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Article

Sustainable Strategies for Improving Humanitarian Construction through BIM and Climate Analysis

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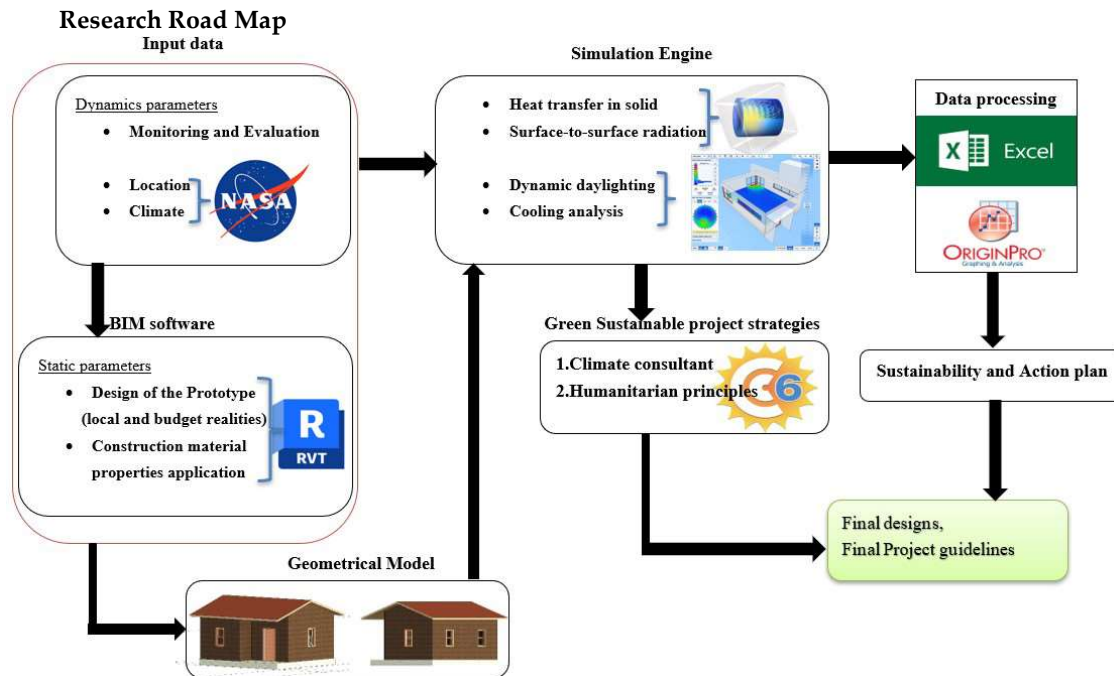
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Abstract: The growing need for effective and sustainable solutions in humanitarian construction has prompted scholars and practitioners to explore technical approaches that address the challenges of natural disasters, health emergencies, armed conflicts and migratory flows. These solutions often encompass temporary shelters, durable shelters and multifunctional buildings designed to balance rapid deployment, cultural sensitivity and environmental sustainability. However, the assessment of sustainability in humanitarian construction remains insufficiently defined due to the complexities of crises, the variability of local materials and the impact of local climatic conditions. This study aims to bridge this gap by integrating Building Information Modeling (BIM) and simulation tools such as COMSOL Multiphysics to study sustainable strategies for humanitarian housing. Using case studies aligned with IFRC, UNHCR and CRL (red-cross of Luxembourg) family shelter standards, the research assessed a Climate and Local Skill-Centered Design (CLCD) by examining the performance of key design elements, including wall material emissivity and reflectance, natural lighting and energy efficiency within the indoor thermal comfort. Simulation results revealed that wall finishing material reflectance significantly influences average daylight factors (D), with variations of 2% to 5% linked to lower reflectance values and changes in the window-to-floor ratio (WFR). Conversely, thermal comfort metrics indicated minimal variations in heat discomfort hours, maintaining indoor temperatures between 19°C and 25°C, consistent with ASHRAE Standard 55 thermal comfort criteria. This paper underscores the importance of integrating advanced IT tools and green Local technics and materials to optimize humanitarian housing for health, comfort and environmental performance, offering actionable insights for future Humanitarian sustainable designs.

Keywords: Humanitarian Housing; Sustainable local strategies; Thermal comfort; Natural Daylighting; Local green materials; Climate and Local Skill-Centered Design

1. Introduction

Millions of displaced individuals worldwide currently live in inadequate shelters, public infrastructure, or with host families, facing compromised health and well-being due to substandard living conditions. Beyond providing immediate housing, humanitarian interventions must address the need for critical social infrastructure, including schools, hospitals, and water, sanitation and hygiene (WASH) facilities. According to the United Nations Refugee Agency (UNHCR), by the end of June 2024 due to persecution, conflict, disasters, violence, human rights violations or events seriously disturbing public order, there were 122.6 million forcibly displaced people globally and about 9 million in Africa Great lakes region [1,2]. However, most emergency shelters fail to provide adequate thermal regulation and air quality, despite being inhabited for years. Poor indoor environments have been identified as critical determinants of health, with indoor air quality (IAQ) and thermal conditions significantly affecting occupants' well-being [3].



Previous research has shown that rapid deployment and cost-efficiency often dominate the priorities for humanitarian construction design [4,5]. Yet, with individuals spending up to 90% of their time indoors, creating livable and healthy environments is essential. Chang Lin and Jun Huang [6,7] demonstrated that exterior shading can reduce overheating risks by 74% in residential buildings, underscoring the importance of passive strategies [8]. Concurrently, the construction sector remains one of the largest energy consumers and contributors to greenhouse gas emissions, accounting for 40% of global electricity consumption and over 30% of CO₂ emissions [9,10]. The extensive use of natural resources in construction has long-term environmental impacts, particularly in humanitarian contexts where emergency and transitional shelters often fail to meet privacy needs, resist extreme weather, or ensure comfort [11]. However, transitional shelters utilizing materials that can be upgraded or reused represent a sustainable alternative, facilitating a gradual transition to permanent structures.

The impact of climatic conditions such as solar radiation, temperature, and wind speed on building performance is substantial and fluctuates year by year [12]. Rossa and Mauro [13] analyzed Humanitarian construction data from numerous disasters over five decades (1970–2020) and found a 20-fold increase in economic damage caused by extreme events. Such findings highlight the need for robust post-disaster reconstruction strategies, as theorized by Amir Aghsami et al. [14] and emphasize human-centered designs that align with sustainability standards, such as those proposed by Hind Al-Shoubaki et al. [15] in the Al-Sahel Region where a multidimensional approach to shelter design considers humanistic needs such as social adequacy, belonging, and community integration. This approach supports the evolution of shelters from temporary solutions to more permanent, culturally appropriate homes.

Researchers [16,17,18,19,20] on post-disaster and post-conflict (PDPC) sheltering highlighted an increasing focus on temporary humanitarian architecture, durable, schools and hospitals. Despite this, only nine out of 60 publications on housing addressed sustainability or life-cycle analysis. Similarly, Bashawri et al. [21] reviewed disaster relief shelters and noted that existing guidelines inadequately address sustainability and inclusivity in diverse locations and different materials. To tackle these issues, many researchers [22,23,24,25,26] emphasized the benefits of earthen construction materials, which provide thermal mass and hygrothermal buffering but are often overlooked in current regulations favoring steady-state performance metrics. However, challenges such as the lack of anti-seismic and thermal performance standards limit the adoption of contemporary earthen

architecture [27,28] while, the coarse fraction (gravel and pebbles) is often reduced and natural fibers are added in the mixtures in order to improve their binding force, with positive effects on the compressive and tensile strength of the final material [24,29]

Optimizing natural lighting is another critical consideration for energy efficiency in humanitarian sector. Strategies such as incorporating transparent elements (e.g., windows and roof lights) and using reflective internal surfaces can significantly enhance daylighting [30]. The emergence of Building Information Modeling (BIM) has further streamlined sustainable design, offering digital tools to model and assess green building performance throughout all project phases [31]. Leveraging BIM alongside local construction materials provides an opportunity for sustainability in humanitarian architecture, particularly when combined with simulation engines to evaluate thermal comfort and energy performance.

This paper aims to expand the understanding of sustainability in the humanitarian and charity sectors by investigating thermal comfort, daylighting, and cooling strategies in Construction assistance. Considering varying local climatic conditions and project-specific approaches, the research proposes a Climate and Local Skill-Centered Design (CLCD) by providing actionable insights into sustainable technical practices essential for project action plans and decision-making. The study evaluates the performance of available traditional Eco-friendly materials and their impact on beneficiary indoor comfort using BIM and simulation tools under diverse environmental boundary conditions. Despite prior research into thermal performance and sustainability, few studies have intensively evaluated local materials for energy and carbon optimization through a combined BIM–weather data–simulation engine approach. This research, therefore, integrates these methodologies, applying them to CRL’s shelter projects at Nakoyoya, in Democratic Republic of Congo (*report of Environmental Impact Study of House Model “Maison Adobe Type Uvira”*), and Muyinga, Republic of Burundi (*report of Burundi Environmental Impact Study of the House Model “Maison Adobe Type Muyinga”*) [32,33] in the Great Lakes Region of Africa. The findings contribute a framework for sustainable Humanitarian Habitat design, offering guidelines for project leaders, humanitarian and charity organizations, practitioners and scholars seeking to balance durable sheltering needs with long-term environmental and socio-traditional sustainability.

2. Research Methods

2.1 Design Models Towards Humanitarian Habitat

2.1.1 Climate and Local Skill-Centered Design

This study introduces an updated approach called “Climate and Local Skill-Centered Design” (CLCD) which is a mixing-based on 2 approaches: Firstly, the **Design for climate**: Design for climate means that your home is designed to keep you at a comfortable temperature throughout the year, based on where you live [34] and Secondly the **Traditional architecture (skills)**: Traditional architecture is a style of building that is rooted in the culture and traditions of a place. It uses local materials, techniques, and symbols, and is often developed by local communities without the involvement of specialists [35,36]. This updated approach CLCD tailored for shelters intended for internally displaced populations and host communities. This holistic framework emphasizes the needs, preferences and cultural backgrounds of beneficiaries, striving to create living environments that not only provide essential shelter but also uphold dignity and promote well-being. CLCD integrates traditional construction techniques, locally available materials and climate-adaptive solutions to ensure relevance to the local context. In emergency, transitional and durable scenarios, CLCD underscores the importance of flexibility, cultural sensitivity and sustainability in shelter design and implementation, addressing the immediate and long-term needs of both host communities and displaced populations.

A key tenet of this approach is the flexibility of housing assistance to adapt to diverse family sizes and evolving needs by the incorporation of local skills and incremental design principles to

enable shelters to be reconfigured over time, fostering a sense of permanence and belonging among occupants. This strategy enhances the cultural and social appropriateness of shelters, reinforcing occupants’ sense of identity and ownership such as, integrating local cultural contexts into shelter design, improves socio-cultural compatibility, making these living spaces more comfortable and acceptable to by all parties.

2.1.2 Sustainability and Environmental Considerations

Sustainable practices are critical in housing projects to achieve energy efficiency and environmental harmony. Leveraging locally available materials and traditional construction technics not only reduces costs but also minimizes environmental impacts. Incremental improvement strategies in shelter design can significantly enhance energy efficiency and indoor environmental quality, thereby contributing to the long-term sustainability of refuge settlements and internally displaced persons (IDPs) habitation in Urban system and reconstruction context.

2.1.3 Addressing Psychological and Social Needs

Effective shelter design must go beyond physical protection to address the psychological and social needs of occupants. Alain et al. [37] showed that the reflectance of the wall has a consequence in certain way on mental well-being. Shelters should align with the humanistic needs of occupants by ensuring social and cultural adequacy, fostering a sense of belonging and promoting community integration, all while adhering to international standards. The CLCD as a comprehensive approach requires attention to both architectural and non-architectural factors, such as the fulfillment of basic needs and facilitation of evacuation processes as depicted in Figure 1.

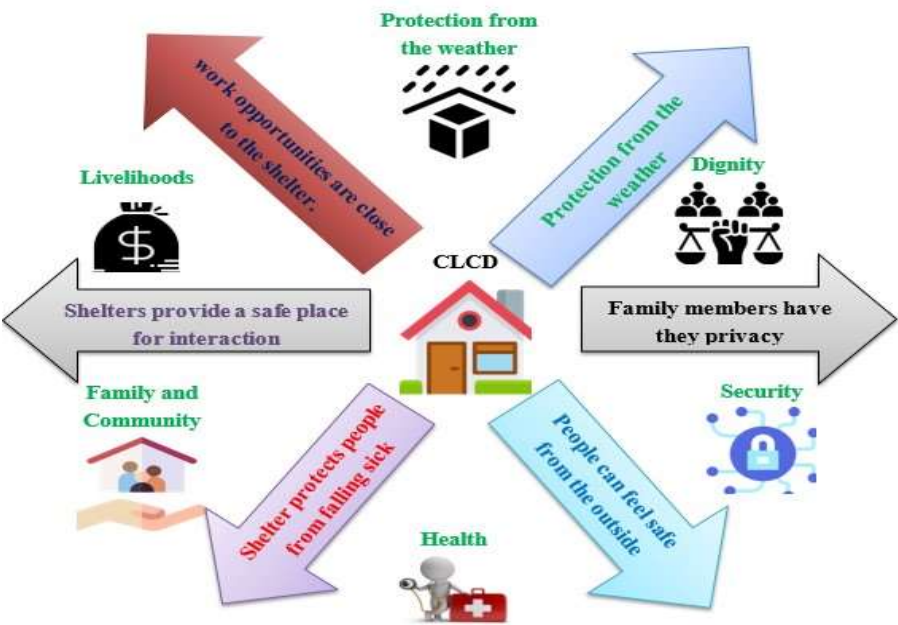


Figure 1. The purpose of a humanitarian shelter. Source: Authors’ work, 2025.

2.2 Study Design typology

2.2.1 Case of CRL Sheltering in Africa great lakes region

As of 30 June 2024, the East and Horn of Africa and the Great Lakes (EHAGL) region was host to 5.4 million refugees and asylum-seekers. Additionally, there were 20.8 million internally displaced in both regions as a result of conflict and climate related disasters [38].The Shelter Cluster in the region emphasizes the importance of sectoral interventions incorporating exit strategies or long-term

solutions to aid recovery and resilience among affected households. However, ongoing conflicts in the region compel many individuals and families to remain in protracted displacement, highlighting are rarely implemented in the medium term due to persistent instability. The region is also highly vulnerable to adverse climate conditions and natural disasters. Communities frequently face extreme events such as floods, landslides and intense storms, exacerbated by the region's location in an earthquake-prone zone [38,39]. These challenges disproportionately affect peri-urban and rural areas, causing extensive damage to both lives and land. Against this backdrop, a humanitarian approach to shelter design must prioritize adaptability to both socio-political instability and environmental hazards.

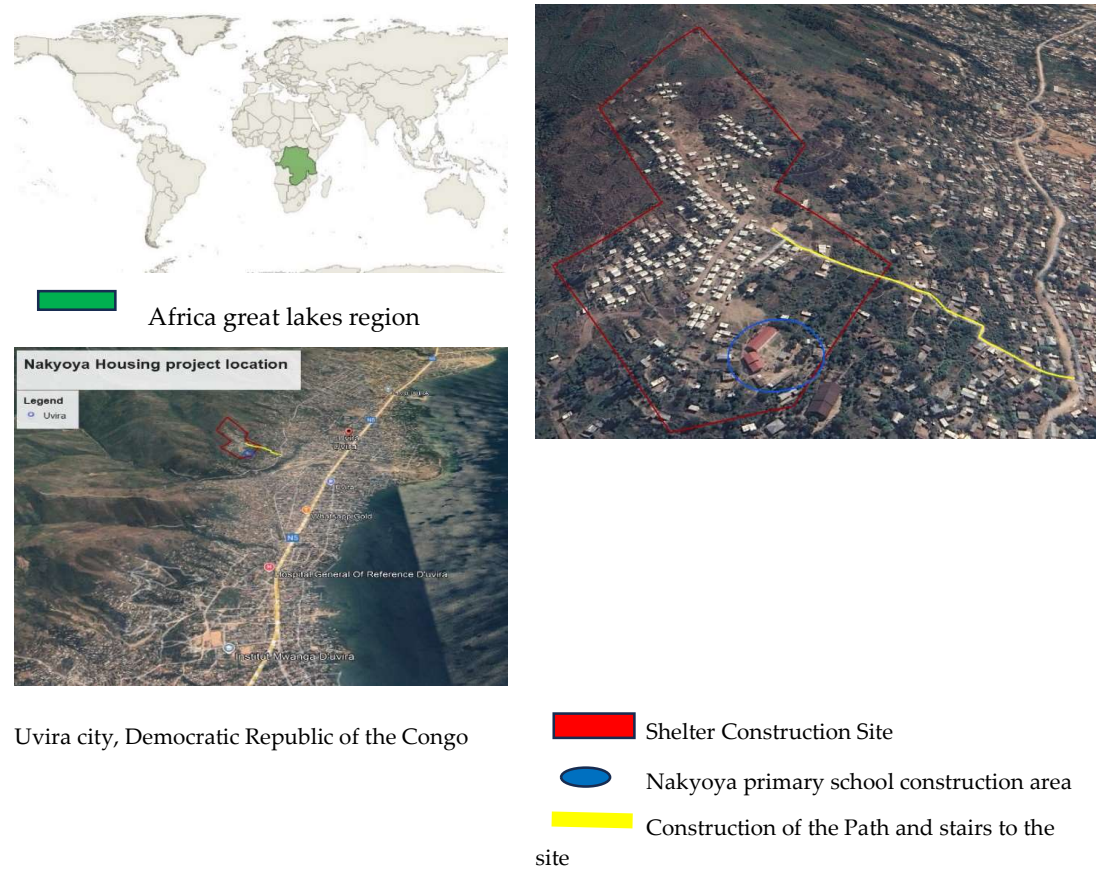


Figure 2. Humanitarian sheltering project location in Great lakes region: Source: Authors’ work, 2025.

Our analysis of neighborhood urban design typologies within communities in the Great Lakes region offers critical insights into designing humanitarian habitats that align with local building cultures and social dynamics. Traditional architecture in the region effectively leverages locally available materials, such as mud bricks, wood and incorporates passive cooling techniques, demonstrating resilience and sustainability [40]. Key features of this architectural approach include optimizing building orientation based on wind and rainfall patterns, as well as designing appropriately sized window openings to enhance ventilation and mitigate climatic stress. Incorporating these traditional practices into CLCD is essential for creating culturally relevant and sustainable living environments.

2.2.2 Current Typologies of Shelter Designs in Humanitarian Contexts

In addressing the diverse needs of displaced populations, shelter designs typically fall into four main categories, each serving a distinct purpose in the continuum of humanitarian response:

- *Emergency Shelters:*

- Emergency shelters are specifically designed to provide immediate and short-term protection for refugees and internally displaced persons (IDPs) following a crisis or displacement. Organizations such as UNHCR and AICRL focus on deploying these shelters during the initial phases of a humanitarian emergency [41,42]. These structures are rapidly deployable, often consisting of tents or simple, prefabricated units that prioritize speed and ease of assembly. They are typically removed or replaced as the situation stabilizes and communities transition into subsequent phases of recovery.
- Transitional Shelters:
- Transitional shelters provide intermediate solutions for displaced individuals and families, bridging the gap between emergency response and long-term housing solutions. Constructed with more durable materials and designed for improved thermal regulation and air quality, these shelters offer enhanced living conditions compared to emergency structures. Transitional shelters support a more stable environment, fostering a sense of normalcy and helping displaced communities rebuild their lives.
- Durable Shelters:
- Durable shelters are intended for long-term habitation, offering sustainable and secure housing solutions for displaced populations. These structures prioritize stability, sanitation and improved living conditions, including access to clean water and adequate space for families. Durable shelters support self-reliance by providing an environment conducive to rebuilding livelihoods, pursuing education and engaging in income-generating activities. Additionally, they can be integrated into host communities to foster social cohesion and alleviate pressure on local infrastructure. Organizations such as UNHCR, IFRC and CRL play a significant role in promoting durable shelters to enhance the quality of life for displaced populations while fostering resilience and recovery.
- Multifunctional Buildings:
- Multifunctional buildings encompass infrastructure projects such as hospitals, schools, office and other community-oriented facilities. These constructions go beyond shelter provision to address broader development needs, supporting both the host communities and displaced populations. By strengthening local infrastructure, such projects contribute to livelihoods, improve access to essential services and foster integration during and after crises. For instance, constructing schools or healthcare facilities can support long-term recovery by ensuring education and medical care for both displaced individuals and the host community.

For this study, a Climate and Local Skill-Centered shelter (CLCS) was designed to accommodate five individuals per family with an allocation of 3.5 m² per person by CRL, adhering to local Sphere standards. The shelter incorporates locally sourced and readily available materials, as illustrated in Table 1, with design objectives outlined in Figure 1. The walls were made by adobe bricks due to their distinct advantages in addressing the socio-environmental needs of the displaced populations in the Great Lakes region [43]. Additionally, adobe is environmentally sustainable, as its production requires minimal energy and emits negligible greenhouse gases compared to industrial materials like cement. These qualities make adobe a suitable choice for humanitarian shelters, as it meets the dual criteria of cultural appropriateness and environmental sustainability while supporting the long-term well-being of displaced populations. By focusing on adobe-based shelters, the study aims to explore scalable, community-driven solutions that integrate traditional knowledge with modern humanitarian needs. For this case study, the shelter utilized 20 cm thick adobe walls, the roof was constructed using aluminum tiles, chosen for their high thermal conductivity and low emissivity, allowing effective heat dissipation [43]. Additionally, ventilation dynamics, facilitated by strategically positioned windows and doors, were optimized to enhance airflow and regulate indoor temperatures. The daily temperature variations in the study area ranged from 21°C to 34°C during summer and 15°C to 22°C during the rainy season, directly impacting the thermal comfort of the shelter. This prototype illustrated on figure 3 and Figure 4, demonstrates the potential of integrating

local materials and design strategies to achieve sustainable and climate-resilient humanitarian housing.

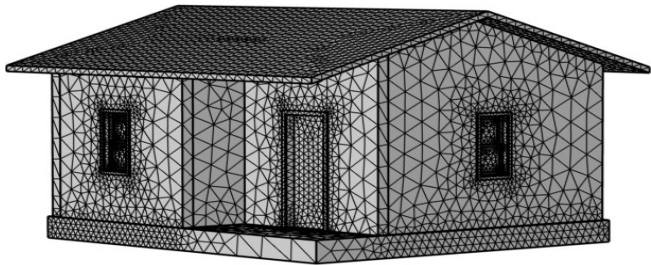


Figure 3. Materials application and geometry Meshing. Source: Authors owns work

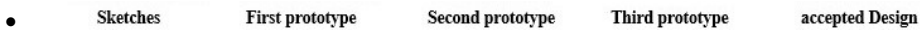


Figure 4. Discussed sketches CLCD based

2.3 Local Construction Materials

The Great Lakes region of Africa relies heavily on locally available materials such as wood, adobe, cob construction materials, compressed earth blocks (CEB), cement bricks, earth-bags, rammed earth, sheet metal, laterite-sand bricks, and mixed materials for humanitarian shelters as appear in Table 1. These materials are abundant, cost-effective and well-suited to the region's environmental conditions, making them a practical choice for construction in resource-limited settings. Their accessibility allows displaced communities to quickly assemble shelters using locally sourced materials, reducing reliance on external aid and fostering community participation in reconstruction efforts. Moreover, many of these materials, like adobe and CEB, have favorable thermal properties, providing natural insulation to maintain comfortable indoor temperatures in a region with significant diurnal temperature variations. The use of these materials also aligns with sustainable construction practices, minimizing the environmental footprint and promoting resilience against adverse climatic and geological challenges common in the region.

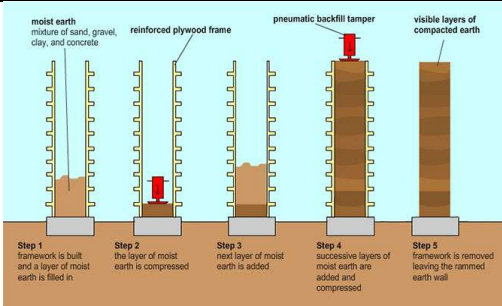
Table 1. Local construction Material in the region. Source: the author, 2025

Material Name	Description	Advantages	Disadvantages	Examples
Wood	A traditional building material extracted from trees with variable forms. They can be as tree trunk, plank or rafter.	-Locally available; - often inexpensive; - Flexible to architectural design and color application. As speed up construction; -lower carbon footprint compared to steel, concrete, or brick; - Wood is a renewable resource when sourced responsibly from managed forests :100% recyclable; - Wood has good thermal insulation properties.	- Wood is prone to termite infestations, fungal growth, and decay in humid or wet environments unless treated; -Not soundproofing; -Wood can warp, swell or crack when exposed to high humidity or direct contact with water; -Moisture retention can also lead to structural instability over time; -Not fire proof.	 [44]
Adobe (Sun-Dried Mud Bricks)	A Local building material made by mixing earth, sand, straw, or other organic materials, and water. The mixture sleeps one day then, placed in molds and compressed, then left to dry on the sun for some days.	-Eco-friendly materials; -Locally available; -Cost-effective; -Good thermal properties providing insulation against the region’s hot daytime; -Temperatures and cool nights; -Durable when properly maintained;	-Susceptible to erosion and water damage (rain and flooding); -Regular maintenance and reapplication of mud plaster is needed; -Not withstand strong earthquakes and the drying process take much time;	
Cob construction materials	Traditional technics of Mixing dried mud with tree sticks for wall building. Mostly it a good way of using fiber and recycle concrete materials, aggregate with mud. This does not need any skills.	-Low carbon materials; -Cost-effective; - Temperatures and cool to nights; -Durable when properly maintained;	-Not waterproofing; - Not ideal for long-term or permanent structures;	 [45]

CEB (Compressed Earth Block)	Manufactured with a mechanical press, these blocks are denser and more uniform than adobe bricks. Compare to traditional adobe, Compressed Earth Blocks have superior resistance water damage.	-Ensuring the longevity of materials available in the local area; -The thermal mass aids in regulating indoor temperatures, resulting in reduced heating and cooling expenses; - Aesthetically appealing; -CEB has good thermal insulation properties, helping to maintain comfortable indoor temperatures in both hot and cold climates.	-Susceptible to moisture; -Limited Structural Strength; -To enhance the stability of Compressed Earth Blocks, it might be necessary to include stabilizers such as cement, lime and fiber.	
Block-cement bricks	This consist of compressing mortar with little cement content in a form and wet it on sun for several days while drying it with little water daily.	- In tropical climates, cement blocks can help maintain a stable indoor temperature due to their thermal mass; -Incorporate recycled aggregates in block manufacturing to reduce environmental impact; - Cement blocks require minimal maintenance, particularly when treated with finishes like plaster or paint.	- Without proper ventilation or insulation, cement blocks can retain and radiate heat, making interiors uncomfortable in tropical climates. - Cement blocks lack flexibility and can crack under shifting ground or seismic activity unless reinforced properly; - Cement production has a high carbon footprint, contributing significantly to greenhouse gas emissions.	
Earthbag Construction	They are special bags which are made of local soil and are placed on top of each other up to form the structure. It is a very easy and quick construction process.	-Ease of Construction: simple to fill and stack, making them suitable for unskilled; -Low Cost and use minimal additional materials. Soil is abundant and often free; -Sustainability: it minimizes the use of non-renewable resources and reduces waste;	-Aesthetics: walls may not suit everyone's aesthetic preferences; -Stabilization: depending on the soil type, stabilizers like cement may be needed to ensure durability; -Skills Requirement: Engineering expertise is needed to ensure stability for large structures;	

	-Resilience: earthbag walls can be resistant to weather, fire and pests and maintained; regulating indoor temperatures. -Adaptability to various shapes and sizes.	-Weather influence: construction might be stopped during rainy seasons due to soil moisture.
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Rammed Earth	The method consists compacting earth (soil, clay, gravel along with small amounts of cement and water) into wooden molds. It requires specialized techniques	-Excellent thermal mass properties, regulating indoor temperatures; -Durable; -Fire-resistant; -Unique aesthetic.	-Wood is needed for the molds; -Require specialized equipment; -The quality of the soil mix and proper stabilization are critical for durability.
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Sheet Metal	This technic of fast construction is about making a wood structure covered by sheet to make wall. Use metal sheets primarily for roofing and other durable materials for walls.	-Metal sheets are lightweight, making them easy to transport and install; -Emergency or temporary shelters can be rapid deployment and affordability are key; -Properly treated sheet metal (e.g., galvanized or coated) is resistant to weathering, pests, and rot. It has a long lifespan if maintained properly.	-Needs more other materials: Add insulation (e.g., foam panels, fiber blankets) under the metal sheets to reduce heat and cold transfer. Use rubber gaskets or padding to reduce the sound of rain and wind impact; - not soundproofing; -Do not resist to rust and corrosion; -The production of sheet metal has a high carbon footprint compared to some traditional building materials.
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Laterite-sand Bricks	It is made from a natural sedimentary rock called laterite. These bricks are commonly used in tropical and subtropical regions, including parts of Nigeria, due to their availability and suitability for construction. Laterite bricks have unique properties that make them suitable for specific applications	-Locally Sourced: This can reduce transportation costs and the environmental impact; -Natural Insulation: Good thermal properties, this can help maintain comfortable indoor temperatures in hot climates; -Durability: They can withstand weathering, particularly in regions with a tropical climate; -Low Carbon Footprint; -Fire Resistance: The dense earth-filled bags offer thermal mass, regulating indoor temperatures.	-Low structural strength compared to concrete or fired clay bricks; -Inconsistent Quality: the quality of laterite bricks can vary significantly depending on the specific composition of the manufacturing process; -Maintenance Requirements; -Construction might be limited during rainy seasons due to soil moisture; -Aesthetics: walls may not suit everyone's aesthetic preferences.	
Mix-Materials	This method consists of building with different materials by each level. It has the same properties and performance of the materials used.			

2.4 Weather Condition Analysis

This study focused on designing naturally ventilated building spaces to enhance the thermal comfort of occupants based on Climate and Local Skill-Centered Design (CLCD) approach. To achieve this, annual temperature, solar radiation and precipitation data were sourced from NASA (*sustainable designs section*) used to construct the simulation model. These climate parameters were collected based on the project location's specific latitude and longitude coordinates as detailed in Table 3.

Table 3. Yearly weather data from Project’s location

Location: Nakyoya, Uvira, D.R. of the Congo					Latitude: -3.3754				Longitude: 29.14				
					Year: 2022								
					Parameters	Jan.	Feb.	Mar.	Apr.	May	Jun	Jul.	Aug.
Earth Skin Temp. °C	21.5	21.1	22.8	21.7	21.3	19.6	19.3	20.7	22	22.4	21	21.2	21.2
Relative Humidity at 2 Meters (%)	77	78.8	75.8	79.4	79.4	73.8	68.5	65.3	66.2	62.8	78.5	78.5	73.6
Cooling Degree Days Above 18.3 °C (°C -d)	99	78.4	132	102	94.3	44.8	44.3	85.8	118	139	81.4	88.6	1108
All Sky Surface													
Shortwave Diffuse Irradiance (W/m^2)	119	110	117	114	102	91	78.4	93.7	107	122	107	102	105

For indoor environments, it was assumed that the mean radiant temperature closely approximates the dry bulb temperature. The comfort zone for the occupants was determined using the Predicted Mean Vote (PMV) model, a widely recognized framework for evaluating thermal comfort. In residential settings, occupants often adapt their clothing to seasonal conditions and are comfortable with higher air velocities, which broadens the acceptable comfort range compared to buildings with centralized HVAC systems. The simulation adhered Standards, as outlined in the *ASHRAE Handbook of Fundamentals*. The comfort zone was represented graphically by the blue quadrilateral shown in Figure 5, illustrating the range of environmental conditions that support occupant comfort in the analyzed shelter.

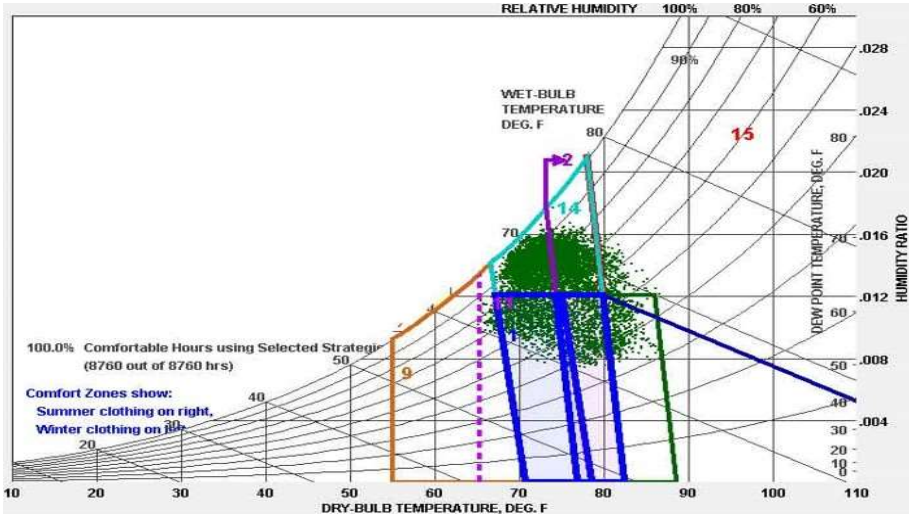


Figure 5. Comfort zone based on weather condition. Source: Authors’ work, 2025

To align all critical parameters within the comfort zone, the Climate Consultant proposed year-round design strategies, illustrated in Figure 6, to enhance the building’s sustainability. These

strategies were informed by the weather data summary provided on table 3 and Figure 7. Achieving sustainability in this context requires an integrated approach that considers energy efficiency, thermal comfort, and natural lighting. It is not a matter of prioritizing one parameter over another but rather making a series of informed decisions based on the specific weather conditions collected at the project site. This comprehensive approach not only improves building performance but also ensures cost savings and creates healthier living environments for vulnerable populations. Simulating these interrelated parameters facilitates the development of technical responses that yield several significant outcomes, including:

- Reduced energy consumption,
 - Enhanced thermal comfort,
 - Improved occupant comfort,
 - Application of neutral carbon materials,
- Greater connection with natural,
 - Conservation of natural resources,
 - Better visual comfort, and
 - Advancements in sustainable design principles.

These outcomes highlight the importance of integrating climate-responsive strategies to achieve a balance between environmental sustainability and the well-being of building occupants, particularly in humanitarian contexts.



Figure 6. Design strategies from Climate Consultant.

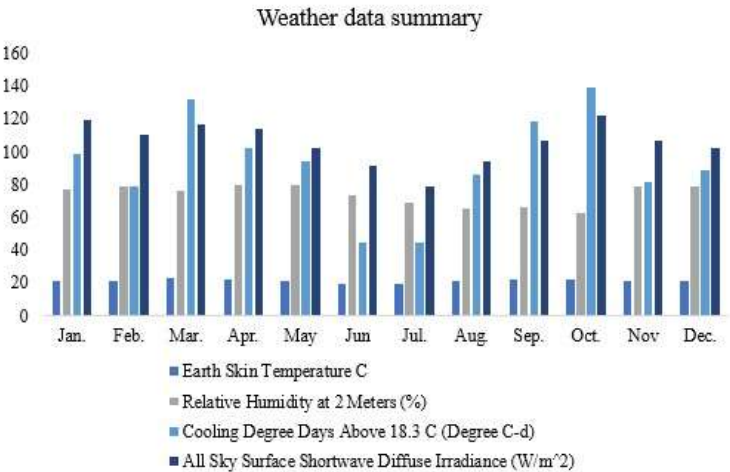


Figure 7. Site weather data summary.

2.5 Simulation Models

This study utilized solid model simulations incorporating specialized physics modules for Heat Transfer in Solids and Surface-to-Surface Radiation to explore thermal performance and emissivity in a building context. A time-dependent analysis was conducted to evaluate temperature variations influenced by ambient conditions and the thermal properties of construction materials. A domain probe was strategically placed on the building's walls to monitor interior temperature dynamics. Solar radiation data for the hottest month of the year, sourced from NASA POWER, enabled the creation of a detailed graph of daily solar radiation. By examining data from domain probes on the building's walls and roof, the study assessed the shelter's interior thermal comfort and informed the development of sustainable strategies. Key metrics included average interior temperature, thermal insulation, and conductivity relative to ambient temperature and material properties. The emissivity values derived from the simulations further enhanced the thermal performance evaluations.

Beyond thermal assessments, the study addressed luminance levels influenced by the building's geographic location and environmental factors during the sunniest month of the year. An illuminance model was implemented, incorporating a prototype ceiling to measure the impact of contextual factors and radiation on the indoor environment over time. Despite the computational demands of updating the sky distribution model, optimization measures such as toggling updates or disabling real-time processing enhanced efficiency. Material properties, particularly the transmittance of openings and wall surface reflectance, emerged as critical determinants of daylighting performance. These findings underscore the importance of integrating material properties and strategic design interventions to optimize both thermal and visual comfort in humanitarian housing contexts.

3. Simulation study and Parameters

3.1 Estimation Parameter study.

This parameter estimation study is based on the above experiment weather data and help to match the simulation result to the experiment data through the solves least squares problems based on time dependent measurement entered through either an interpolation function or user defined reference expression. These include user cases such as: Curve fitting, parameter estimation PDEs (Partial differential equations) and Inverse modeling problems. It requires a time dependent model, needs reference Data and optimization module for use. This Paper applied on the Prototype of a durable shelter the temperature amplitude on the exterior boundary to plot the temperature variation graph through the expression (1):

$$293.15[\text{K}] + \text{Tamp} * \sin\left(\frac{2\pi t}{1\text{day}}\right) \quad (1)$$

Where: Tamp: temperature amplitude and 293.15[K]: average temperature of one day of September (the high sunny month of the case study).

3.2 Heat in solid and surface-to-surface radiation

For the Heat flux boundary condition, the h_o (heat transfer coefficient) used according to the construction materials used, the material density and the Heat capacity at constant pressure. the Convective cooling interior the shelter is obtained by running the q_o : convective heat flux equation (2):

$$q_o = \text{Tewt} \cdot T \quad (2)$$

Estimate the value of k (thermal conductivity) so that the simulated result best match with the reference data, then, the incorporation of the experiment data into interpolation function to obtain the preview of that function using SNOPT (SN Optimization algorithm) as parameter estimation method model, any constraints can be applied here by using the analytic interpolation expression (3).

$$T_{avg} + dT * \cos\left(\frac{2\pi(t - 14)}{24}\right) \quad (3)$$

3.3 Daylighting factor

To estimate the mean change in wall reflectance, it is essential to understand the ratio of the unobstructed area to the total wall area, as well as the contributions of glass, doors, and other surfaces that are less likely to undergo color alterations. Reasonable values for room dimensions were selected based on the Shelter Standards of AICRL and FICR. These dimensions informed the calculations of daylight performance within the prototype shelter. The approximate average daylight factor within an enclosed space was calculated using the methodology outlined in the *CIBSE Guide* (2006):

$$D = \frac{B}{A(1 - R_a.R_a)} \quad (4)$$

Where $B = T.A_w.\gamma.M$ have no dependence on R_a . T is the Diffuse transmittance of the glazing material, A_w is the Net glazed area of the window m^2 , R_a is the area-weighted average reflectance of the interior surfaces (including glazing), γ is the Vertical angle subtended by sky and M is the Maintenance factor (upkeep of window). Although this relationship provides an approximate estimation, it is valuable for architects and engineers during the early design stages to assess the potential impact of material reflectivity on natural lighting. This approach considers the linear relationship between changes in mean surface reflectance and variations in daylight factor by writing:

$$R_a = \frac{A_c R_c + A_f R_f + A_w R_w + A_{win} R_{win} + A_o R_o}{A} \quad (5)$$

Where: A_c is the area of ceiling m^2 , R_c is reflectance of ceiling, A_f is area of floor, R_f is reflectance of floor, A_w is area of unobstructed walls, R_w is reflectance of unobstructed wall, A_{win} is area of windows, R_{win} is Reflectance of windows, A_o is Area of obstructions and R_o is the average reflectance of obstructions.

Additionally, the correlation between average surface reflectivity and the unobstructed wall reflectance was analyzed. By expressing this relationship mathematically, the study provides insights into the influence of surface material properties on daylighting performance. These findings serve as a critical guide for optimizing wall and surface designs to enhance natural lighting while maintaining alignment with sustainable building objectives.

4. Results and Discussion

4.1 Analysis of heat variation

To interpolate the analytical temperature with a time argument of one hour, the ambient temperature curve, represented by the analytical function was plotted based on Equation (3), expressed on (Figure 8). This curve illustrates the average temperature and its hourly variations during the hottest month of the year. The analysis incorporated meteorological data specific to the construction site, including radiance levels, derived from local weather. The standard defines a comfortable temperature range of 20–27°C (68–81°F), depending on seasonal factors, clothing insulation levels, and air velocity, which should remain between 0.1 and 0.8 m/s to ensure adequate ventilation and prevent drafts.

Thermal modeling was performed using Fourier's law of heat transfer to estimate indoor temperatures, incorporating assumptions related to time lag and attenuation to account for material thermal mass and climate dynamics as defined in Section 2.5. The results demonstrated the influence of these factors on maintaining thermal comfort within the specified range. Figure 9 illustrates the modeled indoor temperature, showcasing the relationship between external conditions and the shelter's thermal performance. These insights are critical for optimizing the design of humanitarian shelters to ensure thermal comfort while considering local climatic conditions.

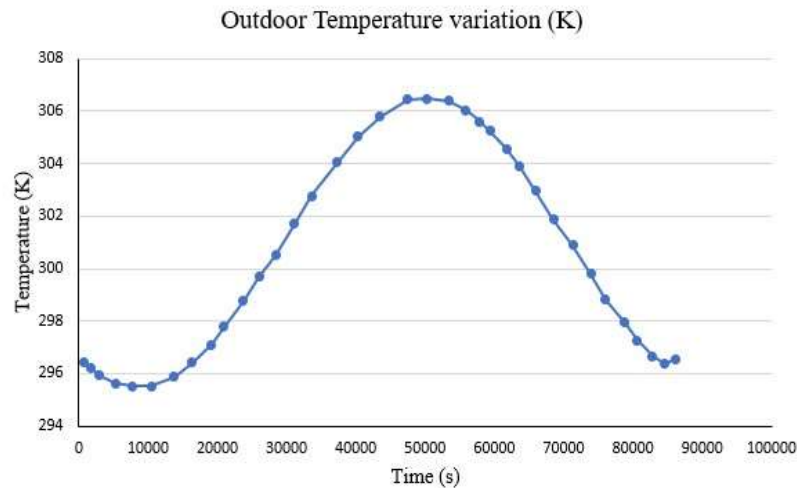


Figure 8. Outdoor average temperature.

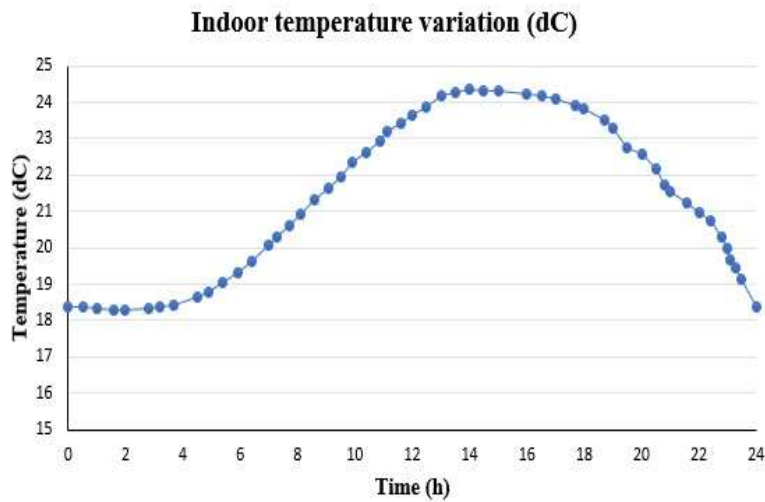


Figure 9. Indoor average temperature.

Adobe, known for its high specific heat capacity, plays a crucial role in moderating indoor temperature fluctuations by absorbing and releasing heat over time. As shown in Figures 10(a) and 10(b), outdoor temperatures peak between 2 PM and 3 PM, causing indoor temperatures to rise to approximately 30°C, nearing outdoor levels. By 6 PM, as outdoor temperatures begin to decline, the heat inside stabilizes, and the adobe walls gradually release stored heat. At 8 PM, this heat release maintains an indoor temperature of approximately 22°C, which remains slightly higher than outdoor levels at 10 PM. This thermal inertia helps retain warmth indoors as temperatures drop outside, effectively reducing nighttime chill.

Clay soil floors complement this thermal behavior by contributing localized cooling effects, as illustrated in Figure 10(c) and defined in Section 3.2. These floors naturally feel cool underfoot due to their heat-absorbing capacity, providing relief during hot periods. Slightly dampening the clay enhances this cooling effect through evaporative cooling, particularly in well-ventilated spaces where the evaporation process cools the air above the floor. Nighttime ventilation, achieved through open windows or doors, accelerates heat loss from the clay floor, aiding in lowering indoor temperatures. This strategy, combined with insulated floors and walls (see Table 4(b)), demonstrates significant potential for maintaining comfortable indoor conditions, as shown in Figure 10(d) which align with the findings of Oluwafemi and Andreas [47].

However, clay floors also impact nighttime thermal behavior. Without proper ventilation or shading, these floors can retain heat, contributing to warmer indoor environments. The heating effect is more pronounced when the floor is dark or moist, as these properties enhance heat absorption. Coverings such as mats or rugs reduce heat transfer to the room by insulating the floor. As temperatures drop at night, the clay floor gradually releases stored heat, maintaining indoor temperatures slightly above outdoor minimums, which can prevent excessive nighttime cooling. By optimizing ventilation strategies (see Table 4(a)), the clay floor can act as a heat sink, dissipating stored heat into the cooler nighttime air, thereby improving indoor thermal comfort.

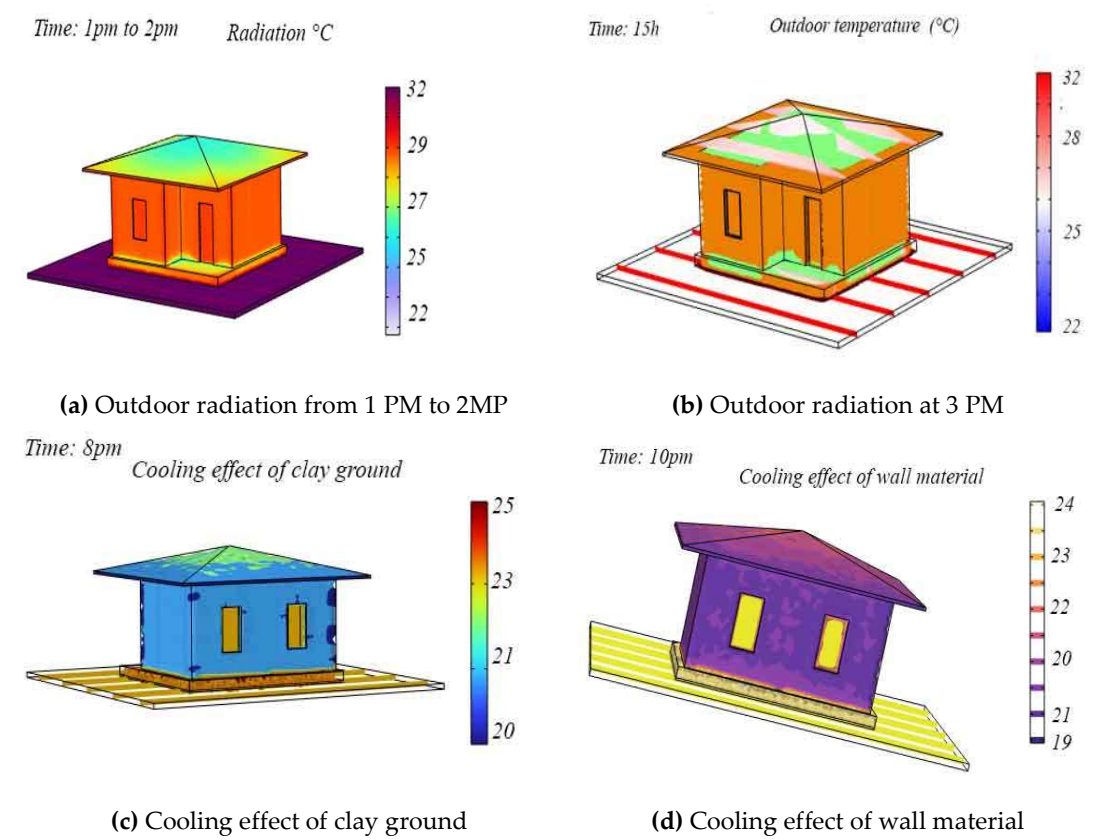


Figure 10. Heat transfer.

To facilitate cross ventilation, locate door and window openings on opposite sides of building with larger openings facing up-wind if possible. To produce stack ventilation, even when wind speeds are low, maximize vertical height between air inlet and outlet (open stairwells, two story spaces, roof monitors). To produce stack ventilation, even when wind speeds are low, maximize vertical height between air inlet and outlet (open stairwells, two story spaces, roof monitors). Use light colored building materials and cool roofs (with high emissivity) to minimize conducted heat gain. Use open plan interiors to promote natural cross ventilation, or use louvered doors, or instead use jump ducts if privacy is required. Window overhangs (designed for this latitude) or operable sunshades (awnings that extend in summer) can reduce or eliminate air conditioning.

Adobe bricks with adequate finishing material have a high thermal mass, meaning they store heat during the day and release it at night as observed on Figure 11(a) and Figure 11(b) from 2am to 4am, the Heat stored in adobe walls is slowly being released as the heat from walls; indoor temp slightly above outdoor and at 6m the Adobe Walls continue releasing heat; minimum temperature reached. This maintains the indoor temperature between the interval of 19°C to 21°C up to 8 am as on Figure 11(c). At 10 am Solar heating begins; walls absorb heat slowly due to thermal properties which does not allow high increase of indoor heat up to 23 °C as on Figure 11(d). Continuous heat

dissipation keeps indoor temp stable, influenced the positive variation at midnight between 21 °C and 24°C as showed on Figure 11(e) and Figure 11(f).

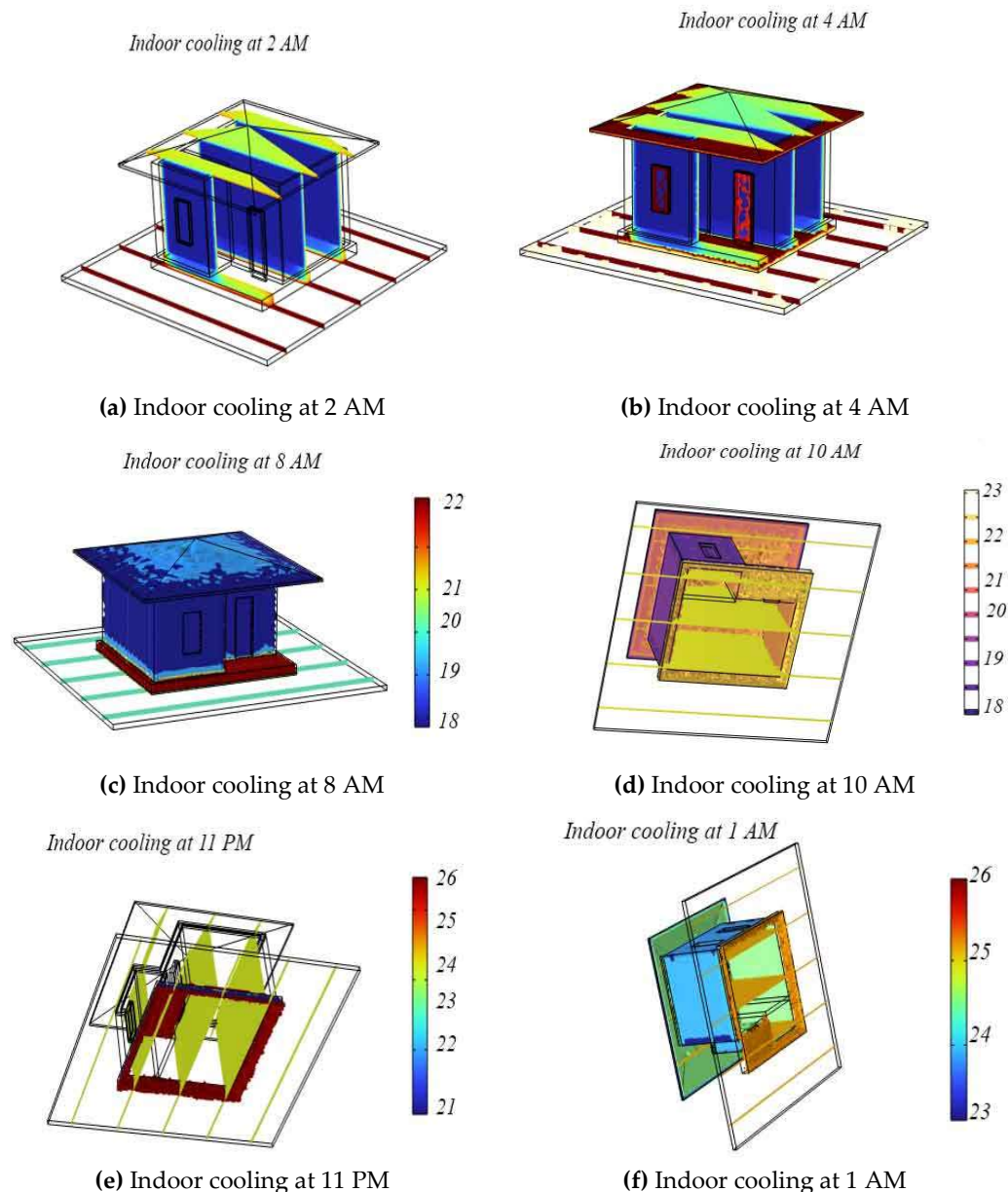


Figure 11. Surface to surface Heat transfer.

The Periods of 6 AM - 10 AM (20-23°C) and 6 PM - 10 PM (23-25°C) as showed on Figure 12(a) and Figure 12(b), are the most comfortable time because of pleasant temperatures for people due to minimal solar heating, door indoor air quality if the design strategy of Cross-Ventilation Design and Passive Design Principles of orientation are applied for ventilation and Cooling of outdoor air coupled with gradual heat release from walls ensures comfort. Thermal comfort range for humans are typically 20-25°C with moderate humidity. Temperatures above 27°C can cause discomfort, especially in humid environments, Heat retention in adobe walls ensures moderate cooling at night [48], enhancing comfort. Good natural ventilation can reduce or eliminate air conditioning in warm weather, if windows are well shaded and oriented to prevailing breezes. Minimize or eliminate west facing glazing to reduce summer and fall afternoon heat gain. On hot days ceiling fans or indoor air motion can make it seem cooler by 5 degrees F (2.8C) or more, thus less air conditioning is needed.

The periods 12 PM - 4 PM (26-28°C) on Figure 12(c) and Figure 12(d) is the uncomfortable time as High outdoor temperatures and aluminum roof transfer heat into the house and the Lack of ceiling exacerbates heat influx, making it less tolerable moreover the Aluminum has low thermal resistance, so heat is conducted into the house quickly during the day. Focus on the risks, levels and reduction, high levels of radon can cause lung cancer, particularly for smokers and ex-smokers. Radon produces tiny radioactive particles in the air we breathe. Radiation from these particles damages our lung tissue, and over a long period may cause lung cancer. Modern buildings are often well insulated to save on energy bills. However, little airflow can allow radon to build up to high levels and cause long term exposure. Ventilation, which can be as simple as opening a window, is often the solution to keep radon levels safe. By long term monitoring, you can know when levels start to rise and act accordingly.

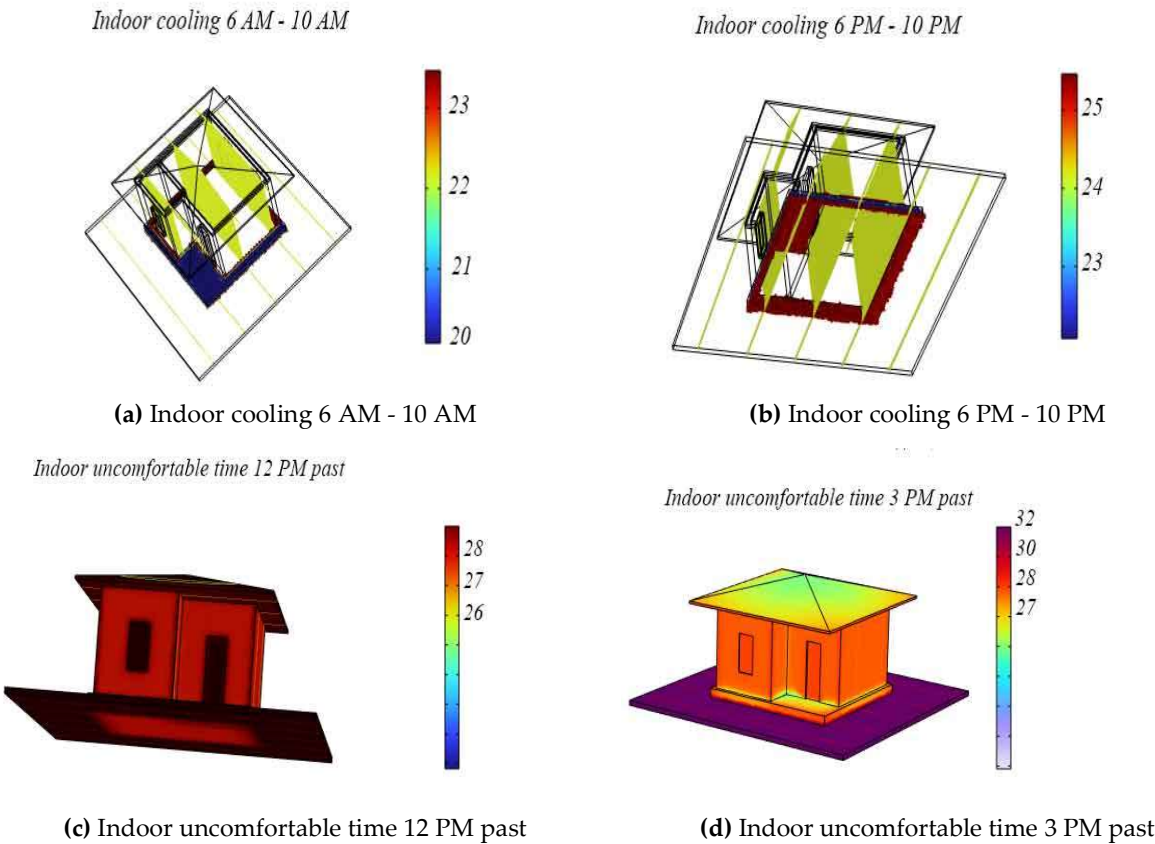


Figure 12. Comfortable and uncomfortable time during 1 day.

The time it takes for heat to travel through adobe walls (thermal lag/ Time Lag) results in delayed indoor temperature changes compared to outdoor variations. To align the sustainability with the bellow design guideline, the natural Ventilation; the orientation and number of windows/doors significantly affect airflow, aiding cooling during cooler periods. Absorbs heat during the day and releases it slowly at night, stabilizing temperature swings that reduces reliance on artificial cooling systems. Works effectively in ventilated homes with high ceilings or cross-ventilation. Furthermore, bare clay floors can produce dust, affecting air quality. This can be mitigated by sealing the surface with natural oils or wax, also excess moisture can cause dampness, which will lead to mold or discomfort. To ensure adequate ventilation and avoid over-dampening during extreme heat waves, clay floors can store too much heat or use insulating mats and floor coverings during hot daytime hours.

4.2 Analysis of Daylighting

The natural daylighting as defined in Section 3.3, is one side influenced by the local weather conditions and other side by the design model based on the sustainable sketches' guidelines applied on the final Green Design. The Illuminance Analysis results during interval of hot hours from 12 am to 3 pm which created shadows as showed on Figure 13(a), 13(b) and 13(c), findings in the interior cooling environment as observe on Figure 11(d), influenced by the shadow directions as appear on Figure 13(e) and Figure 13(f) because of the openings (doors and windows) positions. At analysis plane weight of 1 inch above the floor with a resolution of 12 inches' grid across the space. The provision of sufficient lighting is often seen as having an important contribution to occupant comfort, by achieving a high level of illumination through the use of natural light, it is hoped that the energy consumption associated with artificial lighting can be significantly cut,

The natural light distribution depends on window placement, orientation, and material properties, based on our case study, in the morning (6 AM - 12 PM), Light enters predominantly through the door and east-facing windows Figure 13(e), illuminating the interior, the light distribution may be uneven, leaving parts of the interior dim. Afternoon (12 PM - 6 PM) Light enters from the west-facing windows, which receive direct sunlight, the Adobe walls may absorb significant light, reducing reflectivity inside the house.

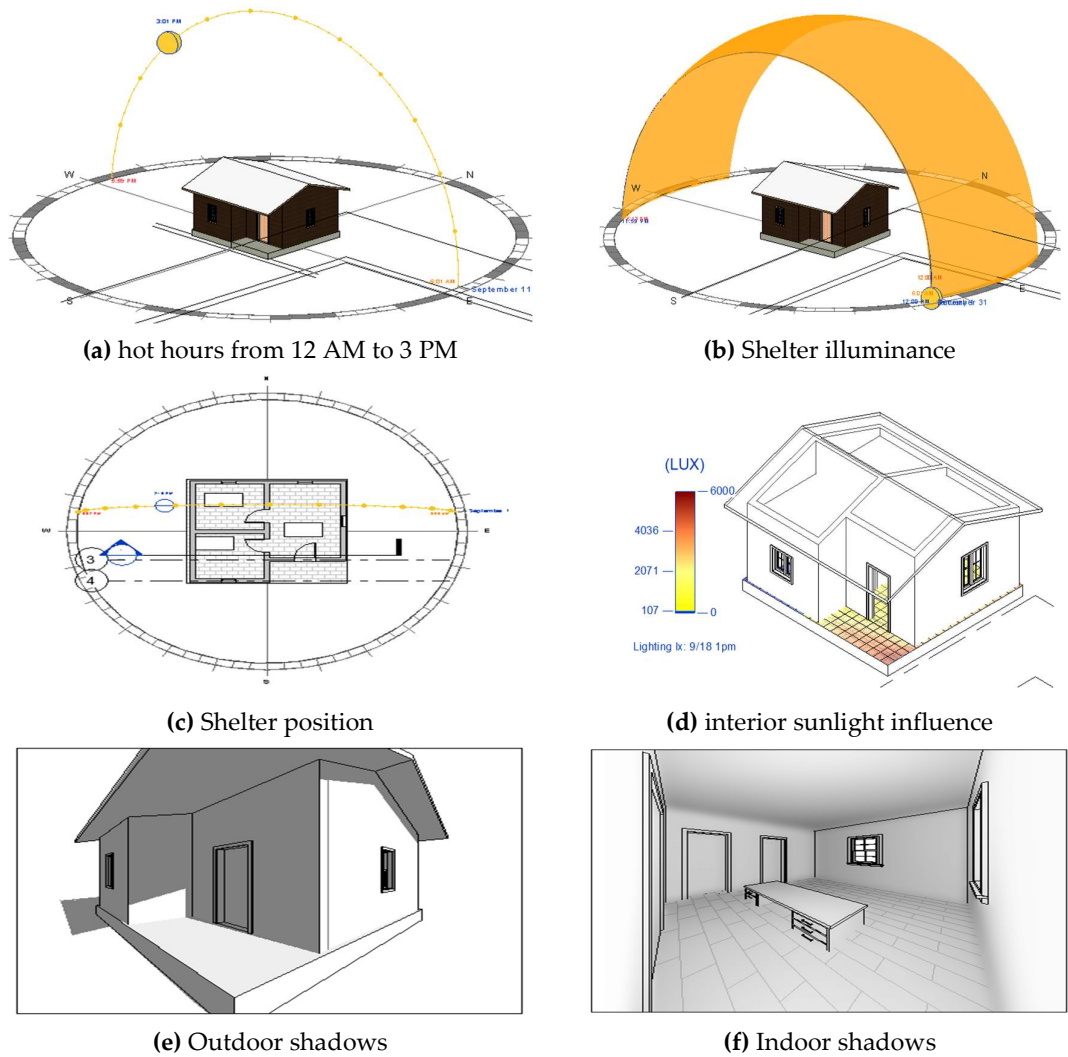


Figure 13. illuminance under the local weather condition.

In fact, a qualitative survey of classroom and office walls found typical obstruction proportions to be in the range 50–70%. This limits the region of likely average reflectance as on Figure 13(f) plots D (eq (4)). To deal with the luminance (the quantity of light) wanted in the in the House, the exterior obstructions out of the design must be taken into account (sustainable strategy table 4(b), Vegetative Barriers). In the case of urbanization, the result show that the alignment and position of building have an impact on the luminance of a specific house. For the humanitarian camps, the distance between two shelters must allow access to the acceptable light quantity. The target is to meet 4% to 5% of daylight on the sunlight exposure as shown on Figure 14(a). The amount of the Daylighting will vary depend up on the Type of Design, the Size and the openings' position, for a classroom [49], 4% is the strict minimum but 2% of daylight Factor (DF) tends to be the strict minimum for an Office (see Figure 14(b)) and more than 15% make the room uncomfortable for work and rest. The Window/Door-to-Floor Ratio (WFR), Maintain a WFR of at least 20% (we considered all the openings in our case), with windows strategically placed for uniform light distribution and the glare Control like using shading devices or frosted glass to minimize glare and improve visual comfort by ameliorate the dark as on Figure 14(c).

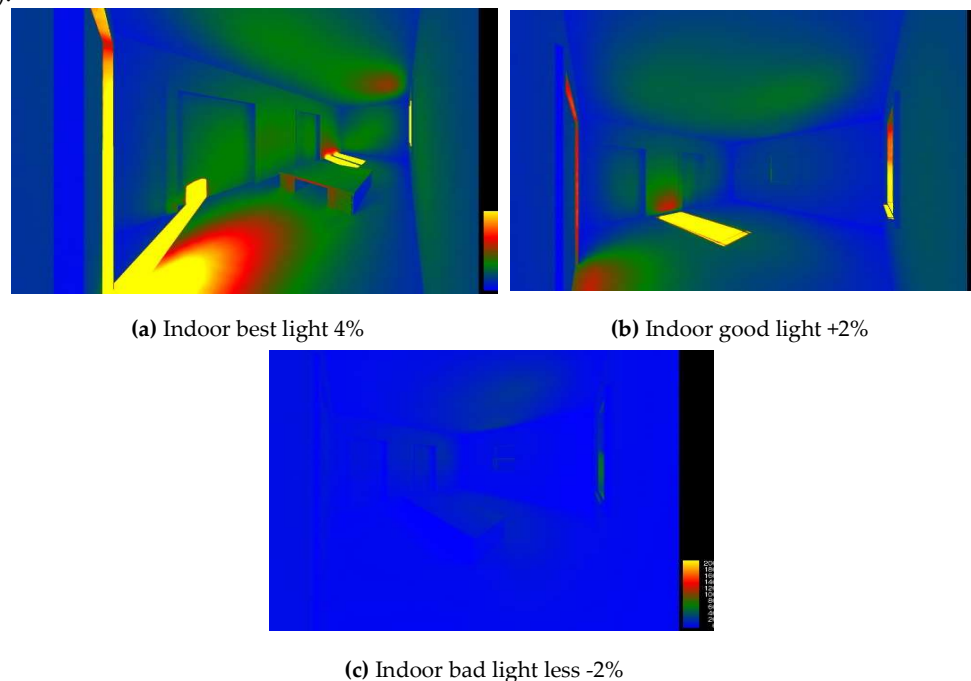


Figure 14. Daylighting index.

The natural daylight, heat comfort and cooling have significant impact on Health such as:

- Improved Air Quality;
- Reducing humidity levels minimizes mold and mildew growth, lowering respiratory illness risks;
- Thermal Comfort: Stable indoor temperatures decrease heat stress, improving sleep and general well-being;
- Mental Health: Adequate ventilation and thermal regulation reduce feelings of suffocation and discomfort, contributing to better mental health in challenging environments;
- Poor distribution of light may lead to "hot spots" in certain parts of the house.

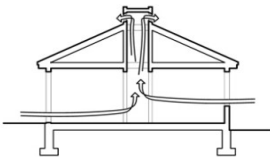
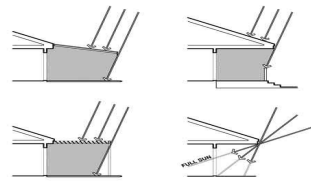
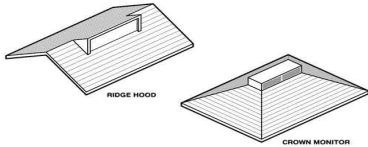
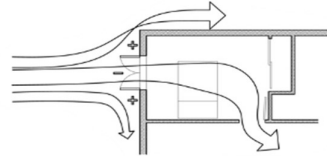
Install vents or open windows at night to maximize heat dissipation from the floor. Smooth and seal the clay floor to reduce dust while retaining its thermal benefits. Use controlled moisture on the floor in dry conditions to enhance cooling without causing excessive humidity. Prevent direct sunlight from reaching the floor during the day to minimize heat absorption. Direct sunlight entering

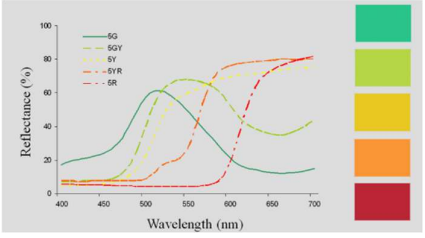
through windows can warm the house during cooler periods (e.g., mornings and evenings), Good natural lighting reduces the need for artificial lighting, which can generate additional heat, Direct sunlight through west-facing windows in the afternoon can cause indoor temperatures to rise, especially with aluminum roofing, which retains heat. Apply a light-colored plaster to adobe walls or consider alternatives like glass blocks for natural light diffusion. Plant trees or shrubs near west-facing windows to reduce excessive afternoon heat while still allowing indirect light.

4.3 Comfort analysis

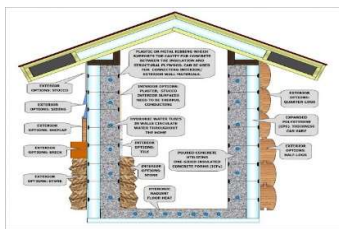
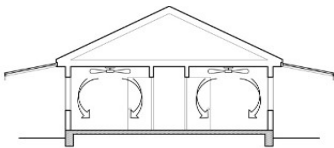
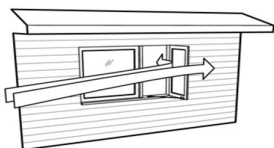
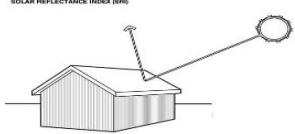
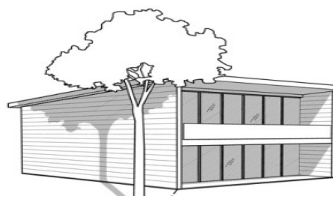
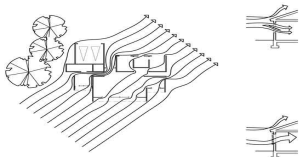
The above Design strategies showed on the psychometric chart are important to meet the comfort in a very specific zone of project, unfortunately they all not aligned with the spirit and logic of humanitarian construction projects that stipulate to do not use some Chemicals, Machine like interior heating machine in rural area, or whatever high-cost tools. The UNHCR Guidelines for Refugee Housing Encourage designs with passive heating and cooling features, ensuring that interior temperatures remain livable without mechanical systems. Through the simulation researches and after familiarizing with technical reports, annul reports from Humanitarian organizations, Spheres and Existing literatures, this study combines findings into Lighting-Neutral carbon strategies and Heating-Humidity-Neutral Carbone Strategies as summarized in Table 4(a) and Table 4(b).

Table 4. Sustainable Design strategies

N o	Design Strategies	sketches Guidelines		Materials
		Lighting-Neutral carbon		
		Sketches	Description	
1	Optimize d Openings		Place windows on opposite walls to maximize cross-lighting and uniform distribution. Use high window placement to enhance daylight penetration.	On Roof, Wall and windows materials
2	Light Shelves		Install horizontal projections above windows to bounce light deeper into the shelter while shading lower areas from direct sun.	On windows materials
3	Transpare nt Roofing with Solar Films		Use transparent polycarbonate sheets coated with photovoltaic films to provide both daylighting and solar energy harvesting.	On Roof materials
4	Locally Sourced Timber		Incorporate locally harvested, sustainably managed timber for window frames and shading devices.	On Roof and Wall materials
5	Natural Insulation		Employ cork or hemp-based insulation with reflective surfaces to enhance light dispersion and thermal regulation.	On Roof, Wall and windows materials

6	High-reflectance colors [50]		It should be noted that changes in wall reflectance might also change the perceived brightness of a space, which may in some cases have a larger impact than the change in daylight factor.	On ceiling, Wall finishing materials
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(a) Lighting-Green Construction material strategies

Nº	Design Strategies	sketches Guidelines		Materials
	Heating-Humidity-Neutral Carbone			
		Sketches	Description	
1	Thermal Mass Materials, [51]		Use materials like compressed earth blocks or rammed earth, which absorb and release heat slowly, maintaining a stable indoor temperature.	Roof, Wall windows, grounds pavement and finishing materials
2	Cross-Ventilation Design,		Position openings to allow cool air intake and hot air exhaust, especially in humid climates.	On Roof, Wall and windows materials
3	Insulated Floors and Walls,		Employ materials like straw bales or recycled denim to limit heat gain/loss.	On Wall, and grounds pavement materials
4	Desiccant-Based Materials,		Integrate lime plaster or activated charcoal into wall finishes to passively absorb excess moisture.	On, Wall finishing materials
5	Roof Overhangs and Gutters:		Design wide roof overhangs to reduce rain penetration and manage water runoff.	On Roof materials
6	Vegetative Barriers:		Surround shelters with drought-tolerant plants or green walls to create microclimates that lower local humidity and temperature.	Around the house
7	Passive Design Principles of orientation		Align shelters to maximize natural ventilation (e.g., positioning openings perpendicular to prevailing winds).	In the case of refugee camps or new Urbanization

(b) Cooling-Green Construction material strategy

From the Design strategies such as Thermal Mass Materials, Cross-Ventilation Design, Insulated Floors and Walls, Desiccant-Based Materials and Roof Overhangs and Gutters in Table 4, the Alternative Construction Materials for Better Illuminance reflect more light within the house, improving brightness as Clay or cement plaster over the adobe can enhance light reflectivity. Glass Blocks allow natural light to penetrate while maintaining privacy and diffuse light, reducing glare and hotspots similar to Concrete walls coated with high-reflectivity paint can bounce natural light effectively and Reflective Roofing Material like clay tiles or insulated metal panels with reflective coatings to reduce heat absorption and overheating. Tiles or Polished Cement reflect light upward and enhancing overall illuminance. Dark-Colored or Matte Finishes Stabilizes indoor temperatures by absorbing heat during the day and releasing it at night and highly Polished Floors can create excessive glare, straining the eyes. Moreover, Soft Neutral Colors such as Off-white, beige, or light gray ensures good light reflection without being overly harsh on the eyes and Pastel Shades; Light blue or green can be calming and reduce eye strain, especially in bright light, these in common is what we called Sustainable green Design as shown on Fig. 15.

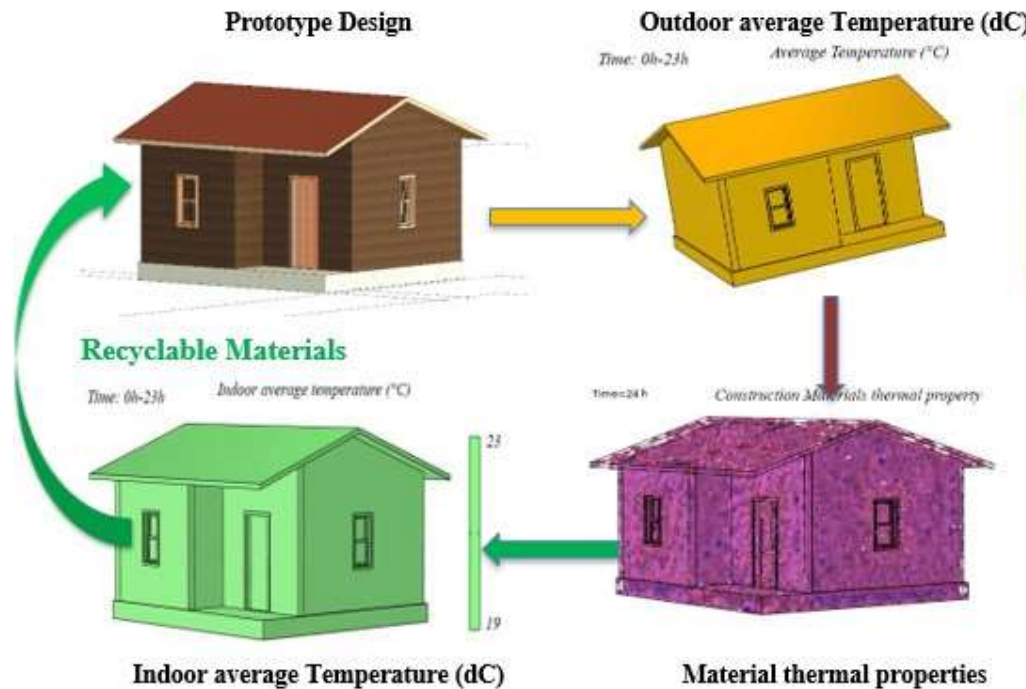


Figure 13. Sustainable green Design. Source: Authors' work.

To verify the Sustainability of the findings, the current research results were applied on EDG app. The estimations of all sustainability benefits that can be achieved during the project in term of Energy Efficiency, Measures saving, water saving, operational CO₂ saving and embodied carbon. The results show that after applying used parameters for the prototype from the base to the roof, and the strategies based on simulation results, the Design achieved 52% of material efficiency, 37,15% OF Energy efficiency and 0.04 tCO₂ per 1 month per 1 house as the Final operational CO₂ Emission which is far better than the simulation application requirement of 20% each [52].

5. Conclusions

This study developed a framework for sustainable humanitarian construction, integrating Building Information Modeling (BIM) and climate simulation tools to analyze thermal comfort, natural lighting and energy efficiency through a Climate and Tradition-Centered Design (CTCD) in

the Nakoyoya and Muyinga sheltering project. By emphasizing the use of locally sourced materials such as adobe walls and clay floors, combined with optimized design strategies, significant advancements in shelter performance were achieved. Key findings include:

- 20% to 24% reduction in thermal discomfort during peak heat hours due to the thermal inertia of adobe walls, which effectively moderated indoor temperatures. These walls absorbed heat during the day, maintaining indoor temperatures between 22°C and 24°C at night, consistent with ASHRAE Standard 55. Additionally, clay flooring contributed localized cooling effects, further enhancing comfort by stabilizing temperature fluctuations.
- Daylighting analysis revealed that wall finishing material reflectance and optimized window-to-floor ratios improved daylighting performance by 2% to 5%. This was critical in achieving energy savings, as improved natural lighting reduced the dependency on artificial lighting during daylight hours. Moreover, reflective materials and the strategic placement of windows enhanced illuminance, maintaining an acceptable daylight factor (DF) of 3% to 5%, which is ideal for comfort without glare.
- The use of climate-responsive construction materials and passive design strategies contributed to a 37.15% improvement in energy efficiency and a 52% enhancement in material efficiency, while achieving a final operational CO₂ emission rate of 0.04 tCO₂ per month per house. Roof overhangs, vegetative barriers, and reflective roofing further minimized heat influx and maximized cooling potential, ensuring that indoor conditions aligned with the comfort thresholds of 20°C to 25°C during 80% of occupied hours.

These results demonstrate the potential of locally adapted, sustainable design strategies to balance immediate housing needs with long-term environmental sustainability, setting a benchmark for humanitarian shelter designs in diverse climatic conditions. This study offers actionable insights for practitioners, humanitarian organizations, and policymakers striving to optimize health, comfort, and ecological performance in future humanitarian construction projects. This study did not include the cost analysis and logistic assessment as part of to let others researchers span their contribution.

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Conflicts of Interest: The authors declare no conflict of interest.

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