replaced by a fired clay brick wall about 20 years ago.
[c] A kind of bamboo which is very small.
[d] The thatch layer was replaced by fired clay tiles about 20 years ago.

***Table 3** Most used materials and their properties.*

Materials' name	Advantages[a]	Notes
Bamboo	High durability[b], local availability, easy fabrication, multi-purpose usage, high tensile strength (up to 200 MPa), compressive strength up to 70 MPa, light - weight material (about 630 kg/m^3)	Fire prevention
Laterite stone	Very high durability, local availability, high moisture absorption, suitable for walls (compressive strength 20-30 MPa)[c]	Only available in some regions
Ramped earth	Available in most regions, multi-purpose usage, easy fabrication, low compressive strength (0.84-0.92 MPa)	Humidity control
Clay-straw mixture	Available in most regions, easy fabrication, low thermal conductivity (0.18 W/m K)	Low compressive strength (<4.6 MPa), erosion by rain
Thatch	Extremely low thermal conductivity (0.07 W/m K), local availability, light - weight material (240 kg/m^3), easy fabrication	Insect and fire prevention (about 180 J/kg K), durability

[a] Physical properties of these materials were obtained from references [10-14].
[b] According to vernacular experience, bamboo will have long life-expectancy and remain free from insects if it is soaked in water, under a layer of mud for 2-3 months before use.
[c] Value proposed by the authors.

3.3. Step 3: invesngation of housing climate responsive design strategies

Popular climatic strategies used in the built environment in hot humid regions were categorised and numbered as 17 architectural solutions as follows:

1. Building orientation and shape
2. Solar shading
3. Natural ventilation (cross ventilation (a), stack ventilation (b), single-side ventilation (c))
4. Natural lighting techniques
5. Light weight construction
6. High thermal mass
7. Evaporative cooling
8. Earth cooling
9. Passive cooling by using colour
10. Thermal insulation by material
11. Thermal insulation by design (e.g. well ventilated attic, double-skin facade...)
12. Passive solar energy
13. Storm prevention
14. Flood prevention
15. Rainwater discharge
16. Moisture and condensation prevention
17. Others

These 17 strategies applied in these selected houses were qualitatively investigated and evaluated using the "*Descripnon and Image*" approach. In this approach, the criteria of assessment is that if there is at least one climate responsive solution which corresponds to each of the local climatic features, the house is considered completely adapted to its local climate. Conversely, if no adaptation measures are found, the house is regarded as completely unadapted. In practice, most of the houses are neither completely adapted nor completely unadapted and are usually within this range. Subsequently, the following points were carefully examined: the advantages and disadvantages of local climatic features were identified; the drawings and photos of the buildings were analysed to show climate responsive solutions and their effectiveness; qualitative assessments were then derived based on the criteria and analysis illustrated in Table 4-6.

Detailed analysis in Table 4-6 reveals that vernacular housing in different regions of Vietnam has adapted relatively well to the climate as well as adverse weather conditions. Though the solutions employed are considered simple, inexpensive and easy to apply, they proved to be very effective, demonstrating a deep understanding of the ancestors about the building and its surrounding environment.

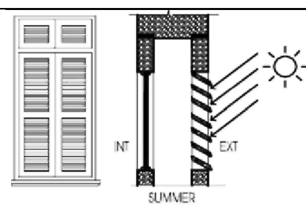
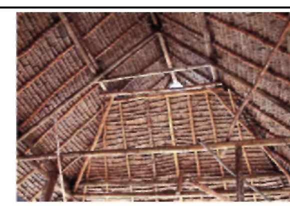
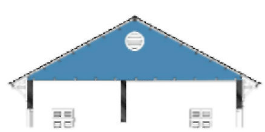
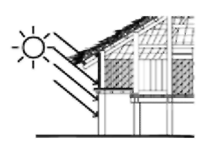
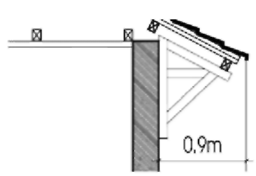
Other findings were also obtained. All strategies used were numbered and their usages were listed in Table 4-6. Consequently, the frequency of use of each strategy in these houses was found and illustrated in Fig. 6. This graph shows that in all regions natural ventilation was the most used strategy whereas earth cooling and passive solar energy were not employed. Sophisticated technical requirements may be the main reason that passive solar energy was not employed for heating in vernacular housing, but solar heating has a potential to be applied in Vietnam and needs to be investigated further. Other findings are that it is suitable and effective to employ natural ventilation, building orientation — building shape and solar shading strategies in Vietnamese climatic conditions while earth cooling, thermal insulation and high thermal mass are inappropriate. Storm prevention was only found in central Vietnam where tropical storms usually hit. Due to time and resource limitations, this preliminary investigation included only six buildings. The findings can be consolidated by larger investigations.

3.4. Step 4: full-scale measurement of micro-climate in a house

In order to have a more accurate assessment than the qualitative one mentioned above, an in-situ survey and measurement was carried out in Hanoi. Since investigations on all six houses would not be feasible, this study targeted the house at N°102 Bui Thi Xuan street in Hanoi as the unique building of full-scale measurement. The survey was continuously conducted from 8 h to 21 h on a typical summer day and winter day in Hanoi (16 December and 22 August).

All measurements were in relation to four physical climatic indexes: air temperature, relative humidity, wind velocity and natural illuminance. The results shown here are the averaged values of 10-min measurements (for mean wind velocity) and of 3-min measurements (forothervariables). The measuring points were distributed as shown in Fig. 7. The indoor air temperature, humidity, wind velocity and natural illuminance were measured at head level of a sitting person (height of 1.1 m) as recommended by ISO 7726 [15]. During measurement periods, openings of the house were operated by the occupants, adapting to outdoor conditions. Measuring instruments are listed in Table 7. The results for illumination were compared with requirements in the Vietnam building code [16] as shown in Table 8.

Table 4 *Qualitative investigation of bioclimatic design strategies used in traditional architecture - North of Vietnam.*

Climatic features	Ancient house in Hanoi centre (house A)			Traditional stilt house of small ethnic group on the mountain (house B)		
	Description of strategies used	Ca.	Image	Description of strategies used	Ca.	Image
High solar radiation, especially on West and horizontal surfaces	Openings with wooden louvres shades the glazing well	2		Thick thatch roof (about 200 mm) provides ideal insulation (U-value 0.25-0.35 W/m^{2}K). Thatch roof absorbs moisture which reduces overheating by evaporative cooling effect	10, 7	
	- Large, well ventilated attic acts as a well insulated roof	11		- Deep eaves shade short walls, protecting all walls and openings from direct sun	2	
	- Deep eaves (0.9 m) provide shading for walls. Shade tree in the courtyard provides more shade - Minimisation of heat absorption by the facades by painting them white or light colours	2, 9		- Well ventilated attic by funnel-shaped holes at the gables	11	

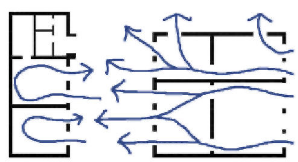
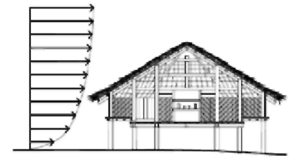
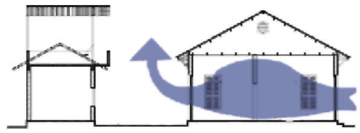
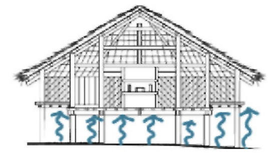
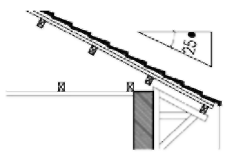
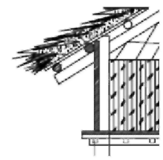
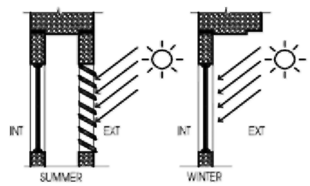
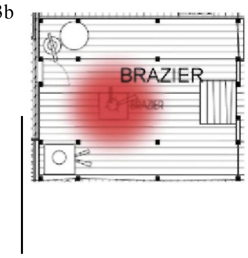
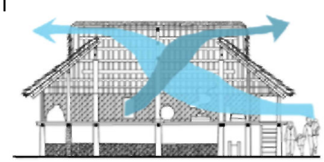
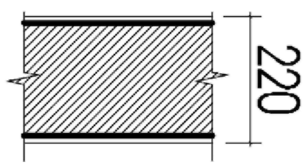
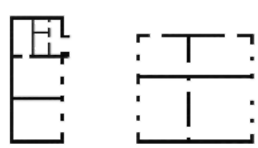
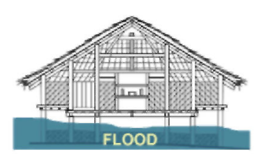
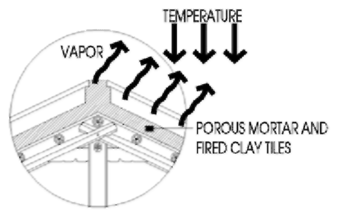
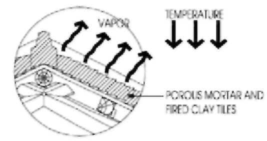
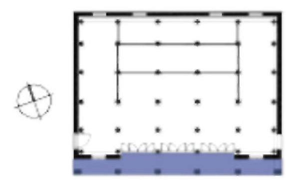
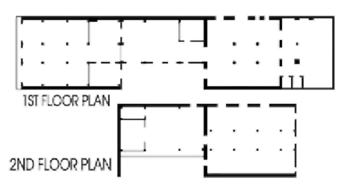
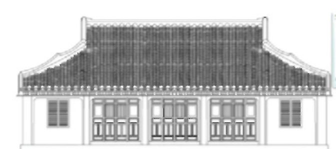
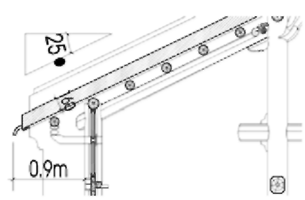
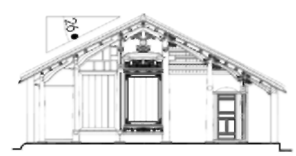
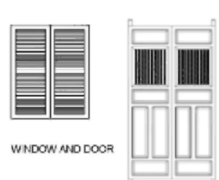
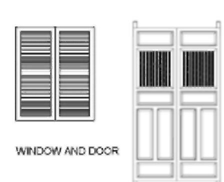
High average temperature and humidity	- Room height is 3.9 m-4.2 m and many large openings improve ventilation	3a		Stilt house easily meets airflow at higher speed. Wind speed at height 2 m can be 2 times as high as that at 1 m. The air near the ground is often stagnant	3	
	- Large and long courtyard helps e nhance natural ventilation and reduces humidity. Side corridor induces wind into the courtyard.	3a		The house is raised 1.6 m above ground to prevent moisture entering from the ground	16	
Heavy rain	- Steeped roof (25°) and deep eaves (0.9 m from the wall) - High bases of the wall prevent humidity from the ground	15		- Steeped roof (32°) and deep eaves (1 m from the wall) enhance rainwater discharge	15	
Sun path on the South sky	Strategies NOT clear due to its location in city centre			Not highly influential because of the deep eaves around the house		
Two different seasons (hot and fairly cold)	- Two layered window (French window) provides flexible and operable control of openings during hot and cold periods	17		- Cooking (brazier) is done right at the middle of the house to keep warm in winter. - Openings on the gables enhance stack effect and release smoke from the brazier	17, 3b	
North cold wind, South-East cool wind	Building orientation strategy for prevailing wind is NOT available due to its location in the city centre			Windows are oriented to the South; cross ventilation through door, windows, and openings on the gables. When there is no wind, stack effect increases airflow	1, 3a	
Low diurnal and seasonal temperature -humidity range	- Light weight construction (thin load bearing wall — 220 mm) has average time lag (about 6-7 h) - Insulation was not used	5		Light weight building components: thatch roof, bamboo lattice enclosure with high porosity, bamboo floor and wooden column	5	See Fig. 5
Others	Indoor lighting is fairly good due to many large openings and light from the courtyard	4		House on stilts adapts well to floods (from high mountain) and prevents wild animals (snakes, centipedes, insects etc.) from entering	14	

Table 5 *Qualitative investigation of bioclimatic design strategies used in traditional architecture - Centre of Vietnam.*

Climatic features	Traditional urban house in Hoian (house C)			Traditional house in Quangnam province (house D)		
	Description of strategies used	Ca.	Image	Description of strategies used	Ca.	Image
High solar radiation, especially on West and horizontal surfaces.	Thick porous roofing materials absorb moisture at night and release it during daytime cooling the roof.	7		Thick and porous roofing materials absorb moisture at night and release it during daytime cooling the roof. Main building is oriented to the South to avoid East-West solar radiation.	7 1	
	Creeper in front of the house, shade trees in the courtyard and backyard (see Fig. 5).	2		Front corridor covered by the roof protects inner space from the sun and heavy rain.	2	
				- Many shade trees, fruit-trees (e.g. jackfruit, plum...) on the West. - Heat absorption of the facades is minimised by its light colour.	2, 9	See Fig. 5
High average temperature and humidity	On outdoor walls, there are 17 windows in total (19.7 m^2) and 8 doors (23.42 m^2). S_o/ S_f = (19.7 + 23.42)/293.92 = 14.7% effectively enhances airflow	3		Many large openings facing South include: 2 windows (1 × 1.2 m), 3 grand doors (1.9 × 1.9 m), enhancing natural ventilation.	3	
Heavy rain	- Pitched roof (25°) and deep eaves along with special roof tiles at the end of the roof help to drain away the rain.	15		- Pitched roof (26°) but no deep eaves (to stabilise the house from strong wind since the building site is uncovered).	15, 13	
Sun path on the South sky	Strategies NOT clear due to the location in city centre			South shading device is dominant while North, East and West counterparts are very short to avoid strong winds.	-	
Hot and a mild season, no cold season	- Louvres window allows natural wind to go through. - "lattice above - panel below" door style allows wind to go through during operation.	3		- Louvres window allows natural wind to go through - "lattice above - panel below" door style allows wind to go through during operation.	3	

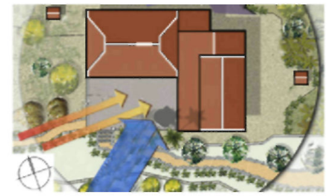
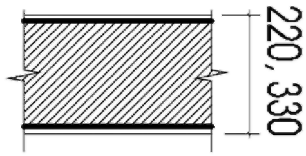
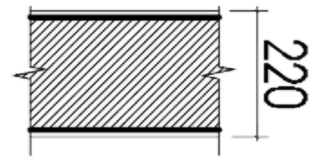
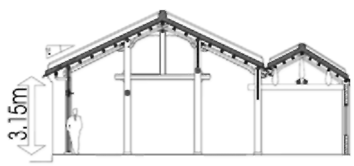
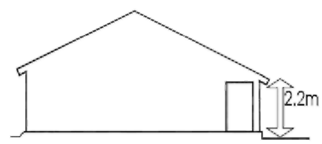
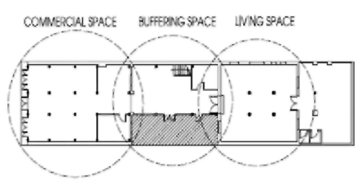
East and South-East cool wind	- Building orientation strategy is NOT available due to its location in city centre. - Front street, large courtyard and backyard improve cross ventilation. - Lighting condition is improved by the courtyard.	3, 4		- The house is oriented to the South to catch the prevailing wind. Building blocks were separately distributed - Banana trees behind the house block cold wind. Front yard enhances wind induced ventilation	1,3	
Small diurnal and seasonal temperature - humidity range	- Light and porous wooden partitions allow wind to go through - Load bearing wall (220 mm and 330 mm) are only used on two sides next to other houses. Insulation was not used.	5		- Light weight construction (thin load bearing wall - 220 mm) - Insulation was not used	5	
Strong tropical storm, wind speed up to 220 km/h)	- Low, thick and heavy roof (height 3.15 m from the ground)	13		- Low, thick and heavy roof (only 2.2 m from the ground), short eaves on other sides of the house - Strong wind (from the East) can only attack side walls of the house	13, 1	
Flood - up to 2.5 m (in 1966)	Due to its location very close to the river mouth by the sea, building a two-storey house helps to minimise inconvenience caused by annual floods as the second floor level was always higher than the peak flood.	14		Not flooded because of its location on a midland region		
Others	The front part served as commercial space, facing the crowded street while the living space was separate towards the back and isolated from the front part by a large courtyard	17		Except the front yard, shade trees have been planted around the house, providing effective shading and cooling down the air temperature	17	

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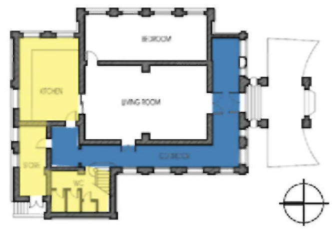
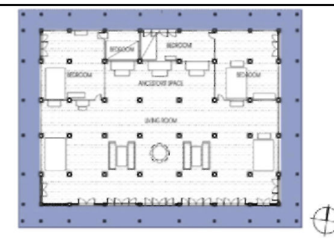
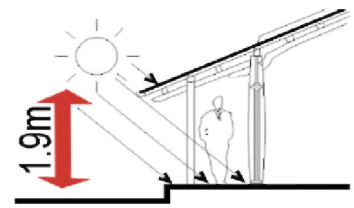
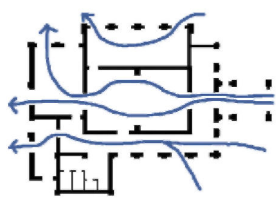
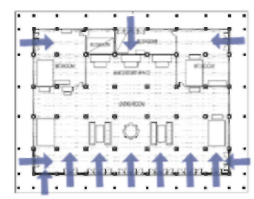
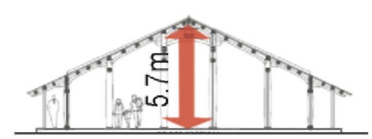
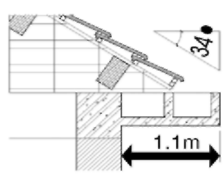
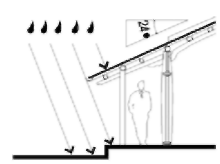
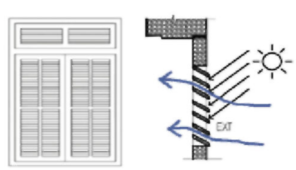
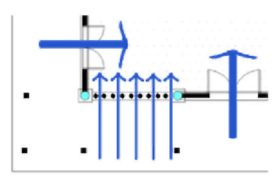
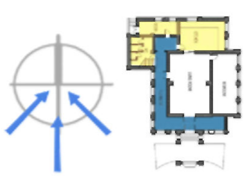
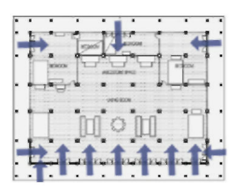
Table 6 *Qualitative investigation of bioclimatic design strategies used in traditional architecture - South of Vietnam.*

Climatic features	Old urban house in Hochiminh city (house E)			Traditional house in Tiengiang province (house F)		
	Description of strategies used	Ca.	Image	Bioclimatic strategies used	Ca.	Image
High solar radiation, especially on West and horizontal surfaces.	Wide corridors on the west and south façade protect the house from high solar radiation. Room arrangement: Stair, WC and store facing West. Main rooms are protected from direct Sun. Main façade is oriented to the South to avoid East-West solar radiation.	2 1		Corridor and deep eaves around the house protect it from direct sunlight. Main façade is oriented to the South.	2 1	
	Minimisation of heat absorption by painting the facades light colours. - Large and well ventilated attic acts as well insulated roof.	9 11	See Fig. 5 	Height of the front roof is minimised, producing an effective solar shading solution.	2	
High average temperature and humidity all year round	Many large openings in all directions including windows (1.34 m × 2.10 m) and grand doors (1.85 m × 3.40) enhance natural cross ventilation.	3		12 large openings on all the façades allow effective natural ventilation	3	
	Ceiling height is significant: 4.8 m on ground floor and 4.0 m on second floor. Ground floor is raised 0.75 m above the ground to prevent humidity	17 16	See building section in Fig. 5	Ceiling height is significant (max 5.7 m)	17	
Heavy rain	- Pitched roof (34°) and deep eaves (1.1 m from walls) with large gutter	15		- Corridor and deep eaves around the house protect it from wind driven rain. - Pitched roof (24°) and gutter operate well under heavy rain	15, 15	
No cold season, only dry and rainy season	- All louvres windows and doors create an "open" architecture, connecting the indoor and outdoor environment	3		- Vertical wooden bars replace the wall panel, allowing wind to pass through 12 large openings 24/24 h.	3	
South East to South West cool wind	- South orientation and window positioning allows airflow from the prevailing wind. WC and kitchen windows were positioned at the end of the wind flow	1		- Building is oriented to the South to catch the prevailing wind and has 9 large openings on the south façade.	1,3	

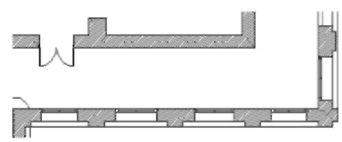
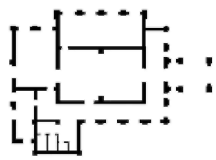
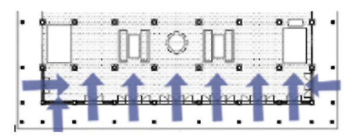
Small diurnal and seasonal temperature - humidity range	- Thick load bearing wall (400 mm on average), combined with many large openings and transitional space (corridor), provide flexible control of the indoor environment.	6		- Light weight construction (wooden walls and partitions) quickly releases heat at night (night cooling).	5	
Others	The many openings provide enough natural light for occupied rooms	4		More openings on the south façade obtain more natural light as the sun mainly moves in the south sky	4	

__Fig. 6.__ Frequency of use of different climatic responsive strategies.

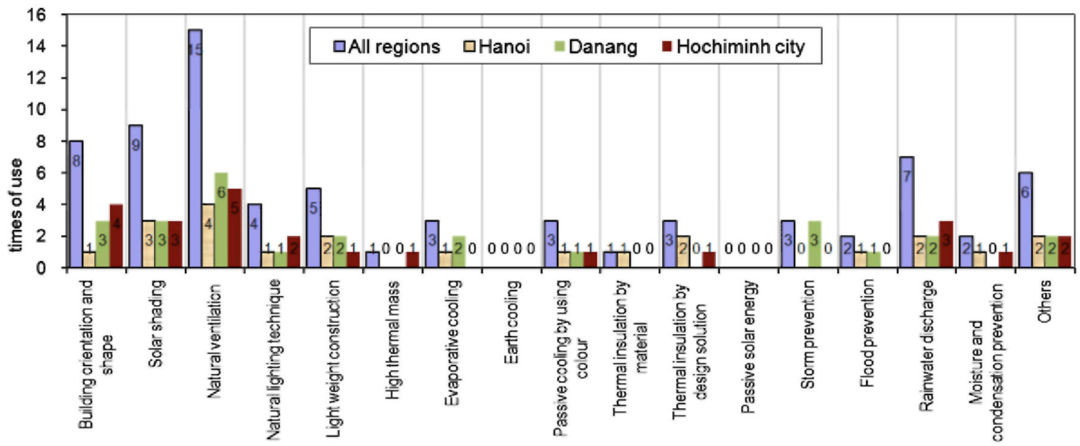


__Fig. 7.__ Distribution of measuring points (1,2,..., 10 are illumination measuring points; A, B,..., E correspond with measuring points of other variables).

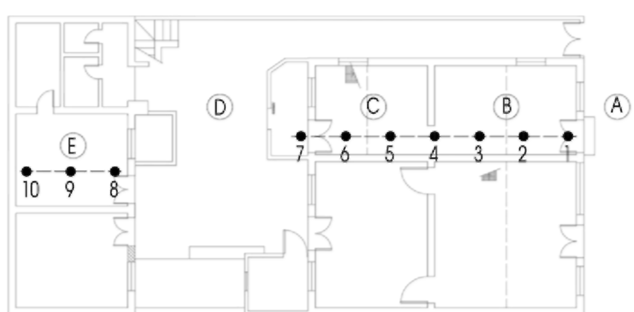


__Table 7__ Measurement instruments and their properties.

Environmental indicator	Instrument	Quantity	Accuracy	Response time
Temperature	Asman	3	± 0,2 °C	60 s
Illumination	Testo	3	± 1%	1 s
Wind velocity	Kata	2	± 2%	Depended on the wind
Humidity	Asman	3	± 3%	60 s

Table 8 *Vietnam building code of natural illumination for residential facilities.*

Index	Main room	Toilet and store
Illumination coefficient	0.5%	0.3%
Minimum illumination	50 lux	30 lux

3.4.3. Results recorded

Average air temperature, humidity and wind velocity at survey points were plotted on a combined diagram shown in Fig. 8. As can be seen from Fig. 8, there are no significant disparities between indoor and outdoor temperature as well as humidity except humidity at point E (in the kitchen) which was a little higher because of its earthen floor. This demonstrates that good ventilation of indoor space was achieved. However, daytime ventilation in summer was not appropriate since outdoor temperature was rather high. This corresponds to the study carried out by Kubota et al. [17] in which they reported that in a hot humid climate, night ventilation effectively reduces indoor operative temperature and improves thermal comfort, but the majority of occupants tend to apply not night ventilation but daytime ventilation mainly due to insects, security risks and rain. Fig. 8 also reveals that indoor wind velocity achieved in the survey was not sufficient to remove heat and humidity in summer, but was a little high in winter. High indoor wind velocity in winter could be easily reduced by an appropriate openings control. Natural ventilation performance and humidity at point E was worst since this room uses single-side ventilation.

Indoor and outdoor hourly temperature, humidity and wind velocity were also compared as shown in Fig. 9. It is clear that indoor parameters were similar to those measured outdoors. The fluctuation of indoor humidity might be caused by occupants' activities (cooking, washing et cetera). These confirm the "open" characteristics of this house which are generally recommended for hot humid climates. Another finding is that the wind velocity at point D (in the courtyard) was independent of wind conditions at point A (in front of the house). This improves natural ventilation of the rooms facing the courtyard.

In order to evaluate indoor thermal comfort, PMV index at point C in the summer and winter day was calculated using measured results. In this study, PMV calculation is based on PMV — calculator of professor de Dear [18] and on the following assumptions: average occupant's height: 1.65 m, weight: 60 kg(A_{dubois} = 1.65 m^2), wearing clothes at 0.5 clo in summer and 1.0 clo in winter at sedentary work (70 W/m^2), exposure time of 60 min, mean radiant temperature is also assumed to be equal to air temperature.

Although PMV-PPD model is the basis of comfort standards ISO 7730 [19] and ASHRAE 55 [20], it was assumed to be inaccurate in predicting thermal sensation of the occupants in a naturally ventilated building in hot humid climate since it neglects human physiological, behavioural and psychological adaptations [21]. Thus, PMV results from the summer day are corrected by an expectancy factor e = 0.6 (for Hanoi - assumed to be equal to Bangkok) [22].

As shown in Fig. 10, PMV of a winter day was completely in the comfort range and could be improved by an appropriate control of openings. However, PMV of the summer day was well between slightly warm and warm scale. This PMV analysis reveals that the house performs fairly well in winter, but it needs other strategies to maintain human comfort in summer. Two possibilities are proposed: (1) combining better thermal insulation for the enclosure with night ventilation or (2) employing mechanical support during extreme conditions.

Natural illuminance of the 10 survey points on the winter day (16 December, 15 h) is illustrated in Fig. 11. During the measurement period, the sky was completely obstructed by the cloud cover and outdoor illuminance was around 5000 lux. Although the house has many openings, it is a little surprising that some indoor points did not have enough light according to the current Building code of Vietnam while others exceeded. This suggests that many openings should be appropriately distributed to achieve better lighting.

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Fig. 8. *Average air temperature, relative humidity and scalar wind velocity at surveyed points in a typical summer and winter day (measurement at point E in summer was unavailable due to construction work being done there).*

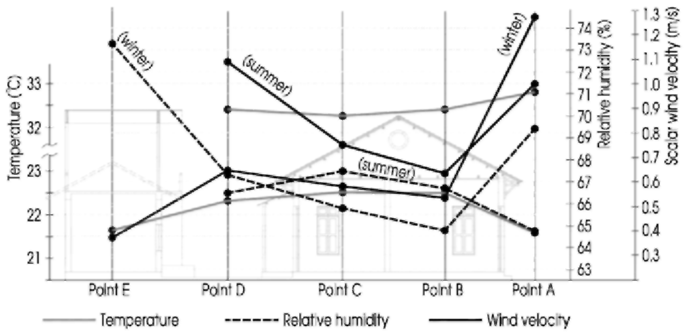


Fig. 9. *Change of temperature, humidity and wind velocity at some survey points during a typical summer and winter day.*

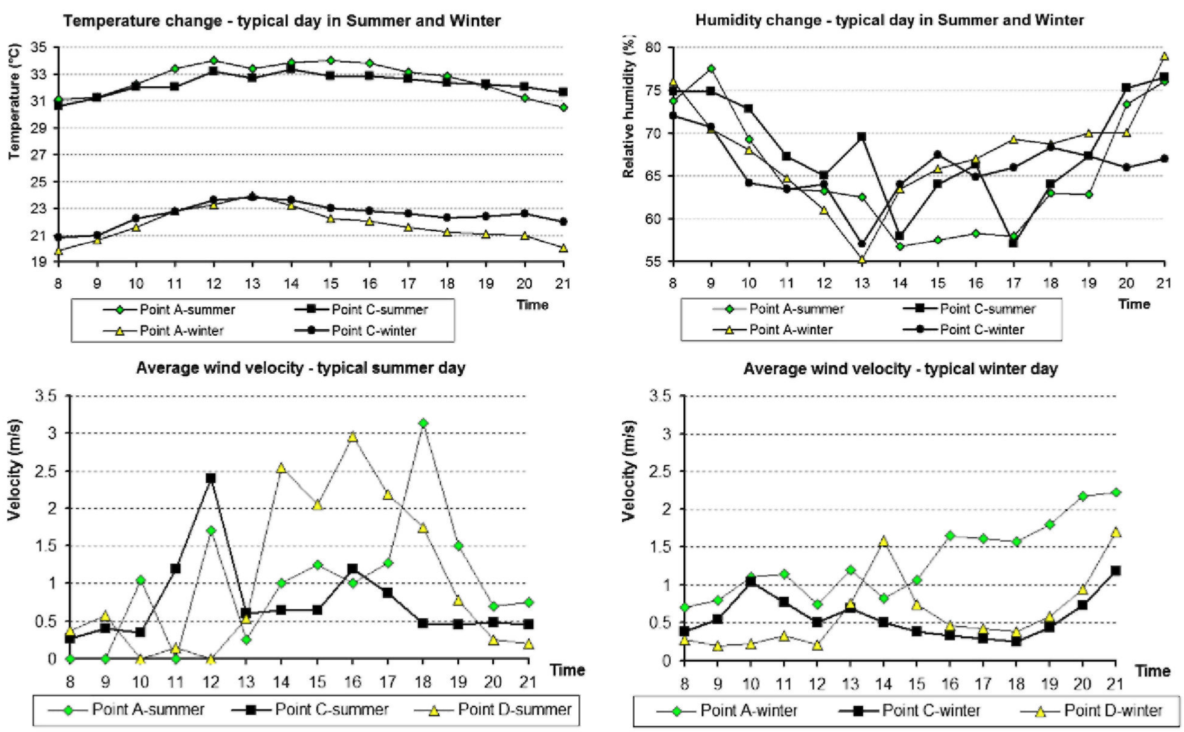
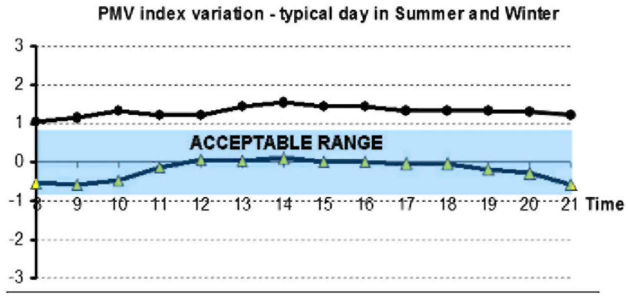


Fig. 10. *Indoor thermal comfort evaluation through PMV model.*



3.5. Step 5: whole - year simulation of building performance

In recent years, building simulation has become an effective method to predict building performance and save time and resources. It also gives predictions for numerous different cases and can simulate extremely complicated circumstances which people rarely examine by experimental methods. Nevertheless, it is recommended that the reliability of simulation results be carefully validated before use. The present study employs three simulation tools, including CFD tool, solar tool and thermal prediction tool which will be presented in the following sections.

3.5.1. Study on natural ventilation performance of the house

Natural ventilation of various situations of house A was examined using Computational fluid dynamics (CFD) method. RNG k-ε turbulence model in conjunction with Phoenics code was used as it was reported to be one of the most reliable two-equation turbulence models for indoor and outdoor airflow applications [23,24]. RNG k-ε turbulence model was also proved to be effective in predicting cross ventilation by the authors [25]. Although CFD simulation needs validation to verify its reliability in predicting airflow for any specific case, in preliminary assessments it is assumed that the accuracy of this turbulence model and CFD code is acceptable. The following boundary conditions were applied : power-law wind velocity profile with exponent $\alpha = 0.22$; zero external ambient pressure; no heat transfer; structured grid distribution: 106, 72, and 39 in the *x*-, *y*- and *z*-axes, respectively; Hybrid convection schemes; equilibrium Logarithmic wall-function, SIMPLES algorithm [26], global convergence criteria of 0.01, converged iteration of around 3500. Average wind velocity of 1 m/s at height of 1.1 m in the in-situ measurement was adopted in all simulations. All windows were assumed to be opened while doors were closed, reflecting normal operating conditions of the house. Urban context was included into the model by adding neighbouring houses and creating a street canyon. Airflow field in the living room, retail shop and courtyard in five cases as well as their simulation results were examined as shown in Table 9.

Fig. 11. *Indoor illuminance compared with Building code (15 h, 16th December).*

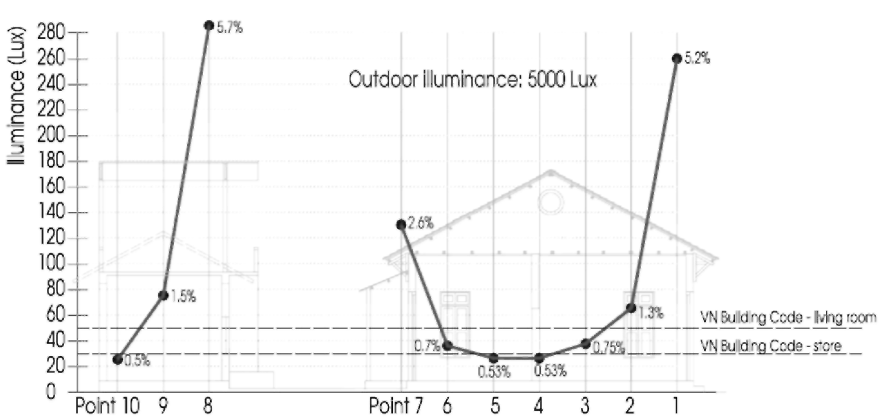


Table 9 *Characteristics of airflow field through the model.*

Case	Wind angle of attack[b]	Ventilation flow rate (m^3/s)		Average wind velocity on working plane 1.1 m above floor level (m/s)					
		Living room	Retail shop	Living room		Retail shop		Courtyard	
				Velocity	STDV[a]	Velocity	STDV[a]	Velocity	STDV[a]
A	0°	0.264	0.147	0.047	0.036	0.022	0.030	0.202	0.065
B	30°	0.204	0.229	0.075	0.077	0.079	0.082	0.234	0.084
C	45°	0.188	0.258	0.070	0.083	0.132	0.130	0.234	0.090
D	90°	1.272	1.567	0.331	0.219	0.300	0.285	0.324	0.173
E[c]	90°	1.370	1.619	0.366	0.253	0.323	0.304	0.181	0.152

[a] Standard deviation.
[b] Prevailing wind direction of Hanoi in summer (90° wind direction is perpendicular to the front façade).
[c] Side corridor was closed by the front door.

In cases A, B, and C, ventilation flow rates were low due to the "slide-effect" caused by inertial force of the wind and the row house (wind slides on building surface without entering the room). This detailed CFD analysis found that in these cases, courtyard-facing windows sometimes played a more important role than street-facing windows did. The "slide-effect" can be reduced by providing each of two front windows with vertical wing walls. Case D and E had significantly higher flow rates since "slide-effect" did not occur. Standard deviation is shown in Table 9 as well as that wind motion in the Living room was more homogeneous than that in the Retail shop; and outdoor wind was generally more homogeneous than its indoor counterpart.

3.5.1.1. Effects of side corridor. Comparison between case D (side corridor open) and case E (side corridor closed) shows that ventilation flow rate and average indoor velocity increased noticeably when the side corridor was closed (case E). Another effect was that average velocity in the courtyard dropped significantly in this case. These phenomena can be explained by employing the principle of static pressure drop. Fig. 12 illustrates pressure and velocity filed in these two cases. It is clear that case E had a larger static pressure drop between the windward and leeward wall than that of case D. According to Bernoulli's equation of flow rate ($Q = C_d A u_{\text{ref}} \sqrt{\Delta C_p}$; where ΔC_P is mean pressure coefficient across the openings), this high pressure drop leads to higher flow rate in case E. Average velocity in the courtyard in case D (0.324 m/s) was, in contrast, far higher that that of case E (0.181 m/s), proving that the side corridor played the role of a wind tunnel which induced more wind into the courtyard.

Since natural ventilation conditions in the front and back part of this house is a function of wind conditions in the courtyard, the side corridor and the courtyard are a good way to control natural ventilation. Closing the side corridor gives better ventilation in the front part while opening the side corridor improves wind induced ventilation in the back part.

3.5.1.2. Comparison with standard and code. ASHRAE standard 62.1 [27] recommends that in residential facilities Air change rates should be higher than 0.35 ACHs and 7.5 1/s. person to ensure indoor air quality. Flow rates shown in Table 9 were far higher than these requirements (minimum air change rate occurred in case A and was 3.01 ACHs). However, the average indoor wind velocity of case A, B and C were lower than the minimum wind speed (0.2 m/s [20]) needed to improve human thermal sensation.

3.5.2. Simulation of shading effect by solar shading devices

Shading effectiveness of the shading devices was examined by using the solar tool embedded in Ecotect analysis® software [28]. Three cases are presented in Fig. 13. Case B reflects the current context in which the house exists whereas case A and case C are the control case and comparative case, respectively.

Percentages of the shaded area on different vertical surfaces are compared in Fig. 14. It can be seen that in the current context (case B), the house is currently suitably protected by its shading system since all walls achieved very high shaded percentages (over 90%) in summer and much of the sunlit area in winter. In its previous context (case C), the shading system also performed well with over 80% average shading area in summer. Certainly, case A performed worst among these cases although north and south walls were protected well in summer. In brief, the shading system of the house almost satisfies the shading requirement, especially in the current context.

Fig. 12. *Distribution of static pressure and time-averaged velocity in case D with side corridor opened (above) and case E with side corridor closed (below).*

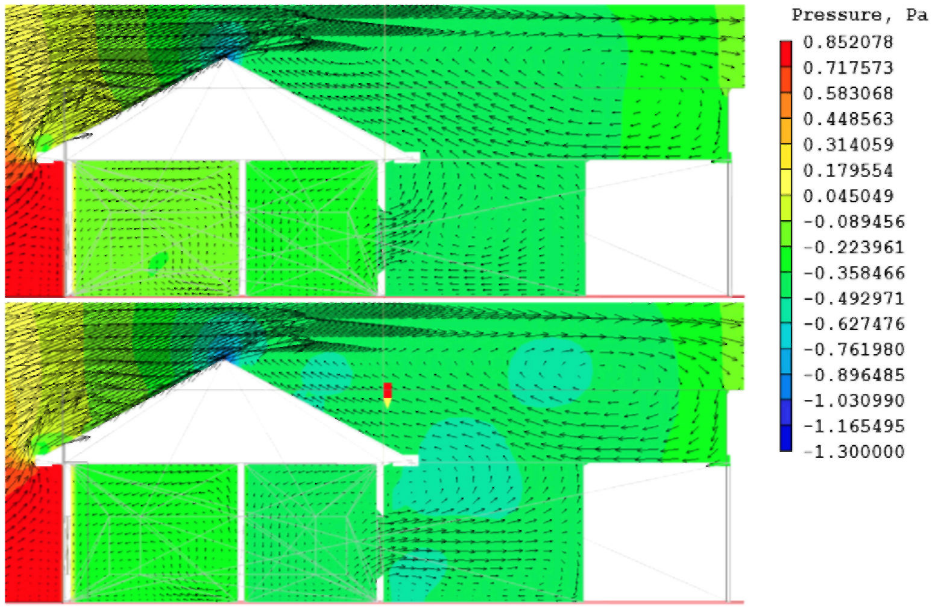
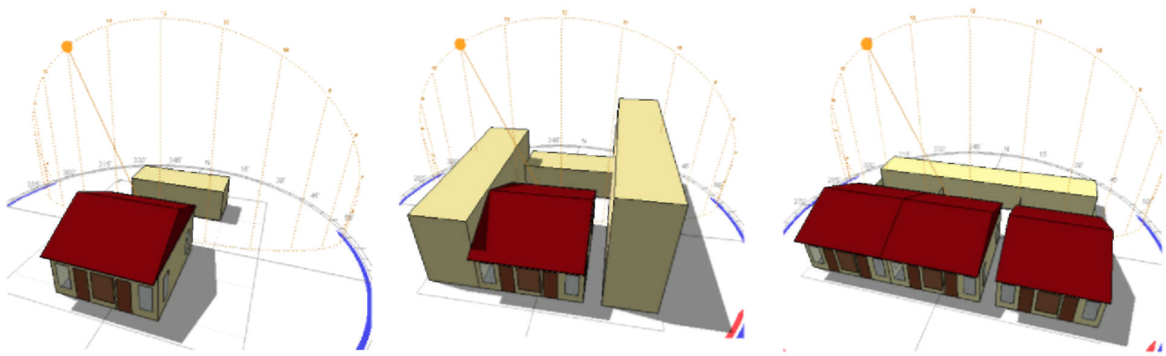


Fig. 13. *Three cases in the study of solar shading effectiveness (14 h; 11th July).*



3.5.3. Simulation of thermal performance

This study employed COMFIE [29] thermal simulation tool developed by "Centre d'Énergétique de l'École des Mines de Paris". This software requires information regarding global characteristics of the buildings in question: materials, composition, building finishes, ventilation schedules, surrounding conditions and so forth. COMFIE's performance was validated by Peuportier [30] by comparing simulation results with those of similar tools like DOE2, TRNSYS, TAS, SIMULA, CODYBA, confirming COMFIE successfully predicted the building thermal environment. However, the calibration procedure for this case which helps to improve the accuracy of simulation results was overlooked due to lack of experimental details. Therefore, the following scenarios were assumed: operating scheme reflects the activity of a typical Vietnamese family (maximum of 4 occupants during night time); three natural ventilation strategies (night, daytime and full-day ventilation) with different flow rates were separately applied for summer, winter and the mild season using a maximum flow rate of 0.258 m^3/s obtained from the CFD simulation; the attic was ventilated at 1 ACH during daytime and 0.5 ACH during night time; the average internal heat gain was 25 W/m^2 and varied according to the house's occupancy; the weather data was exploited from a Typical Meteorological Year (TMY) weather file of Hanoi, then converted into Test Reference Year (TRY) format for COMFIE. All building parameters were reproduced in the model as shown in Fig. 15 and Appendix.

Temperature variation during a year shown in Fig. 16 shows that indoor temperature was relatively stable, regardless of the fluctuation of outdoor temperature. However, the house failed to protect indoor environment from extreme outdoor conditions although these conditions did not last very long (see highlighted points in Fig. 16). For the rest of the year, the indoor environment was almost thermally acceptable.

Thermal comfort in the living room was examined by plotting hourly temperatures on an adaptive comfort model proposed by de Dear and Brager [31]. The optimum comfort temperature underlined in this model is as follows:

$$T_{\mathrm{comf}} = 0.31T_{\mathrm{a;out}} + 17.8 \qquad (1)$$

where: T_{comf} is comfort temperature and $T_{\mathrm{a;out}}$ is mean outdoor dry bulb temperature.

The plotting result in Fig. 17a shows that 58.21% of the total time was found to be thermally acceptable, corresponding with 90% acceptability. About 70% of the uncomfortable period dropped into the cold zone, showing that the house needs further thermal insulation against the cold in free running mode. Fig. 17b shows that there was only 6% of the total time in which indoor temperature exceeded 31 °C, proving that the house performed better in hot weather. According to ISO 7730 [19] and ASHRAE standard 55 [20], this warm sensation (about 2 °C higher than comfort temperature) can be completely eliminated by a wind speed of 0.6 m/s, e.g. created by a ceiling fan. This finding does not coincide with that in Section 3.4, indicating that a short-term in-situ survey cannot always provide an overview of a buildings' performance.

Fig. 14. *Shading effectiveness on the hottest day - 11th July (above) and monthly average shading percentage of the vertical façades (below).*

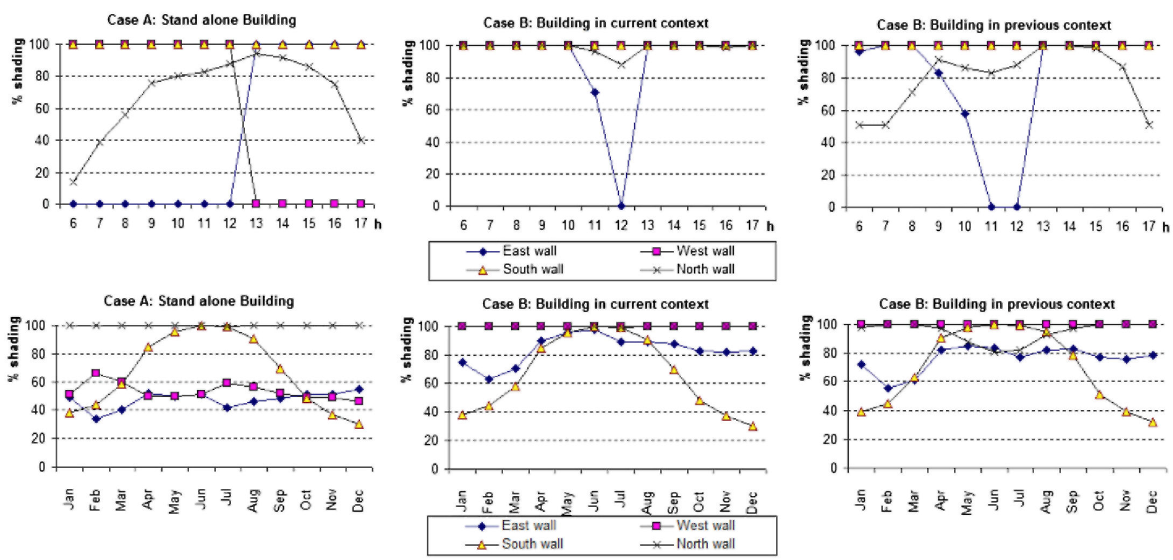
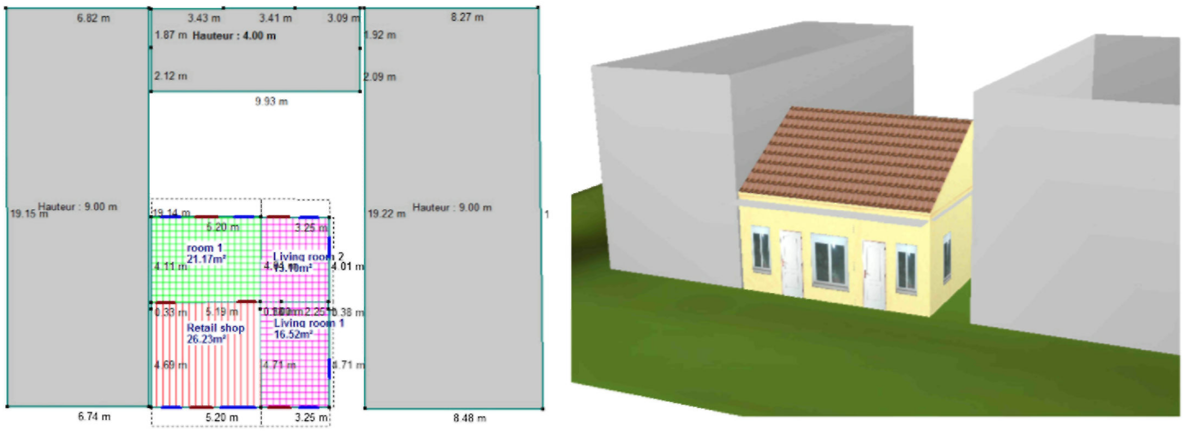


Fig. 15. *Building model for the simulation on thermal performance.*



3.6. Step 6: discussion and conclusions

This study thoroughly assessed the design principles employed in simple, durable and eco-friendly vernacular dwellings in Vietnam and their effectiveness by qualitatively and quantitatively assessing their performance. The new approach launched in this study to evaluate vernacular architecture proves to be effective and adequate and may be employed in the research of vernacular housing in other regions. Nevertheless, necessary modifications would be strongly recommended due to the differences in climate, geographical features and so forth.

The results of this study clearly indicate that not all vernacular buildings have perfect building physics. Through this study, the advantages and disadvantages of these buildings were thoroughly investigated, with the aim to effectively exploit their positive attributes for current developments. The evaluation of a vernacular building should employ suitable objective methods; otherwise the process leads to incorrect or inaccurate findings as described in Section 3.5.3. Since the weather might change from day to day, in some cases short-term in-situ measurement cannot give an accurate overview of building performance. It would be better to combine short-term in-situ measurements with other long-term prediction tools, such as building simulation.

Fig. 16. *Temperature variation in the living room over one year.*

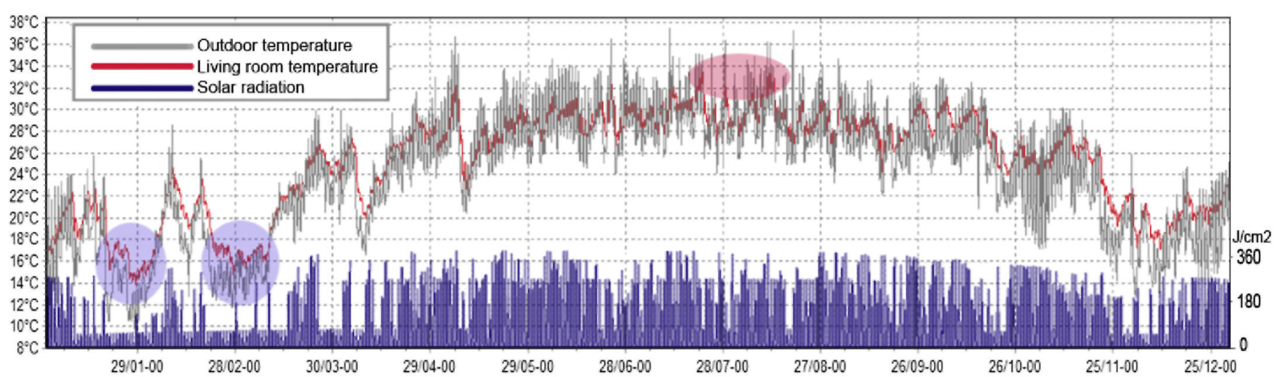
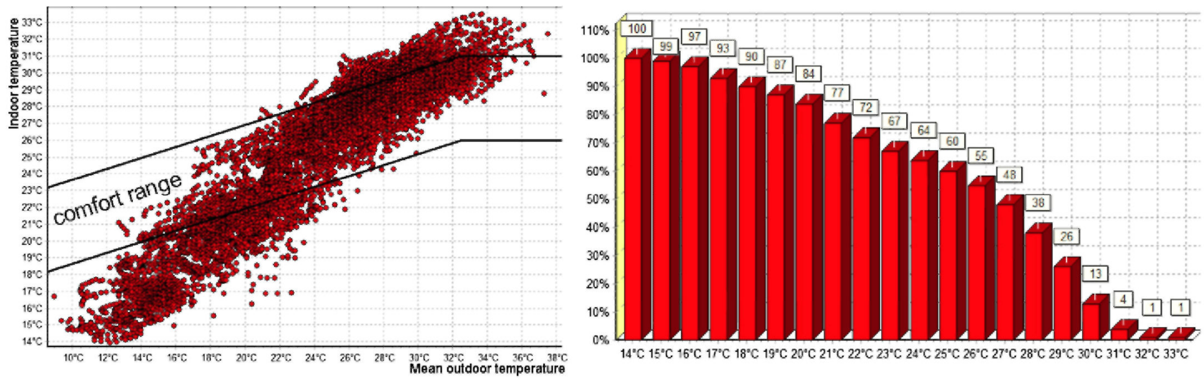


Fig. 17. *Hourly plot of air temperature on an adaptive comfort model (left) and cumulative distribution of indoor temperature (right) in the living room over one year.*



Generally, vernacular housing in Vietnam has adapted fairly well to climatic conditions in different locations by using low-energy design principles that basically ensure human comfort and health. Natural ventilation, building orientation - building shape and solar shading were the strategies most commonly employed whereas earth cooling and high thermal mass seemed inappropriate. Although thermal insulation was not used in the six investigated dwellings, but the above - mentioned analyses suggested that thermal insulation will improve indoor thermal comfort during the cold weather in the Northern areas of Vietnam. The survey on a house in an urban area showed that the shading devices performed quite well, but the distribution and configuration of the openings should be adjusted to improve natural lighting and ventilation. Building courtyard played a significant role on ventilation flow rate of the rooms facing the courtyard.

In the relatively severe climate of Vietnam, relying entirely on traditional design strategies to maintain thermal comfort is not completely possible. Therefore, under extreme conditions the building would benefit from low-energy mechanical systems, such as mechanically assisted ventilation, evaporative cooling, passive solar heating... or occupants' adaptive responses such as clothing insulation, activities, opening controls and the use of fans.

The present study has limitations as the quantitative assessment of only one house was carried out. A larger investigation is therefore needed. Besides, further study to include comparative assessments between vernacular and more modern architecture is necessary to better evaluate their performance and provide recommendations for sustainable housing design in Vietnam.

In conclusion, this study has emphasised the importance of climate conscious appropriate building design for the living environment without excessive use of natural resources. Vernacular housing in Vietnam is evidence that humans can live in harmony with nature, confirming the need to preserve vernacular architecture there.

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Appendix

Compositions of building enclosures used in the thermal simulation units

Characteristic	Nomenclature	Unit
Thickness	*Ep*	cm
Conductivity	λ	W/(m K)
Density	*D*	kg/m^3
Specific heat capacity	C_p	Wh/(kg K)
Coefficient of surface transmission	*U*	W/(m$_2$.K)
Thermal resistance	*R*	(m^2.K)/W

List of composition used.

Simple composition	Traditional floor					
Component	*Ep*	λ	*D*	C_P	*U*	*R*
Ramped earth	25.0	0.850	2000	0.280	0.29	3.40
Broken brick with mortar	10.0	1.050	1700	0.256	0.10	10.50
Mortar	3.0	1.150	2000	0.233	0.03	38.33
Tile 200×200×20	2.0	0.143	790	0.222	7.14	0.14
					7.56	0.13
Simple composition	Tiled roof					
Component	*Ep*	λ	*D*	C_P	*U*	*R*
Fired clay roof tile	2.5	0.042	1700	0.220	1.67	0.60
Light timber	0.5	0.150	500	0.333	0.03	30.00
					1.70	0.59
Simple composition	Wooden ceiling					
Component	*Ep*	λ	*D*	C_P	*U*	*R*
Cellulose insulation	4.0	0.045	55	0.390	0.89	1.13
Light timber	2.0	0.150	500	0.333	0.13	7.50
					1.02	0.98
Simple composition	220 mm brick wall					
Component	*Ep*	λ	*D*	C_P	*U*	*R*
Mortar	2.0	1.150	1700	0.278	0.02	57.50
Cruel brick of 10 cm	10.0	0.480	690	0.250	4.76	0.21
Void 1.1-1.3 cm	1.2	0.080	1	0.340	6.66	0.15
Cruel brick of 10 cm	10.0	0.480	690	0.250	4.76	0.21
Mortar painted by lime	2.0	0.700	1400	0.280	0.03	35.00
					16.23	0.06

Doors and window.

Name	*U* value
Exterior wooden doors	3.03
Wooden panel window	3.68
Two-layer French window	1.70
Interior wooden door	2.40

Scenarios of the coefficient of albedo.

Name	All year
Concrete	0.2

Surface conditions.

Name	Emissivity	Absorptivity
Red Brick	0.92	0.68
Cement	0.88	0.60
Smooth white colour	0.85	0.25
White mixture of lime and water (dried)	0.80	0.3

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