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ARTICLE

Analysis of the Effects of Passive Design for Improving Building's Hygrothermal Comfort in the Sahelian Climate

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ABSTRACT

The present study aims to analyzse alternative passive design solutions for enhancing building energy and hygrothermal efficiency in the Sahelian zone. To achieve this, a model representing a standard single-storey cement-hollow block dwelling building and its relevant parameters was input into EnergyPlus, combined with OpenStudio or SketchUp. Scenarios were then analyzed to evaluate the effects of roof solar reflectivity, wall external insulation, natural ventilation, and their combined options. First, the base case, serving as a reference model, was validated using measured and simulated temperatures by calculating the scientific criteria, such as the NBME and CVRMSE coefficients recommended by the ASHRAE and IPVM standards. Additionally, the numerical simulation was used to compare interior temperatures, discomfort hours, thermal parameters, and the hygrothermal index (IHT) across seven cases studied. The reference model simulation indicated that cement-based hollow blocks are less effective for building envelopes in the Sahelian climate, with 51.48% discomfort hours and an IHT of 1.6, as shown in the Givoni diagram. The results revealed that the wall external insulation was the most effective passive solution, with 56% of comfort hours and an IHT

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of 0.7, which indicates the expected position of the model within the hygrothermal comfort zone of the Sahelian climate. Combining passive strategies yields the best scenario, resulting in a 28.25% reduction in annual total discomfort hours compared to the base case. These simulations demonstrated the effectiveness of accessible passive design solutions applicable in dwelling construction for the sustainable development of countries in the Sahelian climate.

Keywords: Optimization Methods; Passive Solutions; Hygrothermal Comfort; Building's Energy Efficiency; Sahelian Climate

1. Introduction

Burkina Faso is among the countries with low levels of production and access to electricity, essentially based on thermal, hydroelectricity and solar sources, while the potential of irradiation is around 5.5 kWh/m²/day according to statistics results for 2018, according to the Ministry in Charge of Energy of Burkina Faso. It must address numerous energy challenges, including promoting energy efficiency. Since buildings consume about 40% of the primary energy in the world, they are then responsible for the majority of greenhouse gas emissions [1, 2]. The construction sector in Burkina Faso is characterized by two phenomena that are the use of a lot of conventional materials (cement, sheet) in the majority of civil engineering applications, among others, the building construction and its air conditioning. These construction products enrich the exogenous economy, and are not relatively non-insulating materials, resulting in building internal thermal discomfort and the great utilization of mechanical air conditioning (AC) and the increase of the energy demand. The urbanization cartography is marked by a majority of buildings that are relatively inadequate to the harsh climate, where the envelope provokes a severe internal thermal environment [3]. This situation presents the construction sector as a major challenge for the next few decades in Burkina Faso and, likely, in other underdeveloped countries [4]. Indeed, the control over energy consumption aims to improve the population's life quality by reducing the carbon footprint on the environment [5]. From now on, this sector must bring energy efficiency to the construction life cycle [6]. Energy efficiency can be considered a constraint, an assignment, a priority, or a means to reduce infrastructure exploitation costs [7, 8]. In addition, the practice of energy efficiency becomes an expertise and a responsibility in construction management.

To do this, the possible actions to reduce the building's energy needs are based on the construction materials' life cycle, the construction technologies employed and globally, the building. The local and global markets have several varieties of new materials [9]. Indeed, they can be applied to the economic envelope design, the reduction of AC energy needs, by minimizing the thermal leaks and maximizing the recovery of passive solar gain, while limiting the emission of greenhouse gases [10]. Several studies have been conducted on this issue to enhance the energy performance of residential buildings. Nait and Bourbia [11], who concluded that insulating opaque walls and glass parts is beneficial for improving building energy performance. The effect of thermal insulation is visible on the roof and the exposed wall [12]. The analysis of measurement data revealed that direct green façades contribute to improving the outdoor and indoor thermal environment of buildings due to the effect of shading and evapotranspiration [13].

However, according to Ratsimbazafiharivola et al. [14], the condition of efficient insulation is to employ the insulating materials that offer the highest thermal resistance. According to Medjelakh and Abdou [15] the use of local material adapted to the local climate is the source of the realization of hygrothermal comfort and the reduction of energy consumption, with the main role of the thermal inertia in the maintenance of building internal hygrothermal balance. In the study of solar reflectivity, the application of a rough substrate, such as bituminous pavement type of roof waterproofing, shows a decrease in reflectivity compared to the smooth substrate, which exceeds 50% [16]. Abdelouhab Labihi et al. [17] indicated that the standards of controlled mechanical ventilation with double decentralized flow ensure the air quality without overconsumption for heating. In addition, the studies of Benoudjafer et al. [4] showed that thermal insulation, inertia, and ventilation are ways to improve building energy performance.

In Burkina Faso, previous studies suggested a good result. Ricon et al. [18] observed that the same combination of passive measures in the traditional Burkinabe dwelling significantly improves thermal comfort compared to the base case, but it is less effective in providing comfort, resulting in more than 3000 hours and 200 degree-days of annual discomfort. According to Zoure et al. [19], natural ventilation was the most effective passive cooling technique, reducing annual discomfort hours by 40% and yearly energy consumption by 30%. Combining passive strategies is the best scenario, with a year of office occupancy resulting in just 617 hours of discomfort, a 42% reduction in annual cooling energy demand, and a 43% reduction in annual energy consumption.

The standard NF EN ISO 7730 shows the link between thermal comfort and the core equivalent in its assembly. It can be influenced by physical activity, clothing, and environmental parameters [20]. This places the building in an interaction with its environment and makes occupants resent the perception of consequences of the climate-changing conditions in internal housing.

The search for energy efficiency in the construction sector is a pressing issue for sustainable construction, and the industry needs a breakthrough in technologies. According to Benoudjafer et al. [4], it requests to examine globally the building thermal behavior. There are many innovations in energy systems and the envelope materials of the building, but they meet the difficulty of technology transfer, the experience sharing to accelerate the put in the market and the integration in current applications [17]. The study of building hygrothermal behavior in the different steps (individual component or global) of its life cycle is an essential parameter to know its real energy efficiency. To do this, the identification of Energy efficiency improving solutions can be done by modeling and simulation and/or by in situ instrumentation [21].

The present study aims to establish the best-adapted passive solution by analyzing the hygrothermal optimization methods of a habitable cell by cement hollow blocks submitted in different design options. The recent studies permit access to performant tools, validated codes, coupling possibilities and methods to simulate globally the building behavior [3, 21]. Among them, see the prediction tools such as Energy+, TrnSys, CoDyBa, Pleiade and PHPP [22], and TRNSYS. To do this, the present study explores the bioclimatic design principle, taking into account the natural ventilation, the walls' insulation, and the roof's solar reflectivity, which are essential parameters and passive methods with less environmental effects. In addition, it's applied in Sahelian climate conditions, with an appropriate description of the materials' properties currently used in local construction projects because the calculated codes of the modeling and simulation tools present a great sensitivity to the variation of physical parameters [22].

The previous theoretical and experimental studies concerned the individual passive solutions applied to the building, with the calculation of time lag and the decrement factor. This work consists of determining experimentally and numerically the thermal amplitude, time lag, decrement factor and the IHT using a single-room building. To do this, an experimental test building is considered in Ouagadougou. The originality of this work, compared to the work mentioned above, lies in the simultaneous calculation of time lag, thermal amplitude, decrement factor, and IHT, utilizing both inside ambient air temperature and average equivalent temperature. The ambient-air temperature characterizes the responses of each passive solution and the simultaneous reactions of the combined passive solution.

2. Materials and Method

2.1. Description of the Study Support

The prototype of the study is a one-piece building measuring 9 m², located in southern Ouagadougou, Burkina Faso, as shown in **Figure 1**. This model is representative in this study because the design and the material concern most of the construction in this area. The occupation scenario in an open evolution without occupants and the characteristics are summarized in **Tables 1**–**3**.

Thermal characteristics of the materials used in the base model and the dimensions are given in **Table 1** [24]. In fact, the knowledge of the material's properties, the climate conditions and the air movement between internal and external environments is important for the modeling and simulation of building thermal behavior [25].

The thermal characteristics of simple glass and steel used and their dimensions are summarized in **Tables 2** and **3**.

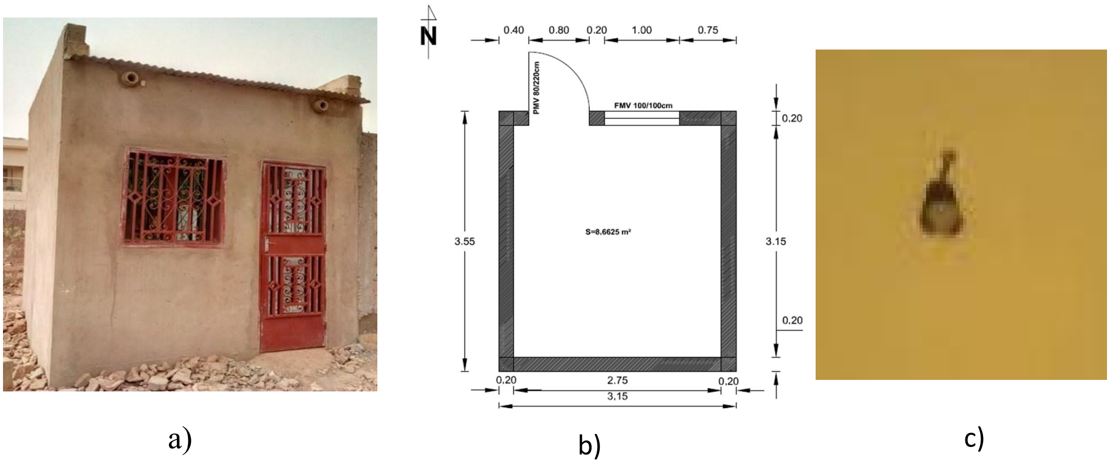

Figure 1. Support of experimental study (**a**) Image, (**b**) level plane, and (**c**) Waranet Thermochip [23].

Table 1. Building envelope characteristics.

Item	Wall's Component	Material Type	L (m)	h (m)	e (m)	λ (W/m.K)	ρ (Kg/m^3)	Cp (kJ/kg. K)
1	North wall							
2	West wall	Cement based hollow blocks 15 × 20 × 40 cm	3	3	0.15	0.67	1250	0.88
3	South wall							
4	East wall							
5	Coating	Cement mortar	3	3	0.02	0.87	2200	1.05
6	Roof	Replied iron	3	3	0.05	0.7	7800	0.8
7	False ceiling	Plywood	2.5	2	0.006	0.14	600	2.72
8	Ground	Concrete	3	0.1	0.1	0.9	2200	0.85
9	Door	Steel	1	2.5	0.0015	50	7800	0.115
10	Window		1	2.5	0.0015	50	7800	0.115

Table 2. Characteristics of the simple glass of doors and windows.

Materials	eg	λ	g	T_L	ε	FSSR	BSSR	FSVR	BSVR
Unit	cm	W/m.K	-	-	-	-	-	-	-
Simple glass	0.30	0.93	0.87	0.90	0.92	0.075	00	0.081	00

Table 3. Characteristics of steel used for doors and windows.

Materials	L_f	e_f	$α_s$	$α_{th}$	ε	Uf
Unit	cm	cm	-	-	-	W.m^2/K
Steel	5.00	1.35	0.90	0.90	0.70	3.30

2.2. Experimental Analysis of Building's Thermal Behavior

Experimental analysis of the base case has been conducted in the building in Ouagadougou with Sahelian climate. The present study used a part of one-year monitoring data from a single house analyzed by Malbila [23]. The hygrothermal behavior of this building was carried out by measuring the temperature and the relative humidity, as illustrated in **Figures 2** and **3,** where Te and Ti are respectively the external and internal measured temperatures. The model in **Figure 1** was instrumented by using Waranet measurement devices to study the influence of some parameters, such as orientation or building materials of the envelope. These findings are used to validate the designed model in the present work.

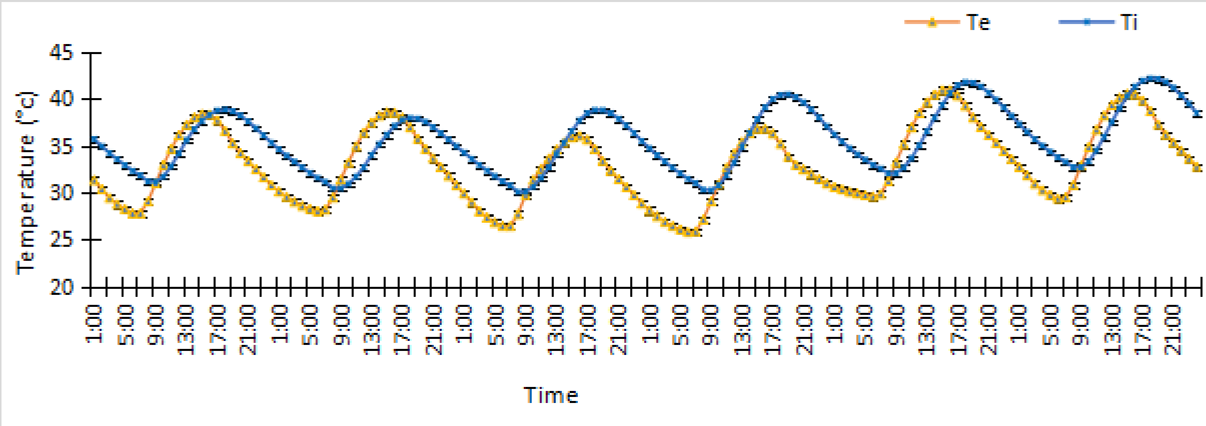

Figure 2. Indoor/outdoor temperature of base case building in open evolution [23].

From these curves in **Figure 2**, we observed that the building's internal temperature is subject to important variation (30 °C to 42.1 °C), in function of the fluctuations of external ambient temperature. The variation in the mean difference of temperature (maximal and minimal) during the hot month of April is α = 12.11 °C inside the building.

Figure 3 illustrates the evolution of relative humidity in the reference building. The curve presents the evolution according to the local Sahelian climate conditions with values ranging from [24% to 64%]. Then, the average value throughout the test for the relative humidity is 44%.

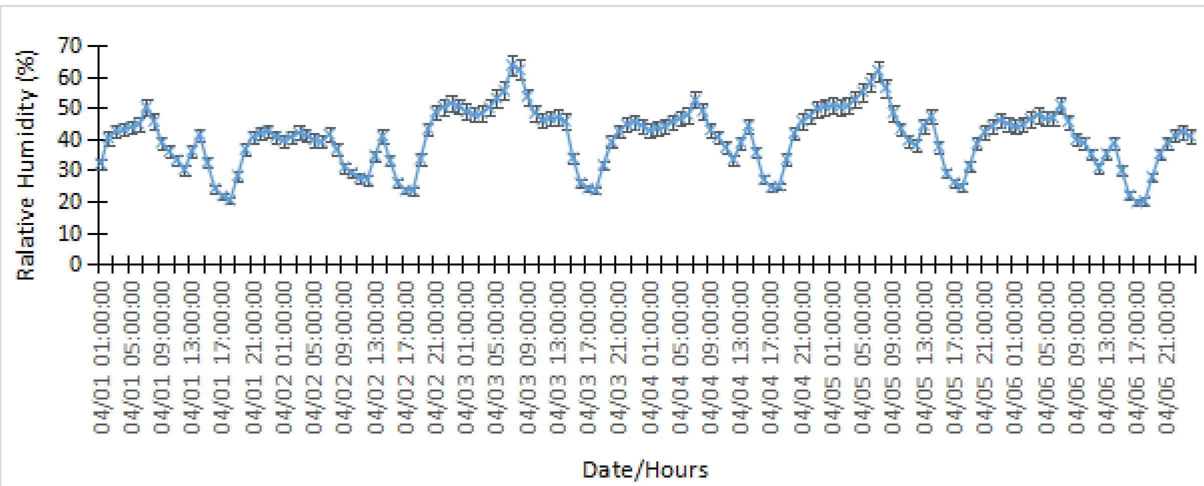

Figure 3. Variation of the relative humidity in the base case reference building in open evolution [23].

2.3. Criteria for the Validation of the Base Case Hygrothermal Simulation

Numerical validation of the hygrothermal simulation model has been conducted in Ouagadougou (Burkina Faso) with Sahelian climate. For model validation, the criteria permit an assessment of the design model's quality and its ability to represent the study. Two statistic index such as the normal mean bias error (NMBE) and the coefficient variation of root mean squared error (CVRMSE) recommended by ASHRAE and IPMVP are initially retained to evaluate the quality of the design and the simulation results [23, 26] according respectively monthly calibration (n = 12) or hourly calibration (n = 8760) to the model (**Table 4**). Then, the more the value of these coefficients tends to zero, the more the model correctly represents reality. These coefficients are determined by applying Equations (1) and (2), where x_S *is the value of simulation results,* x_m *is the value of experimental measures,* n *is the number of elements in the function of the calibration model, and* $\overline{x}_m$ *is the mean of measured values.*

$$NBME = \frac{\sum_1^n (x_s^i - x_m^i)}{(n-1)\bar{x}_m} \quad (1)$$

$$CVRMSE = \sqrt{\frac{\sum_1^n (x_s^i - x_m^i)^2}{(n-1)}} * \frac{1}{\bar{x}_m} \quad (2)$$

Table 4. Model validation criteria reference values.

Standards	Monthly Calibration Criteria		Hourly Calibration Criteria	
	NMBE (%)	CVRMSE (%)	NMBE (%)	CVRMSE (%)
ASHRAE Guideline14	5	15	10	30
IPMVP (2002)	20	--	5	20

2.4. Design and Simulation of Habitable Cell Hygrothermal Behavior

2.4.1. Hygrothermal Simulation Studies Cases

Several passive design strategies in building hygrothermal behavior used in the Sahelain or Soudano-Sahelian climate are to be studied in the simulation tests. The charactersitics of the construction materials used in Energy + Software are presented in **Table 5**. The different cases are described in the following paragraph.

Table 5. Characteristics of white-painted Galvanized steel sheet in energy + software.

Building Components	Material	Properties			
		e (m)	λ (W/m.K)	ρ (Kg/m^3)	Cp (kJ/kg.K)
Roof		0.002	50	7800	0.115
Wall Coating	Lime	0.002	0.87	1600	0,94
Insulation material	Cotton	0.15	0.060	1600	40

The benefit of using Roof reflectivity, insulation material, and cooling down building by taking advantage of natural ventilation during night are analyzed and compared with the base case.

Case 1: Roof Solar Reflectivity

In the reference model, the roof is made of a steel sheet, which has a high capacity to absorb and store heat and humidity. These steel sheets will be replaced by the Galvanized steel sheet painted in white color. Due to this, the effect of reflectivity is evaluated by replacing the current steel sheet with the white-painted Galvanized steel sheet.

Case 2: Walls External Insulation

The building thermal insulation consists of an envelope of internal and/or external building by insulating material. The walls are built of porous materials in which we can observe heat and mass transfer. For this reason, in the present study, the walls are insulated in an external part, which is more adapted to the local context [23] by using cotton-based insulating material.

Case 3: Natural Ventilation

Natural ventilation utilizes a simple physical principle of natural thermal convection within the building. The application of this option consisted of increasing the airflow at 20v/h in the habitable cell.

Case 4-7: Combined effects

A simulation case including the combined effects of Roof solar reflectivity, Wall external insulation, and natural ventilation is also presented and discussed, both for the building's hygrothermal behavior in the Sahelian climate.

2.4.2. Mathematical Equations and Principles of Heat and Mass Transfer in Building

Modeling is a scientific method for studying complex technological processes or technical systems using models (physical or mathematical), which allows us to analyze the influence of structural and operational parameters of a process or system on their effectiveness [27].

Heat Transfer

Heat transfer processes in porous or multiphase media are conduction, convection and radiation, described by the following Equations (3)–(5).

$$\boldsymbol{\varphi_{cd} = -\lambda \times S \times \nabla T} \quad (3)$$

where:

- φ_{cd} **:** *Heat flow by conduction [W]*
- **λ:** *Thermal conductivity of the material [W. m^{-1}. K^{-1}]*
- ***S:*** *Section [m^2]*
- ***T:*** *Temperature [K]*

$$\boldsymbol{\varphi_{cv} = h \times S \times (T_{surf} - T_\infty)} \quad (4)$$

Where:

- φ_{cv} **:** *Heat flow by convection [W]*
- ***h:*** *Convective heat exchange coefficient [W. m^{-2}. k^{-1}]*
- ***S:*** *Section [m^2]*

- T_{surf}: *Transfer fluid surface temperature [K]*
- T_{∞}: *Fluid temperature away from the wall [K]*

The heat flux emitted by radiation from a surface to the ambient environment is determined by Stefan-Boltzmann's law, as shown in Equation 3.

$$\varphi_r = \varepsilon \times \sigma_{SB} \times S \times (T_{surf}^4 - T_a^4) \tag{5}$$

Where:

- φ_r : *Heat flux radiated by the material to the ambient environment ambient [W]*
- σ_{SB}: *Constant of Stefan-Boltzmann which value is* σ_{SB}: = 5,67. 10^{-8} [$W.\ m^{-2}.\ k^{-4}$]
- S: *Section [m^2]*
- ε: *Emissivity of surface of wall or roof. ε = 1 for black surface and ε < 1 for gray materials*
- T_{surf}: *surface temperature of the material [K]*
- T_a: *Air-ambient temperature[K]*

Mass Transfer

In the case of buildings, the element most involved in mass transfer is water in its two phases: liquid and gas. The total flow of moisture can therefore be written, following **Equation (6)**, as the sum of a vapor partial pressure gradient component and a mass water content gradient component.

$$j_h - \delta_p \nabla P_v - D_w \nabla w \tag{6}$$

Where:

- j_h: *Total moisture flow density [kg. m^{-2}. s^{-1}]*
- j_l : *Density of liquid flow in material [kg. m^{-2}. s^{-1}]*
- j_v : *Density of vapor flow in material [kg. m^{-2}. s^{-1}]*
- δ_p : *Vapor Permeability of material [kg. Pa^{-1}. m^{-1}. s^{-1}]*
- P_v: *Vapor Pressure [Pa]*
- D_w : *Liquid diffusion coefficient under water content gradient [m^2. s^{-1}]*
- w: *Water content by mass [kg. kg^{-1}]*

Integral Conservation

Energy and Mass conservation are obtained by applying Equations (7) and (8), respectively.

$$\rho C_p \frac{\partial T}{\partial t} + \nabla j_q = 0 \tag{7}$$

with ρ *the density,* C_p *the specific heat at constant pressure and* j_q *total heat flow.*

$$\rho_s \frac{\partial w}{\partial t} = \nabla(\delta_p \nabla P_v + D_w \times \nabla w) \tag{8}$$

with ρ_s *the density of solid phase,* w *the mass water content,* δ_p *the vapor permeability,* P_v *the vapor pressure and* D_w *Liquid diffusion coefficient under water content gradient.*

2.4.3. Choice of Simulation Software

Energy+ the software used in the study, because it's available and adapted to the treatment of the case studied. Indeed, this software permits the simulation of several mechanical equation systems and analyzes the building energy performance [28]. However, we associated with Energy+, the interfaces such as Open Studio and Sketchup for the graphic design of the building (**Figure 4**).

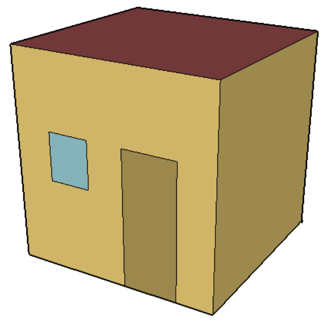

Figure 4. Design of a habitable cell with sketchup device.

2.4.4. Simulation with Software Energy+

The evaluation of the habitable cell hygrothermal performance consisted of a series of dynamic thermal simulations of the base model and seven (07) other optimization options, which are indicated in **Table 6**.

Table 6. Description of the cases studied.

No	Option	Applied Methods	Descriptions
1	Option 1	Modification of Roof solar Reflectivity	Current steel sheet is replaced with galvanized steel sheet painted in white color.
2	Option 2	Walls external Insulation	The walls are modified par insulating layer composed by cotton-based material and covered by mortar.
3	Option 3	Natural Ventilation	The air flow is augmented at 20v/h.
4	Option 4	Combination of options 1–2	
5	Option 5	Combination of options 1–3	

Table 6. *Cont.*

No	Option	Applied Methods	Descriptions
6	Option 6	Combination of options 2–3	
7	Option 7	Combination of options 1–3	

The main steps of the building design and thermal simulation are presented in **Figure 5**.

For a better appreciation of the hygrothermal behavior of the habitable cell in the simulated various variants, we have reduced the number of comfort/discomfort hours and the IHT.

The IHT is an indicator that permits the quantification of the combined gap of temperature and relative humidity in relation to the comfort zone for the points placed out of this zone. This indicator permits a better visualization of the position of the model or variant in relation to the comfort zone, by giving the real repartition of the discomfort temperature points around the hygrothermal comfort zone. The lower the value of IHT, the more the discomfort temperature points are reduced, and the closer the variant is to the comfort zone.

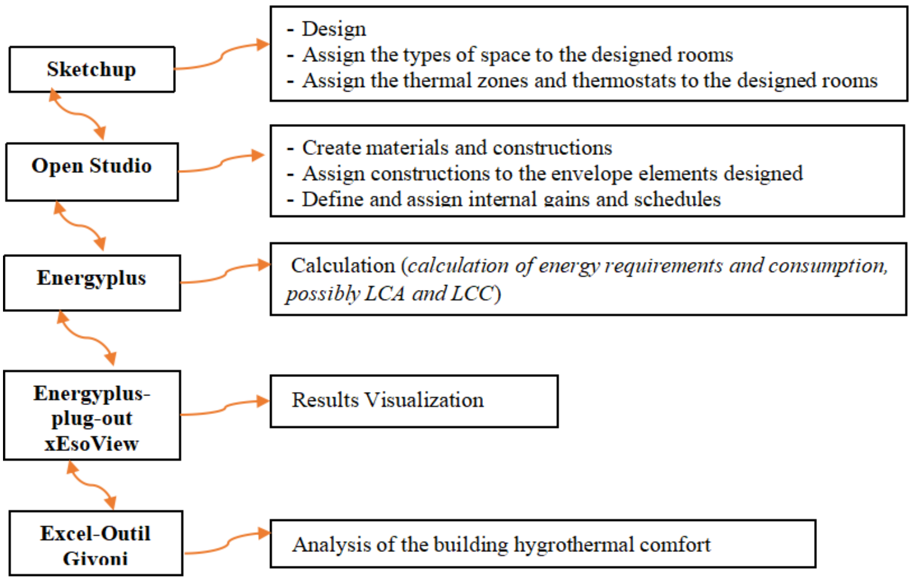

Figure 5. Synthesis of the main step of the design and simulation.

2.5. Thermal Phase Shift and Thermal Damping Through Building Wall

Thermal phase shift is the time that separates the outer and inner maxima of temperature. The damping or reduction of thermal amplitude is the difference between the external and internal maximum temperatures. These parameters are used to evaluate the improvement in the building's thermal comfort and then deduce its energy efficiency. The time lag or thermal phase shift (Ø *in hours*), the damping of thermal amplitude (*α in °C)* and the decrement factor (*f in %)* are obtained by applying, respectively, the following Equations (9)–(11).

$$\emptyset = t_{max} - t_{min} \quad (9)$$

Where, $t_{max,}$ and t_{min} are respectively the time for maximal temperature and the time of minimal temperature

$$\alpha = \Delta T = T_{max.ext} - T_{max.int} \quad (10)$$

Where $T_{max.ext}$ and Tmax.int are respectively the external and internal maximal temperature

$$f = \frac{\Delta T_{int}}{\Delta T_{ext}} = \frac{T_{int.max} - T_{int.min}}{T_{ext.max} - T_{ext.min}} \quad (11)$$

With $T_{int.max}$, $T_{int.min}$, $T_{ext.max}$ and $T_{ext.min}$, are respectively the internal and external maximal and minimal temperature.

3. Results and Discussion

3.1. Simulation of the Base Model

results obtained concerned the twelve (12) months of the year. The Givoni diagram was used to evaluate the building's hygrothermal comfort during this period. This diagram uses a humidity diagram, which indicates a thermal comfort zone for each region. About **Figure 6**, all the points located in this zone represent the hours of comfort, and the other points indicate the hours of discomfort.

To better evaluate the habitable cell hygrothermal comfort, the results from the Givoni diagram are imported and processed in the Excel software designed by HES-SO, allowing for the creation of multiple graphs as illustrated in **Figure 7**.

Figure 7 illustrates the evolution of the hygrothermal and thermal discomfort hours for a year. From these results, it is evident that the internal ambient temperature of the building is high during this period, and April presents a higher number of discomfort hours (448 hours), accounting for 62.22% of the total (**Figure 7a**). Moreover, the building is too wet that dry during this period and the month of October presents the most discomfort humidity hours number (456 hours) (**Figure 7b**), i.e. 61.29%.

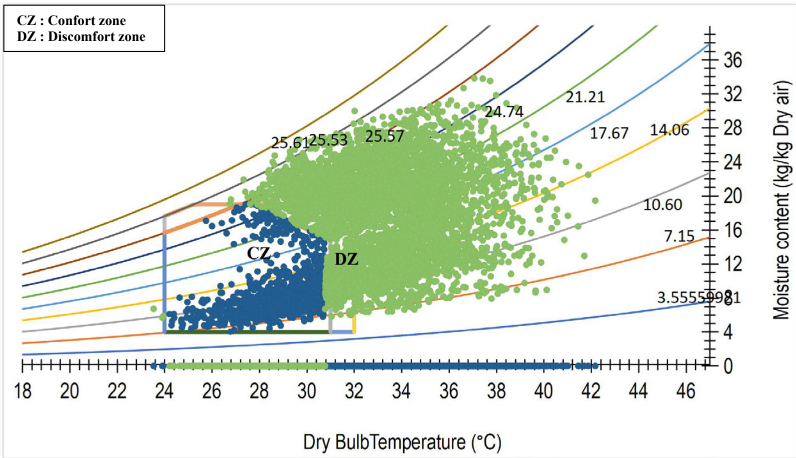

Figure 6. Diagram of Givoni applied to the base model.

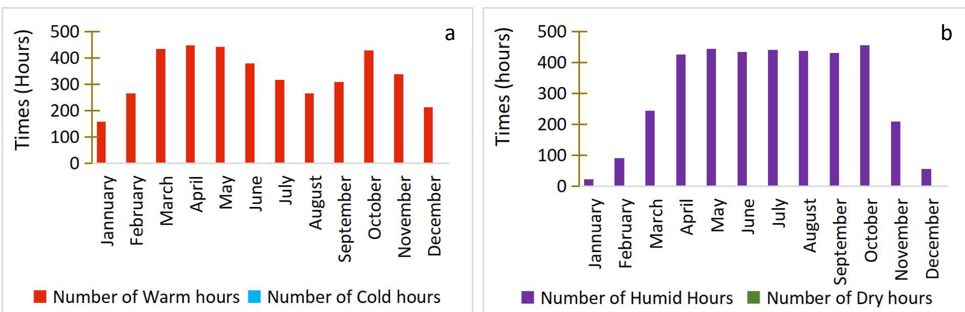

Figure 7. Monthly Hours of discomfort (a) thermal (b) hygrothermal.

3.2. Validation of the Base Model

3.2.1. Comparison of Measured and Simulated Temperatures in the Base Case

Figure 8 shows the evolution of internal temperature in the base model, as measured by *in-situ* instrumentation and simulated using Energy+ during April, which is the hottest month in the local context.

The maximum gap between the measured and simulated temperatures is about T = 0.12 °C, which indicates that the curves are practically superimposed. This allows us to note that the simulated temperature with Energy+ is close to the measured one, and they are representative of the thermal behavior of the reference building. The observed differences between the two curves were due to the incertitude on the thermal properties of the material, the precision of the devices used and the simplified hypothesis of the complex physical phenomena in the software. However, the verification of the model's quality with international scientific coefficients is necessary to be carried out in the following paragraphs (3.2.2.).

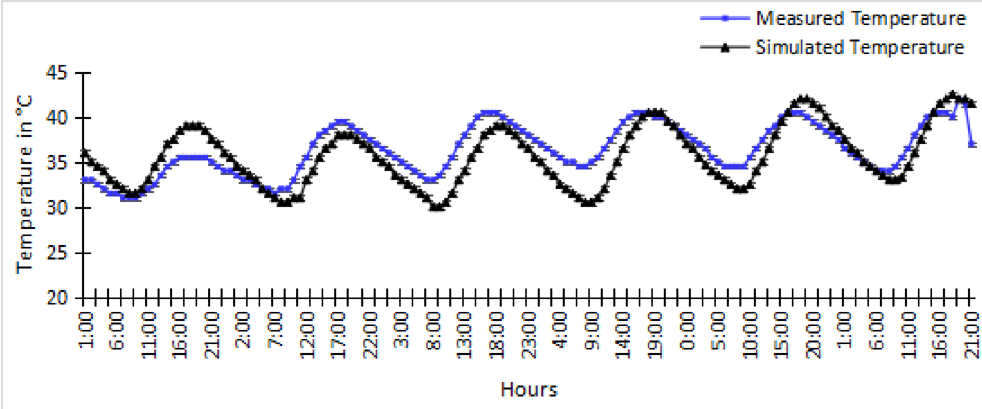

Figure 8. Comparison of the evolution of measured and simulated temperatures.

3.2.2. Evaluation of the Quality of the Building Base Model

The statistical parameters for the model quality evaluation, such as the NBME and CVRMSE coefficients, are calculated and summarized in **Table 7**.

Table 7. Summary of the Coefficient NMBE and CVRMSE.

No	Coefficient	ASHRAE Guideline14	IPMVP, 2002	Results
1	NMBE	≤ 5	≤ 20	-0.03
2	CVRMSE	15		0.08

The analysis based on **Table 7** shows that the values of the NBME and CVRMSE coefficients met the prescriptions of the standard ASHRAE Guideline 14 and IPMVP (2002). The simulated results more accurately reflected reality according to these validation criteria. However, a comparison of other parameters from the present study with those from the previous study is presented in **Table 8**.

Table 8. Comparison with previous study to validate the building base model.

Parameters	Previous study [23]	Present study
Measurement time steps	1.0 h	1.0 h
Mean value $\Delta T = Ts - Tm$	-2.21	-0.74
Maximal value of $\Delta T = \max \lvert Ts - Tm \rvert$	6.87	4.5
Mean standard deviation $\left(\sqrt{\left(\left(\frac{1}{n}\right)\sum_1^n (Ts - Tm)^2\right)}\right)$	1.99	0.74

Table 8 presents better-quality parameters than some previous studies [23]. So, from above, with the quality of the coefficients and parameters, we can conclude the validity of the building reference model and its capacity for the prediction of the habitable cell hygrothermal behavior. After the validation step, this mathematical modeling is ready to use and can be used for further studies.

3.3. Simulation of Passive Solutions for Improving the Model Thermal Comfort

The scenarios simulated for improving the thermal comfort of the reference building are presented in the following figures and tables.

3.3.1. Case 1: Modification of Roof Solar Reflectivity

Figure 9 presents the evolution of the internal temperature of the habitable cell with the modified roof solar reflectivity . Case 2 depicts the effect of Galvanized iron steel on the thermal comfort of the habitable cell, where the internal temperatures range from 28.7 °C to 41.9 °C and are less than those of the reference base model.

The comparison of the curves in **Figure 9** revealed that the temperature gap, which indicates that the peaks of temperature arrive later in the model with roof solar reflectivity improved than in the reference model. The findings suggest a dampened temperature amplitude of α = -0.98 °C, a time lag of Ø = 3 hours and a decrement factor of f = 0.86, resulting in a reduction of the discomfort hours by 11.24% from the base case. This Roof option, with Galvanized steel sheet painted white color did not influence the indoor temperature. This observation can be explained by the enormous quantity of solar radiation in the Ouagadougou area and the fact that the roofing option design without a false ceiling is not enough to reduce the heat radiation inside the building. Doya [16] has shown, through spectrophotometric measurement of adjusted solar reflectivities, a reduction of the coefficient by 15-30% for colored samples and less than 10% for white samples compared to non-exposed samples. Another study on roof solar reflectivity indicated a significant impact on the climatization need by a reduction of 39.15% [3]. Mansouri et al. [29] indicated the impact of roof reflectivity on building thermal behavior. Furthermore, Benoudjafer et al. [4] have noted that roof-insulated systems and horizontal protection permit reductions of 32.53%, 20.067%, and 39.15%.

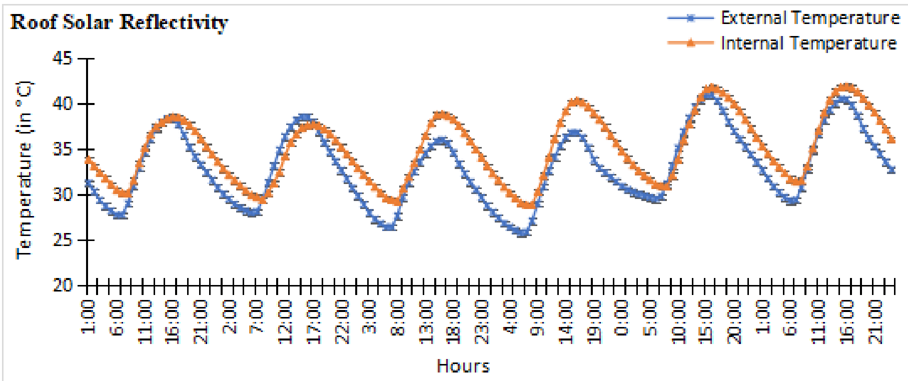

Figure 9. Evolution of the internal temperature with the passive design of modification of RSR.

3.3.2. Case 2: Wall External Insulation

The type of material used in this study is cement hollow blocks, which are commonly used in this area. The changes in the composition of the vertical wall by adding an insulating layer produced the results presented in **Figure 10**. It presents the internal temperature evolution in the building reference model and the habitable cell with an insulated wall.

With the cotton as an insulating material, the internal temperature ranges between 30.3 °C and 35.7 °C. So, the insulated habitable cell is located in the thermal comfort zone (28 °C–35 °C) of Ouagadougou city. The outcomes show a dumping of temperature amplitude of α = 5.2 °C, a time lag of Ø = 3h with a decrement factor of 0.34 and a reducing ratio of discomfort by 15.01% fromm the base case. These effects were observed by Benoudjafer and Zemmouri [3] and Benoudjafer et al. [4]. In particular, the effect produced by vertical and horizontal insulation prevented heat penetration inside the building, resulting in a reduction rate of 56.08%. Then, we deduce that adding an insulating layer to the wall option in the design and the realization contributes to dampen the temperature, to improve the thermal comfort, further reduce the building's energy requirement, and therefore increases its energy efficiency, without necessarily mechanical air conditioning. These results are consistent with Bekkouche et al. [12] and Bouaha and Zeghradnia [9].

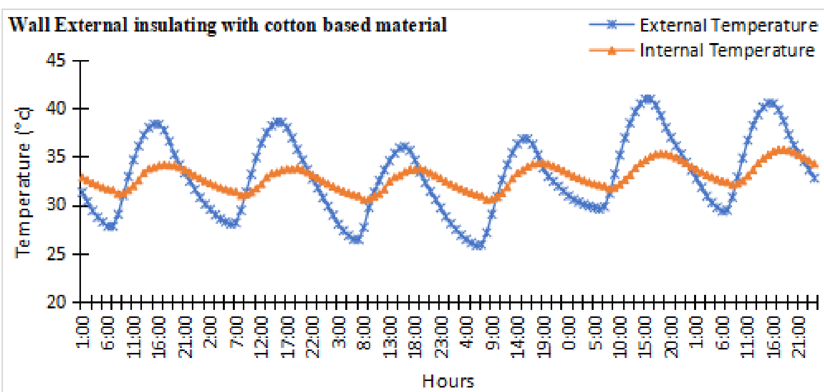

Figure 10. Evolution of the internal temperature with the passive design of the wall external insulation.

3.3.3. Case 3: Natural Ventilation

The effect of natural ventilation (NV) in the building thermal behavior demonstrates an adaptive and proactive response on the part of building users by opening windows and allowing airflow inside with 20 v/h, which has given results which are presented in **Figure 11**. We observe the evolution of the internal temperature of the passive variant compared to the base case.

Figure 11 shows that the internal temperature with natural ventilation in the building varies from (27.2 °C –40.4 °C) and are less than the reference model or base case. The situation explains the heat flow regulation by the natural ventilation inside the building and permits to dampen and to dephase the temperature peaks respectively by α = 0.48 °C and Ø = 2 hours with a decrement factor of 0.87. These effects were observed by Toguyeni and Malbila [25] studying the impact of the air infiltration rate on the building's thermal behavior. In addition, the results show that the use of natural ventilation helps reduce the discomfort hours by 24.61% compared to the base case. These effects were observed by Santos et al. [2] and Zoure and Genovese [19]. New trends in the construction industry are moving toward energy-efficient buildings, and there is growing interest in natural ventilation [30].

3.3.4. Case 4: Combined Effect of RSR and WEI

This passive option addresses the simultaneous effect of Roof surface reflectivity and the Wall External Insulating on the building's thermal behavior.

Figure 12 shows the evolution of internal temperature due to the combination of RSR/WEI in the habitable cell compared to the reference model. The curves suggest that the internal temperature of the RSR/WEI combined option is less than that of the base case and ranges from 29.6 °C to 38 °C. Case 4 shows the damping of temperature amplitude, and the decrement factor is about α = 2.72°C and f = 0.32, and the discomfort hours reduction of 23.32%. So, this option contributed to improving the building's thermal behavior.

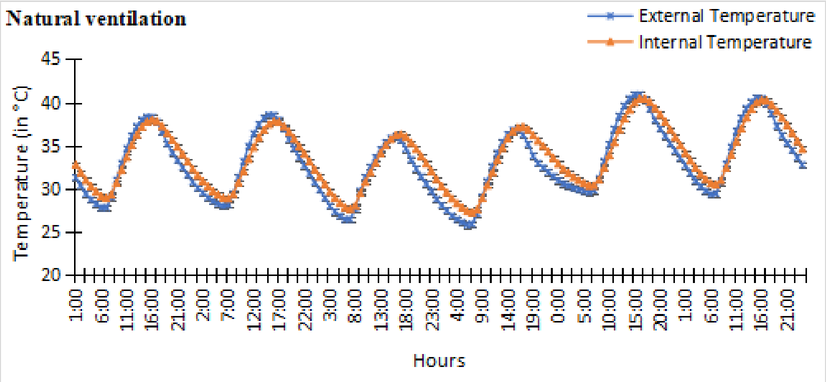

Figure 11. Evolution of the internal temperature in the passive design of natural ventilation.

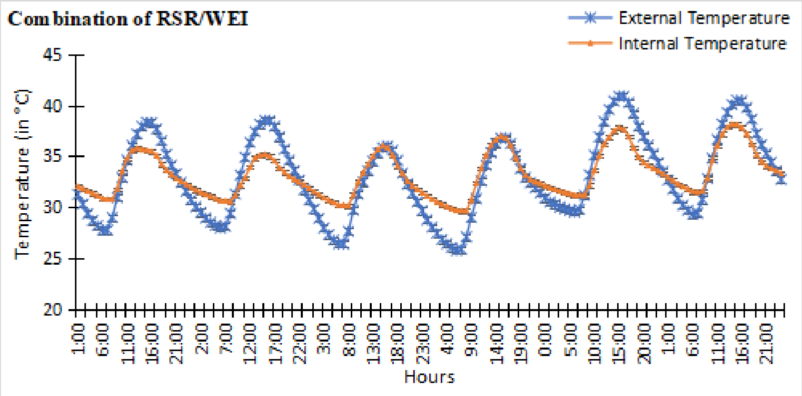

Figure 12. Evolution of the internal temperature with the combined option of RSR/WEI.

3.3.5. Case 5: Combination of RSR and NV

The combination of Roof surface reflectivity and Natural ventilation is addressed to appreciate their simultaneous effect on the building's thermal behavior.

Figure 13 illustrates the evolution of the internal temperature of the option, which combines RSR/NV in habitable cells, and the reference model. We observed that the internal temperature in the habitable cell with the combination option RVR/NV ranges between 26.7 °C and 41.2 °C. The findings with case 5, demonstrate that the temperature damping, the time lag and the decrement factor are respectively α = 0.41°C, Ø =1 hour and *f*=0.56 and a reduction of discomfort hours by 24.36% from the base case. This option contributes to improving the building's thermal behavior.

3.3.6. Case 6: Combined WEI and NV

The combination of Wall External insulating and the Natural ventilation is addressed to appreciate their simultaneous effect on the building's thermal behavior.

Figure 14 shows the evolution of internal temperature in case 6, compared to external ambient temperature. The thermal amplitude in the combination WEI/NV passive option is less than that of the reference model, with temperature values ranging between 27.6 °C and 38.6 °C. The outcomes reveal a reduction of the annual discomfort hours by 33.34%, a damping of temperature amplitude of α = 2.26°C and a decrement factor of f = 0.72. From the form above, we noted that this combined option contributes to improving the building's thermal behavior.

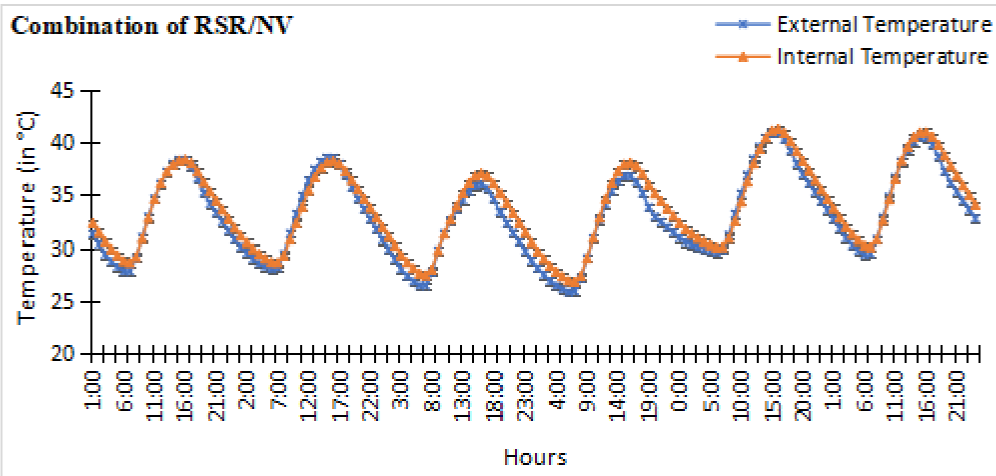

Figure 13. Evolution of the internal temperature with the combined option of RSR/NV.

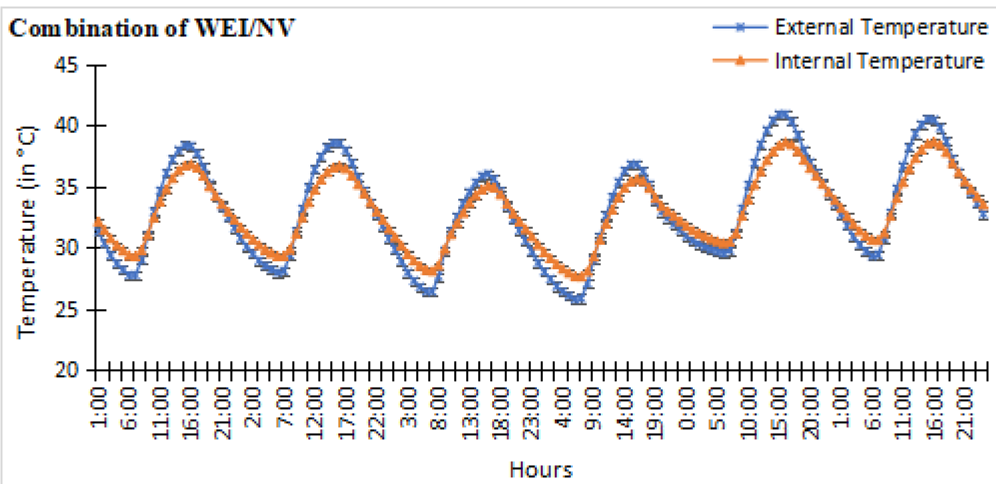

Figure 14. Evolution of the internal temperature with the combined option of combination WEI/NV).

3.3.7. Case 7: Combination of RVR, WEI and NV

This scenario points out the simultaneous effect of three passive designs combined to improve the building's thermal behavior, and the results are presented in **Figure 15**.

Figure 15 presents the internal temperature evolution in the habitable cell with the option of a combination of RVR/WEI/NV compared to the external ambient temperature. They vary between 27.2 °C and 39.5 °C, and allow us to conclude that the thermal amplitude in the combination RSR/WEI/NV passive design is less than that of the base case. The findings indicate that this case 7 induces a reduction of annual discomfort hours by 1.97%, a temperature damping of about α = 1.33 °C, a time lag of Ø = 1 hour and a decrement factor of *f*=0., compared to base case. These parameter values indicate the good effect of this combination option.

3.4. Evaluation of the Hygrothermal Behavior of the Different Model Variants

3.4.1. Indoor Comfort

The indoor comfort is measured through the indicator amount of discomfort hours, indoor/outdoor air temperature and the IHT. The discomfort hours were calculated based on the total number of discomfort hours for the building for a whole year. **Figure 16** summarizes the effect of each passive design option on the annual discomfort hours, and **Table 9** summarizes the IHT.

The diagram shows that the hot and humid discomfort hours of the reference model are respectively higher and lower than those of the other variants.

The analysis of the simulation results revealed that the thermal behavior depends on the applied variant option. The following observations are made:

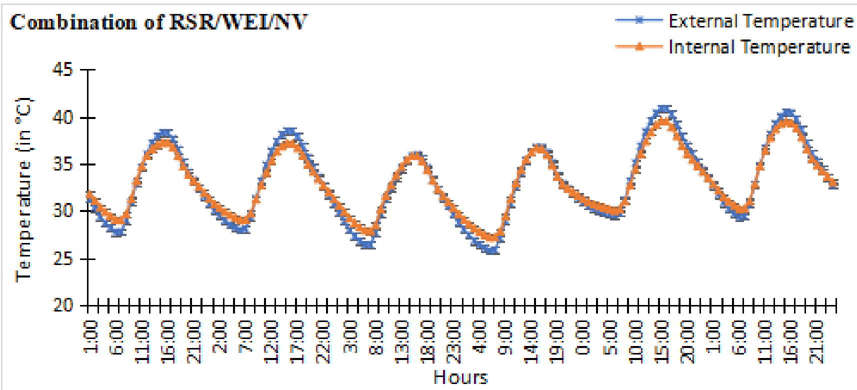

Figure 15. Evolution of the internal temperature with the combined option RVR/WEI/NV.

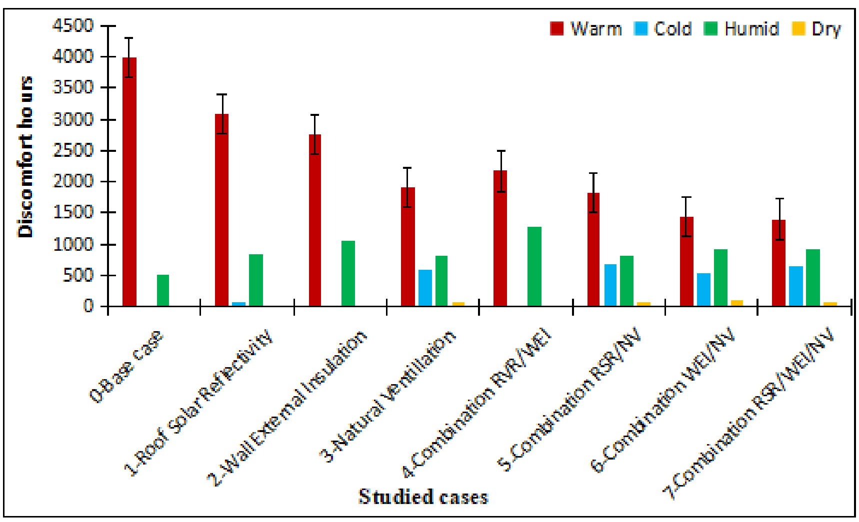

Figure 16. Average discomfort hours. All studied cases.

– It appeared that the base model had the highest total annual discomfort hours.
– The internal temperatures of the base case endure excessive variations compared to external temperatures, and this can justify that the cement hollow blocks allow the external heat to enter the building.
– The presence of temperature pics in the simulated variants indicates that applying only some individual method may not be enough in bioclimatic design. Furthermore, all temperatures are under those of the reference model and the external temperature. Better, we noted the damping and the dephasing of temperature pics from the external to the internal environment of the building. This constitutes a contribution to improve building internal thermal comfort during the considered period.
– All studied passive designs offered improved the habitable cell's hygrothermal behavior, but reducing the total annual hot discomfort hours.
– The combined passive design is the best scenario for improving building hygrothermal efficiency in the Sahelian climate [19].

Table 9. Summary of the number of discomfort hours and IHT of variants.

No	Variants	Symbol	Total Discomfort (hours)	Percentage of Discomfort (%)	IHT
0	Reference model or Base case	RM	4511	51.48	1.6
1	Roof Solar Reflectivity	RSR	4004	45.83	1.6
2	Wall External Insulation	WEI	3834	43.77	0.7
3	Natural Ventilation	NV	3401	38.82	1.3
4	Combination12	RSR/WEI	3459	39.49	0.8
5	Combination 13	RSR/NV	3412	38.95	1.4
6	Combination 23	WEI/NV	3007	34.44	1.0
7	Combination123	RSR/WEI/NV	3069	35.03	1.1

3.4.2. Comparison of Thermal Comfort Range for the Studied Variants Option

In **Table 10**, only the comfort range of the Wall external insulation option met the recommendation in the literature. The monthly variation varies from 5.4 °C to 12.99 °C (i.e., -22.86% to +85.57%). Moreover, the mean deviation ranges from 4.76% to 14.50% for the various variants regarding the values of the thermal comfort zone in the study area. These values allow us to conclude that the option of wall external insulation is the best passive design, permitting the obtaining of a habitable cell in this study, without necessarily a climatzation system [3, 4, 9].

Table 10. Synthesis of the variants' thermal comfort range

Types	Comfort Range	Maximal Variation (°C)	Relative Average Deviation (%)
Reference value	28 °C to 35 °C	-	-
Results			
RM	30.01 °C to 42.13 °C	12.12	+14.50
RSR	28.86 °C to 41.85 °C	12.99	+12.22
WEI	30.30 °C to 35.70 °C	05.40	+04.76
NV	29.65 °C to 38.15 °C	08.50	+07.61
RSR/WEI	26.78 °C to 41.28 °C	14.50	+08.03
RSR/NV	27.61 °C to 38.65 °C	11.04	+05.17
WEI/NV	27.20 °C to 39.64 °C	12.44	+06.09

3.5. Strengths and limitations

We have studied seven passive design options for habitat cells. We determined their effects on improving single storage buildings' hygrothermal behavior efficiency in Sahelian climate. The features of this study are:

– The validation of base case with measured and simulated temprature, as represented in the present work;
– The simulation of each three passive design and four combined options applied to the habitabel cell, which revealed an improvement in the hygrothermal efficiency;
– The use of several criteria and parameters to evaluate the quality of responses for each passive design option.

This study is far from perfect, but the outcomes obtained must be seen as a substantial contribution to research and development of a necessary approach for building energy efficiency in the Sahelian and Sudnao-Sahelian climate. In addition, the study's context was marked by some constraints such us:

– The study support was single storage housing
– The experimental and numerical studies were carried out considering the building in open evolution without occupants;
– The insulation material construction engineering specification is not described.

3.8. Implications in Practice and Research

This study highlights the complementarity of passive design options in improving building hygrothermal behavior efficiency. From these results, we noticed that all passive design option reduces annual total discomfort hours compared to the base reference cement-hollow blocks-based building and natural ventilation and wall external insulation are the best options in this study. Furthermore, the combined passive design offers effective results, particularly in reducing the total annual discomfort hours. They thus open an interesting prospect in terms of building construction with a view to thermal comfort. However, in terms of research prospects, we will be interested in Further experimental studies on the combined passive design option to better appreciate their effects.

4. Conclusion

The present paper concerns the modelling and numerical simulation of the building's hygrothermal behavior by various passive solutions. The study aims to identify the best option of a passive solution for building design and realization to meet the local thermal comfort zone. At the end of the study with the various tests, the following conclusions were reported:

– Cement hollow blocks for building envelope permit to dampen external temperature with 4,250 comfort hours without reaching the Sahelian context thermal comfort zone. This confirms that the building's bioclimatic design is indispensable to achieving thermal comfort and energy efficiency.
– Passive methods for improving the building's hygrothermal comfort, such as Roof Solar Reflectivity, Wall External Insulation, Natural Ventilation, and the three (3) combined design act to regulate heat and mass coupled transfer between the external and internal environments of the building. These temperatures are less than those of the reference model.
– Analysis of the various variants revealed that the option of building envelope external insulation with cotton insulating material was the best passive solution for thermal comfort according to bioclimatic design, with 56% comfort hours and an IHT of 0.7. These indicators of good hygrothermal performance demonstrate that the model with the wall's external insulation achieves the Sahelian climate hygrothermal comfort zone, as indicated in Givoni's diagram.
– The combined passives option revealed a high average of 28.25% reduction in discomfort hours.

However, the engineering study of the cotton-based insulating material needs to be carried out for its adequate implementation in building construction or renovation.

Author Contributions

Conceptualization and methodology, E.M. and L.B..; drawing software, L.B.; validation, EM. and D.T.; formal analysis, E.M. and D.T.; investigation, L.B.; resources and data curation, L.B. and E.M.; writing—original draft preparation, L.B. and E.M.; writing—review and editing, E.M.; visualization, E.M and L.B.; supervision, D.T. project administration, D.T. All authors have read and agreed to the published version of the manuscript".

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Institutional Review Board Statement

Not applicable.

Data Availability Statement

The authors declare that data will be available on a request.

Conflicts of Interest

The authors declare no conflict of interest.

Nomenclature

Symbol	Description
h	Coefficient of thermal exchange by convection in $W.m^{-2} K^{-1}$
T_1	Temperature at time 1 (hot) in °K
T_2	Temperature et time 2 (less hot) in °K
C_p	Specific heat in $J. kg^{-1} K^{-1}$
e	Material thickness in m
ΔT	Temperature difference in °C
β	Sensor angle inclination in degree
λ	Thermal Conductivity in $W.m^{-1} K^{-1}$
α	Dumping of Temperature amplitude in °C
f	Decrement factor
Ø	Time lag or Thermal phase shift in hour
v	Air Cinematic Viscosity in Pa.s
σ	Constant of Boltzmann ($5{,}667.10^{-8}$) in $W.m^{-2}.K^{-4}$
ε	Absorber surface Emissivity
T	Surface transmission Coefficient
ρ	Surface reflectivity Coefficient
τl	Luminous transmission Coefficient

Abreviation

Table . *Cont.*

Symbol	Description
ASHRAE:	American Society of Heating Refrigerating and Air Conditioning Engineers
BSSR:	Internal Solar Reflection Factor
BSVR:	Internal Luminous Reflection Factor
CVRMSE:	Coefficient variation of root mean squared error
FSSR:	External Solar Reflection Factor
FSVR:	External luminous reflection factor
IHT:	Hygrothermal index
IPMVP:	International Performance Measurement and Verification Protocol
NMBE:	Normal Mean Bias Error
NV:	Natural Ventilation
RSR:	Roof Solar reflectivity
STD:	Dynamic thermal Simulation
WEI:	Wall External Insulation

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