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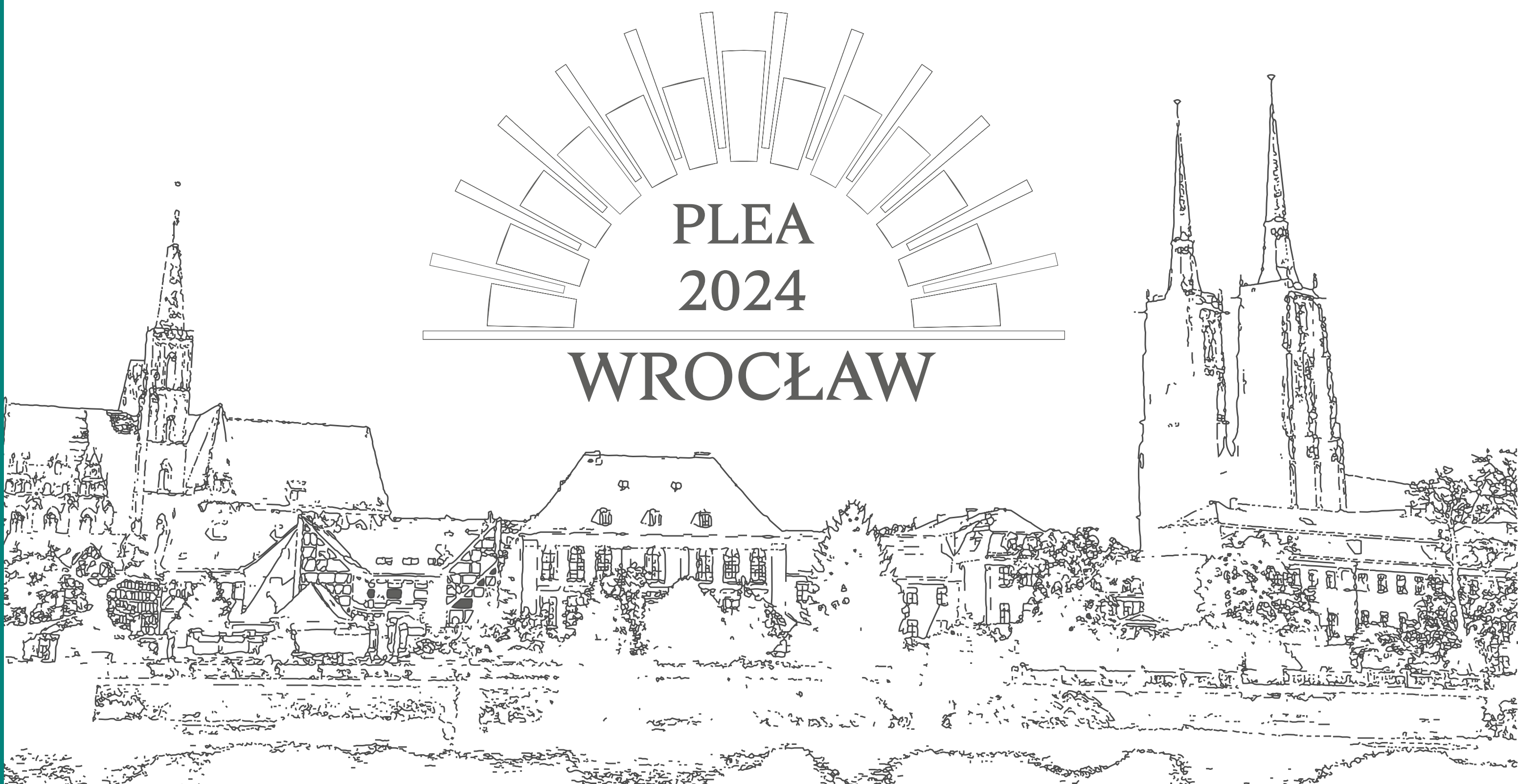

Fusing Environmental Technologies with Attached Housing in Rural Vietnam:

A Synergistic Approach

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ABSTRACT: This paper presents the design, development, and performance evaluation of a Net-Zero attached housing project in the hot and humid climate of Northern Vietnam. Integrating bioclimatic design principles, contemporary environmental technologies, and local building materials. The project aimed to minimize energy consumption while improving the quality of life for the local Tay ethnic group with respect to their traditional lifestyles. A careful examination and adaptation of the traditional local house layouts enabled the integration of efficient passive design strategies such as natural cross-ventilation, shading, solar heating, thermal mass, and daylighting. The use of indigenous building materials and renewable energy sources, including solar panels, was crucial in achieving optimal thermal and lighting performance, resulting in net-zero energy consumption. The successful outcome of this project demonstrates the potential of environmentally friendly, economically viable, and culturally sensitive building practices in achieving sustainable development in the region.
KEYWORDS: Energy, Comfort, Net-Zero, Bioclimatic Design

1. INTRODUCTION

The project is situated in a rural village within the mountainous region of Cao Bang, at an elevation of 289 m above sea level. This village is inhabited by members of the Tay ethnic group, and its population consists of 14 multigenerational families. The local economy predominantly depends on agricultural and forestry activities, along with providing homestays for tourists.

Our team had the opportunity to visit the village and conduct surveys on neighbouring houses. Measurements were taken for indoor illuminance, dry bulb temperature, and air velocity to evaluate the indoor environmental quality in November 2022. The findings revealed that the residents inhabit poorly ventilated spaces with dim interiors (127-136 lux) and cold environments (with no auxiliary heating).

The project is in a region characterized by a temperate climate, experiencing a dry winter season and a hot summer season (Cwa) at a latitude of 22°N, according to the Koppen-Geiger climate system. It falls under the International Energy Conservation Code (IECC) climate zone 2A, which is categorized as hot and humid. The average highest temperature reaches 31°C, while the lowest temperature can drop to 11°C. Additionally, the global horizontal radiation can reach up to 503 W/m². By employing a modified comfort range tailored explicitly for Vietnamese individuals [1], which is 20°C-27.7°C, we have determined that passive design strategies such as internal heat gains and natural ventilation can effectively provide thermal comfort for approximately 80% of the year. Supplementary heating and cooling measures would be necessary only during the remaining 20% of the year. This approach ensures minimal reliance on energy consumption (refer to Figure 1).

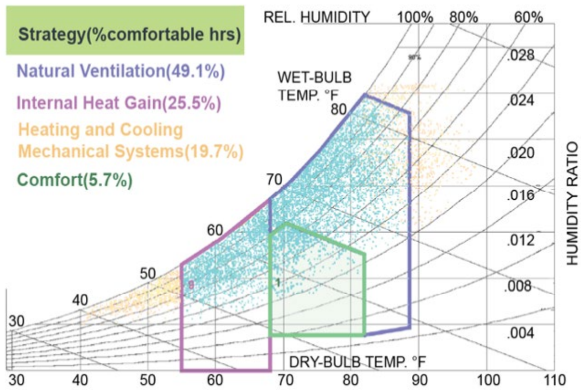

Figure 1: Adapted psychrometric chart for Vietnam.

Our design approach encompasses five overarching objectives. Firstly, in terms of “quality of life,” our focus is on enhancing the well-being of the local community in Khuoi Ky Village. This involves addressing issues related to indoor environmental quality, with a particular emphasis on improving daylighting, natural ventilation, and thermal comfort.

Secondly, sensibility plays a crucial role in our design philosophy. We acknowledge and respect local people's unique way of life and specific building attributes. Thus, our project aims to incorporate and honour local customs and architectural features seamlessly. Thirdly, passive design is integral to our strategy. We employ natural ventilation, daylighting, and shading strategies to ensure occupant comfort, reduce energy consumption, and enhance indoor environmental quality. Fourthly, constructability considerations were meticulously studied, considering the village's location, community setting, and accessibility. We prioritized utilizing locally sourced materials and low-skilled construction techniques while still achieving the desired insulation levels. Lastly, resilience is a crucial aspect of our design, with the project aptly responding to common hazards like flooding and landslides in the area. This holistic approach ensures a comprehensive and sustainable solution that aligns with the unique context of Khuoi Ky Village.

2. METHODOLOGY

The optimization of energy and lighting performance of the three attached housing units involved utilizing software tools, such as ClimateStudio [2], Sefaira SketchUp [3], ALFA, IESVE [4], Meteonorm [5], Rhino, OneClickLCA [6], and Ekotrope [7]. These programs facilitated a comprehensive assessment and refinement of environmental technologies to enhance the overall project. Performance metrics included Energy Use Intensity (EUI) for energy consumption efficiency, Home Energy Rating System (HERS) for overall energy efficiency, and Spatially Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) for natural lighting assessment. Equivalent Melanopic Lux (EML) addressed circadian lighting impacts, while Daylight Glare Probability (DGP) ensured visual comfort. Air quality was evaluated through Air Changes per Hour (ACH) and Local Mean Age of Air (LMA) using the CFD tools available in IESVE. Lighting Power Density (LPD) gauged lighting efficiency, Solar Production (kW) measured solar energy generation, and Carbon Footprint Target (LCA) provided an environmental impact assessment.

3. RESULTS

This project is a sensible intervention aimed at addressing existing issues regarding access to energy, living conditions, lifestyle, and the economy. The houses were conceptualized to accommodate a multi-generational family, following the typical pattern of development in the local village. Additionally, they were designed to be an adaptable and affordable housing prototype for future development in the region. Due to the growing tourist homestay market, the project also lends itself to a homestay typology that a family could administer from one of the housing units.

The houses were designed to adapt to future weather changes, explicitly considering the years 2050 and 2090 (see Figure 2). The building envelope, shading, and ventilation systems were carefully designed to respond and adapt effectively to variations in solar radiation, temperature, and relative humidity. This was accomplished through detailed simulations to assess the future thermal loads and optimize the design accordingly.

Figure 2: Future climate projections 2020-2090, temperature (T) and global horizontal solar radiation (R).

3.1 Architecture

3.1.1 Site & Programming

The Khuoi Ky Houses consist of three independent housing units attached to an outdoor veranda that serves as the main entrance, a gathering space, and a shaded area. The houses are labelled as Modules A, B, and C in Figure 3. Modules A and C have a living room, dining room, two bedrooms, bathroom, and kitchen for a total internal net area of 90.6 m^2. Module B has the same programming but with only one bedroom for a total of 76.6 m^2.

The site is elongated along the NE- SW axis and can only be accessed from a road on the eastern side. A vegetated mountainside borders the western side of the site. Importance was given to the south-eastern orientation due to local customs, access to views, and prevailing winds during the hot season.

Figure 3: Site Plan.

3.1.2 Architectural Strategies

The building massing aligns with the NE-SW axis of the site's geometry. The three housing units are intentionally separated from each other to allow the placement of windows on opposite sides of each room, promoting natural cross-ventilation and uniform daylighting. The massing of the three units was deliberately kept as a shallow floor plate to allow for cross-ventilation and daylighting, with the deepest space being 4.5 m. The northern facade of the houses has an azimuth angle of 31° offset from True North. The houses cast shade on each other to help regulate solar heat gains. An outdoor veranda facing southeast connects the units and acts as a shading device while promoting access to morning circadian light.

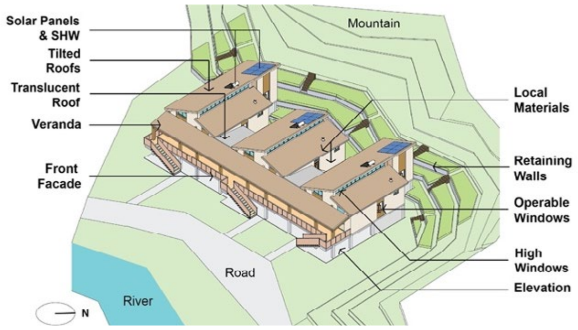

Figure 4: Main design features

Given that the users rely on agricultural practices, the backside of the housing units was designed as planting terraces. This helped to create a buffer zone to avoid landslide hazards. The initial site survey also revealed that the locals use exterior gathering spaces. Thus, the front side of the project was designed as a veranda that connects all the housing units.

The decision to elevate the building responds to natural hazards and local customs, where the ground level is often used for storage and multifunctional spaces. Elevating the building also provides a better sense of privacy, access to unobstructed views, and a summer breeze. The roofs were designed for efficient solar power generation and to provide an area for north-facing clerestories. The operable clerestory windows provide even distribution of daylighting and take advantage of the stack effect to enhance natural ventilation further.

3.2 Integrated Performance

3.2.1 Structure and Building Materials

The project adopts a hybrid structural system tailored to meet the unique requirements of the rural Cao Bang region, focusing on efficient thermal insulation, low embodied carbon, and resilience against natural hazards. Also, the construction system is designed to be implemented by low-skilled laborers.

Structural System: We incorporated a stone foundation and frame to elevate the ground floor. This decision was influenced by the local availability of materials and techniques and the reduced need for specialized labour and long-haul transportation. The stone foundation is environmentally sustainable and offers superior flood resistance and waterproofing capabilities. For the upper structure, a wooden and bamboo frame was selected.

Insulation System: The project features a thermal insulation system comprising two key concepts:

1. Continuous building envelope insulation. Rigid insulation panels (Expanded Polystyrene, EPS) were used over the envelope to minimize heat transfer, eliminate thermal bridging over shading devices, and reduce dependency on air conditioning.

2. R-values of series heat transfer. The R-value for each building component (roof, floor, and wall) and U-value for windows were determined based on climate characteristics, parametric energy simulations, and future climate change.

Table 1: R-values for various building components.

Building components	R-value SI (IP)
Wall	3.79 (21.54)
Roof	5.37 (30.52)
Floor	4.71 (26.76)
Windows	**U-value:** 1.42 (0.25)

3.2.2 Mechanical Equipment

In Khuoi Ky homes, all equipment, including a mini-split air conditioner, is Energy Star certified, offering 30% more energy efficiency compared to standard models. Advanced exhaust fans equipped with humidity and temperature sensors efficiently regulate moisture levels. The air conditioning system, rated at 21 SEER and 1.16 kW, alongside fans with varied CFM and Sones ratings, dynamically adjusts to human activities, conserving energy. Compliant with ASHRAE, LEED, and other local standards, this setup ensures optimal performance and energy conservation in varying humid conditions.

3.2.3 Energy Use Intensity

The Khuoi Ky houses will consume 93-99% less source energy than the LEED Source Energy Budget limit. The American Institute of Architecture (AIA) 2030 Challenge serves as a viable climate strategy, outlining a comprehensive framework of benchmarks and objectives aimed at achieving net-zero emissions within the built environment. Khuoi Ky houses' Energy Use Intensity (EUI) exceeds the current AIA 2030 Challenge target of 8, signifying a remarkable energy efficiency standard that represents a 94% to 97% improvement compared to the RESNET's Home Energy Rating System (HERS) [see Table 2]. Electric lighting was distributed based on the visual tasks and use of each space, resulting in 0.2 LPD. The thermal comfort simulation included the natural ventilation and air conditioning operating hours.

Table 2: Rating systems & energy targets.

Rating System	Target	Results		
		A	B	C
AIA 2030 Challenge Energy Use Intensity	8	0	0	0
HERS index	0	-1	-5	-1
Zero tool	-	100%		
Carbon footprint	Less than 500 $kgCO_2e/m^2$			

3.2.4 Solar Panel Design

The photovoltaic panel (PV) capability is 675-700W, and its capacity lasts at least 30 years. The PV panels are placed on the roof and are oriented Southeast, at 211° and tilted 22° to maximize the incident solar radiation. The total collector irradiance is 1,232 kWh/m², producing 2,868 kW per house annually. The total operational hours of the PV panels in Khuoi Ky Village are 4,616 hours a year. The module type BSM700PMB-70SDC has an efficiency of 22.81%, and the energy production for locations A, B, and C is 8.4 kW.

3.2.5 Solar Water Heater

The solar water heater was designed to preheat water to minimize energy consumption during the heating process. The solar water heater features a durable SUS 304 stainless steel insulated tank. The interior of the tank is equipped with a 2-inch-thick layer of polyurethane foam insulation, which can maintain heat for up to 72 hours. The solar water heater is oriented southeast, at 211°, tilted 22 °, and placed on the roof to maximize the performance [Table 3]. The electric water heater is tankless, resulting in lower energy usage.

Table 3: Solar water heater characteristics.

Demand for hot water in households	110 l/day
Hot water supply flow in 1 second	5.766 l/s
Required heat capacity	603 kW
Hot water heating needs of households	3.2 kWh/day
Hot water demand for the whole year (200 days)	640 kWh/year
Total heat required in a year	914 kWh/year

3.2.6 Life Cycle Assessment

We conducted the three houses' life cycle assessment (LCA), adhering to EN 15978 guidelines and ISO 14044 framework. We evaluated the environmental impacts across the entire lifecycle, from raw material extraction to end-of-life stages [Table 4]. Our analysis aimed to scrutinize the environmental efficiency of these houses and explore avenues for diminishing their ecological footprints. Achieving the design goal, each house and its shared veranda successfully maintained a carbon footprint below 500 $kgCO_2e/m^2$.

Table 4: Embodied carbon rating of LCA for House A&C, House B, and the shared space - Veranda.

Structures	$kgCO_2e/m^2$	Rating
Module A & C	291	B
Module B	243	B
Veranda	140	A

3.3 Durability and Resilience

The project's unique location, adjacent to a river and a mountain, required strategies to mitigate natural hazards like floods and landslides, inherent due to the area's topography and rainy climate. Conversely, this setting offered an opportunity for sustainable water management through rainwater harvesting, enhancing environmental sustainability.

3.3.1 Flooding Measures

To combat flooding risks, the project integrated architectural and landscaping measures. Elevating the main living areas was a crucial architectural step to minimize flood damage. A strategically placed drainage system diverts the mountain runoff into the river, preventing water accumulation near the buildings. Additionally, a retaining wall built from local stone along the river's north bank was designed to prevent river overflow and floodwater encroachment, combining architectural foresight with effective landscaping.

3.3.2 Landslides Prevention

Bamboo is used for soil stabilization for landslide prevention, leveraging its strength, resilience, and extensive root system. This approach, proven in various Asian countries, effectively prevents landslides. To control bamboo spread, a root barrier system and the integration of native trees like Teak and Acacia were employed. Additionally, minimal retaining walls offered extra protection against landslides, blending biological and structural methods for comprehensive risk management.

3.3.3 Rainwater Harvesting System

The rainwater harvesting system was calculated in two steps. The first one quantified the potential rainwater collection from the roof based on the local average monthly rainfall, roof catchment area, roofing material's collection efficiency, and a conversion factor, estimating a monthly harvest of approximately 31,000 liters.

The second step assessed the outdoor water needs, particularly for the planting area. It was estimated that the natural rainfall is sufficient for irrigation, eliminating the need for a supplemental irrigation system. Therefore, all harvested rainwater is allocated for indoor use, such as in bathrooms, laundry, and car washing. This efficient use of rainwater enhances the project’s sustainability and water resource management.

3.4 Occupant experience and environmental quality

3.4.1 Daylighting & non-visual comfort

The predominant annual sky types of the local EPW weather file, generated by Meteonorm, were evaluated. It revealed predominantly cloudy sky conditions for approximately 81% of the year, whereas clear days constituted less than 1%, as illustrated in Table 5 and Figure 5. The evaluation of sky types by hours confirmed similar annual percentages.

Table 5: Annual sky types of Khuoi Ky Village.

Annual Sky types	Days (%)	Hours (%)
Clear	3 (1%)	44 (1%)
Partly cloudy	66 (18%)	892 (19%)
Cloudy	296 (81%)	3,699 (80%)

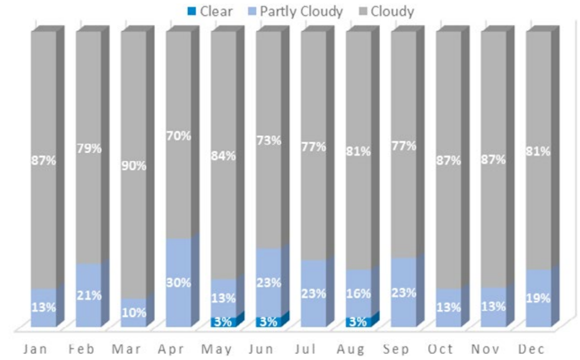

Figure 5: Monthly sky types in Khuoi Ky Village.

Due to the reduced annual daylight availability, multiple daylighting systems were integrated to provide high indoor daylighting levels throughout the year. This strategy entailed installing high-performance windows positioned strategically in various orientations in conjunction with high-operable clerestories for natural ventilation. These measures guarantee extensive natural light penetration within the houses, consequently reducing dependence on electric lighting and augmenting healthy circadian light for occupants. The effectiveness of these interventions was evaluated using climate-based daylight modeling, yielding the results summarized in Table 6, Figures 6 and 7.

Table 6: Summary of dynamic daylighting simulation results.

	House A	House B	House C
UDI (% hrs)	77.4 %	68.8 %	77.0 %
sDA (% space)	99.5 %	92.8 %	96.8 %
ASE (% space)	3.3 %	0 %	1.6 %
DGP (% space)	5.9 %	2 %	5.6 %
EML (% space)	81.5 %	75.5%	78.7 %

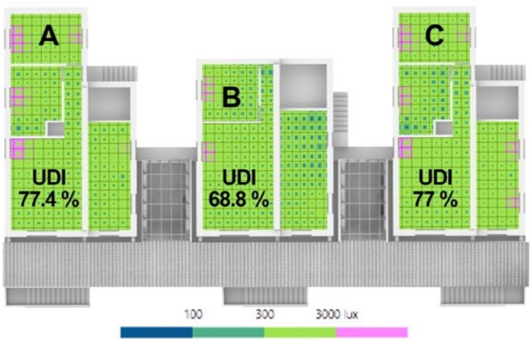

Figure 6: Useful Daylight Autonomy (UDI) results.

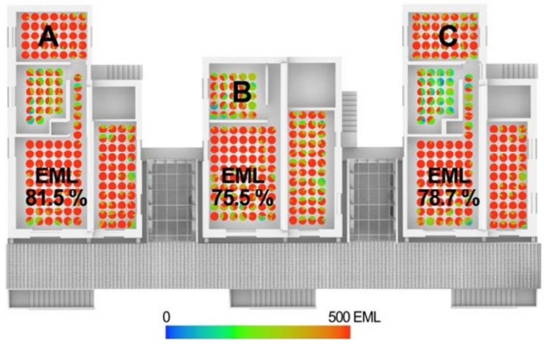

Figure 7: EML simulation results for December 21, 9 AM.

3.4.2 CFD analysis

In the design phase, an in-depth examination of indoor air quality was conducted for the housing units, with a particular focus on natural ventilation. This analysis involved the use of IESVE's CFD tools to simulate indoor air conditions with fully open windows. A key aspect of this simulation was enhancing air circulation through the introduction of operable clerestory windows. Figure 8 presents the velocity vectors in the living room on a typical summer day, illustrating that high windows promote air streams of greater velocities, thereby enhancing the efficiency of air exchange rates.

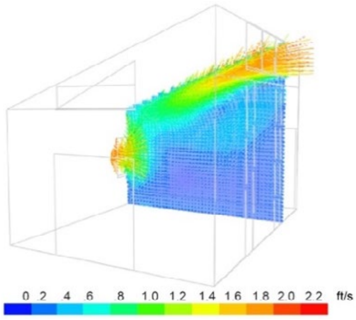

Figure 8: Velocity vectors in living room on a summer day.

Further analysis was carried out to examine the air changes per hour (ACH), a crucial metric for assessing ventilation efficacy. Our simulations for June conditions revealed that several window openings in the living room yielded an average of 25 ACH (Figure 9.) This result underscores the effectiveness of natural ventilation in maintaining recommended ventilation levels during the warmer seasons.

The Local Mean Age (LMA) of air quantifies the average time required for air to traverse from the supply inlet to various locations within a typical kitchen. Figure 10 depicts a maximum LMA value of 2.4 minutes on a typical summer day (June 21). The LMA simulation confirms an efficient air turnover and mitigates the risk of stagnant air conditions within the housing units.

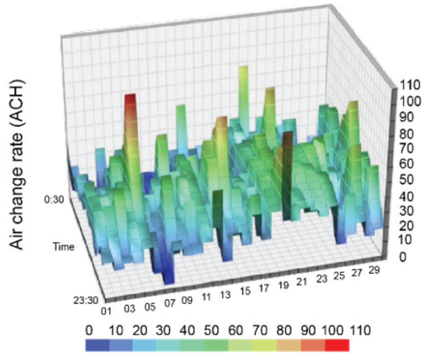

Figure 9: ACH results in the living room of house C.

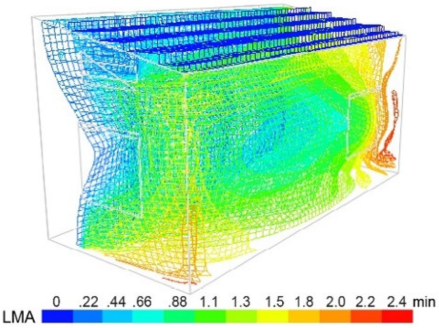

Figure 10: LMA contours in the typical kitchen.

4. DISCUSSION

4.1 Natural Ventilation and Humidity Control

In the humid climate of Cao Bang, our project leverages natural ventilation, particularly operable clerestory windows, to reduce high humidity, as confirmed by CFD analysis (refer to Figure 6). This approach cools the indoor environment and manages humidity, which is essential for comfort. Smart systems with humidity-sensitive exhaust fans automatically adjust to humidity and temperature changes, although they may pose maintenance challenges in Khuoi Ky Village.

4.2 Daylighting and Its Impacts

Addressing limited natural light in a cloudy region (see Table 5), our design uses high-performance and clerestory windows to maximize daylight, improving visual comfort and circadian health, as shown by daylighting simulations (Table 6). The night-time lighting selected is also crucial for circadian rhythm and energy efficiency.

4.3 Local Material Use and Low-skilled Labor

Emphasizing community engagement and sustainability, our approach was centered on using locally sourced materials and straightforward construction techniques accessible to low-skilled labour. This strategy bolsters the local economy and encourages residents to partake in constructing their homes, easing economic pressures. The chosen materials and thoughtful design enhance thermal efficiency and comfort. Considering the rural areas of northern Vietnam, local biodiversity offers a significant opportunity for future housing projects.

4.4 Net-Zero and Climate Adaptation for Future

Our design considered the future climatic changes up to the year 2090 (Figure 2), incorporating adaptable daylighting and ventilation systems for resilience. Strategic solar panel placement contributes to economic and ecological benefits, aligning with our net-zero goal and ensuring the long-term adaptability of the housing units.

5. CONCLUSION

In summary, the Khuoi Ky Houses project in rural Vietnam is an example of innovation in local, sustainable housing development. This project skilfully balances energy efficiency, environmental quality, and community engagement using advanced architectural and technological solutions. Key achievements include exceptionally low EUI, optimized natural lighting and ventilation, and enhanced occupant comfort while respecting local cultural contexts. The use of local materials and construction methods has bolstered the economy and encouraged community participation. Looking ahead, the project's design response to future climatic change ensures long-term resilience and sustainability. This initiative sets a precedent for the future of rural housing in Vietnam, combining traditional practices with modern technology to create a sustainable and culturally sensitive future.

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