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Study of the Energy Efficiency and Climatic Resilience of Building Envelopes in the Republic of Congo

Alain Symphorien Ndongo[1], **Charmolavy Goslavy Lionel Nkouka Moukengue**[2], **Harmel Obami-Ondon**[1], **Yuriy Yevdokimenko**[3]

[1]Laboratory of Mechanics, Energy and Engineering, Marien NGouabi University, Brazzaville, Congo
[2]Laboratory of Electrical and Electronic Engineering, Marien Ngouabi University, Brazzaville, Congo
[3]Kyiv National University of Construction and Architecture, Kyiv, Ukraine
Email: ln999kouka@gmail.com

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Abstract

Climate change is increasing thermal constraints on buildings in humid tropical areas, where air conditioning accounts for up to 60% of residential electricity consumption. In Congo, energy demand is growing while electricity production remains insufficient, exacerbating load shedding. This study analyses the thermal performance of existing building envelopes and proposes construction solutions adapted to the Congolese context. Based on local climate data, architectural surveys and exergoeconomic analysis, various insulation scenarios were simulated. The results show that 50 to 150 mm of mineral wool insulation reduces heat transfer by 2.5 to 5.5 times, leading to a proportional decrease in the exergy costs associated with air conditioning. These results confirm the need to introduce low thermal conductivity materials and energy performance standards for new and existing buildings. The study thus contributes to the implementation of sustainable design strategies adapted to tropical climates.

Keywords

Energy Efficiency, Building Envelope, Air Conditioning System, Humid Tropical Climate, Republic of Congo

1. Introduction

The energy efficiency of buildings is a major issue in global energy transition policies (Wörsdörfer, 2018) [1]. In tropical regions, extreme climatic conditions of high temperatures and high humidity make the design of building envelopes crucial for indoor comfort and energy consumption (Mirrahimi *et al.*, 2016) [2].

Various studies have shown the importance of architectural design and material selection in reducing the energy requirements of buildings (Ahmadian *et al.*, 2021 [3]; Yi & Malkawi, 2009 [4]). The use of materials with low thermal conductivity is recommended to limit heat transfer (Borel, 1990 [5]; Chabane-Sari, 2022 [6]). In addition, multi-criteria optimisation methods have been developed to maximise thermal efficiency while taking economic constraints into account (Frossard *et al.*, 2018) [7]. These joint thermodynamic and economic approaches (exergoconomics) make it possible to find solutions adapted to local contexts (Techniques Ingénieur, 2025) [8]. Exergoeconomic analysis is an approach that links thermodynamic inefficiencies (exergy destruction) to economic costs, in order to determine where and how to simultaneously optimize a system's energy performance and costs. The result is more economical, more efficient and more sustainable buildings [9].

In 2021, Ahmadian *et al.* in [3] established the subtle relationships between urban form, density and building energy performance using two density indicators, namely site coverage and land use coefficient. They first examined the geometric variables of four traditional urban forms to study their relationship with density indicators. Energy analyses were carried out on geometric models representing residential buildings, using the city of London as an example of a temperate climate.

In 2024, Elenga *et al.* in [10] assessed the feasibility of achieving a net-zero energy building by combining energy-efficient design practices and renewable energy systems in the climatic conditions of the Republic of Congo. To achieve the set objectives, DesignBuilder software was used for building modeling, energy load assessment and multi-objective optimization of building energy efficiency measures, and multi-criteria energy optimization was carried out using the HOMER tool. In the same context, in 2025, Elenga *et al.* in [11] implemented a multi-objective genetic algorithm used in conjunction with EnergyPlus building energy models to determine the optimal balance between total building energy consumption, life-cycle cost and CO_2 emissions. The proposed approach is applied to a single-family residential building located in six locations in the Central African sub-region classified as having a tropical savannah climate (Aw), a warm semi-arid climate (Bsh), a tropical rainforest climate (Af) and a tropical monsoon climate (Am).Two different PCM technologies (InfiniteRPCM and BiocPCM) have been applied to four wall types (brick, concrete block, poured concrete and earth), and their parametric models are developed in EnergyPlus to simultaneously optimize the melting temperature, thickness and location of each PCM layer.

In 2025, Ning Liu *et al.* [12] set up a system to reduce energy consumption on university campuses. An information framework aimed at standardization can be effective in motivating individual energy behavior. To assess the effectiveness of normative information intervention strategies in motivating students to save energy, their study innovatively adopted a new method combining traditional pathway-of-influence analysis and field experimentation, which compensates for the shortcomings of the traditional single-questionnaire survey method.

In tropical areas, demand for air conditioning is constantly on the rise, resulting in high energy consumption and increased operating costs.

In Congo, the majority of residential and administrative buildings are built without thermal insulation, using high-conductivity materials such as cement blocks. These existing buildings often have thermal characteristics that are unsuited to Congolese climatic conditions, limiting their energy performance.

These envelopes accumulate heat during the day, amplifying the need for air conditioning at night. The absence of national thermal regulations accentuates this inefficiency, contrary to the standards defined in Directive 2010/31/EU on the energy performance of buildings.

The aim of this study is to propose an integrated approach linking architectural design, energy performance and environmental sustainability. It seeks to define the building envelope parameters best suited to reducing energy requirements for air conditioning and ventilation in the Republic of Congo, while ensuring thermal and acoustic comfort for occupants. The study is based on climatic data, architectural observations and heat flow simulations performed according to European standards and energy optimization models (Gossard *et al.*, 2012 [13]; Tuhus-Dubrow, D., & Krarti, 2009 [14]).

2. Congo's Climate and Energy Context

Congo's climate is hot and humid, with average temperatures between 25˚C and 27˚C. Maximum daytime temperatures are often between 30 and 35˚C in the hot season, with relative humidity often over 70%, and little daily variation (IEA, 2023). Minimum night-time temperatures can fall as low as 22˚C, sometimes a little lower. The year is divided into two main seasons: the dry season (May to September) and the wet or rainy season (October to April).

According to the World Bank (2021), only 48% of the Congolese population has access to electricity, and power cuts are frequent. The thermal inefficiency of buildings exacerbates this situation by increasing the energy demand for air conditioning, responsible for almost 60% of building electricity consumption (Ferrara *et al.*, 2014) [15].

Average monthly minima for several months (December, February, May, October and November) are around 22˚C. This is a realistic and frequent minimum temperature in the Republic of Congo, and is used as a reference for climate calculations and modelling.

3. Methodology

The study is based on an approach combining thermal analysis, exergoecomic evaluation and numerical simulation. The data used include:

- Local climatic parameters (temperature, humidity, solar radiation) for Brazzaville, over a 30-year period;
- Physical characteristics of existing buildings (wall thickness, materials, roof type);
- European energy efficiency standards (Directive 2010/31/EU).

3.1. Calculating Air-Conditioning Requirements

Heat consumption for air-conditioning ($Q_{c,nd}$) was calculated using the heat balance equation (Bichiou & Krarti, 2011) [16]:

$$Q_{c,nd} = Q_{tr} + Q_{sol} + Q_{ve} + Q_{in} \quad (1)$$

where:

Q_{tr} : heat gains by transmission through the external envelope in Wh,

Q_{sol} : direct and diffuse solar gains in Wh,

Q_{ve} : heat due to ventilation in Wh,

Q_{in} : internal heat due to occupants and equipment in Wh.

In practice, in order to compare different technical solutions according to the accepted thermo-technical characteristics of the external OK, the value of the specific heat consumption is noted $q_{AC,nd}$ in (W/m^2) and the volumetric specific flow $q_{VC,nd}$ in (W/m^3) are given by the following formulas:

$$q_{AC,nd} = \frac{Q_{C,nd}}{AC}\left(\text{Wh/m}^2\right) \quad (2)$$

$$q_{VC,nd} = \frac{Q_{C,nd}}{VC}\left(\text{Wh/m}^3\right) \quad (3)$$

With

AC - conditioned surface area of buildings and structures, m^2;

VC - air-conditioned volume of buildings and structures, m^3.

In addition, in accordance with the provisions of Directive 2010/31/EC, specific energy consumption values for cooling buildings and structures for air-conditioning purposes are regulated. In this case, for residential buildings, the building area-specific factor $q_{AC,max}$ is applied, and for commercial premises, the volume-specific factor $q_{VC,max}$ is applied:

$$q_{AC,max} \geq q_{AC,nd} \quad (4)$$

$$q_{VC,max} \geq q_{VC,nd} \quad (5)$$

The requirements and recommendations of Directive 2010/31/EC aim to reduce the energy consumption of buildings and structures by rationalizing the unit costs of air-conditioning, hot water and heating, introducing certain minimum energy cost levels depending on the type of building and structure.

3.2. Heat Transfer Assessment

The heat transfer coefficient U_i was calculated according to Formula (6) [17]:

$$U_i = \frac{1}{R\sum g_i} = \frac{1}{\frac{1}{\alpha_{ext}} + \sum\left(\frac{\delta_i}{\lambda_i}\right) + \frac{1}{\alpha_{in}}} \tag{6}$$

where α_{ext} and α_{in} are the external and internal convection coefficients respectively.

Simulations were carried out for thermal insulation thicknesses of 0.50, 100 and 150 mm in mineral wool ($\rho = 90$ kg/m^3, $\lambda = 0.054$ W/m·K), in order to assess the evolution of the heat flux transmitted and the associated exergoeconomic costs.

3.3. Exergoeconomic Analysis

Specific exergy costs ($C_{qi,\max,\Sigma}$) were determined from the national electricity cost and the energy performance factor (EER = 3.0), using the method of Moran (1989).

4. Climatic Data for Congo Brazzaville

Figure 1 shows a graph of the distribution of daily average maximum and minimum outdoor air temperatures by month of the year for Brazzaville, Congo. The graph is based on climate modeling results for the last 30 years of observation. **Figure 2** shows standing outdoor air temperature data over the course of the year. As can be seen, there are 197 days a year when the outside air temperature is in the 30˚C… 35˚C range. Days with outdoor air temperatures below 25˚C account for less than 1% of the days per year.

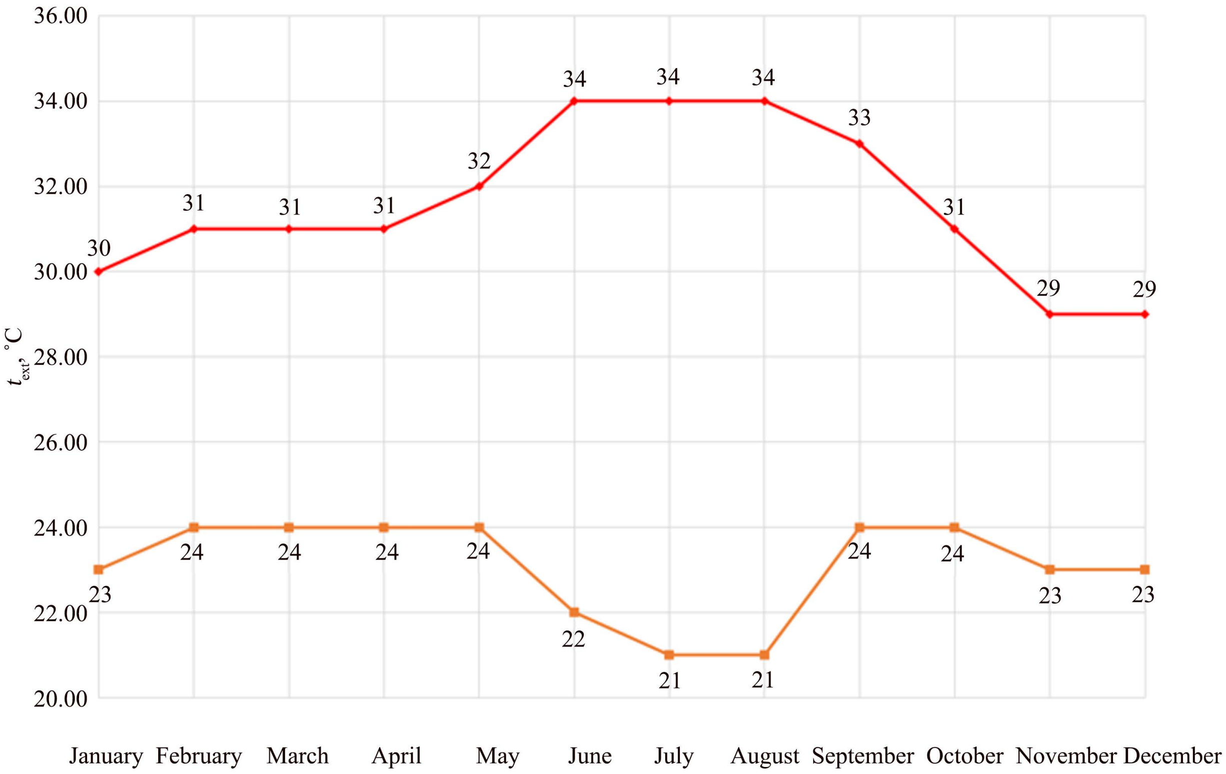

Figure 1. Distribution of outdoor air temperatures by month of the year for Brazzaville, Republic of Congo.

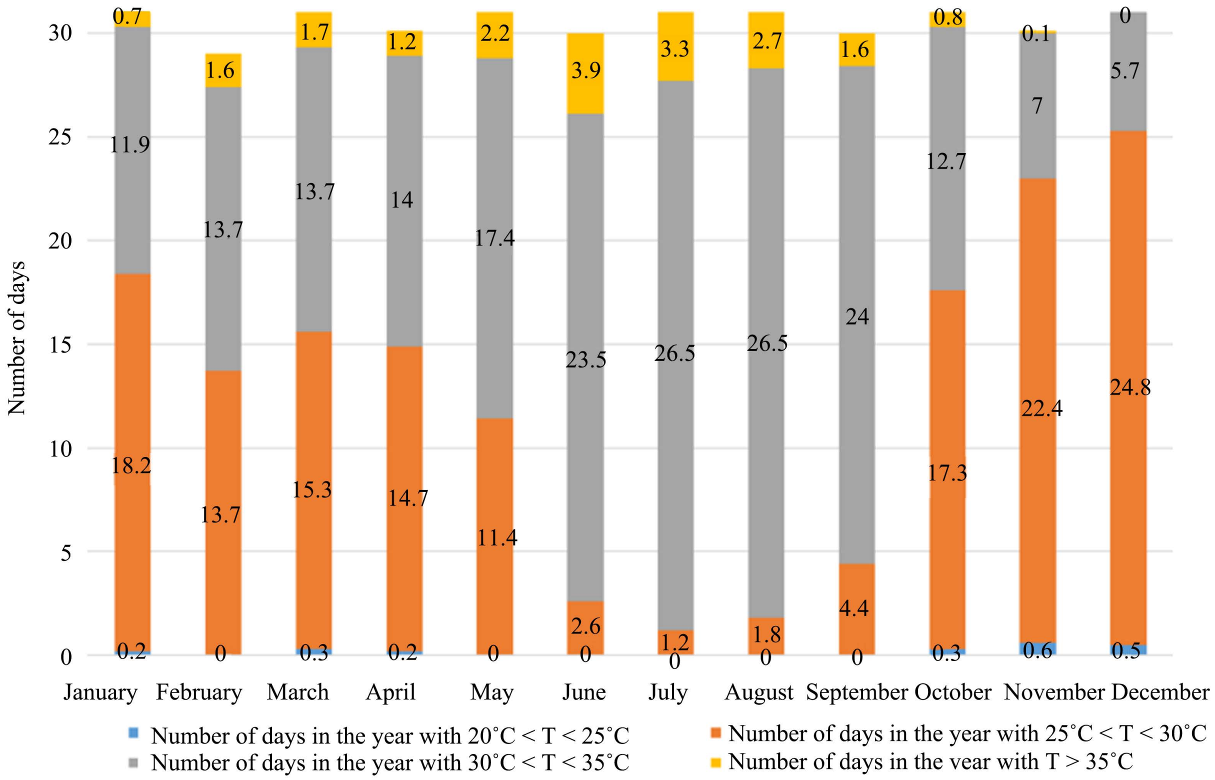

Figure 2. Outside air temperatures throughout the year.

To ensure comfortable living conditions in hot, humid climates, insulated buildings need to be designed to function properly. Total air conditioning (artificial cooling and dehumidification) is preferable.

5. Calculation of External Envelopes

Achieving the specified energy efficiency class is ensured, among other things, by controlling heat gain by transmission through the external envelope (EC) structures. Transmissible heat gains are common to both translucent and non-transparent envelopes. The problems of reducing heat transfer through translucent envelopes are considered in detail in many works, among which will not be considered in this work.

The currently known means of reducing heat loss by transmission through envelope structures are the reflection of thermal energy and the absorption of thermal energy by an alternating current network. There are also variant combinations of the above methods. Reflection of thermal energy is mainly achieved by using materials with low absorption coefficients, e.g. by applying special paints. The thermal energy absorption of a CB network is achieved by preliminary design and calculation of the CB composition to achieve the required value of heat transfer resistance. Generally speaking, the transmission heat flux Q W (**Figure 3**) in building cooling mode and the building volume passing through the CB is calculated as follows [16]:

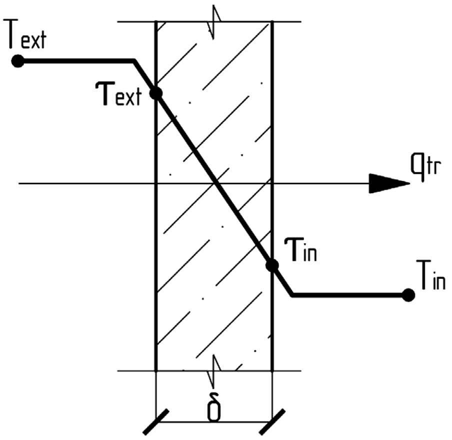

Figure 3. Heat transfer through the enclosure.

$$Q_{tr} = H_{tr,adj} - \left(T_{int,set,C} - T_c\right) - \tau \tag{7}$$

With:

$H_{tr,adj}$: heat transfer coefficient of total transmission for temperature difference W/K;

$T_{int,set,C}$: indoor air temperature, K

T_c: average monthly outdoor air temperature, K

τ: time period for which heat gains are calculated, hour.

Generally speaking, the transmission heat transfer coefficient for enclosures is calculated according to the formula:

$$H_{tr,adj} = \sum A_i - U_i \ (\text{W/K}) \tag{8}$$

where:

A_i -surface area of the i-th building envelope element, m^2;

U_i -reduced heat transfer coefficient of the ith building envelope element, W/m^2·K.

To calculate U_i use the expression:

$$U_i = \frac{1}{R\sum g_i} \tag{9}$$

where:

$R\sum g_i$: reduced heat transfer resistance coefficient of the i-th building envelope element, m^{2}K/W, calculated for opaque elements and taken from literature or manufacturers' catalogs for translucent elements.

$$R\sum g_i = \frac{1}{\alpha_{ext} + \sum \frac{\delta_i}{\lambda_i}} + \frac{1}{\alpha_{in}} \tag{10}$$

where:

α_{ext} - external air heat transfer coefficient W/(m^2·K), assuming the surface temperature is the same as that of the external air, we take the value α_{ext} 9.74 W/(m^2·K) for vertical and horizontal surfaces.

δ_i - thickness of the i-th building envelope element layer, mm

λ_i - thermal conductivity coefficient of the i-th building envelope element, W/m;

α_{in} is the internal air heat transfer coefficient W/(m^2·K), equal to α_{ext} 8.7 W/(m^2·K) for vertical and horizontal surfaces.

As calculations show, the main influence on heat transfer resistance is exerted by the thickness of the structure itself and the thermal conductivity coefficient. Therefore, in order to improve the thermal properties of the envelope must either increase the thickness of the envelope (δ), which can have a negative impact on the investment costs for building construction due to increased costs for: the construction of the outermost envelopes, changes in foundation design, increased total construction time, or the use as part of the building envelopes of materials with a minimum thermal conductivity coefficient (λ). These materials belong to the category of thermal insulation materials and are widely used for the construction of outer enclosure structures in areas with low and negative outside air temperatures, thus reducing building heating costs.

6. Principles of Structural Design for Buildings in the Congo

Today, in the construction of buildings and structures in the Congo, lightweight concrete masonry materials of quality M50 … M200. The masonry blocks are transformed in molds into concrete blocks measuring 120 × 120 × 250 mm. The blocks have vertically oriented hollows on the inside to reinforce the walls during masonry work. The outer walls are 120 mm thick. Masonry work is carried out using a sand-cement mortar to fill the joints between the blocks. No finishing work is carried out on the exterior walls, nor is any plastering done with a 20 to 50 mm thick sand-cement mortar. Interior finishing of exterior walls is carried out in a similar manner.

Floor slabs will be monolithic with slab reinforcement, slab thickness 200 mm. Floors will be laid on the site with backfill of various fractions of crushed stone. A sand-cement screed 50 … 100 mm will be used to level the floor.

The floor must be monolithic with slab reinforcement, with a floor thickness of 200 mm. The top layer is waterproofed with bitumen-based membranes.

Windows and doors are metal-plastic with sealed glazing. To reduce insolation from translucent structures, awnings and rotating blinds are widely used.

When building external enclosure structures, the horizontal and vertical translucent planes are not thermally insulated, resulting in a reduction in thermal resistance indicators. As shown, the use of thermal insulation of external building envelopes can increase resistance to heat transfer by 2 to 3 times. Advantage is given to vapour-permeable fibrous insulation materials based on mineral wool boards with the following exterior cladding arrangement.

To ensure the thermal stability of the building envelope, if the outside air temperature fluctuates during the day, insulation layers should preferably be placed on the outside of the building envelope. This increases the attenuation of the outside air temperature amplitude. The schematic diagram of the thermal insulation system and the heat flow in cooling mode for vertical building envelopes are shown in **Figure 4**.

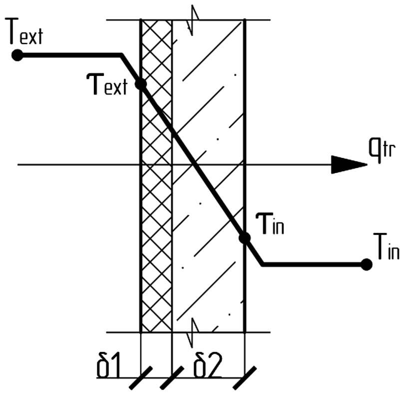

Figure 4. Heat transfer through the envelope.

The thickness of the insulation layer must be chosen for both thermal and technical reasons. For economic reasons, to guarantee the specific energy consumption specified for cooling buildings and structures, including air-conditioning.

7. Results and Discussion

7.1. Thermal Performance of Existing Envelopes

Current envelopes have an average thermal resistance of 0.35 m^2·K/W, resulting in interior temperatures 4˚C to 6˚C higher than the average outside temperature. These values corroborate those observed in uninsulated buildings in equatorial climates (Mirrahimi *et al.*, 2016) [2].

Heat loss through transmission of accounts for around 45% of the air-conditioning load, confirming the decisive role of the envelope (Ferrara *et al.*, 2014) [15].

7.2. Effect of Insulation on Thermal Flow

The results in **Table 1** show that 50 mm of insulation is enough to reduce the heat flux transmitted by 60%, and that at 150 mm, losses are divided by more than five. This performance confirms the findings of Bichiou & Krarti (2011) [16] on the effectiveness of low-conductivity insulation in hot zones.

Table 1. Insulation on thermal flow.

Insulation thickness (mm)	Average thermal flux (W/m^2·h)	Reduction (%)
0	120	-
50	48	60
100	30	75
150	22	82

External insulation performs better than internal insulation because it reduces the daily thermal amplitude and phase shift of heat flows (Gossard *et al.*, 2012) [11].

7.3. Impact on Energy Consumption

The cost-benefit analysis shows that the best compromise is at 50 mm insulation thickness, offering a payback time of less than three years.

These results concur with those of Lachheb *et al.* (2019) [18], who point out that excessive increases in insulation thickness lead to diminishing returns.

In parallel, an average 56% reduction in electricity consumption in a 500 m^2 administrative building is equivalent to 12 tonnes of CO_2 avoided per year, according to the emission factor of Costa *et al.* (2013) [19].

7.4. Design Issues and Recommendations

The results demonstrate the need for national thermal regulations. At present, no standard in the Congo sets a minimum energy performance threshold.

Adopting a framework inspired by Directive 2010/31/EU would enable buildings to be classified according to energy efficiency levels and promote low-conductivity materials.

Studies by Wörsdörfer (2018) [1] and Mebarki (2021) [20] show that energy efficiency can only be achieved through coordination between public policy, scientific research and technological innovation.

Finally, building a national database of local materials (conductivity, density, availability) would facilitate energy modeling and the standardization of solutions adapted to the Congolese context.

The electricity tariff in the Republic of Congo is set at \$0.09 for low-voltage bands. The sources are decrees and the ministerial decree.

8. Results of the Comparative Exergoeconomics Calculation of Building Envelopes

Exergoeconomics is a powerful technique for analyzing and optimizing energy systems. It is based on the union between the thermodynamics of irreversible processes, using the concept of exergy, and economic analysis. In the optimization procedure, exergoeconomic analysis not only succeeds in indicating the optimum functional and constructive solution for a certain constructive structure, but also offers the direction to follow in finding the optimum system structure.

In order to assess the savings in material costs for air-conditioning residential and administrative buildings with the use of thermal insulation of external envelope structures, we carried out calculations of the specific amount of heat, passing through external envelope structures without thermal insulation and with the use of mineral wool thermal insulation ($\rho = 90$ kg/m^3, $\lambda = 0.054$ W/m) with different insulation layer thicknesses: 50, 100, 150 mm. Calculations were made for maximum and minimum outside air temperatures for each month of the year, for an inside air temperature of 22˚C. Minimum temperatures in Central Africa hover around 22˚C, thanks to the very humid equatorial forest, numerous clouds, frequent rainfall, intense evaporation and equatorial atmospheric circulation. All this acts as an immense natural thermal regulation system [21].

A comparative analysis of exergy and exergy flow costs was also carried out for different insulation thicknesses of the external envelope. The exothermic heat flux was calculated as follows. Exergoenomic calculations were carried out using the cumulative exergoenomic costing method.

Figure 5 and **Figure 6** show the results of calculations of the specific amount of heat that arrived through the outer envelope constructions without thermal insulation and with the use of mineral wool thermal insulation with different insulation layer thicknesses: 50, 100, 150 mm at the maximum and minimum values of Techt, max (**Figure 5**) and Techt, min (**Figure 6**) of the monthly average outside air temperature during the year.

As can be seen from the graph, for Congo conditions, using 50 mm thick thermal insulation for the outer wall, the specific heat flux is reduced by a factor of 2.5. Using 100 mm and 150 mm thick insulation, the specific heat flux is reduced by a factor of 4.0 and 5.5 respectively.

To calculate the accumulation of exogenous costs from transmission heat gains for cooling in space conditioning, the exogenous heat flow through the walls was determined. The exergy rate ci, Euro-10^{-3}/W was assumed taking into account the cost of electricity for the Republic of Congo at current energy prices for the population. To determine the cost of cooling (thermal) energy, an estimated EER conversion factor of 3.0 was used. The results of calculating the accumulation of thermal exergy costs due to transmission heat flux Cqi, max, Σ, Euro-10^{-3}/(m^2·h) for space cooling at Teht, max for the envelopes compared are shown in **Figure 7**.

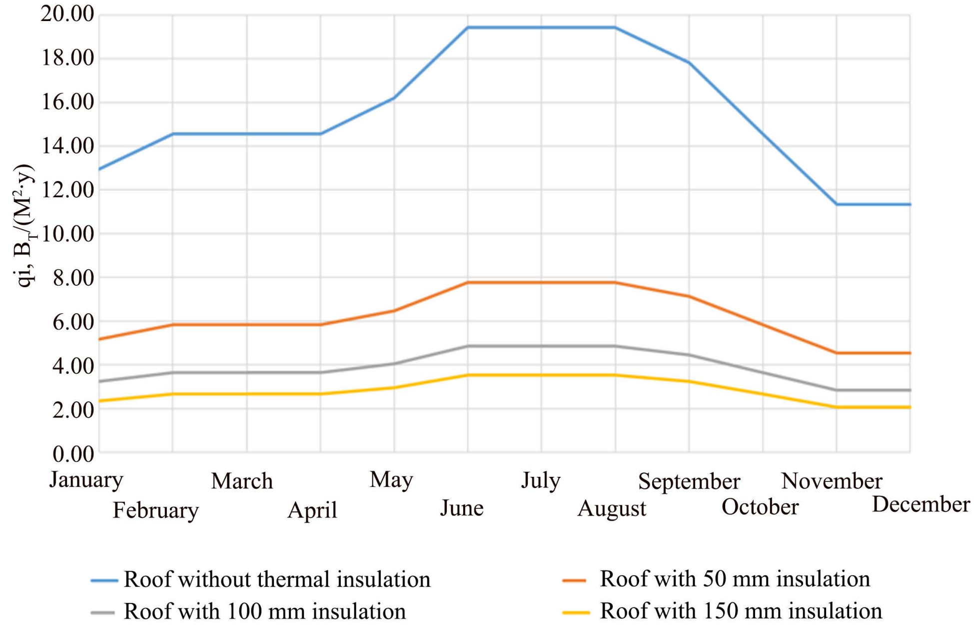

Figure 5. Specific hourly transmission thermal flux ($q_{i,\max}$, W/(m^2·h)) at Teht, max during the calendar year.

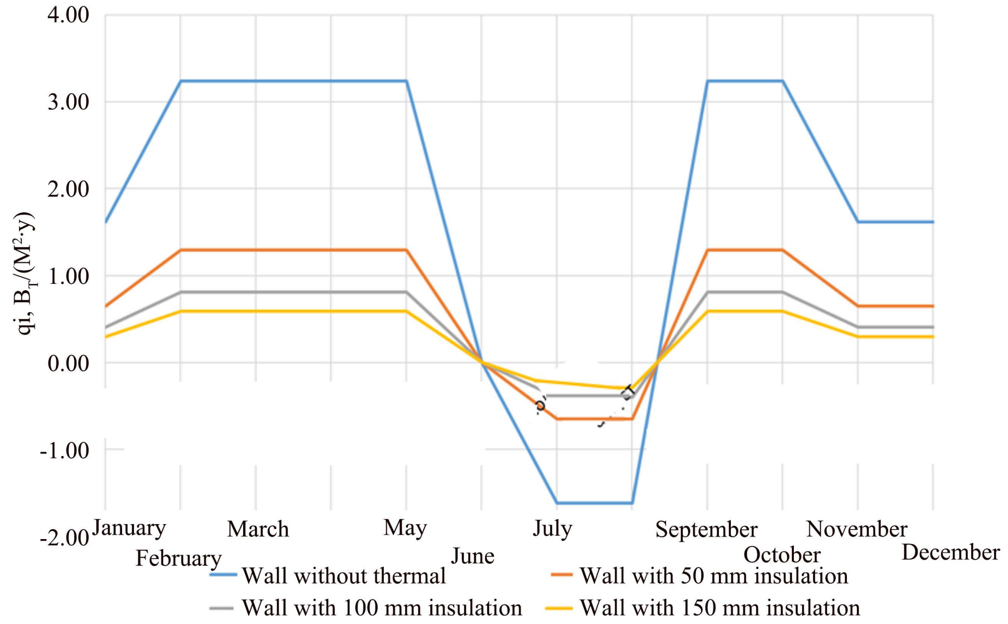

Figure 6. Specific hourly transmission thermal flux ($q_{i,\ min}$, $W/(m^2{\cdot}h)$) at Teht, min over the calendar year.

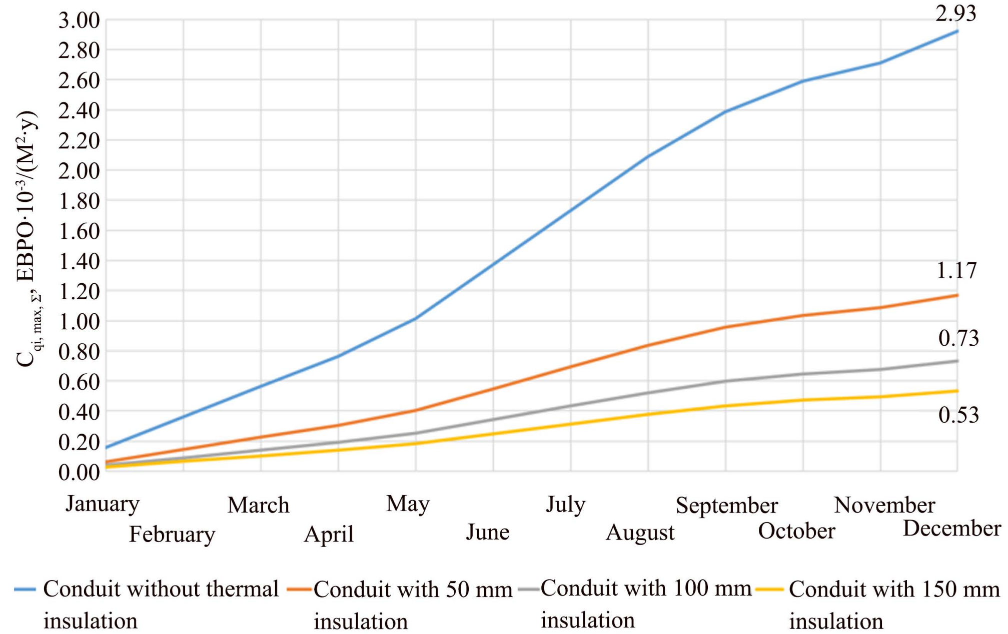

Figure 7. Accumulation of specific energy costs $C_{qi,\ max,\ \Sigma}$ due to transmission heat flux for space cooling at Teht, max.

As can be seen from the graph (**Figure 6**), the use of thermal insulation in external envelopes will reduce the specific exergy costs Cqi, max, Σ for air conditioning in proportion to the value of the reduction in heat flow through the AC. The use of mineral wool thermal insulation ($\rho = 90\ kg/m^3$, $\lambda = 0.054\ W/m$) with a layer thickness of 50 mm results in a 2.5-fold reduction in specific exergy consumption due to transmission heat flux.

However, the choice of the required thickness of the insulation layer must be made on the basis of thermodynamic and economic considerations, taking into account: the purpose and operating conditions of the building, the ratio between the surfaces of translucent and non-translucent OCs, the insulation system required, and the specific energy costs estimated for air-conditioning.

9. Conclusions

This study highlights the crucial role of the building envelope in the energy performance of buildings in humid tropical climates. The results show that improved thermal insulation can significantly reduce air-conditioning loads, operating costs and associated CO_2 emissions.

Existing Congolese buildings, built without insulation, have significant thermal deficiencies. The addition of 50 mm mineral wool insulation represents a technically simple, cost-effective and climatically appropriate solution.

Extrapolating the results to the national scale, a generalization of this approach could reduce electricity consumption in the residential sector by 25% - 30%, thus contributing directly to Sustainable Development Goals 7 and 13 (clean energy and climate action).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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