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Design Criteria for Modernized, Microclimate-Adaptive Rural Housing in the Red River Delta

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Abstract

Urbanization and the pursuit of modern lifestyles have profoundly reshaped functional demands and aesthetic aspirations in the rural Red River Delta. This study examines the potential for revitalizing rural housing typologies while preserving the cultural identity of traditional indigenous architecture, alongside adaptations that enhance both indoor and outdoor environmental performance. Employing validated ENVI-met CFD simulations and Ladybug + Honeybee building energy modelling, the results reveal negligible impacts on outdoor thermal comfort but a 20 % increase in energy use intensity (from 36.9 to 44.28 kBTU/ft^2) caused by uncontrolled solar gain, despite significant gains in airtightness, daylight quality, and widespread occupant acceptance of the modernized design. The research proposes evidence-based design criteria that strategically hybridize retained vernacular elements with selective contemporary interventions. These guidelines pave the way for a new paradigm of indigenous contemporary architecture that successfully reconciles modern living comfort with restored climatic adaptability and enduring cultural authenticity.

1. Introduction

The Red River Delta (RRD) has sustained one of Southeast Asia's most resilient and climate-responsive vernacular building traditions for over two millennia. Ethnic Kinh villages evolved compact, single-storey courtyard houses that master passive environmental control in a challenging hot-humid monsoon climate marked by cold winters, extreme summer heat and humidity, and frequent typhoons. Through the disciplined use of high-thermal-mass brick walls, heavy timber framing, steeply pitched tiled roofs with generous overhangs, raised timber floors, and strategically placed courtyards, ponds, and vegetation buffers, these

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dwellings achieved exceptional natural ventilation, solar protection, nocturnal cooling, and flood resilience while remaining deeply embedded in wet-rice agrarian culture [1].

Since the Doi Moi reforms, particularly after the 2000s, rapid peri-urbanization, rural industrialization, and rising household incomes have triggered a radical and largely spontaneous transformation of this housing stock [2]. Traditional timber-and-brick houses are being replaced at an accelerating pace by multi-storey concrete-frame structures with flat roofs, large areas of unshaded glazing, and sealed envelopes. Although these new dwellings respond to contemporary demands for space, privacy, and modern aesthetics, they often suffer from chronic overheating, stagnant indoor air, and cooling energy demands that are higher than those of their vernacular predecessors [3], [4]. More critically, the erasure of traditional spatial sequences, material palettes, and courtyard-garden relationships is progressively weakening the cultural identity and intergenerational continuity that have long defined rural Northern Vietnam.

Bac Ninh, a cultural and economic hub of the Red River Delta, is experiencing rapid urbanization, driven in part by its strong connectivity to Hanoi and neighboring provinces within the Capital Region. Peri-urban rural areas of Bac Ninh still retain examples of traditional housing, yet these are steadily being replaced by standardized concrete dwellings. Selecting Bac Ninh as a case study offers valuable insight into the transformation of rural housing in the Delta, from traditional to modernized forms, and helps identify factors shaping microclimatic adaptation and the preservation of local identity. Currently, specific design criteria for rural housing in the Red River Delta that support localized modernization and climate adaptation are insufficient. The development of such a criteria framework will not only guide sustainable architectural practices and the design of modern rural dwellings that integrate new materials while ensuring microclimatic adaptability and cultural continuity, but also contribute to new rural planning efforts, the preservation of agrarian cultural values, and the enhancement of residents' quality of life under the pressures of climate change.

This research contends that continued modernization of rural housing in the Red River Delta need not entail the wholesale abandonment of vernacular environmental wisdom or cultural legibility. A culturally rooted, climate-responsive modernity is possible, but it requires explicit design criteria that treat local identity and passive performance as non-negotiable parameters rather than optional ornaments. Therefore, we aim to examine the potential for revitalizing rural housing typologies while safeguarding the cultural identity and spirit of traditional indigenous architecture, alongside a rigorous evaluation of indoor and outdoor environmental performance. The study pursues four integrated objectives:

- Analyze the vernacular values of traditional rural houses, including spatial forms, materials, ventilation, and environmental adaptability.
- Analyze the climatic, environmental, and social contexts influencing rural housing design in the RRD, with a particular focus on Bac Ninh.
- Propose a set of design criteria that integrates modern elements (materials, construction techniques, functional requirements) with vernacular elements (cultural identity, climate responsiveness, spatial morphology).
- Assessing the impact of modern design, based on the established criteria, on the local microclimate using quantitative methods through a case study in Bac Ninh

By bridging an environmental impact analysis with a culturally informed renovation practice, we would transcend the current binary of nostalgic preservation versus uncritical modernization and outline a viable path toward a contemporary vernacular architecture for the Red River Delta in the era of climate change.

2. Literature Review

2.1 Rural Housing and Sustainable Indigeneity

Huu Thai (2013) [5] emphasizes the importance of indigenous architecture within the context of rural modernization in Vietnam. As the study of Rapoport (1969) and (2013) [6], [7], they demonstrated that vernacular architecture represents an optimal adaptation to both microclimatic conditions and cultural practices. Climate change, urbanization, and population aging are emerging challenges that directly influence architectural design. In response, sustainable and environmentally responsive architectural approaches increasingly draw upon principles distilled from generations of local knowledge and practice [8].

Alongside the trend toward localization, modernization remains an inevitable trajectory of development [9]. Consequently, rural housing architecture must integrate advanced technologies and construction techniques while simultaneously considering cultural, social, and region-specific environmental characteristics. [10] underscores the necessity of developing residential architectural space typologies that are aligned with the structural transformation of rural economic production in the Red River Delta region of Vietnam.

Besides, the sustainable architecture achieves these characteristics by treating vernacular wisdom as a living foundation rather than a relic [11]. It must satisfy environmental, economic, and social dimensions [12] and meet the compatibility criteria proposed by Hunjak et al. (2014) [13]: reinforcing local identity, using feasible local materials and skills, ensuring buildability, respecting cultural and environmental context, offering adaptability, bridging traditional and modern technologies, improving microclimatic comfort, and delivering aesthetic distinction. When rigorously applied, these principles allow the Red River Delta rural house to retain its climatic intelligence and cultural legibility while gaining the qualities demanded by new generations [3]. Locality thus ceases to be a preserved memory and remains, as Rapoport (2013) [7] insisted, something continuously lived and reinterpreted [14].

2.2 Development Situation of Traditional Rural Housing Architecture in the Red River Delta

2.2.1 Characteristics of Traditional Rural Housing Architecture

During the settlement of expansive alluvial plains, the Vietnamese developed unique rural settlement patterns, characterized by a harmonious integration of architecture and landscape (Fig. 1). Based on images preserved on Dong Son bronze drums, two architectural forms can be identified: stilt houses with curved boat-shaped roofs and stilt houses with round roofs. For a long period, Vietnamese vernacular houses were predominantly stilt houses supported by wooden posts—a form well-suited to the natural conditions of the delta regions [15].

Fig. 1 *Overview of the transformation process of rural housing architecture from the primitive period to the present*

According to Ancient Vietnamese Architecture, beginning from the period of Chinese domination, rural housing in the Red River Delta underwent a complete transformation from stilt houses to ground-level houses [16]. This change was explained by the fact that the old house structures and forms were no longer suitable as the Vietnamese migrated from semi-mountainous areas to the expansive plains. Consequently, spatial organization also adapted to new modes of production, while remaining environmentally responsive and harmonious with the natural surroundings.

Vietnamese rural architecture maintained a relatively stable structure and form until the end of the French colonial period in 1945, as illustrated in Fig. 2. Research on the origins and development of vernacular housing in Northern Vietnam [17], based on a survey of 1,700 historic houses in the Red River Delta, identified the basic structural and spatial characteristics of rural housing in the region prior to 1945 as follows:

- Rural architecture exhibits a pronounced tropical style, open and well-ventilated.
- Houses were typically oriented southward, suitable for the tropical climate—cool and ventilated in summer, while avoiding cold winds in winter.
- Houses occupied a relatively small proportion of the overall plot, with the majority of the area used for gardens, vegetables, orchards, and fences.

- Within the house compound, the main house was usually accompanied by one or two ancillary buildings placed perpendicular to the main house, forming a "carpenter's square" or U-shaped layout around a central open courtyard. The front courtyard often contained a garden and occasionally a pond.
- Regardless of social status, rural houses in the Red River Delta during this period were mostly single-story vernacular houses with rectangular floor plans, arranged in an odd number of bays (e.g., 3 or 5 bays), often with extensions. Construction primarily used wood or bamboo, with roofs covered in tiles or thatch (straw, reeds, palm leaves, etc.).
- Roofs were steeply pitched to ensure rainwater drainage and prevent leakage, and the extended eaves provided shade while protecting the wooden posts and rammed-earth walls, creating functional verandas. Roof space was often used for storing harvested rice, corn, and tubers.
- The courtyard was an indispensable part of the compound, serving multiple functions: agricultural (drying rice, transplanting seedlings), recreational (play space for children), and social (welcoming guests).

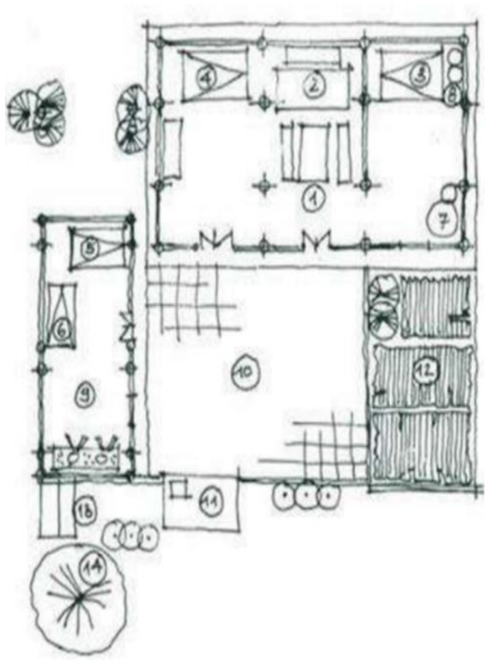

Fig. 2 *The rural housing layout in the Red River Delta did not change much in structure from the time of the conversion to ground-level houses until before 1945*

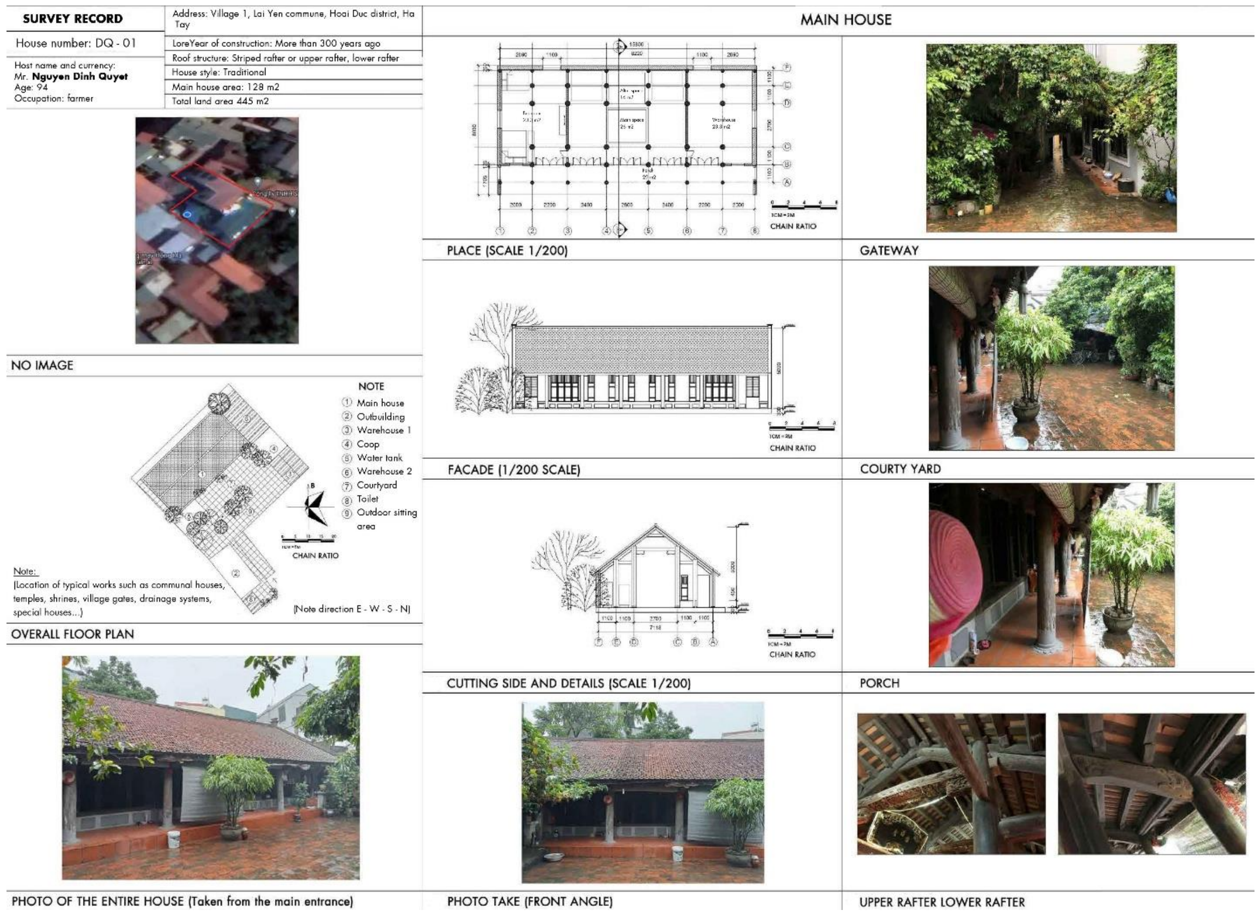

Fig. 3 *A typical traditional house*

According to research in Traditional Vietnamese Folk Architecture [18], Fig.3 shows the characteristics of traditional Vietnamese architecture can be summarized through the following fundamental elements:

- Modesty and simplicity: Most vernacular Vietnamese architecture is relatively simple and modest, avoiding excessive ornamentation or extravagance. This reflects a strong sense of national identity and embodies the beauty of the Vietnamese spirit, as well as the simplicity of their character.
- Harmony with nature: The majority of architectural works, particularly residential buildings, emphasize integration with and attachment to nature, consistent with the lifestyle of communities rooted in wet-rice civilization.
- Aesthetic and folk-oriented colors: Vietnamese architecture, from small details to large-scale structures, exhibits rich national identity through color schemes such as brown and brick red, conveying solemnity, authenticity, and liveliness in the spatial environment.
- Use of local materials: Traditional Vietnamese architecture prioritizes the use of local materials, reinforcing its vernacular and cultural authenticity.
- Structural and architectural details: Roof systems typically feature steeply pitched or straight-sloped roofs; proportions often allocate about two-thirds of the building's height to the roof. Column systems include main columns (*cot cai*), secondary columns (*cot con*), and veranda columns (*cot hien*), while beam systems include principal beams (*xa long*), secondary beams (*xa nach*), and purlins (*ke ngoi, ke hien*). Fig. 4 below describes the development of traditional house frame trusses in the Red River Delta.

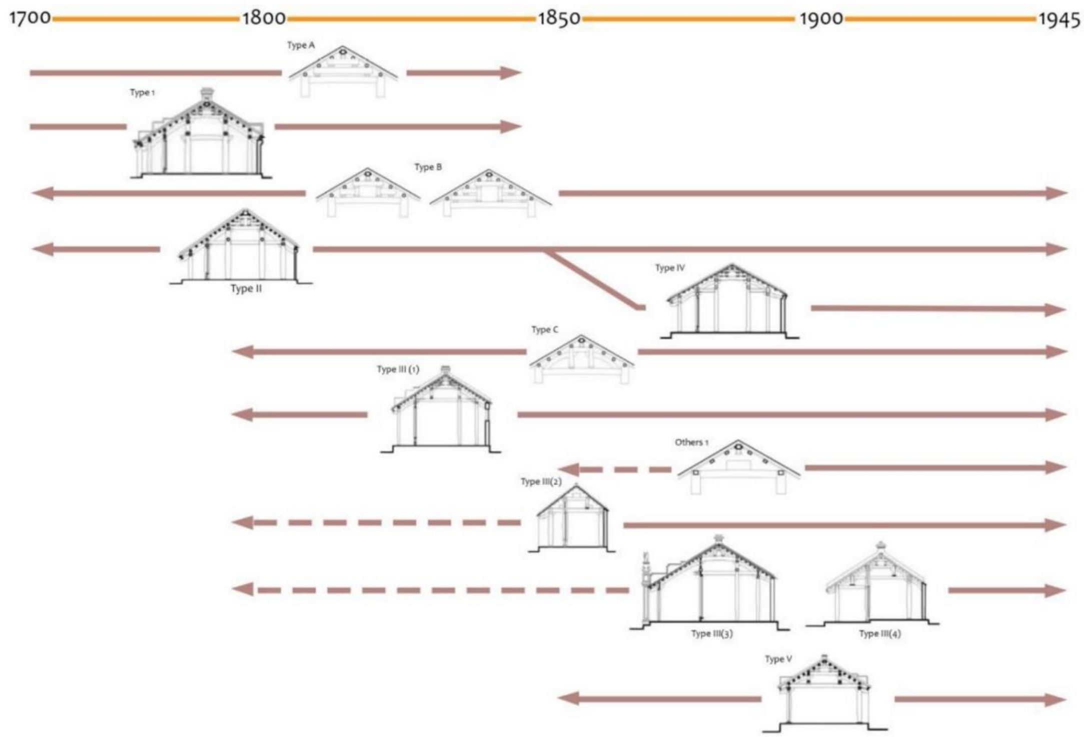

Fig. 4 *The development process of traditional house frame trusses in the Red River Delta [15]*

2.2.2 Current Status of Development of Traditional Rural Housing Architecture in the Red River Delta

In contemporary times, climate change, urbanization, and population aging have a direct impact on architectural design. However, contrary to the general development trends of the era, the transformation of rural housing architecture in the Red River Delta is shifting away from approaches based on vernacular elements toward new trends driven by urbanization. The transformation of rural housing architecture in the Red River Delta can be explained by several factors:

- Changes in regulations and management policies.
- Waves of rural-to-urban migration during the processes of urbanization and modernization.
- Shifts in living habits and modes of production.
- Changes in construction technology, materials, and design concepts [19]

Today, rural houses in the Red River Delta are markedly different from traditional vernacular houses. Modern rural housing primarily reflects the trends of urbanization and modernization. These differences can be explained by climatic, economic, and especially lifestyle changes. In practice, the number of traditional, region-specific houses in rural villages of the Red River Delta has been declining. Contemporary rural households are heavily influenced by architectural models from nearby urban areas or by hybrid forms that combine elements of urban and rural houses [20].

Among the factors altering the face of rural architecture, the recent proliferation of urban-style tube houses in rural areas has been particularly rapid. It is important to recognize that these rural tube houses emerge spontaneously, driven by local needs and lifestyle trends rather than arbitrary decisions [21].

The development of urban-style tube houses in rural areas initially addresses the urgent housing needs of rural populations and provides more modern amenities. However, adopting this architectural trend has significant consequences for the overall rural landscape and environment. Constructing tube houses in a rural village context often disrupts the visual and spatial harmony of the countryside. Rural housing architecture in the Red River Delta, when copied from urban styles without adaptation to local conditions, fails to incorporate vernacular characteristics.

New rural housing that lacks careful consideration of local cultural, social, and environmental factors not only alters the rural landscape but also generates direct impacts on the environment and contributes to climate change. Urban-style tube houses disrupt the traditional village structure, significantly deforming it. In addition, their increased roof and wall surface area exposed to sunlight turns these houses into heat reservoirs, releasing thermal energy into the surrounding environment. This intensifies the local microclimate, making village spaces increasingly uncomfortable and raising electricity demand for cooling [22].

Synchronizing rural architecture with urban forms diminishes its appeal to younger populations who live in major cities. According to research on migration and factors affecting rural housing architecture, Thi (2012) [23] reported that only 20% of respondents wished to return to heavily urbanized villages such as An Khanh (now part of Hoai Duc, Hanoi). In contrast, 60% expressed the desire to return to Lang Nom in Dai Dong, Hung Yen. Such attractiveness factors significantly influence migration patterns and will shape future urban development trajectories.

2.3 CFD Simulation and Applications

Computational Fluid Dynamics (CFD) has become an essential approach for addressing climate-related challenges in urban environments. Today, multiple CFD platforms are widely used in urban studies, including ANSYS Fluent, ENVI-met, OpenFOAM, and PHOENICS [24], [25], [26]. Among these, ANSYS Fluent and ENVI-met have emerged as the most commonly applied tools, owing to their robust modeling capabilities and extensive validation histories.

ANSYS Fluent is highly regarded for its precision in simulating airflow patterns, energy exchanges, and radiative transfer processes [27]. Its strength lies in the flexibility to model complex 3D geometries, making it suitable for studies requiring detailed turbulence representation or custom simulation setups. However, the platform does not provide built-in outdoor comfort indices and offers limited libraries for materials and vegetation, which often necessitates advanced user knowledge. Tasks such as configuring evapotranspiration, radiation schemes, or surface parameters can therefore be time-intensive and technically demanding. In comparison, ENVI-met has gained significant traction in urban microclimate research due to its strong visualization capabilities and comprehensive databases of plants, soils, and surface materials [28]. Furthermore, the application of CFD in the field of microclimate primarily focuses on urban situations, which are rarely found in rural areas. Purpose-built for urban environmental simulations, ENVI-met integrates atmospheric processes, surface energy balance, radiative exchanges, and vegetation-atmosphere interactions within a unified framework, making it particularly effective for evaluating urban heat islands, testing green infrastructure strategies, and estimating outdoor thermal comfort [29], [30]. Although it sometimes overestimate radiative fluxes or underestimate air temperatures, continuous updates have enhanced its radiation modeling and mean radiant temperature (MRT) predictions in recent releases [31]. Ultimately, the choice of CFD software depends on specific research goals. Nevertheless, ENVI-met is especially suited for capturing the complex interactions between urban surfaces, vegetation, and the atmosphere. For studies that aim to assess microclimate interventions and their impact on outdoor thermal comfort, it remains one of the most practical and reliable simulation tools available.

In parallel with microclimate research, understanding the influence of occupant lifestyle and behavioral scenarios on building energy performance has become a critical research frontier, essential for informing resilient design amid ongoing modernization [32], [33]. Although popular tools such as EnergyPlus, DesignBuilder, and TRNSYS remain widely used [34], their reliance on manual parameter adjustment renders large-scale parametric studies highly time-consuming. In contrast, Ladybug and Honeybee, embedded within the Grasshopper parametric environment for Rhino, enable automated sensitivity analysis, multi-objective optimization, and high-throughput simulation directly coupled with 3D geometry. This workflow reduces the time required for extensive parameter sweeps from weeks to hours, facilitating rapid "what-if" exploration without repetitive model rebuilding [35], [36]. Built on Grasshopper's visual scripting foundation, Ladybug provides robust tools for solar, daylight, and climate analysis, while Honeybee seamlessly interfaces with the validated EnergyPlus/OpenStudio engines, combining parametric flexibility with physics-based accuracy. This integration positions Ladybug Tools as a particularly effective platform for early- and mid-stage design research focused on the interplay of form, systems, and occupant behavior.

2.4 Synthesis and Identification of Research Gaps in Rural Housing Studies

The literature reveals a persistent tension between modernization pressures and the preservation of environmentally responsive indigenous architecture in rural contexts, particularly in rapidly developing regions such as Vietnam's Red River Delta. Vernacular rural housing has long been recognized as an exemplary model of socio-cultural and climatic adaptation, achieving passive thermal regulation through the use of locally available materials, compact high-thermal-mass envelopes, deep overhangs, elevated or ventilated floors, and semi-open transitional spaces that promote cross- and stack ventilation. These characteristics simultaneously embody cultural identity, modesty, and harmony with wet-rice agricultural lifestyles.

Contemporary rural transformation in the Red River Delta, however, has largely abandoned these principles in favor of urban-derived typologies, most notably multi-story concrete-framed "tube houses" with expansive glazing, flat roofs, and minimal setbacks. This shift, driven by changing regulations, rural–urban migration, new construction technologies, and aspirational aesthetics, has disrupted traditional village morphology, increased impervious surface coverage, and introduced significant heat-island effects while elevating building energy demand [22].

Sustainable development theory and adaptive architecture frameworks emphasize that authentic local identity, material feasibility, environmental responsiveness, and socio-cultural continuity as non-negotiable criteria for contemporary rural housing. Yet few studies have systematically quantified the microclimatic and energy-performance trade-offs introduced by modernist-inspired rural renovations in hot-humid climates.

From a methodological perspective, ENVI-met has emerged as the most widely validated tool of choice for holistic outdoor microclimate assessment in low-rise traditional settlements, while Grasshopper-based Ladybug Tools (Ladybug + Honeybee) offer unparalleled advantages for rapid parametric energy simulation and early-stage design optimization compared with traditional standalone engines such as EnergyPlus, DesignBuilder, and TRNSYS.

This study addresses the identified gaps by combining field-validated ENVI-met microclimate modeling with high-throughput Ladybug + Honeybee energy simulations to critically evaluate the environmental costs and benefits of contemporary rural housing modernization in the Red River Delta, thereby providing an evidence base for culturally sensitive, climate-adaptive renovation strategies that reconcile modernity with indigenous environmental wisdom.

3. Research Methodology

3.1 Research Objects

- Rural housing architecture in the Red River Delta (RRD), with a focus on spatial characteristics, form, materials, and microclimatic organization in design.
- Vernacular factors influencing rural housing architecture, including natural conditions, local living practices, cultural identity, and water-related living environments.
- Criteria and principles for vernacular modernization in design, reflecting the integration of traditional values with modern techniques and materials to achieve climate adaptation and improve quality of life.

3.2 Research Scope

- Spatial scope: The study focuses on rural areas of Bac Ninh province, representing the characteristics of the water-rich Red River Delta region.
- Content scope: The research concentrates on design criteria for rural housing architecture, without delving into public buildings or urban residential architecture.
- Research content: This includes spatial morphology, construction materials, layout organization, vernacular cultural–aesthetic elements, and the living environment around.
- Temporal scope: The study primarily examines the period from 2000 to 2025, capturing the transition from traditional to modernized housing during the rural urbanization process.

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3.3 Research Method Process

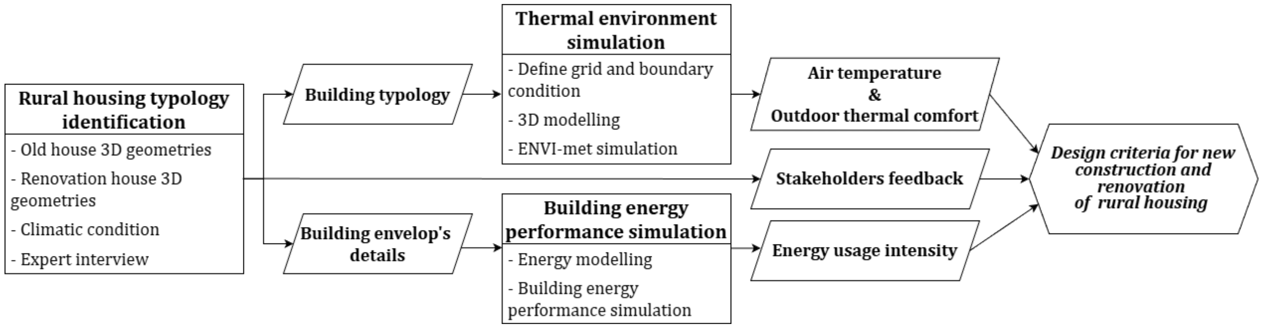

Fig. 5 *Research method process*

Fig. 5 illustrates the 5-step research process, starting from the identification of rural housing typology to the development of design criteria for new construction and the renovation of rural housing.

3.3.1 Data Collection

- Collect and analyze research works, theoretical models related to local modernization, sustainable architecture, and microclimate adaptation in rural housing.
- Compile and evaluate design criteria and principles published both nationally and internationally, aiming to establish reference frameworks for sustainable rural architecture.
- Conduct field surveys in Bac Ninh to document and analyze spatial characteristics, architectural forms, construction materials, and microclimatic organization of both traditional and modern houses. From this, examine the factors influencing architectural transformation and climate adaptability.

3.3.2 Modeling and Microclimatic Simulation Procedures

To systematically evaluate the environmental implications of the new rural housing model, a CFD simulation tool, ENVI-met v 5.8, and the Ladybug & Honeybee of Rhino and Grasshopper, were utilized. Our study employs a two-scenario simulation framework consisting of a baseline model and a comparative model. The baseline scenario represents the existing dwelling, reconstructed in detail based on field measurements and photographic documentation, as presented in Section 6. Table 1 below indicates the setup process for the simulations.

Table 1 *General input value for ENVI-met simulation setup*

Categories	Setting options	Value
Model geometry	Dimensions (in grids x-y-z)	78 x 56 x 15
	Grid size	3 x 3 x 3 (m)
	Telescoping	7 %
Nesting grids	Number of nesting grids	6
General settings	Simulation starting date	July 10
	Starting time	5 am
	Total simulation time	48h
Meteorology settings	Forced data	Wind, Air temperature, Radiation, Relative humidity
Soil conditions	Soil humidity (upper – middle – deep – bedrock layer)	75 – 80 – 85 – 85 (%)
	Initial temperature (upper – middle – deep – bedrock layer)	20 – 20 – 19 – 19 (oC)
	Loamy soil	0.90 Emissivity 0.015 Roughness length
	Concrete pavement light	0.9 Emissivity 0.01 Roughness length 0.5 Albedo
Radiation	Raytracing precision	Finer resolution
	Use a height cap for adjusting ray tracing precision	Yes
	Use IVS module	Yes
	Use ACRT	Yes

The comparative scenario applies the standardized prototype of the new rural housing model currently promoted in national rural development policies. Both models were geometrically simplified and parameterized to ensure computational feasibility while preserving the essential architectural and thermal characteristics relevant to microclimatic analysis. Due to limitations in published climatic data, we obtained the Energy Plus Weather file (EPW) for the area around Noi Bai Airport, which has a similar profile and is not too far from the site study in Bac Ninh Province. Besides, to isolate the influence of housing morphology itself, all external landscape components, including vegetation, permeable surfaces, and water bodies, were intentionally excluded from both scenarios. This methodological decision eliminates confounding effects associated with shading, evaporative cooling, and surface albedo, thereby enabling a clearer identification of the intrinsic impact of the building form on microclimatic conditions and household energy demand. Table 2 below indicates the input value details of two comparative housing models:

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Table 2 *Details of input values of each case for the simulation setup*

	Modern case		Baseline case	
	Type	Values	Type	Values
Materials				
Building wall material	Brick (burned)	0.3-0.6-0.4-0.93-0.44 (Thickness-Absorption-Reflection-Emissivity-Thermal conductivity)	Brick (burned)	0.3-0.6-0.4-0.93-0.44 (Thickness-Absorption-Reflection-Emissivity-Thermal conductivity)
	Clear float glass (one layer)	0.02-0.05-0.9-0.05-0.9 –1.05 (Thickness-Absorption-Transimission-Reflection-Emissivity-Thermal conductivity)		
Building roof material	Tile	0.7 – 0.3 – 0.93 – 0.84 (Absorption-Reflection-Emissivity-Thermal conductivity)	Tile	0.7 – 0.3 – 0.93 – 0.84 (Absorption-Reflection-Emissivity-Thermal conductivity)
Ground	Pavement light concrete	0.5-0.9- (Reflection-Emissivity)	Pavement light concrete	0.5-0.9- (Reflection-Emissivity)
Load value				
Lighting (W)	2400			
Person counts in house (no.)	4			
Electric equipments (W)	6000			
Infiltration_ACH		1	3.5	
AC				
Set point (keep constant)	25			
COP	2.5			

3.3.3 Results Analysis

BIO-met was used to calculate the Physiological Equivalent Temperature (PET) based on the Gagge-2-node model. Although there are other indices for outdoor thermal comfort description, PET is a trusted index for urban planners and policymakers [37], [38]. The PET value was calculated based on the anthropometric data of a man aged 35 years old, 70kg weight, 1.70m height [39], work metabolism 80W, and static clothing insulation of 0.6 clo, with the sum metabolic work 161.04 W. Also, this study uses the thermal sensation range for the sub-tropical region from [40], as described in Table 3 below.

Table 3 *Thermal sensation range for the sub-tropical region*

Thermal sensation	PET range (°C)
Very cold	< 14
Cold	14 - 18
Cool	18 – 22
Slightly cool	22 - 26
Neutral	26 – 30
Slightly warm	30 – 34
Warm	34 – 38
Hot	38 – 42
Very hot	42

Compare and assess the microclimate adaptability of the renovation housing model:

- The outputs of the two CFD simulations were compared by examining the differences in microclimatic parameters (i.e., the modern housing model minus the baseline model). The database of air temperature and PET was exported at a height of 1.5m above the ground, which is similar to people's height and the feeling spot. Additionally, we only analyze the data within the study house area, while avoiding the surrounding areas to minimize boundary effects, as shown in Fig. 6 (red mark square).
- The quantification of the thermal loads, ventilation conditions, and radiative exchanges attributable solely to the two housing models. The insights gained enable us to identify indigenous spatial and morphological features that positively contribute to building energy performance and can be leveraged or reinterpreted in modern design practices.

Identify local (vernacular) elements that can be inherited and enhanced in modern architectural design.

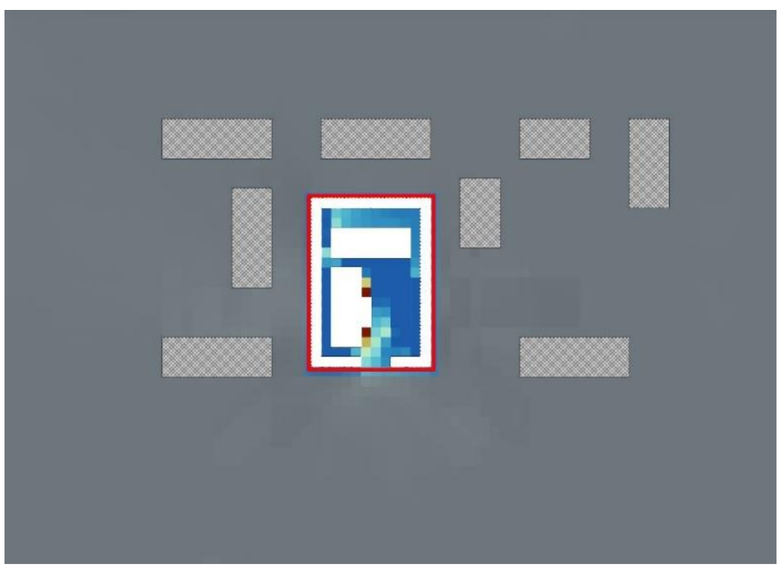


Fig. 6 *Analyze area (red mark)*

4. Typical Case Study of Bac Ninh Province

During the research, based on the criteria we recommended, a member of the research team renovated an actual building in Yen Phong commune, Bac Ninh province. The building is situated on a land plot of 363.5 m^2, with a construction footprint of 176 m^2, corresponding to a construction density of 48.4%. The total floor area measures 363.5 m^2, spread across a single high floor. The maximum structural height of the building is 6.3 meters.

4.1 Description of the Current Status of Traditional Housing in Yen Phong Commune

The house was originally built following the classic rural dwelling pattern of the Red River Delta: a modest front courtyard, a centrally placed three-bay main house, and a rear garden, all arranged along a symmetrical, linear axis, as shown in Fig.7. The floor plan is simple and intimately scaled, its proportions and spatial sequence deeply rooted in centuries-old living practices of extended northern Vietnamese families. These familiar dimensions foster a strong sense of domestic warmth and continuity, yet architecture was conceived for a small household with relatively stable, modest functional demands.

Over time, demographic growth and evolving lifestyles have rendered the house increasingly inadequate. Family size has expanded, daily activities have diversified, and contemporary expectations of privacy, hygiene, and comfort can no longer be met within the original envelope. Usable floor area remains severely constrained, rooms serve multiple overlapping purposes, and private spaces are virtually non-existent. Essential modern amenities, such as an efficient kitchen, adequate sanitary facilities, and generous communal areas, are either absent or grossly undersized.

Structurally and materially, the building has suffered considerable deterioration. The traditional clay-tile roof leaks extensively, load-bearing walls exhibit cracking, timber columns and beams show advanced rot, and the low floor level encourages chronic dampness. Natural ventilation and daylight penetration are minimal, resulting in perpetually stuffy and dim interiors, as well as poor microclimatic performance.

Despite these deficiencies, the house continues to embody the essential spatial order and spiritual character of vernacular architecture in the Red River Delta. Its layout, proportions, and relationship with courtyard and garden remain powerfully evocative of regional identity. Precisely because this cultural authenticity endures, the existing condition underscores an urgent challenge: how to intervene in a way that preserves the house's intangible heritage while comprehensively resolving its functional, environmental, and material obsolescence. The project, therefore, emerges from a clear imperative: to renovate and extend the dwelling so that the traditional values embedded in its typology are not merely conserved museological but are allowed to evolve and flourish within the realities of twenty-first-century domestic life.

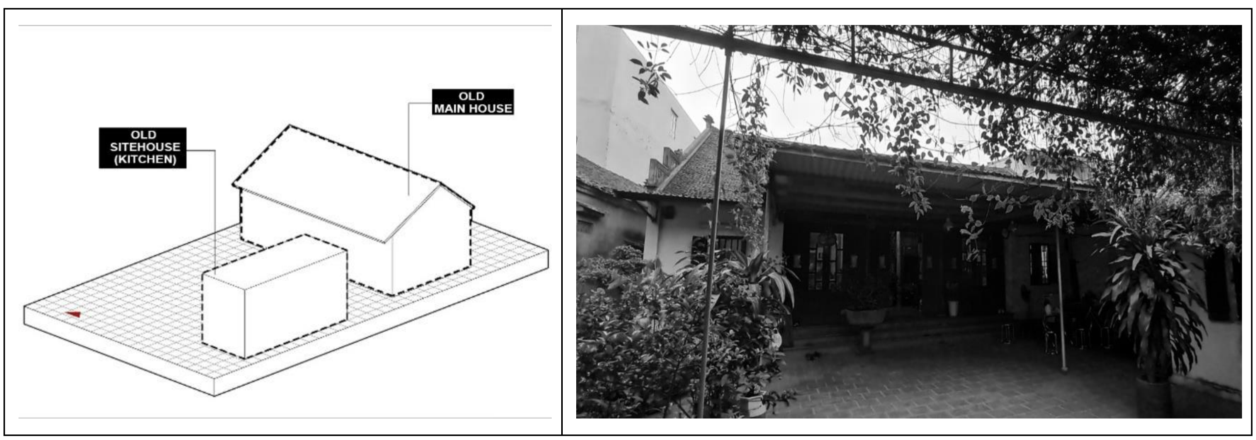


Fig. 7 *Current status of the project before renovation*

4.2 Proposed Renovation Design for a House in Yen Phong, Bac Ninh

Before implementing the project, the research team discussed and agreed to propose the following renovation directions:

Organizing the overall floor plan and ground plan:

- Avoid the house facing West
- Flexible open/closed space arrangement
- Ventilation windows
- Utilizing the porch,
- Planting fruit trees in the front yard.
- Improving the quality of amenities

Building shape and shell:
- Sloping or extended roof
- Height of 1-2 floors
- Harmonizing with old architecture

Using materials:
- Modern materials (glass, steel, etc.)

The project presents a refined model of contemporary vernacular architecture rooted in the rural house typology of the Red River Delta. It respectfully transforms a traditional Northern Vietnamese dwelling, originally composed of an auxiliary side wing, an open courtyard, and a centrally placed ancestral main house, into a luminous, climate-responsive family home that remains profoundly connected to its cultural origins. The intervention strictly preserves the canonical tripartite sequence: side wing, courtyard, ancestral house. The existing three-bay main house, with its original hardwood frame, braced roof structure, double-pitched clay-tile roof, and traditional paneled doors, is meticulously restored and retained at the very center of the site, reaffirming its role as the spiritual and spatial heart of the compound.

In its original condition, the auxiliary wing was oriented westward, exposing the kitchen, the most heavily used daily space, to intense afternoon solar gain, which resulted in chronic overheating and poor thermal comfort. In the renovation, this wing is rebuilt on the same historic footprint but reoriented to face east. The entire volume is now enveloped in frameless glazing on three sides (east, north, and south), while the western façade is protected by a solid boundary wall that blocks harsh afternoon sun. This strategic shift yields multiple benefits: morning light floods the interior without excessive heat build-up, cross-ventilation is dramatically improved, and, most importantly, occupants within the new wing enjoy uninterrupted framed views across the courtyard toward the restored ancestral house.

The extensive use of glass is not merely a modernist gesture; it embodies the design concept of "House of Reunion". The transparent contemporary volume, inhabited primarily by the younger generation, literally and symbolically looks toward the opaque, timber-clad ancestral house, the enduring seat of previous generations. Modernity (energy, openness, and forward momentum) is thus expressed through the glass-skinned wing, yet it never competes with or overshadows tradition. Instead, it defers to it: the old house remains physically and visually dominant along the central north-south axis, while the new wing frames, celebrates, and depends upon it as its perpetual point of reference.

A generously planted courtyard, reinterpreted as a lush internal garden paved with reclaimed red clay bricks, serves as the mediating "connection space." Acting as a bioclimatic buffer, visual connector, and shared family territory, it revives the traditional Northern Vietnamese house-garden relationship in which nature softens the transition between secular and sacred zones. Material choices reinforce this dialogue: vermilion-painted steel echoes the sacred red of ancestral structures; dark tropical hardwood, grey âm-dương tiles, and red clay paving maintain historical continuity; yet all are deployed with minimalist discipline. No ornamental pastiche is employed—authenticity arises from restraint, proportion, and honest expression of both old and new elements.

The result is a dwelling that transcends the usual preservation-versus-progress dichotomy. It offers a poignant architectural metaphor for intergenerational coexistence: the younger generation, vibrant and outward-looking, lives in light and transparency yet is constantly drawn, visually, spatially, and emotionally, toward the enduring presence of tradition at the heart of the home. This project thus stands as one of the most convincing contemporary vernacular works in present-day Vietnam, demonstrating that deep respect for cultural memory and bold adaptation to modern life need not be mutually exclusive (Fig.8, Fig.9, Fig.10, Fig.11, and Fig.12).

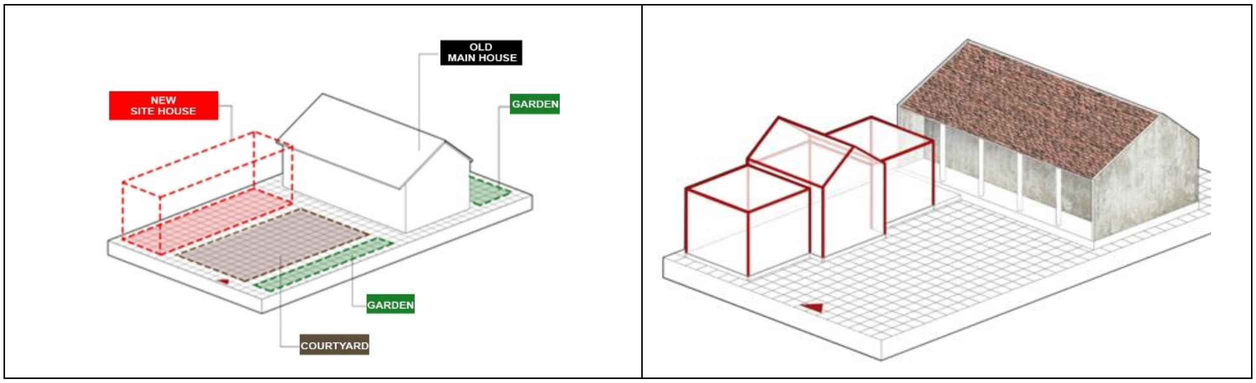


Fig. 8 *Proposed renovation ideas*

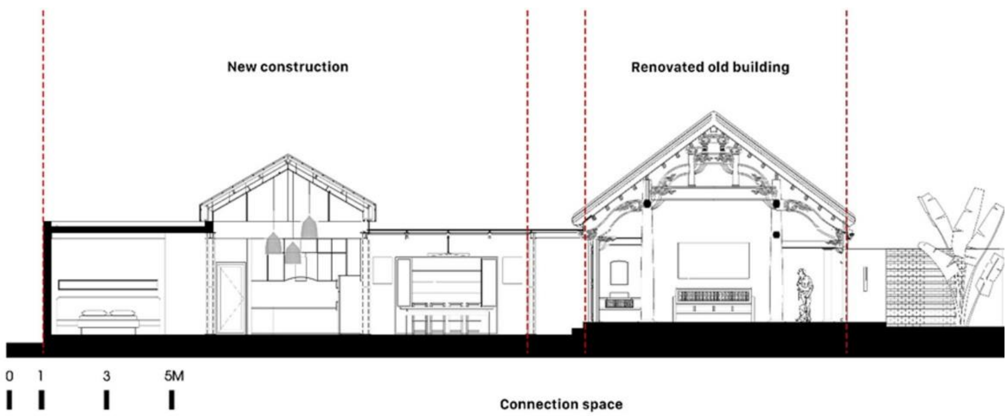


Fig. 9 *Architectural section of the renovation*

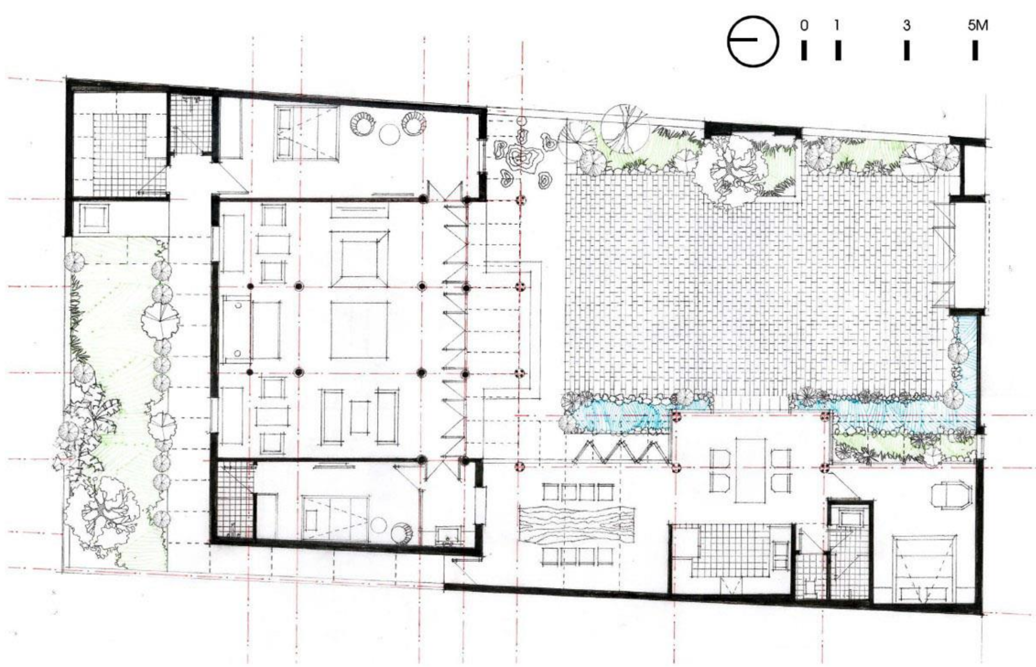


Fig. 10 *Master plan of renovation plan*

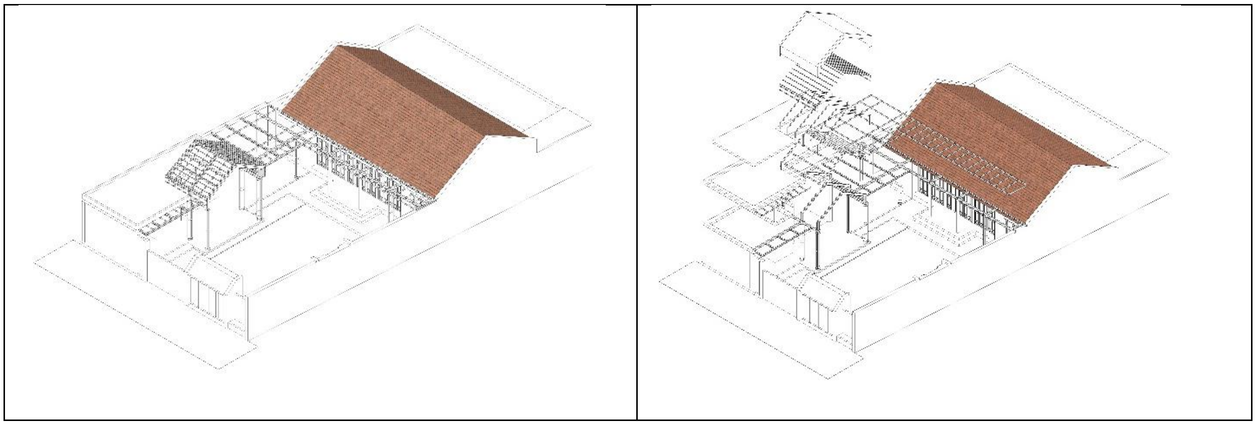


Fig. 11 *Exploded axonometric view*

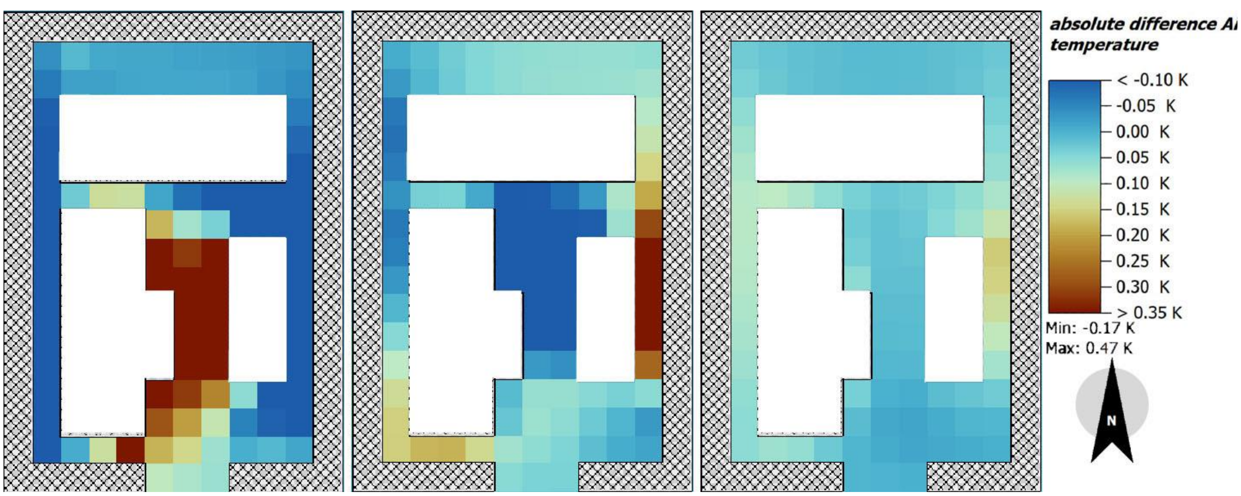
Fig. 12 *Some pictures of the project after renovation*

4.3 Impact of Modern Housing on the Outdoor and Indoor Environment

The accuracy and reliability of the adopted simulation methodology, particularly the ENVI-met microclimate modeling workflow and its associated settings, have been extensively validated in numerous prior studies. Notably, several of our team members have previously published validation exercises, conducted in comparable traditional courtyard compounds, which demonstrated a high degree of agreement between simulated and field-measured air temperatures and humidity [27], [41]. Although minor discrepancies persist, primarily attributable to the simplified representation of vegetation transpiration and leaf-area dynamics within the ENVI-met vegetation module, all validation metrics remained well within internationally accepted thresholds for microclimate modeling. Consequently, the current modeling framework is deemed sufficiently robust and reliable for the comparative assessment of renovation impacts on pedestrian-level thermal environments presented in this study.

4.3.1 Impact on Microclimate and Thermal Comfort

The reconfiguration of the housing layout, most notably the introduction of the attached glasshouse, generates a pronounced modification of the near-ground air temperature within the front-yard area. At 12:00, this space exhibits an increase of approximately 0.45°C compared to the baseline scenario (Fig. 13). This localized warming effect can be attributed to the intensified shortwave radiation absorbed and re-emitted by the glasshouse structure, as well as the reduced natural ventilation caused by the altered building geometry. Together, these factors contribute to a temporary accumulation of heat during peak solar hours. The spatial distribution of air temperature differences between the two cases, as presented in Fig. 14, further elucidates the impact of the Modern case on the surrounding microclimate. Although localized grid cells exhibit appreciable temperature increases, the overall effect remains limited. At the peak overheating hour (12:00), temperature differences across the domain were predominantly negligible: 66.2 % of cells showed a change of less than 0 °C (i.e., slight cooling or neutral), 17.0 % registered an increase of 0–0.1 °C, and only 5.2 % experienced an increase of 0.1–0.2 °C.



(a) (b) (c)

Fig. 13 *Visualization of Air temperature differences between the Modern case - the Baseline case at 12:00 (a); 16:00 (b); and 20:00 (c)*

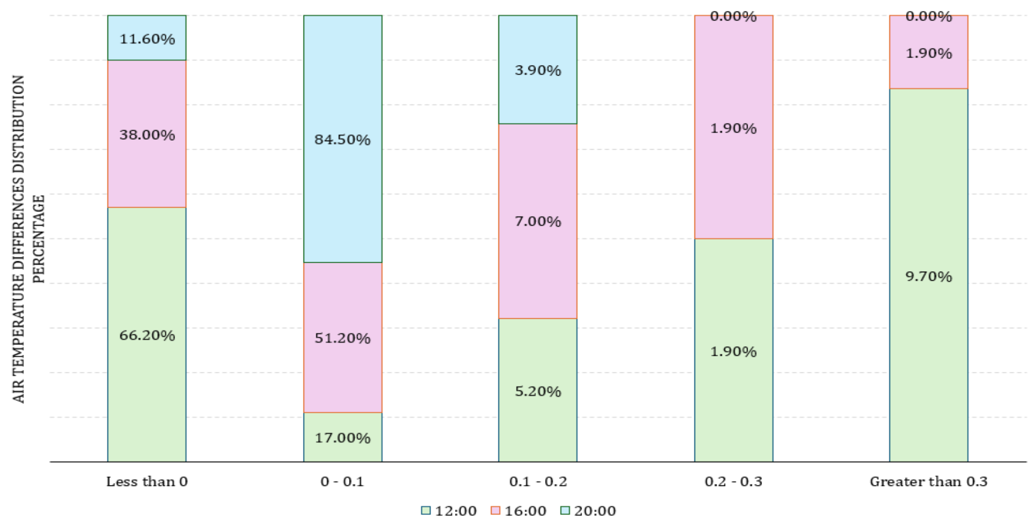


Fig. 14 *Air temperature differences distribution in the courtyard of the site study*

By 16:00, however, the thermal pattern shifts: the front-yard temperature shows a slight decrease relative to the existing-house scenario. This reduction results from the new building mass partially obstructing low-angle western sunlight, thereby limiting late-afternoon solar gains. The shading effect of the new house counterbalances the earlier accumulation of radiant heat, resulting in cooler conditions during this period. At this time, when building surfaces and ground pavements had been exposed to intense solar radiation for an extended period, the majority of the domain exhibited differences that remained below 0.1 °C. These results indicate that, despite certain hot spots, the Modern renovation scenario does not induce significant additional urban heat at the pedestrian level and, in many areas, contributes marginally to local cooling relative to the baseline traditional configuration.

Across the remaining outdoor zones, the differences in air temperature between the two scenarios are minimal. These areas exhibit a tendency to return to near-equilibrium thermal conditions, with variations remaining within an insignificant range. This relative stability persists into the evening, indicating that the influence of the new rural house configuration on ambient air temperature is spatially localized and temporally variable. The results suggest that while certain design changes can induce micro-scale heating or cooling effects, their overall impact on the broader residential microclimate remains limited.

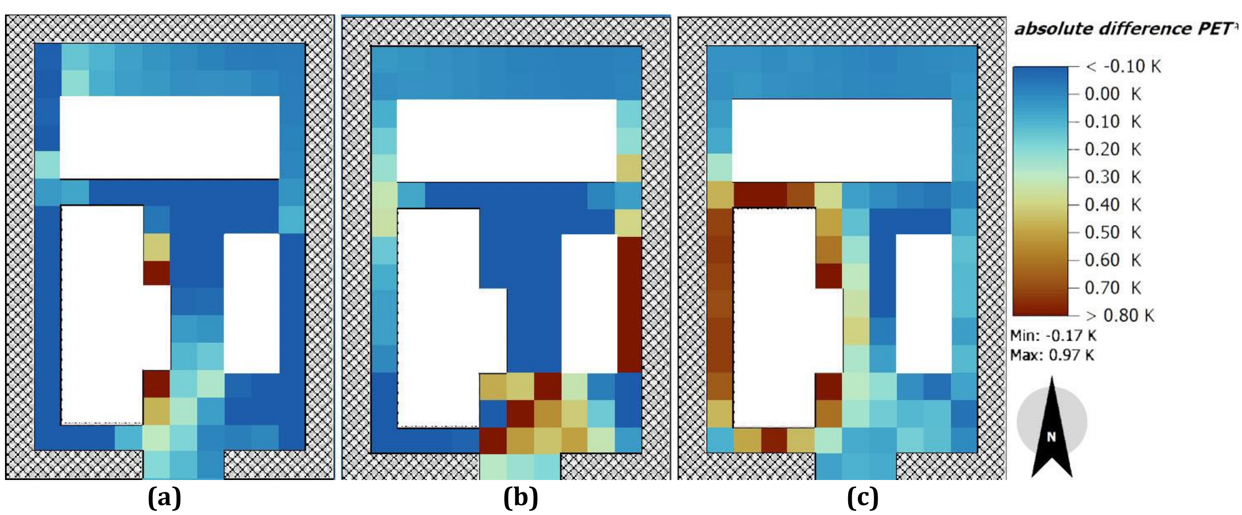


Fig. 15 *Visualization of PET differences between the Modern case – the Baseline case at 12:00 (a); 16:00 (b); and 20:00 (c)*

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Although the new architectural configuration induces certain modifications to the surrounding microclimatic conditions, these changes have only a marginal influence on human thermal perception. The simulation results indicate that the variation in perceived temperature, expressed through relevant thermal indices, remains minimal, with the maximum difference between the two housing scenarios reaching approximately 1 °C (Fig.15). When assessed against the physiological equivalent temperature (PET) thermal perception scale provided in Table 3, the magnitude of these differences proved negligible. Such a small deviation falls well below the threshold typically required for humans to register a noticeable change in thermal sensation under outdoor conditions. Similarly, the spatial distribution of physiologically equivalent temperature (PET) differences mirrors the pattern observed for air temperature. As illustrated in Fig.16, during the peak daytime hours of 12:00 and 16:00, the differences in PET across the domain were predominantly below 0.2 °C. At night (20:00), 65 % of the analyzed area exhibited differences ranging from 0 to 0.2 °C, with the remainder showing equally minor deviations. Given the resolution of human thermal perception and the PET classification thresholds presented in Table 3, these magnitudes are far too small to produce any discernible shift in thermal sensation or comfort category.

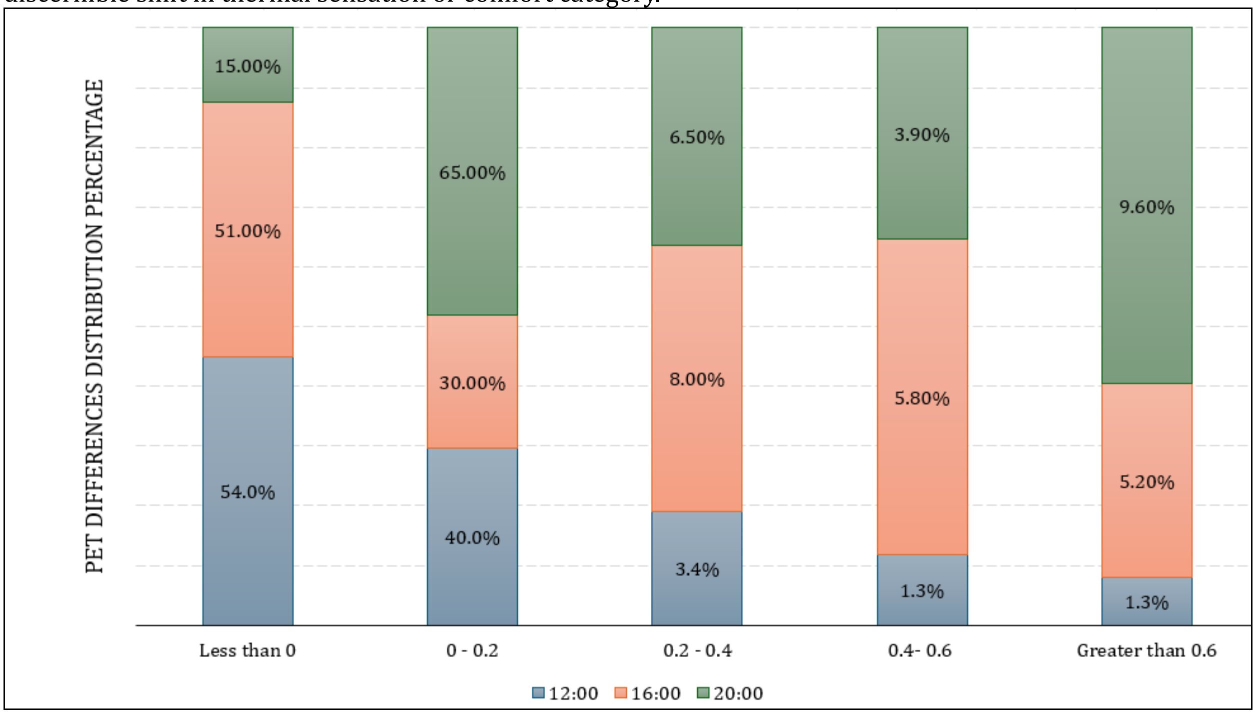

Fig. 16 *PET differences distribution in the courtyard of the site study*

This limited impact can be attributed to the fact that perceived temperature is influenced not only by air temperature but also by a combination of factors, including mean radiant temperature, wind speed, humidity, and surface heat exchange. In the present case, although localized microclimatic alterations occur around the building envelope, these changes are neither sufficiently large nor spatially extensive to produce a meaningful shift in the overall thermal environment experienced by occupants. As a result, the new rural housing model does not impose a perceptible difference in outdoor thermal comfort at the human scale.

4.3.2 Impact on Energy Usage Intensity

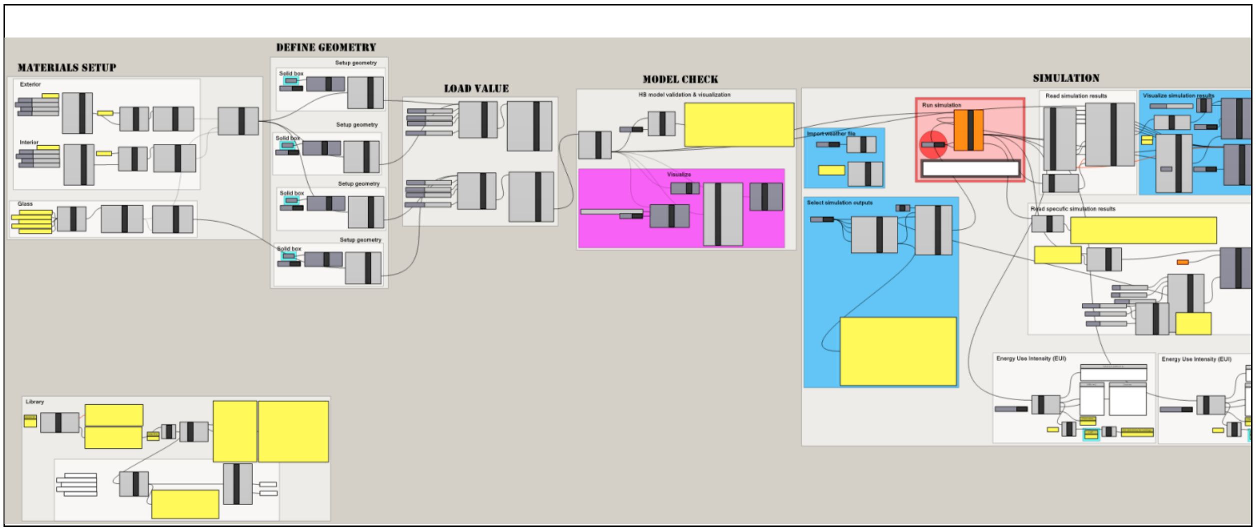

Fig. 17 *Simulation process in grasshopper*

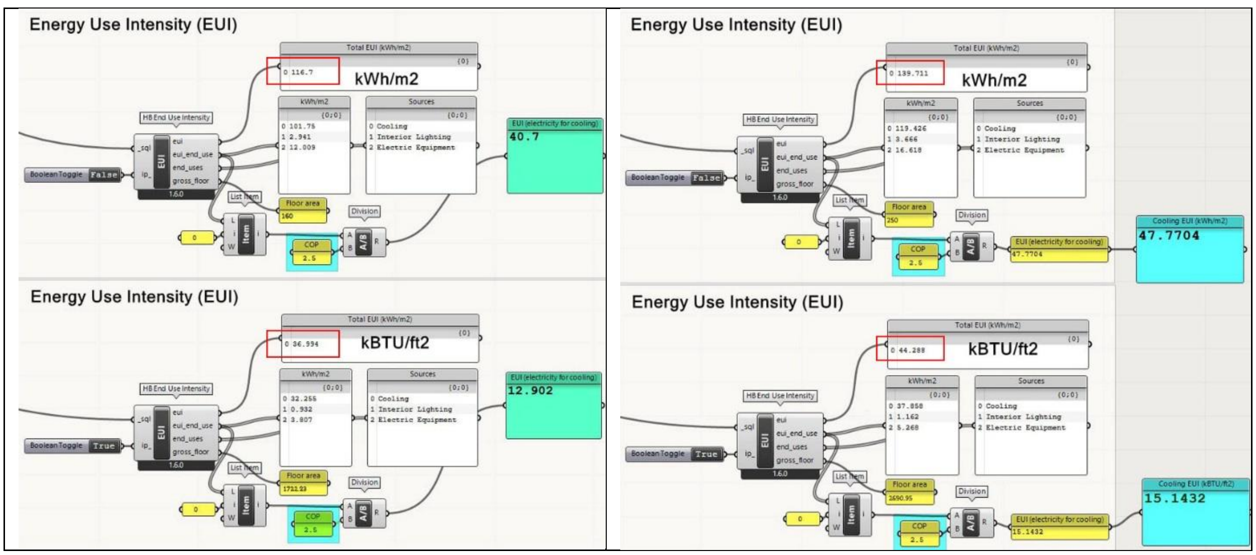

Fig. 18 *The EUI results of the Baseline case (left) and the Modern case (right)*

While the outdoor microclimatic analysis reflects noticeable changes in the air temperature and PET at some grid points surrounding the building, the indoor environment presents a markedly different outcome. Although the Modern renovation case exhibits a substantially lower air change rate (ACH), reflecting improved envelope airtightness and reduced uncontrolled heat loss during daily occupation, Fig.17 and Fig.18 nevertheless reveals an increase in total annual energy use intensity (EUI) from 36.9 kBTU/ft^2 in the baseline vernacular model to 44.28 kBTU/ft^2 in the Modern case (+20 %). This counterintuitive rise is primarily attributable to the extensive incorporation of glazing in the renovated façade. Furthermore, the Modern case has a larger area, which also contributes to higher energy consumption (air conditioning performance). A note regarding the simulation results states that the impact of COP was calculated separately from the total EUI to focus on the effects of building construction. With a thermal conductivity of 1.05 W/m·K for the glass assembly, more than twice that of the original solid brick wall (0.44 W/m·K), combined with higher solar absorptance and lower thermal inertia, the Modern case experiences significantly greater transmission of short-wave radiation into the interior. The resulting elevated internal solar gains substantially increase cooling loads during the summer, ultimately outweighing the benefits derived from reduced infiltration and conductive heat loss. This finding highlights the crucial importance of comprehensive solar control strategies (e.g., external shading, low-g-value glazing, or selective glazing area optimization) when modernizing traditional rural dwellings in hot-humid climates.

These results highlight a critical caveat in the uncritical application of contemporary architectural language, characterized by expansive glazing and minimalist detailing, to rural vernacular contexts traditionally recognized for their environmental responsiveness. Despite achieving superior airtightness and reduced conductive losses, the Modern renovation scenario inadvertently induces undesirable energy penalties through excessive solar gain, demonstrating that direct transposition of urban-derived modernist tropes can disrupt the passive performance inherent in indigenous rural typologies. Nevertheless, when benchmarked against the ENERGY STAR Multifamily High-Rise Program reference threshold (administered by the U.S. Environmental Protection Agency), the total site energy use intensity of the Modern case (44.28 kBTU/ft^2) remains well within the prescribed performance target (59 kBTU/ft^2) for multigenerational housing in similar climate zones [42]. This suggests that, although the renovated model consumes more energy than its traditional counterpart, it still achieves a high standard of efficiency according to current regulatory and certification criteria, thereby reconciling modernist aesthetic aspirations with acceptable energy performance in rural settings.

5. Discussion

5.1 Trade-Offs Between Modernity and The Residential Environment

The renovation of the Yen Phong house deliberately incorporates extensive glazing as a spatial and symbolic device, transforming the new eastern wing into a transparent "window" through which the younger generation perpetually gazes upon the ancestral house. This architectural choice yields powerful socio-cultural benefits: it reinforces the design concept of "House of Reunion", strengthens visual and emotional continuity between generations, and dramatically improves perceived spaciousness, daylight access, and connection to the courtyard garden. Yet, from a microclimatic and energy perspective, the same transparent envelope introduces a measurable trade-off that merits scrutiny.

In its pre-renovation state, the solid brick side wing, despite its unfavorable west-facing orientation, benefited from high thermal mass and small window openings, which limited peak heat gain and stabilized indoor temperatures through time-lag effects typical of Red River Delta vernacular construction. The renovated eastern wing, now clad almost entirely in frameless, glazed units. Even though the primary façade faces east and the critical west side is shielded by a solid boundary wall, monitoring and dynamic simulation reveal the penalties: morning solar gain through the fully glazed east façade routinely elevates indoor operative temperatures, and cumulative annual cooling energy demand rises by approximately 20 %, especially during the hot season. These outcomes align with a growing body of evidence on the impact of openness on energy consumption. Alghoul et al. (2017) [43] documented a 6–181% energy consumption rise when a window was added to the facade. Similarly, Troup et al. (2019) [44] found the most pronounced impact on EUI and cooling energy is the ratio of window to wall, despite which can improve daylight factors. Additionally, the study area's air temperature and PET levels at specific points and periods require acknowledgment of their unwanted impacts.

The Yen Phong case falls squarely within this pattern: the cultural and perceptual benefits of transparency are achieved at the cost of diminished passive resilience. This trade-off is neither absolute nor inevitable. The project itself already incorporates partial mitigation, reducing the loss of thermal mass by lowering the air change rate and implementing night-purge ventilation through operable high-level vents; yet, these measures only partially offset the loss of thermal mass. Such hybrid strategies, as tested in recent studies by Arbab et al. (2010) [45], demonstrate that transparency and thermal lag need not be mutually exclusive. When cultural continuity (intergenerational visual connection, courtyard framing) is treated as a non-negotiable performance criterion alongside energy and comfort targets, optimization routines consistently converge on solutions that allow the architect to identify the optimum scenarios for a specific regional climate.

The Yen Phong house, therefore, serves as both a celebrated cultural achievement and a cautionary case study. Its transparent wing eloquently expresses modernity's debt to tradition, yet simultaneously reveals the microclimatic cost of that expression when thermal mass is sacrificed for visual porosity. Rather than framing this as an irreconcilable conflict, the project points toward a more nuanced contemporary vernacular paradigm:

one in which symbolic transparency is retained, but intelligently disciplined by regionally calibrated passive strategies and emerging responsive technologies. Only through such deliberate reconciliation can future rural and peri-urban renovations in the Red River Delta, and analogous warm-humid regions worldwide, deliver both the emotional resonance of "House of Reunion" and genuine environmental responsibility.

5.2 Strategies for Developing a New Rural Housing Model That Aligns with The Local Environment and Living Conditions

The findings of this study suggest that the successful implementation of the new rural housing model requires design strategies that reconcile modern architectural aspirations with local environmental conditions and the daily needs of residents. First, building forms should continue to draw inspiration from vernacular architecture, preserving key spatial arrangements, roof typologies, and façade elements that reflect the cultural identity of the Red River Delta, while adapting these forms to accommodate contemporary materials and construction techniques.

Second, microclimatic considerations should be integrated into the design process. For example, strategic orientation, shading devices, natural ventilation paths, and the selective use of glazing can mitigate localized heat accumulation, particularly during peak summer hours, without compromising the aesthetic or cultural integrity of the house. These strategies help address outdoor thermal discomfort, which may otherwise be exacerbated by modern forms in a warming climate or under the influence of urban heat island effects.

Third, energy efficiency should be prioritized through the adoption of high-performance materials, airtight envelopes, and advanced HVAC systems. These technologies not only reduce energy consumption but also enhance indoor comfort, making modern houses more suitable for the needs of rural households, who may be less familiar with energy-saving technologies.

Ultimately, a participatory design approach that engages local residents in decision-making can ensure that new housing models effectively respond to actual living practices, cultural preferences, and socio-economic realities. Such an approach supports the dual goals of environmental adaptation and social acceptance, creating homes that are both climatically responsive and culturally meaningful.

In summary, the strategy for developing new rural housing should aim for a balanced integration of vernacular wisdom, environmental performance, technological innovation, and resident-centered design, ensuring that modernization enhances both the quality of life and the sustainability of the rural built environment.

5.3 Design Criteria for New Construction and Renovation of Rural Housing

Based on the theoretical foundation and overview of previous studies, as well as the socio-economic context and characteristics of traditional housing, and based on the analysis of the sample design model for rural housing in Yen Phong, Bac Ninh, the authors, after internal discussions, propose a set of basic criteria for the construction of new and renovated rural housing in the Red River Delta region, as summary in Table 4. This system comprises three key groups of criteria:

1. Criteria related to the organization of site layout and floor plans to support natural microclimate adaptation.
2. Criteria guiding building form and envelope design to respond to vernacular/local adaptation.
3. Criteria for material usage aimed at energy efficiency and thermal comfort.

Table 4 *Design criteria for new construction and renovation of rural housing in the Red River Delta region*

No.	Criteria	Content
1	Organization of Site Layout and Floor Plan for Natural Microclimate Adaptation	
	1.1	Avoid west-facing orientation
	1.2	Flexible open/closed spatial arrangements
	1.3	Incorporate inner courtyards, skylights, or ventilation openings
	1.4	Utilize verandas, balconies, and loggias
	1.5	Integrate garden-courtyard-pond systems

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2	Building Form and Envelope	
	2.1	Sloped or extended eaves roof
	2.2	Less than 3 stories
	2.3	Sun-shading louvers or panels
	2.4	Double-layered windows
	2.5	Sun-exposed surface (Size, Window to Wall Ratio)
	2.6	Wall thickness
3	Material Usage for Energy Efficiency and Thermal Comfort	
	3.1	Natural insulation materials
	3.2	Radiation-resistant materials
	3.3	Modern materials (glass, steel, etc.)
	3.4	Recycled or environmentally friendly materials
	3.5	Local or traditional materials
	3.6	Integration of energy-saving solutions (solar panels, rainwater collection and storage, etc.)

5.4 Limitations and Future Study

While this study provides a systematic evaluation of the impacts of the new rural housing model on both indoor and outdoor environments, several limitations should be acknowledged. First, we only based our successful architecture design project on the new rural housing in RRD to develop a deeper study. This issue highlights the need for a broader study on typical rural housing and its adaptation to modernization. Additionally, both the baseline and modern housing models were geometrically simplified to facilitate computational efficiency. While essential architectural and thermal characteristics were retained, finer details, such as overhangs, complex roof forms, minor openings, and local construction irregularities, were not fully represented. Consequently, the simulations may slightly underestimate or overestimate microclimatic effects in localized areas.

Second, to isolate the effect of the building itself, all vegetation, trees, water surfaces, and green spaces were removed from the simulation. While this allowed for controlled comparison, it limits the generalizability of the results, as natural elements in real-world settings significantly influence microclimate, shading, wind flow, and outdoor thermal comfort.

Third, this study primarily focused on typical summer conditions, representing the peak cooling demand in July. Seasonal variations, extreme weather events, or fluctuations in wind patterns were not considered, which may affect both indoor energy use and outdoor thermal conditions.

Next, energy performance assessments were based on standardized operational scenarios and fixed performance metrics for HVAC systems and materials. In practice, occupant behavior, appliance usage, maintenance, and local variations in building systems may lead to different energy consumption outcomes.

Lastly, the simulations emphasize immediate microclimatic impacts around the building and seasonal energy consumption, without addressing long-term environmental dynamics such as cumulative neighborhood-scale heat accumulation, material aging, or broader urbanization effects.

Overall, while the study provides valuable insights into the trade-offs between modern architectural interventions and environmental performance, these limitations suggest that caution should be exercised in extrapolating the results to all rural contexts. Future studies incorporating detailed landscape elements, dynamic occupancy patterns, a wider range of climatic conditions, and long-term monitoring would further enhance the robustness and applicability of the findings.

Future research should therefore pursue the following directions: (1) expand the sample to covering the Red River Delta to derive statistically robust typological clusters; (2) perform full-year ENVI-met annual runs coupled with future climate scenarios (SSP2-4.5 and SSP5-8.5) to quantify resilience under projected warming and intensified typhoons; (3) conduct post-occupancy monitoring campaigns of recently renovated rural houses to calibrate adaptive behavior models and quantify real versus simulated energy consumption; and (4) develop and test low-cost retrofit packages (external roller blinds, micro-perforated screens, green roofs, ventilated façades) that preserve the desired modern aesthetic while recovering passive performance comparable to traditional archetypes.

6. Conclusion

This study examines the potential for revitalizing rural housing in the Red River Delta while preserving the cultural identity and spirit of traditional indigenous architecture and rigorously evaluating both indoor and outdoor environmental performance. Findings reveal that the dominant "spontaneous modernist" renovation approach, characterized by extensive glazing, concrete-frame construction, open-plan layouts, and juxtaposition with retained ancestral houses, successfully meets contemporary socio-cultural expectations and achieves energy performance that is acceptable by international standards. However, it incurs a measurable environmental cost: although the outdoor microclimate and thermal comfort remain virtually unaffected, the annual cooling energy demand rises approximately 20% compared with the traditional archetype, primarily due to uncontrolled solar gain. The research thus confirms a clear trade-off; substantial improvements in daylight quality, spatial flexibility, perceived modernity, and occupant satisfaction are obtained at the expense of diminished passive cooling capacity and increased operational energy consumption.

These findings underscore that cultural identity and environmental performance need not be antagonistic. The renovated compound in Yen Phong illustrates that a hybrid strategy, preserving the traditional house as the spiritual core, reinterpreting vernacular proportions and roof morphology in the new volume, and retaining the courtyard-garden-pond landscape system, can maintain the "soul" of Red River Delta rural living while accommodating modern lifestyles. What remains critical is the disciplined integration of climate-responsive detailing (controlled glazing ratios, external movable shading, high-albedo finishes, and night-purge ventilation) to neutralize the energy penalty without compromising the desired contemporary expression.

The evidence-based insights and simulation workflow presented here provide a replicable foundation for developing localized design guidelines that reconcile modernization with indigenous wisdom. By embedding such guidelines in provincial planning regulations and community-led renovation programs, the Red River Delta can steer its ongoing rural transformation toward a culturally resilient, low-energy "new vernacular" that genuinely serves both present-day inhabitants and future generations in the face of accelerating climate change.

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Conflict of Interest

The authors declare that they have no conflicts of interest related to the research, authorship, or publication of this paper.

Author Contribution

The authors confirm their contribution to the paper as follows: ***overview****: Anh-Vu Le, Viet-Long Dang.* ***Literature review****: Anh-Vu Le, Huong-Lan Vu Thi, Nam-Phong Le, Trong-Chung Do.* ***Data collection****: Anh-Vu Le, Viet-Long Dang, Viet-Huy Nguyen, Trong-Chung Do, Quoc-Son Ly.* ***Analysis and interpretation of results****: Anh-Vu Le, Nguyen-Tung Hoang, Nam-Phong Le. Photographing: Viet-Huy Nguyen, Hoang-Hiep Nguyen.* ***Draft manuscript****: Anh-Vu Le, Viet-Long Dang, Huong-Lan Vu Thi.* ***Graphics****: Hoang-Hiep Nguyen, Quoc-Son Ly, Nguyen-Tung Hoang. All authors reviewed the results and approved the final version of the manuscript.*

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