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Analysis of the Influence of Envelope Heat Gain on Hygrothermal Comfort in Tropical Housing: The Case of Benin

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The current construction of residential buildings in Benin neglects the importance of thermal insulation of their envelopes. Instead, it relies on active systems as a solution to mitigate over-consumption of electrical energy and guarantee a certain level of thermal comfort inside these buildings. It should be noted that Beninese architects are generally unfamiliar with these thermal aspects.
The main aim of this study is to assess the effects of thermal insulation on walls and roof, determine the optimum thickness of insulating materials, and integrate a controlled mechanical ventilation system to improve thermal comfort in a humid tropical climate. The investigations were carried out on an example of a typical residential building located in Cotonou, Benin, with precise geographical coordinates (latitude 6°38' North, longitude 2°34' East). To analyze the thermal behavior of this

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building, a series of dynamic thermal simulations were carried out using TRNSYS software, which was used both to model the building structure and to run the various simulations.
The results of this study revealed that thermal insulation of the walls and roof, using polystyrene, significantly reduced the need for air conditioning. What's more, the integration of a controlled mechanical ventilation system not only ensured indoor air quality, but also helped regulate indoor humidity, reducing it from 67% to 76%.

Keywords: Thermal comfort; buildings; thermal insulation; cooling requirements; controlled mechanical ventilation; dynamic thermal simulation.

1. INTRODUCTION

The building sector is responsible for consuming 40% of the world's total final energy [1]. In Benin, household final energy consumption is the highest after the transport sector [2]. Increasing demand for housing makes construction one of the country's main growth drivers. This in turn is driving demand for electricity. Moreover, local electricity production varies between 10% and 30% of the country's total supply [3]. As Benin has a hot, humid tropical climate in the south, the quest for thermal comfort in buildings is accompanied by the use of air conditioning and ventilation. These solutions entail high energy consumption, essentially of fossil fuel origin, which is by nature exhaustible and polluting, as it generates greenhouse gases. The energy bill is high, and the high cost of air-conditioning equipment and subsequent maintenance also represent a real financial challenge for consumers.

The current construction of housing and offices in Benin does not take into account the thermal insulation of the building envelope, nor controlled mechanical ventilation (CMV). Yet building insulation is an effective way of reducing heating and cooling energy requirements while improving comfort. Implicit in reduced energy consumption is a reduction in greenhouse gas (GHG) emissions. Occupants and their activities in utility rooms (kitchens, bathrooms, laundry rooms, etc.), and the operation of certain household appliances, release humidity and pollutants. This leads to the deterioration of the building and significant impacts on the health of its occupants. It's important to renew the air with appropriate ventilation systems, such as CMV, to improve indoor air quality by automatically ensuring the required hygienic air flow rates.

To better control energy consumption in buildings, protect them from damp, improve hygiene and health, and ensure comfort, a number of authors have worked on improving thermal comfort, thermal insulation, ventilation and energy performance in buildings. For example, Ikbal Cetiner et al. [4] studied wood waste as an alternative thermal insulation solution for buildings, and found that the thermal conductivity values of wood waste of different densities range from 0.048 to 0.055W/m.K. These values are slightly higher than those of commonly used insulation materials of non-organic origin, although comparable to other natural insulation materials on the market, but have the ecological and economic advantage of being a low-cost by-product. The use of bio-sourced materials has proved to be a panacea for improving the energy performance of buildings. In an earlier work, Hounkpatin et al. [5] demonstrated the impact of local and manufactured roof heat gains on hygrothermal comfort in tropical habitats. Straw was found to have a positive impact on the overall thermal and environmental performance of buildings. Straw reduces the need for cooling by 37%, compared with 15% for terracotta roofing and a 40% increase for zinc sheet roofing compared with a reference slab roof. Gédéon et al. [6] suggest that the most recommendable operating measures for air-conditioning equipment are those favoring an ambient temperature of around 24°. These measures applied to buildings have enabled them to reduce energy consumption by between 38% and 45%. The indoor thermal environment is strongly influenced by the local climate, and air circulation through the building is necessary to reduce indoor discomfort due to overheating conditions in a tropical climate [7]. Other authors have focused on the building envelope. In this context, Fezzioui et al. [8] studied the influence of the building envelope on energy demand, simulating two types of buildings with different climatic conditions, namely the city of Béchar and the city of Tamanrasset, in TRNSYS; they found that increasing the inertia of external walls, roof insulation and window surface area improved thermal comfort. SOBHY et al. [9] went in the same direction, studying the effect of roof and façade insulation on the cooling load of a villa-type house in Marrakech, using thermal simulations with TRNSYS software. The results showed that, in Marrakech's climate, roof insulation is essential to reduce cooling requirements by almost 40%. Moreover, insulating facades with an air gap reduces this load by almost 15%. Aktacir et al. [10] studied the effect of insulation on a simple building in Adana, Turkey (Mediterranean climate). They showed that increasing the thickness of expanded polystyrene led to a reduction in cooling energy requirements. R. Guechchati et al. [11] dealt with the same case, where roof insulation coupled with external wall insulation using 6 cm of expanded polystyrene was chosen as the solution. Roberto Garay Martineza [12] goes in the same direction, studying highly insulated systems for the energy-efficient renovation of comfort facades, and concludes that metal profile systems should be avoided if they are to be laid over the insulation layer, as overall heat transfer is increased by almost 40%, and this problem can be solved by incorporating non-metallic plastic composite profiles.

Kaboré [13] has shown that the use of optimized windows results in a 22% reduction in the energy extracted for cooling the air-conditioned building, and a 5% reduction in the period of discomfort in the freely evolving building. Other aspects are closely linked to the reduction of energy consumption in the building and the thermal environment: occupant activities and ventilation. Several authors have tackled this issue (Hamed N. et al. [14], yang zhang et al. [15], Chen Chang et al. [16], Dong-Hun Han et al. [17], Y. S. Kim et al. [18], Gabriel Bekö et al. [19], Tommy Kleiven [20], Per Heiselberg [21] Juslin Koffi et al. [22], Hekmat, D., Feustel et al. [23], Afshari, A. and Bergsoe, N. C. [24]). Ventilation of premises is one of the parameters for improving ambient conditions and restoring thermal comfort in homes in Benin (Norbert Cossi Awanou [25]. The present study focuses on the effect of envelope and roof insulation on thermal comfort in a residential building in Cotonou. The particularity of this work lies in the optimization of insulation materials for complete insulation in a tropical environment, as well as the integration of mechanical ventilation in a highly insulated building, in contrast to the aforementioned work on thermal insulation.

2. MATERIALS AND METHODS

2.1 Equipment

The aim of this project is to study the effect of thermal insulation of the building envelope on the building's energy performance, and the influence of single-flow ventilation on thermal comfort. Thermal insulation of building or office envelopes is one of the most effective means of guaranteeing thermal comfort with the lowest possible energy consumption. In temperate environments, thermal insulation of building envelopes reduces heat gain in summer and heat loss in winter, Necib et al. [26]. Controlled mechanical ventilation (CMV) aims to maintain good indoor air quality (IAQ) inside buildings. This system ensures that air renewal rates are independent of outdoor conditions. It is widely used in new residential buildings by Rébelion et al. [27]. For our case study, we have chosen a residential building that is representative in terms of construction materials and floor plan typology of the southern zone of Benin. This quantitative study is based on numerical simulation of the building using TRNSYS 17 software during the hottest month of the year (March) with a time step of 1 hour. As input to the software, we introduced the geometric and thermo-physical description of the dwelling, based on its floor plan. We also used meteorological data for the city of Cotonou.

Cotonou is a city with a humid tropical climate, and to maintain occupant comfort, the following temperature and relative humidity guidelines are recommended by Benin's building code (Table 1).

The building identified is a middle-class F3 dwelling in Benin, with a living room, two bedrooms, a bathroom and a kitchen. The characteristics of the building are shown in Fig. 2.

Table 1. Area comfort in Benin [1]

Climate zone	Dry design temperature (°C)	Design relative humidity (%)	Dry setpoint temperature range (°C)	Relative humidity range (%)
Humid tropical climate	24,5	65	24 à 27	30 à 70

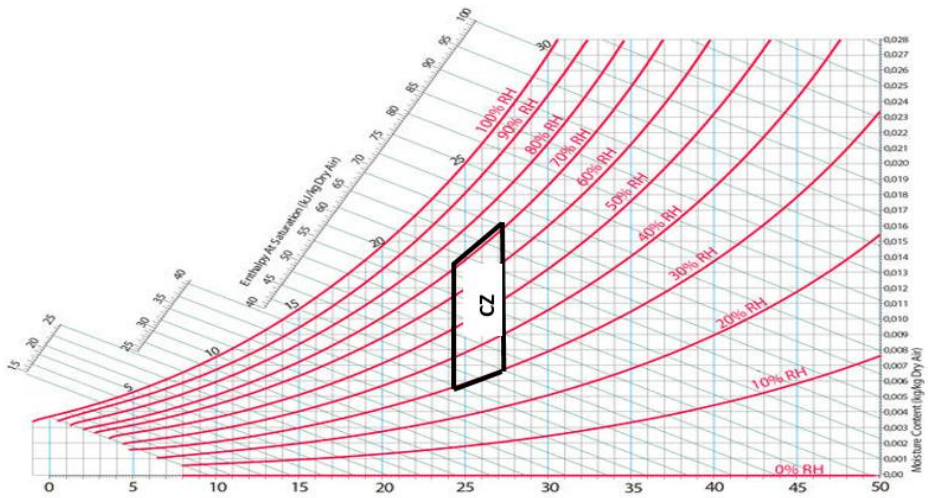

Fig. 1. Comfort zone (CZ) in southern Benin

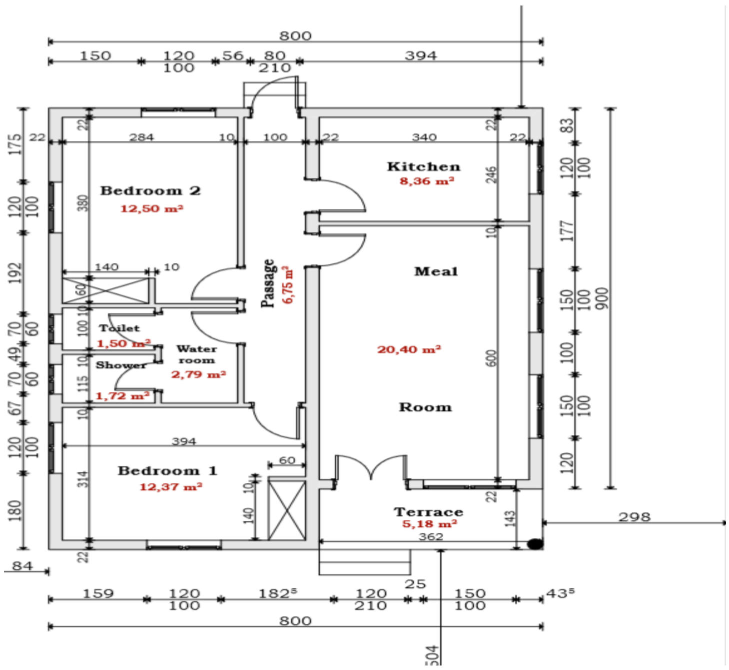

Fig. 2. Plan view of the studied building

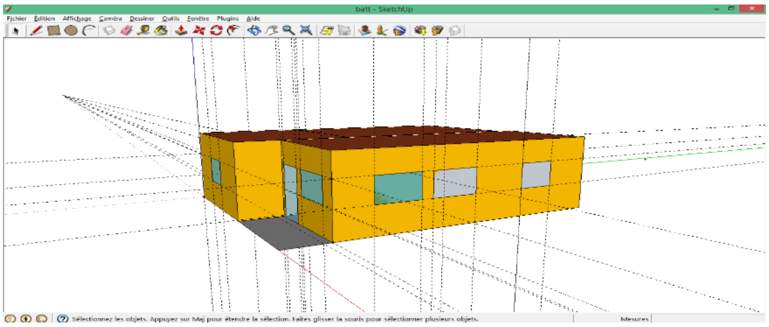

Fig. 3. Diagram of construction of building zones under Google Sketchup

Table 2. Building zones

Zones	Height (m)	Surface area (m²)
Stay	4	95,6 m²
Room 1	4	69,01 m²
Room2	4	52,47 m²
Kitchen	4	50,15 m²
Bathroom/WC	4	47,11 m²

Table 3. Thermophysical properties of Kaboré materials [12,28]

Building envelope	Envelope composition	Thickness (m)	Conductivity Thermal (W/mK)	Specific heat (J/kg.K)	Density (Kg/m3)
Wall	Exterior cement plaster	0,02	1,15	1000	1700
	Hollow brick	0,15	0,833	1000	1000
	Interior cement plaster	0,02	1,15	1000	1700
Low floor	Tile	0,008	1,15	700	1800
	Tile setting mortar	0,02	0,87	1005	2200
	Concrete	0, 2	1,4	1001	2200
Paved roof	Exterior cement plaster	0,02	1,15	1000	1700
	Béton-Hourdis	0,2	1,4	1001	2200
	Air blade	0,9	0,08	1227	1000
	Plywood	0,012	0,32	801	790

The psychrometric diagram (Fig. 1) shows the comfort zone in the south of Benin (Cotonou) with its humid tropical climate.

2.2 Methods

2.2.1 Building geometry modeling

The geometry of the residential building was modeled in multi-zone mode in Google SketchUp, to which we added the Trnsys3d add-on. We created each room in the building by defining five (05) thermal zones (Table 2). We then created the doors and windows, and linked the surfaces to establish a thermal connection between adjacent rooms (Fig. 3).

2.2.2 Wall composition

The composition and thermo-physical characteristics of the walls making up the building envelope are given in Table 3.

To achieve a lower transmission coefficient, double-glazed windows are chosen. It is composed of two 4mm panes of glass and a 12mm air space, giving a U coefficient of 2.8W/m2K and a g coefficient of 0.75. OLISSAN [29]

2.2.3 Occupancy strategy

The house considered for the studies consists of 2 bedrooms, a living room, a kitchen and a bathroom/WC. We assumed a family of 5: a man, a woman, a maid and two children aged 10 and 13 respectively. The level of metabolic activity is 1met, the thermal resistance of clothing is equal to 0.5 clo and a relative air speed equal to 0.1m/s.

Two occupancy scenarios are defined for weekdays and weekends (Fig. 4). Bedroom 1 is occupied by the parents, bedroom 2 by the children, and the maid sleeps in the living room. We notice more people in the living room between 9pm and 10pm on weekdays (Fig. 4a). On weekends, however, the same scenario is repeated for lunch (2pm) and dinner (9pm) (Fig. 4 b). From midnight to 6am, the whole family is asleep.

2.2.4 Occupancy-related moisture production scenarios

Table 4 shows the water vapor production of each occupant as a function of age and activity (awake or asleep) Koffi [30].

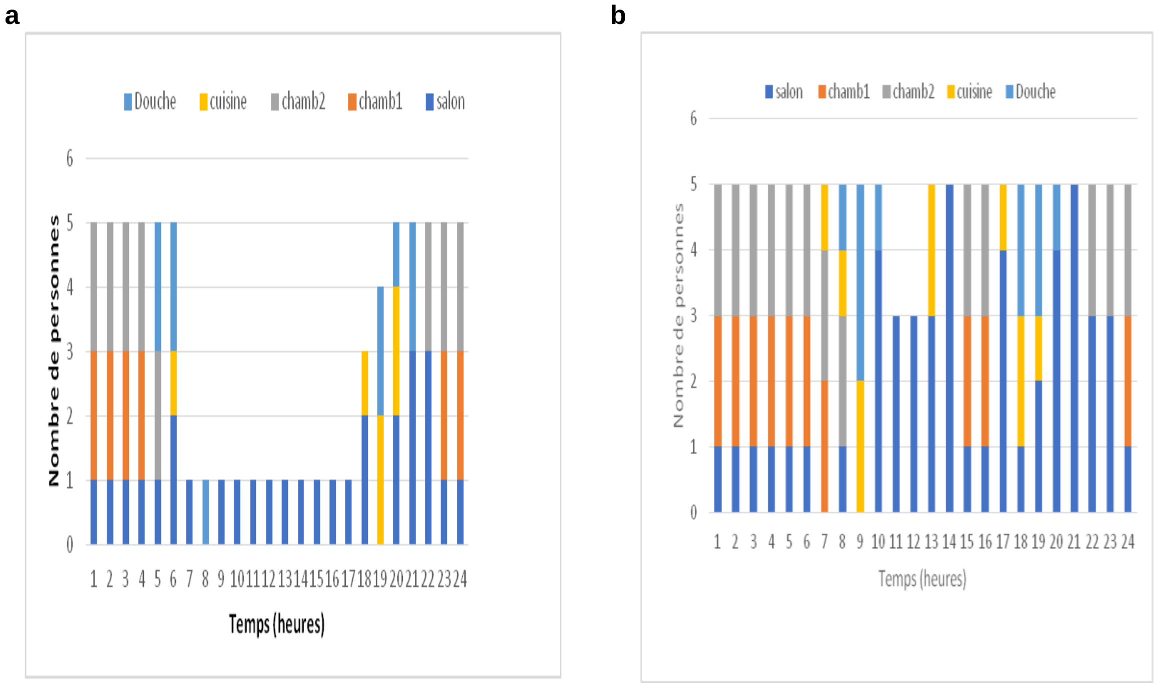

Fig. 4. Occupancy scenarios for different zones: (a) Occupancy profile, weekdays, (b) Occupancy profile, weekends

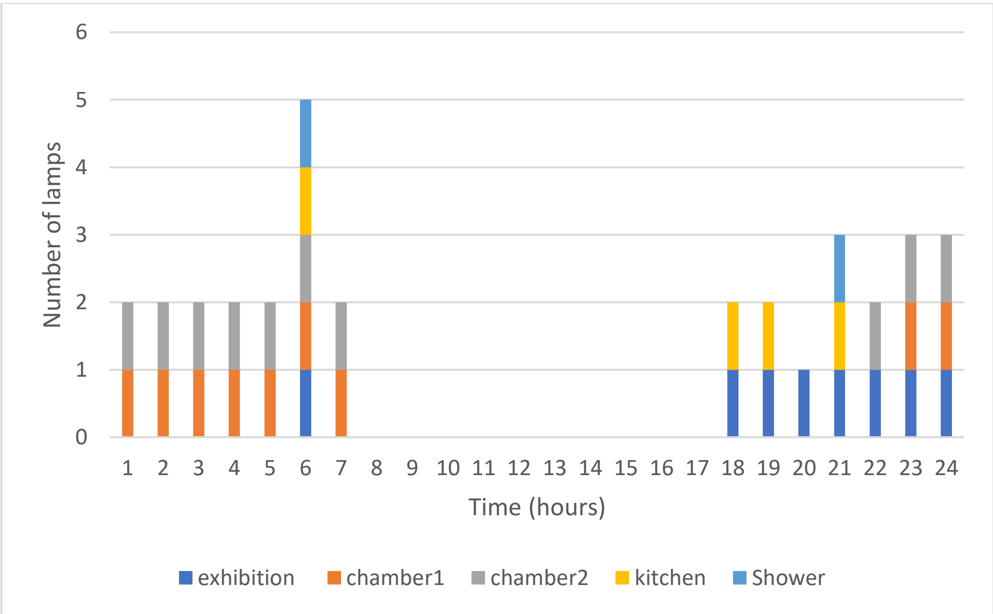

Fig. 5. Lighting scenarios for different zones (Artificial lighting 10 W/m^2)

Table 4. Moisture production by age and activity

Occupant	Activity	H20 steam (g/h/pers)
Adults over 15	Awake	55
	Asleep	30
Children aged 10 and 13	Awake	45
	Asleep	15

Table 5. Power output of household appliances

Device	Zone	Time of use	Power (W)
Television	Stay	9am to 11am and 8pm to midnight	65
Refrigerator	Kitchen	24h/24h	100
Computer	Room 1	20h to 24h	230
Home cinema	Stay	9 to 11 a.m. and 8 to 24 p.m.	300
Radio device	Room 1	06 a.m. to 7 a.m.	10

Table 6. Thermal characteristics of polystyrene

Insulation	Conductivity Thermal (W/mK)	Specific heat (J/kg.K)	Density (Kg/m^3)
Extruded polystyrene	0,028	1000	25

Table 7. Air change rate through air inlet modules [32].

	Window air intake module	Number of air inlet modules	Flow Q_{EA} (m3/h)
Stay	30	2	2×30=60
Room 1	22	1	22
Room 2	22	1	22
Total			104

Table 8. Extract unit airflows

	Extract unit (m3/h)		
Number of parts	Kitchen	Bathroom	WC
3	105	30	15
TOTAL	150		

Steam production for each shower is 300 g/person. In the kitchen, it is 50 g per person for breakfast, 150 g for lunch and 300 g for dinner.

2.2.5 Appliance usage scenario

They are both linked to human presence and activity.

Fig. 5 shows the lighting scenarios for the various main and service rooms.

From 6pm onwards, the lights are switched on according to the scenario. Overall, lamps remain on in bedrooms from 11pm to 7am, and at 6am in all rooms.

2.2.6 Building envelope insulation

This section examines the influence of building envelope insulation (walls and roof) on thermal comfort, using extruded polystyrene respectively. Insulation is used in thicknesses of 3cm, 5cm, 10cm and 15cm. The expected result is to determine the evolution of indoor temperature, relative humidity and cooling requirements for each zone of the building. From this, we can deduce the optimum thicknesses for best comfort inside the building. The thermal characteristics of the insulating materials are shown in Table 6 [31]. This is an interior insulation configuration.

Once the optimum insulation has been found, the next step is to integrate the ventilation system,

2.2.7 Air renewal in the building

The work carried out in this section takes into account air renewal via windows in the first instance, and via the CMV in the second.

2.2.7.1 Air infiltration through windows

In the simulation, the windows are assumed to be open with an infiltration rate of 0.9 vol/h. OLISSAN [29]

2.2.7.2 Air infiltration through modules

Air renewal by infiltration takes place through self-adjusting air intake modules in the living room and bedrooms, even when the windows remain closed, thus enabling air renewal. The modules are installed at the top of the windows in both bedrooms and the living room. It is recommended to install at least 2 air inlets per living room module 22, 30 or 45 and at least 1 air inlet per bedroom module 22 or 30 [32]. In the case of our study, Table 7 shows the dimensions and air renewal rate through the air inlet modules.

2.2.7.3 Controlled mechanical ventilation (CMV)

The modelled "self-regulating" single-flow CMV system features self-regulating extract units in the utility rooms and self-regulating air inlets. These inlets admit fresh air into the main rooms, which then passes through the dwelling, becoming polluted and loaded with indoor pollutants. The extract units draw stale air from wet rooms (kitchen, bathroom/WC), which is discharged outside by the fan. The maximum extracted airflow is less than or equal to the sum of the installed air intake modules plus the permeability of the dwelling [32] :

$$Q_{\max extrait} \leq \sum Q_{EA} + Q_{fuite}$$

For a F3 apartment, $Q_{fuite} = 60\ m^3/h$,

Extraction flow rates are summarized in Table 8.

$Q_{\max extrait} = 150\ m^3/h$ or $\sum Q_{EA} = 90\ m^3$

The choice of air inlets is therefore correct. In fact, the sum of the air intake modules (104 m^3 /h) is greater than 90 m^3/h.

3. RESULTS AND ANALYSIS

In the various simulations we have carried out, we have improved thermal comfort by means of insulation and improved indoor air quality by means of mechanical ventilation, the subject of our work, using TRNSYS software. The study was carried out on a reference building, integrating envelope insulation and infiltration to maintain hygrothermal conditions. The simulations were carried out during March, reputed to be the hottest month of the year. We therefore proceeded to:

Simulation on the same graph of changes in humidity and temperature in zone 1 (living room, bedroom 1, bedroom 2) and zone 2 (kitchen, shower) in the reference building.

Simulation of cooling requirements for zones 1 and 2 on the same graph

Simulating the effect of envelope insulation on thermal comfort

Optimizing the choice of extruded polystyrene thickness for tropical climates

Simulation of the effect of controlled mechanical ventilation (CMV) on the thermal environment

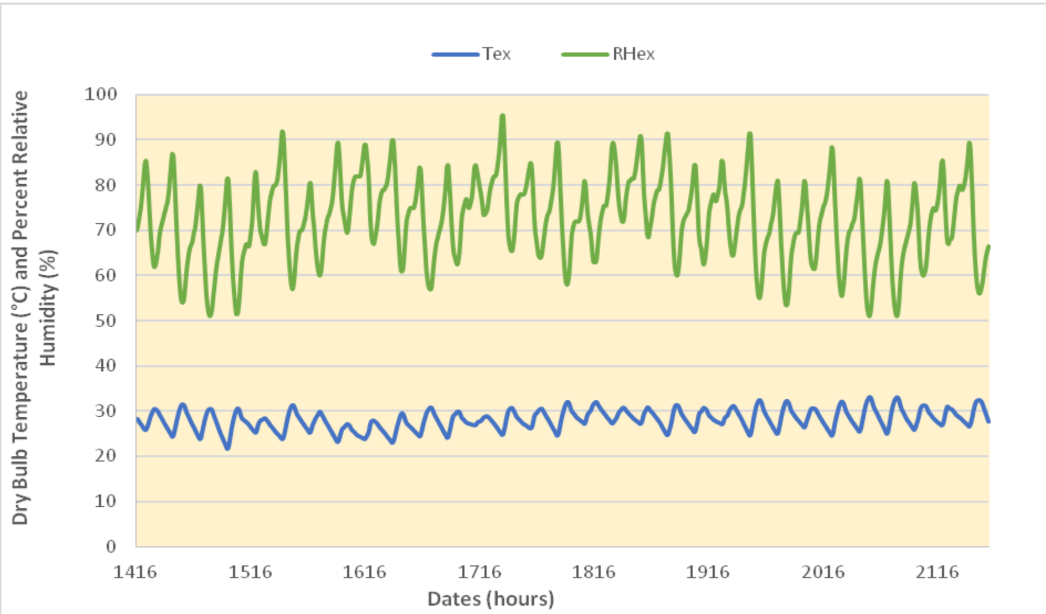

Fig. 6. Variation in outdoor temperature and humidity as a function of time over a month

3.1 Thermal simulation of the reference building

3.1.1 Temperature and humidity trends

Over a period of one month, with a time step of 1 hour, Fig. 6 shows the hourly variations in humidity and outdoor temperature.

Fig. 6 shows that ambient temperatures vary between 22°C and 34°C during March. The lowest values are observed at night, between 1 and 6 am, and the highest during the day, between 8 and 8 pm. On the other hand, relative humidity varies between 51% and 96% during the same month. Unlike temperature, the highest values are observed during the day, and the lowest at night. Overall, we can see that higher humidity leads to lower temperature.

3.1.2 Changes in humidity and indoor temperature

Fig. 7 shows the hourly variation in indoor temperature and humidity in the main rooms of the house.

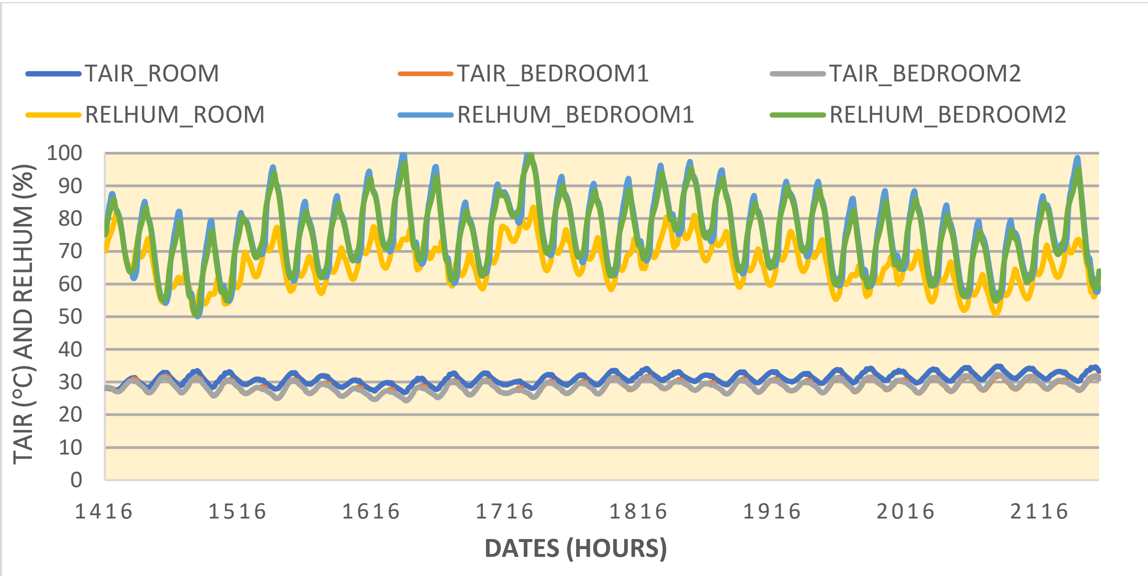

Fig. 7. Variation in relative humidity and temperature as a function of time in the living room, bedroom 1 and bedroom 2 over one month

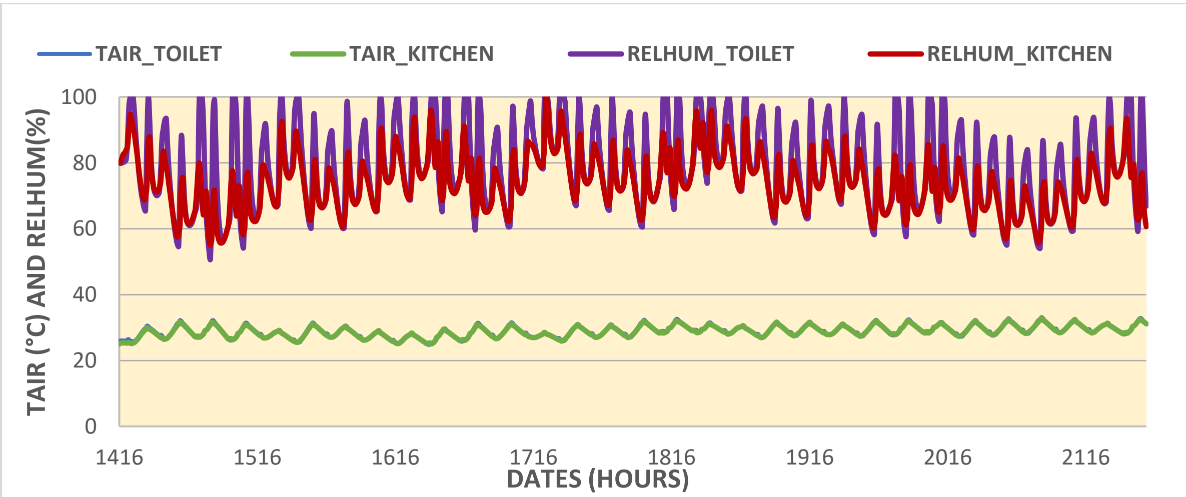

Fig. 8. Variation in relative humidity and temperature as a function of time in the kitchen and bathroom over one month

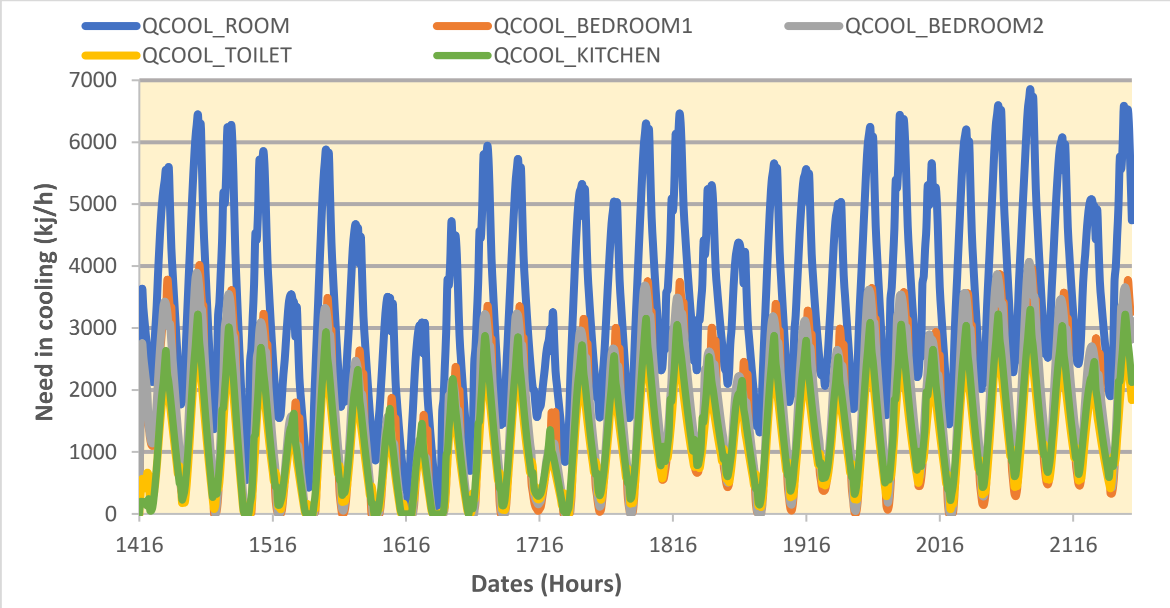

Fig. 9. Variation in cooling requirements for main and living rooms over one month

The interior temperature of the main rooms varies between 24°C and 35°C. The living room, with its large south-facing windows, has a slightly higher temperature than bedroom1 and bedroom2 (24°C to 32°). This temperature difference is of the order of 3°C. As a result, the indoor air temperature in the living room reaches 35°C during the day and remains above 27°C at night. The temperature difference is also justified by the permanent presence of the domestic in the living room. The living room is therefore less humid, with an average value of 50%, compared to bedrooms 1 and 2, which are at 70%.

Fig. 8 shows the hourly variation in indoor temperature and humidity in the house's utility rooms.

Variations in the humidity of service rooms show similar patterns, and are generally high. The average humidity in the kitchen is 73%, with the highest values observed during cooking, due to the release of water vapor. As for the toilet, humidity is higher than in the kitchen, with an average value of 77%. Peaks are observed during showering. On the other hand, the average temperature during this period is 29°C.

3.1.3 Changes in cooling requirements

Fig. 9 shows that the living room requires more energy for cooling. It reaches a maximum value of 6990 kJ/h, followed by the cooling requirements of bedrooms 1 and 2, which are almost identical. By contrast, the cooling requirements of the toilets and kitchens are almost half those of the living room. This inequality in value is explained by the fact that the temperature in the living room is higher than in the utility rooms.

3.1.4 Simulating the effect of envelope insulation on thermal comfort

Fig. 10 illustrates the impact of insulation on thermal comfort in the living room.

The results in Fig. 10 (a) show that insulating the building envelope and roof with 3cm and 5cm of polystyrene reduces the interior temperature of the living room by 4°C. At 10cm, the reduction is 5°C, and 6°C at 15cm. We can see that increasing the thickness of the insulation remarkably improves indoor temperature. As for humidity, Fig. 10 (b) shows an average value of 70% for a thickness of 3 cm, i.e. a 20% increase compared to the living room without insulation. Moreover, humidity increases with thickness.

In the main rooms (Fig. 11, Fig. 12), the difference in temperature is 5°C compared to uninsulated rooms with a thickness of 3 cm. It varies between 22°C and 27°C. For thicknesses of 5 cm, 10 cm and 15 cm, interior temperatures differ by 2°C and 1°C respectively compared with the 3 cm thickness. Average humidity in chambers with a 3 cm thickness is 95%, and virtually constant (100%) for other thicknesses.

This increase in humidity is due to the tightness of the frame.

Figs. 13 and 14 show the impact of insulation on the thermal environment in the kitchen and bathroom. In these two rooms, however, there is a significant variation in temperature of the order of 3°C at 3 cm and 5 cm, then 4°C and 7°C for thicknesses of 10 cm and 15 cm. The difference observed is undoubtedly due to the insulation of the walls in the zone. On the other hand, these service rooms remain the most humid, with an average of 96% for the 3 cm thickness and 100% for the other thicknesses.

3.1.5 Optimizing the choice of extruded polystyrene thickness for tropical climates

To find the optimum insulation thickness, we carried out a study of the variations in costs (insulation, cooling requirement and total energy) using interior insulation with a variable thickness of extruded polystyrene.

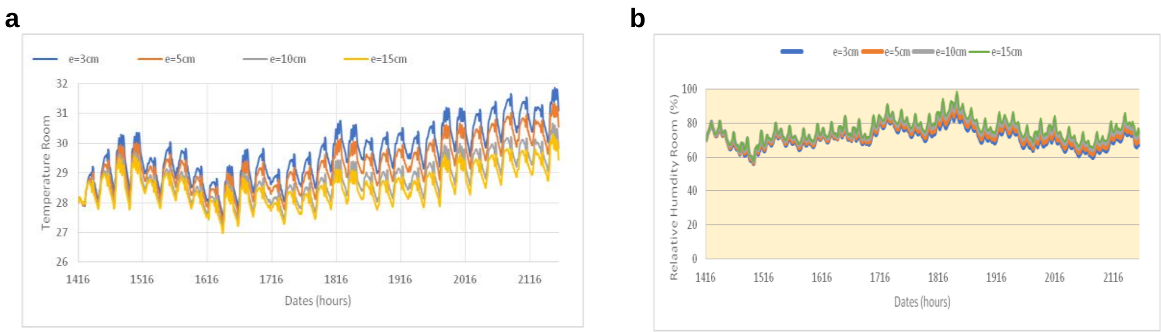

Fig. 10. Monthly variation in the impact of different insulation thicknesses on the thermal environment in the living room: (a) variation in temperature as a function of time, (b) variation in humidity as a function of time

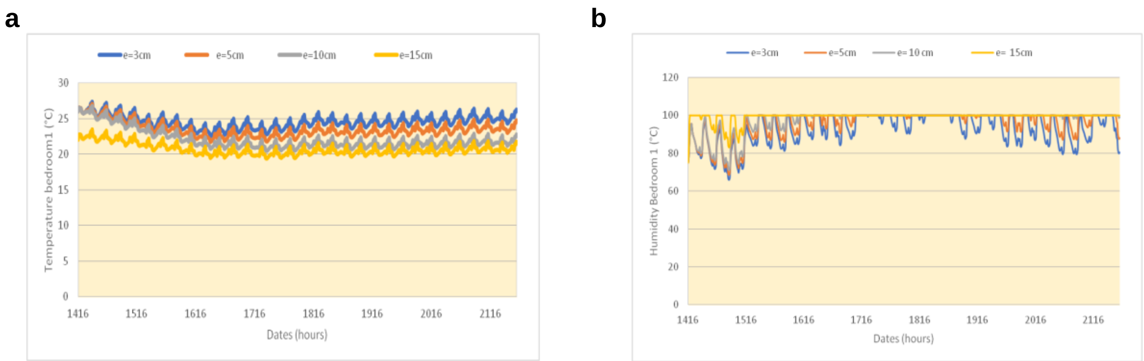

Fig. 11. Variation in temperature (a) and relative humidity (b) as a function of time over several thicknesses in chamber 1

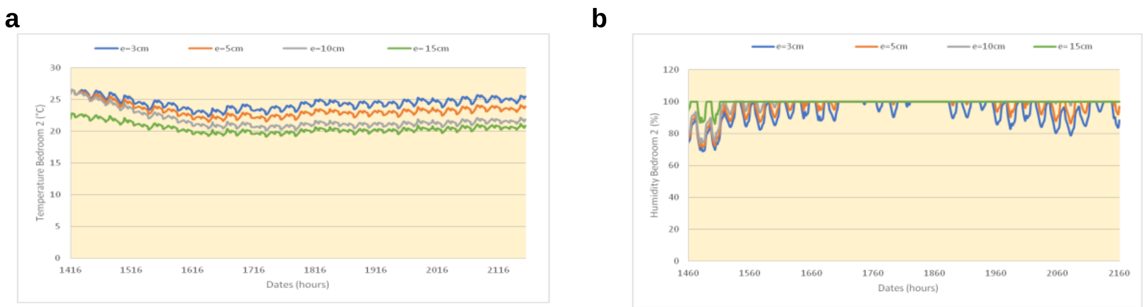

Fig. 12. Variation of temperature (a) and relative humidity (b) as a function of time over several layers in the chamber

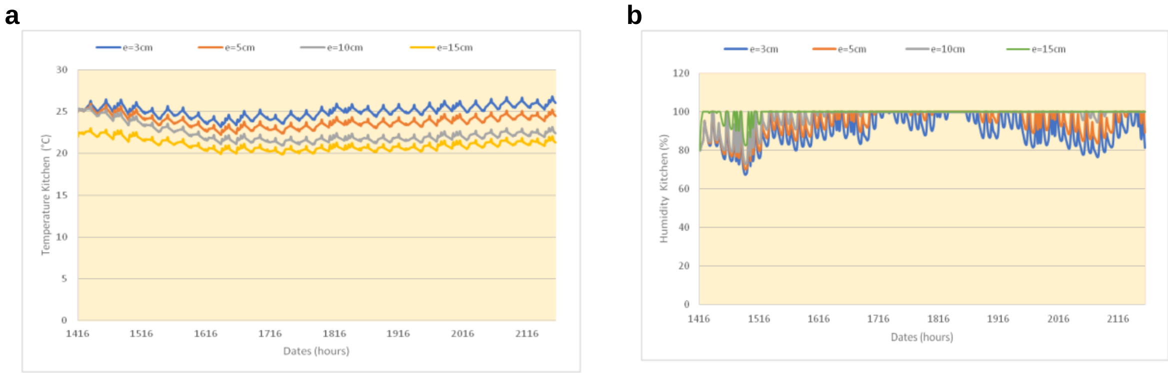

Fig. 13. Variation in temperature (a) and relative humidity (b) as a function of time over several layers in the kitchen

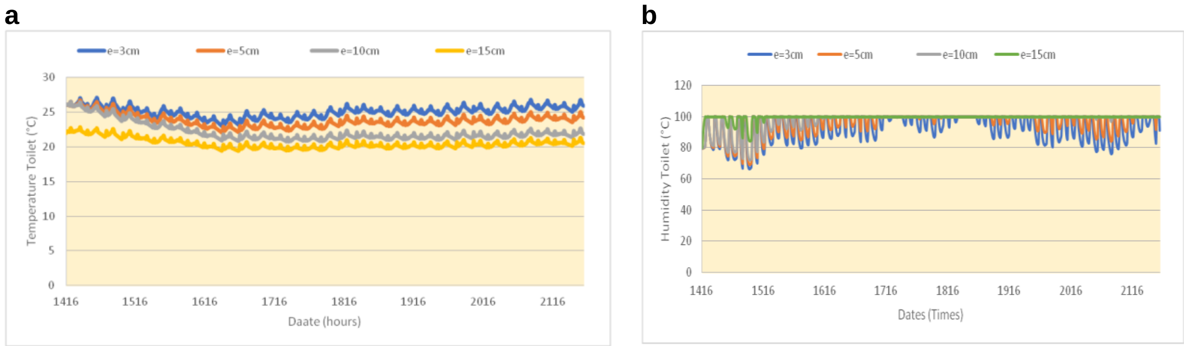

Fig. 14. Variation in temperature (a) and relative humidity (b) as a function of time over several layers in the toilet

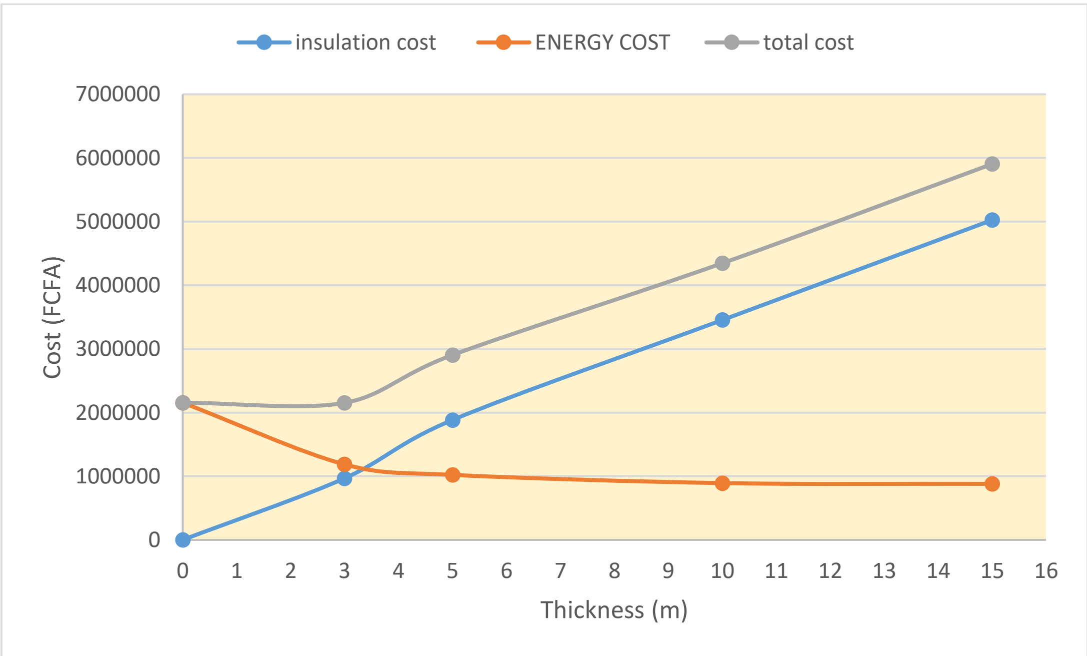

Fig. 15. Variation in insulation, energy and total costs as a function of insulation thickness

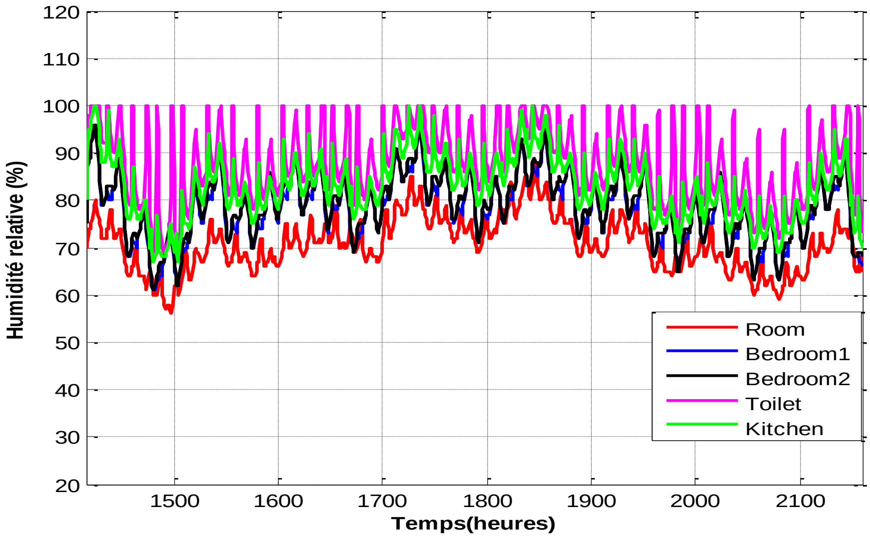

Fig. 16. The effect of controlled mechanical ventilation on thermal comfort

Fig. 15 shows that the increase in insulation cost follows the increase in insulation thickness, while the cooling requirement decreases, as does the total cost, which decreases up to a minimum value of 3 cm insulation thickness and starts to increase after this value. The optimum insulation thickness is the thickness that gives the best energy savings at the lowest insulation cost. The optimum thickness is therefore 3 cm. On the whole, interior insulation improves temperatures, but it also increases humidity in all areas. Ventilation is therefore needed to improve the thermal environment.

3.1.6 The effect of controlled mechanical ventilation (CMV) on the thermal environment

For the rest of the simulation, we choose a 3 cm thickness of extruded polystyrene to extract stale air from inside the building, and in turn reduce humidity thanks to controlled mechanical ventilation.

Integration of the CMV reduces humidity by 2.5% in the living room, 24% in bedrooms 1 and 2, and 25.5% in the utility rooms. We therefore conclude that the CMV improves humidity, achieving a range of 67% to 76%.

4. CONCLUSION

Thermal insulation of the envelope and roof using polystyrene in several thicknesses was studied in a tropical environment in order to reduce energy consumption and ensure a better atmosphere. Two occupancy scenarios were defined, corresponding to weekdays and weekends in the premises. Modeling of the house with integration of insulation using TRNSYS software enabled temperatures in the living room to be reduced from 4°C to 6°C, 1°C to 5°C in bedrooms 1 and 2, and 3°C to 7°C in service rooms. On the other hand, humidity levels rose by 20% in the living room, 25% in the bedrooms and 24% to 30% in the toilets. In terms of optimizing different polystyrene thicknesses, the results suggest that a 3 cm thickness is a good compromise for reducing energy consumption and creating a healthy, more comfortable living space in the Benin building.

Greater thicknesses would encroach on interior living space and cost without any convincing thermal improvement. This 3cm thickness has a direct impact on the electrical energy consumed by the air-conditioning system. The integration of the VMC has purified the air and evacuated humidity to levels of 2.5%, 24% and 25.5% respectively in the living room, bedrooms 1 and 2, and finally in the kitchen and toilet.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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