FUTURE CITIES
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Bioclimatic and Energy Performance by Eco-Efficiency in Buildings of the Metropolitan District of Quito, Ecuador

TECHNICAL ARTICLE

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ABSTRACT

Urban development demands new forms of expansion, among the most common are vertical growth, which at the same time demands sustainable criteria. This form of growth has implemented the concept of eco-efficiency, which seeks sustainable urban development through the proposal of energy-efficient buildings with the use of limited resources. Within this concept, bioclimatic design is one of the most relevant aspects. However, it is important to quantify the energy improvements of the new proposals through a methodology that facilitates understanding. The aim of this study is to characterize the energy performance of buildings that obtained an increase in floors through the application of an eco-efficiency matrix. This proposal for the Metropolitan District of Quito considers sustainable criteria; nevertheless, this study focuses on bioclimatic parameters related to absorbance and reflectance, lighting comfort, and thermal comfort. For this purpose, four tower-type buildings with different numbers of stories were analyzed. From each tower, a typical apartment was evaluated, which constitutes the analysis unit for the study. In this sense, on-site temperature and relative humidity data were used to interpret the climatic behavior of the apartments. Modeling of the apartments based on geometrical and constructive characteristics, and energy parameters, was also performed. These models allowed to perform computational simulations, obtaining results of natural lighting, thermal comfort, and energy performance. A comparison was also made between the case studies and others with the same geometry but without energy efficiency strategies to determine energy consumption, CO_2 emissions, and operating costs. The results showed that buildings that apply bioclimatic design strategies, as well as energy efficiency measures, reduce energy consumption by an average of 33% compared with buildings that do not apply these strategies.

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LIST OF SYMBOLS

DLF	Daylight Factor
DMQ	Metropolitan Distric of Quito
EUI	Energy Use Intensity
IREA	International Renewable Energy Agency
MIT	Massachusetts Institute of Technology
nZEB	Nearly Zero Energy Building
OLADE	Latin American Energy Organization
PAR	Percentage of absorbance and reflectance
RMSE	Standard Deviation of Residual Values
SRI	Solar Reflectance Index
STHV	Secretary of Territory, Habitat and Housing
U-value	Thermal transmittance
WWR	Window to Wall Ratio

1. INTRODUCTION

Building construction impacts health and the environment, affecting the sustainable development of the city and the fulfillment of the Sustainable Development Goals (SDGs) (Omer & Noguchi, 2020). Proposals for green building development seek energy reduction while maintaining a comfortable interior space (Li et al., 2021). This construction must be conducive to the development of energy efficiency in cities by promoting the development of economic aspects through taxation and profit systems, industrialization, and promotion of public services (Zakari et al., 2022). Nevertheless, in contexts with limited development, there are barriers to sustainable construction, such as lack of laws and regulations, low demand for sustainable construction, low awareness of sustainable construction, and fear of the investment cost of sustainable construction (Osuizugbo et al., 2020).

The sustainable approach seeks the development of green buildings, which is defined by government regulations, legislation, and policy improvement (Cao et al., 2022). These regulatory guidelines seek for buildings to acquire a higher environmental value focused on more specific aspects such as building green value indices to assess greenhouse gas reduction (Pan & Kao, 2021). The implementation of sustainable building policies has been developed from tools on sustainable building standards that generally focus on technological solutions in terms of energy performance, water efficiency, and indoor air environmental quality (Zhang et al., 2019).

In South America, laws and standards regarding ecological building have been developed (Zepeda-Gil & Natarajan 2020). However, the lack of knowledge in the implementation of tools against climate change demands the design of new policies and guidelines on climate change and sustainability in the construction industry at the state and municipal levels (Mercado 2020). This limitation is also evident in the implementation of clean technologies that only consider general aspects and not local aspects, and that in the Latin context require an important orientation toward housing (Cubillos-González & Tiberio, 2020). This context makes the local government appear as an important actor because it can provide incentives in policies, which in the Latin context are given in construction permits, sustainable certification, tax reduction, and agility in administrative processes (Liberalesso et al., 2020).

In the local government of the Metropolitan District of Quito (DMQ), since 2016, the eco-efficiency matrix has been proposed, which aims to create a sustainable city and reinforce the concept of a compact city favoring high-rise density and proximity between facilities and infrastructure. Application of the eco-efficiency matrix allows the purchase of buildable area by increasing the number of floors. Metropolitan Regulation No. 003 defines eco-efficiency as the set of concepts and strategies that promote sustainable urban development through buildings that reduce potable water consumption, treat and reuse wastewater, use rainwater, manage urban runoff, optimize electricity consumption, adopt measures to reduce greenhouse gas emissions, classify and manage solid waste, build with materials that have a low environmental impact, implement vegetation and urban trees, and include bioclimatic design criteria (Municipality of the DMQ, 2019).

By Resolution No. STHV-014-2017, the Secretary of Territory, Habitat and Housing (STHV) approved new instructions for the approval of the increase in the number of floors, and within the Environmental, Landscape and Technological Contributions section, new variables were established for the Bioclimatic Design parameter, whose score represents approximately 9% of the total score of the matrix. Bioclimatic design orients the design of the building to optimize its performance, which can follow criteria on energy savings and quality of living conditions, and can also consider innovative design solutions that are integrated according to the climate zone (Couvelas 2020). Thus, the bioclimatic design approach plays an important role in controlling building energy consumption (Boukli & Chabane, 2020). In the matrix, the bioclimatic design considers the following parameters: reflectance and absorbance, lighting comfort, and thermal comfort.

Reflectance is the ratio between the amount of radiation that a material receives and the amount of radiation it emits back. Reflectance is the characteristic of external surfaces that in bioclimatic design refer to cool pavement materials, water surfaces, and vegetation, which can have a positive impact on thermal comfort in hot climates (Karakounos, Dimoudi & Zoras, 2018). The composition of these materials in the city crust has a remarkable influence on the microclimatic effect of urban areas (Boujelbene et al., 2023). Reflectance plays an important role when considering facades, green roofs, and cool roofs, as it contributes to reducing the demand for electricity consumption and the energy required to cool spaces (Heidari & Olivieri, 2023). The other surface characteristic is absorbance, which refers to the ability of materials to transform solar radiation into thermal energy. It will depend on the bioclimatic design; for example, by applying greening of an exterior wall to achieve a reduction in heat accumulation (Shrestha & Shimizu, 2021).

In turn, lighting comfort is related to the optimization of the size of windows to improve the daylight factor (DLF) considering the climate. The DLF depends on the location of the building, and illumination levels vary because of the luminance of the sky and the orientation of the building facade (Mebarki et al., 2021). Daylighting solutions should be adjusted according to building use, window shape, façade treatment, wall composition, shadows from the surroundings, and the shape of the interior space (Lakhdari, Sriti & Painter, 2021).

The above-mentioned variables affect thermal comfort, which is one of the most evaluated aspects for determining the energy performance of a building. Improved thermal comfort can be achieved through computational simulations, and their application in real cases can also reduce energy consumption (Cheong et al., 2020). The simulations evaluate temperature and air velocity variables that ultimately allow the identification of a model for urban geometry from an environmental perspective (Elshafei et al., 2021). Thermal and lighting simulations can also be considered to determine the window-to-wall ratio (WWR) according to different orientations and locations that affect the final energy consumption of the building, whose behavior indicates that the higher the WWR, the higher the energy demand (Goia, 2016; Ma, Ma & Long, 2023). In a similar perspective, different variables of multi-story buildings and for different climates can be analyzed, and that through sensitive analysis, it has been possible to determine that the power density of the equipment is a dominant factor (Kamal et al., 2023).

Additionally, the variables mentioned above not only require analysis to quantify energy consumption, but must also be related to the amount of pollution and the cost they represent. In this sense, through multi-objective simulations and passive strategies, life cycle reductions in CO_2 emissions can be obtained (Xue, Wang & Chen, 2022). Thus, energy consumption is related to the amount of CO_2 emissions from buildings, which is an aspect that appears with large gaps and limited review in the scientific literature (Mata et al., 2021). In addition, the simulations also allow calculation of the optimal cost for minimum energy efficiency requirements (Pikas et al. 2015).

Based on the works cited, key aspects such as methods and research gaps can be highlighted (Table 1). In this regard, the bioclimatic design proposal, as well as energy optimization, also requires studies in other parts of the world, such as the Andean zone climates. On the other hand, it is necessary to integrate all the parameters involved in the design of efficient buildings, bearing in mind that the local climate conditions the parameters to be evaluated. Within this concept, bioclimatic design is one of the most relevant aspects. In addition, it is important to quantify the energy improvements of the new proposals through a methodology that facilitates their understanding. In this sense, this study quantifies the energy performance of buildings that applied the eco-efficiency matrix through bioclimatic design strategies in comparison to cases of the same geometry but without sustainable proposals.

REFERENCES	PARAMETERS	METHODS	CONCLUSIÓN	RESEARCH GAPS
Kamal, Kadam, Hou, Hassan, Wang, Sezer and Rahman (2023)	Number or stories, WWR, orientation, solar transmittance, solar reflectance, U-value, lighting and equipment power, infiltration and ventilation.	Building simulation, parametric and sensitivity analysis	The residential model is developed and obtains a cooling consumption level (227 kWh/m^2/year).	The analysis is performed for a hot and humid climate, the energy load profiles of buildings in other climate zones should be evaluated.
Li, Zhang, Zhang and Wu (2021)	Insulation thickness, heat transmission coefficient of the roof. Heat gain coefficient of the external window, WWR.	Hybrid approach that integrates computational simulation and response surface method (RSM)	The proposed model allows reducing energy consumption and maintaining a comfortable indoor environment in building retrofitting.	Some parameters relating to building typology are ignored in the optimization process, such as building orientation.
Shrestha and Shimizu (2021)	Thermal transmittance of the Wall, temperature.	Field measurements and quantitative analysis.	There is a need for greening to suppress solar radiation in the building façade.	Actual façade greening are required to explore and analyze the passive cooling effect on urban buildings.

(Contd.)

REFERENCES	PARAMETERS	METHODS	CONCLUSIÓN	RESEARCH GAPS
Mebarki, Djakab, Mejedoub, Amrane and Derradji (2021)	Daylight factor, WWR, energy demand, CO_2 emissions.	Multi-objective optimization method based on NSGA-II.	The result shows the building envelope is a key factor directly influencing the energy demand of the building.	The use of improved DF is not sufficient to determine the illuminance uniformity over the entire surface of the room.
Lakhdari, Sriti and Painter (2021)	WWR, wall materials, glass types, Shading devices, daylight, thermal comfort and energy consumption.	Experimental protocol that considers field measurements and parametric approach.	The study proposes multi-objective optimization using genetic algorithms for the initial phase of the design process.	Building envelope parameters used in the optimization must be refining in regard to obtain the best solutions.
Elshafei, Vilcekova, Zelenakova and Negm (2021)	Climatic conditions, passive design measurements and different climate zones.	CFD software combined with energy simulation program and optimization model.	Different building shapes were tested, considering orientation, temperature and air velocity, to identify the appropriate model of urban geometry.	The study suggests considering the impact of outdoor climatic conditions to achieve thermal comfort.
Goia (2016)	WWR, building envelope, energy use for heating, cooling and lighting.	Integrated thermal and lighting simulations, optimal WWR and numerical procedure, and sensitive analyses.	Most of the optimal WWR values are found in a relatively narrow range, i.e. 0.30 <WWR<0.45	The research has been limited to a highly insulated building envelope with a dynamic shading system.
PIkas, Thalfeldt, Kurnitski and Liias (2015)	Cost optimal energy, primary energy level and building envelope.	Simulation model, studied parameters and investment cost	The study proposes the optimal level of energy efficiency and the additional cost of a near-zero energy building.	The model and this method proved to be suitable for optimization in an early design phase.

Table 1 Literature review of previous studies focused on bioclimatic design and energy performance of buildings.

2. MATERIALS AND METHODS

The methodology has an experimental approach with a quantitative purpose. Real cases are studied according to scale according to the number of floors. At the same time, these cases are limited to the study of housing units by department. The study variables refer to construction and energy characteristics. On the other hand, in the selected cases, temperature measurements are taken as a variable that describes the result of the bioclimatic design proposal. These results are compared and complemented with the results obtained from modeling and simulations of the case studies in design software such as DIALux and Climabox web tool. Finally, the actual case studies will be compared to other similar cases without energy performance improvements, so that not only energy use, but also pollution and operational cost can be quantified.

2.1 CASE STUDIES

The city of Quito is located in Ecuador in South America, crossed by the Andes mountain range at the coordinates 0°13'12"S 78°30'45"W at an altitude of 2850 m a.s.l (Figure 1a). According to the Koppen climate classification, the city of Quito is characterized by a Cfb climate, which corresponds to an oceanic mountain climate. This climate is characterized as humid and temperate, typical of mid-latitude regions close to the ocean.

The urban area of the DMQ was studied in a specific zone of Iñaquito (Figure 1b). This zone has special characteristics that govern urban land and habitability conditions. This zone is located within the area of influence of the Integrated Metropolitan Transportation System, and it allows for an increase in the number of stories for projects that privilege the reuse of wastewater, limit energy and water consumption, and constitute a landscape, environmental, and technological contribution to the city. Four eco-efficient projects were analyzed in the area according to scale. Case A: Small up to 6 stories; Case B: medium 7 to 12 stories; Case C: large 13 to 18 stories; and Case D: extra large 19 stories or more (Figure 1c).

2.2 ON-SITE MEASUREMENTS

For continuous measurements of temperature, relative humidity, and wind speed, a Kestrel 5200 Professional environmental meter was used. The device was programed to record information every 20 min, and it was located at a height of 1.10 m above ground level and approximately 3.00 m from the window, taking care to avoid direct sunlight (Behrens, 2013) (Figure 2). Data collection was carried out in the intermediate departments of the buildings, in the living

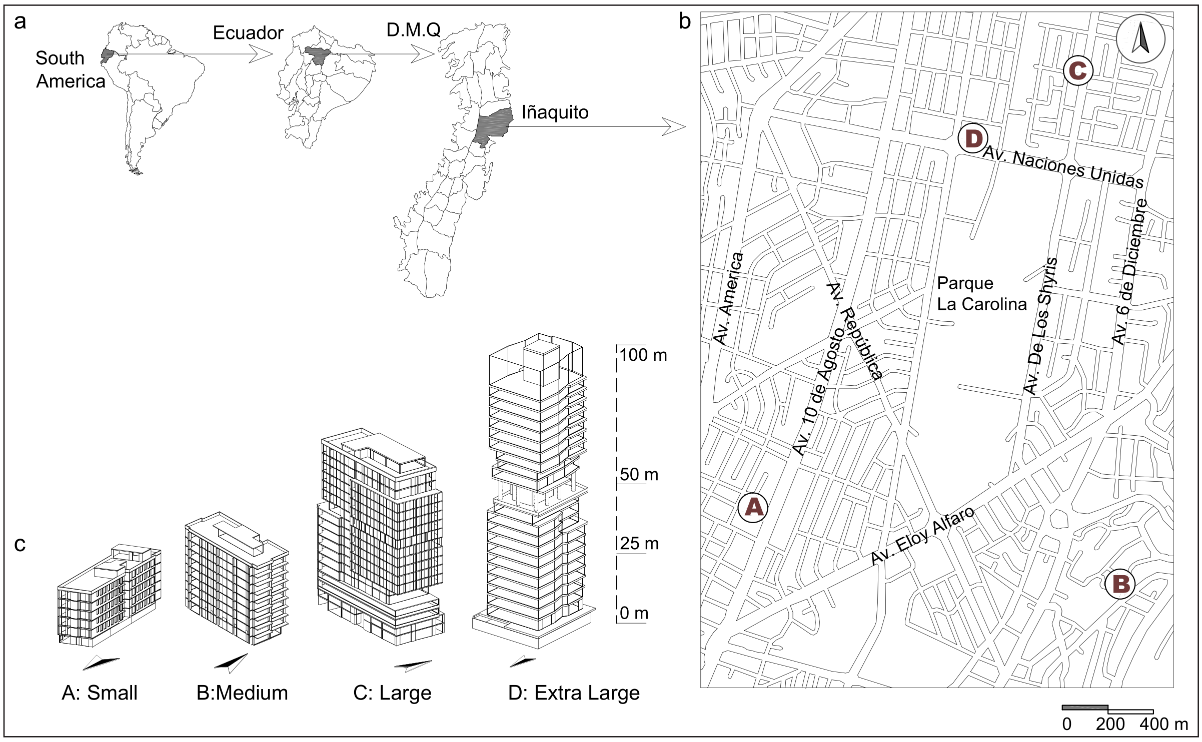

Figure 1 Study cases in Iñaquito, DMQ. **a)** DMQ situation in South America. **b)** Study cases located in Iñaquito, and **c)** Study cases according to scale.

	CASE A	CASE B	CASE C	CASE D
Floor-apartment	3-02	4-02	8-B	10-04
Measurements date	January-2023	August-2022	August-2023	April-2023

Table 2 On-site measurements.

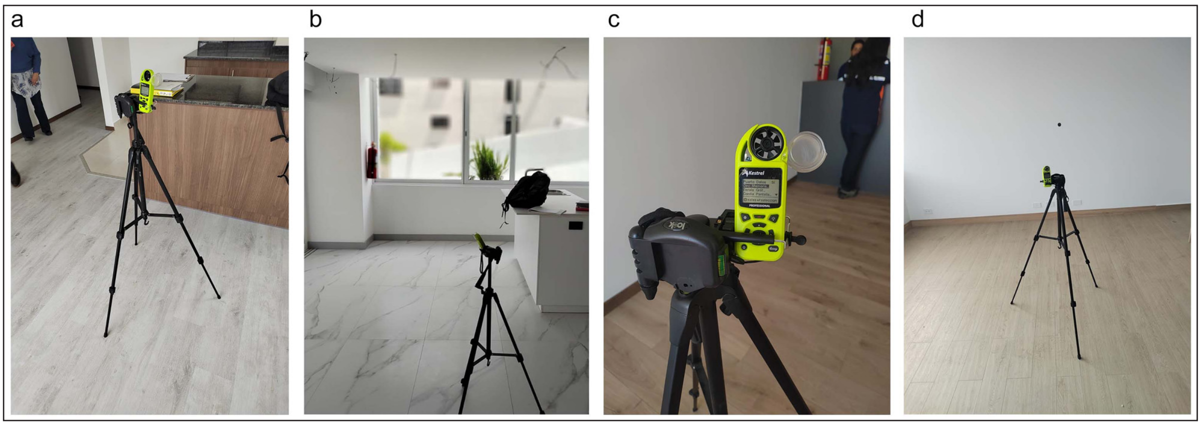

Figure 2 Data collection in different cases of building apartments. **a)** Case A, **b)** Case B, **c)** Case C, and **d)** Case D.

room-kitchen area. In addition, data were recorded for different weeks according to the availability of inspection and according to the facility for the permanence of the environmental meter (Table 2). Note that the weather in Quito makes it possible to take samples in different months because it has a temperature does not vary drastically throughout the year.

2.3 MODELING

For the elaboration of the computational models, the following parameters were verified: dimensions, materials characteristics, WWR ratio, and orientation of the departments. The departments presented irregular profiles; however, rectangular geometries with surfaces equivalent to the irregular ones were modeled (Figure 3). Simplified regular models representing a department were used because either detailed or simple modeling does not significantly impact the calculation of energy demand (Pomianowski, Hu & Larsen, 2023). The analysis models were used to evaluate the bioclimatic design parameters according to the Eco-efficiency matrix.

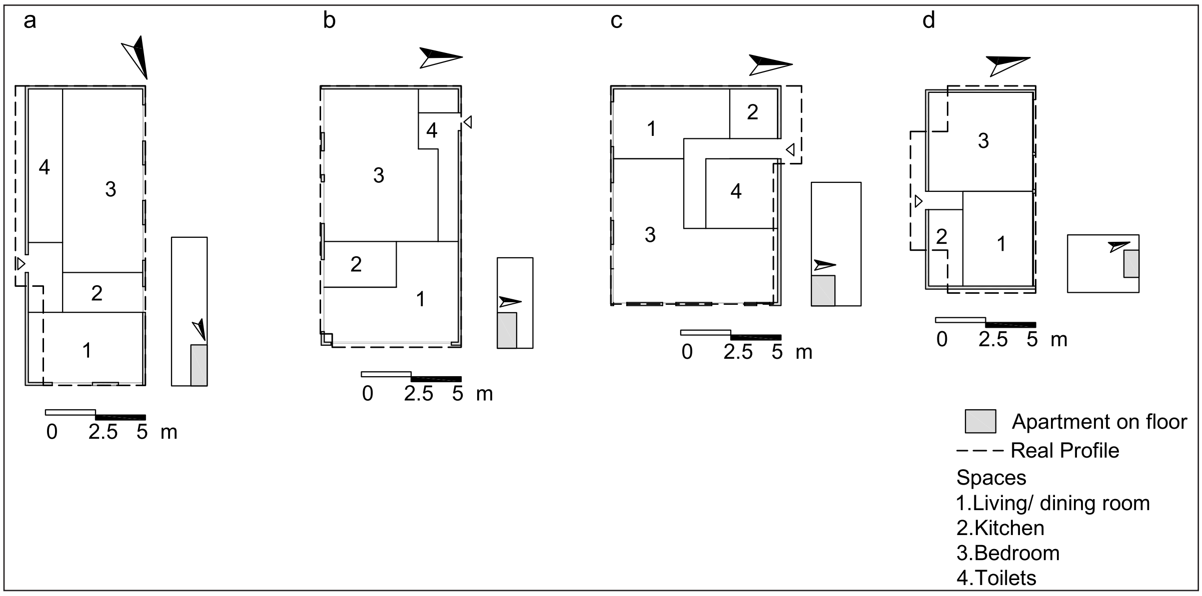

Figure 3 Simplification of the analysis model for case study apartments. **a)** Case A, **b)** Case B, **c)** Case C, and **d)** Case D.

2.4 ABSORBANCE AND REFLECTANCE PERCENTAGES

The characteristics of the materials to be used in the surfaces must comply with neutral reflectance and absorbance values to avoid reflecting solar radiation into public spaces. According to the annex of the eco-efficiency matrix, expression 1 is indicated (STHV, 2017):

$$PAR = (AGI/ACF)*100 \tag{1}$$

Where,
PAR = Percentage of absorbance and reflectance
AGI = Area with strategies (reflectance and absortance)
ACF = Total surface area

The above expression is applied to the external surfaces of each simplified model by apartment. The Solar Reflectance Index (SRI) is an important parameter in building energy analysis and thermal performance, especially for cool reflective surfaces or roof coverings (Nutakki & Kazim, 2022). The exterior surfaces of the investigation had SRI values of 30–70, which are close to the range of neutral values.

2.5 DAYLIGHT

Daylight refers to the degree of light that an interior space receives, considering natural daylight. The distribution of daylight depends on the orientation and size of the windows. The DLF is also considered, which relates the interior and exterior light levels according to the minimum indexes established in INEN 1 152-1984-05 standard. The daylight calculation is based on sky models described in the standard (CIE 110-1994).

Daylight was evaluated in the free software DIALux evo. The software considers the lighting environment, which, through simulations, allows optimizing the lighting design, creating energy savings, and providing comfortable ambient light (Sun et al., 2020). It is also used to evaluate natural light according to different WWR ratios and orientations (Ashrafian & Moazzen, 2019). In addition, the software considers geographic location and window openings that impact daylight scattering (Rahmah & Jurizat, 2022).

For the daylight simulation, models were constructed according to characteristics such as geographic location, apartment dimensions, and window size. The daylight analysis was created from an overcast sky model at noon (12:00) in March (equinox).

2.6 THERMAL COMFORT

Thermal comfort refers to a subjective evaluation of a thermal sensation by a person. Thermal comfort can be identified according to the sensation of heat or cold inside a space. This internal building parameter is affected by variables such as humidity, type of clothing, wind speed and temperature, in addition to building characteristics.

The free software Climaplus, a web-based tool for initial design analysis based on the "Climabox" methodology, was used to assess the potential for low-carbon building strategies in any location (Arsano, 2022).

A thermal zone was modeled using the software to estimate the effect of indoor temperature and energy use parameters. Climate data from the location of Iñaquito (DMQ) were used for the simulations. The models considered solar radiation on facades, one-dimensional heat flow in walls, roofs, and windows, internal gains from solar radiation, equipment, and occupants, and the thermal mass effect. The simulation models considered the geometric dimensions, orientation, and WWR ratio. The Climabox tool allowed the input of information for simulation according to construction characteristics, internal gains, and energy costs (Table 3).

CHARACTERISTICS	CASE A	CASE B	CASE C	CASE D
Construction roof	Adiabatic	Adiabatic	Adiabatic	Adiabatic
Construction wall	Regular U (1.66 W/m^{2}K)	Regular U (1.66 W/m^{2}K)	Regular U (1.66 W/m^{2}K)	Low U (3.5 W/m^{2}K)
Construction Floor	Adiabatic	Adiabatic	Adiabatic	Adiabatic
Construction Glazing	Single U (7.1 W/m^{2}K)	Single U (7.1 W/m^{2}K)	Single U (7.1 W/m^{2}K)	Single U (7.1 W/m^{2}K)
Exposed thermal mass	Medium (floor)	Medium (floor)	Medium (floor)	Medium (floor)
Infiltration	Regular (0.6 ach)	Regular (0.6 ach)	Regular (0.6 ach)	Regular (0.6 ach)
Peak Internal Gain Ligthing	Best (4 W/m^2)	Best (4 W/m^2)	Best (4 W/m^2)	Best (4 W/m^2)
Peak Internal Gain Equipment	Medium (8 W/m^2)	Medium (8 W/m^2)	Medium (8 W/m^2)	Medium (8 W/m^2)
Natural Ventilation	Operable Windows	Operable Windows	Operable Windows	Operable Windows
Conditioning system heating	No heating	No heating	No heating	No heating
Conditioning system cooling	No cooling	No cooling	No cooling	No cooling
Emissions Electricity	0.145 kgCO$_2$e/kWh	0.145 kgCO$_2$e/kWh	0.145 kgCO$_2$e/kWh	0.145 kgCO$_2$e/kWh
Emissions Gas	0.18 kgCO$_2$e/kWh	0.18 kgCO$_2$e/kWh	0.18 kgCO$_2$e/kWh	0.18 kgCO$_2$e/kWh
Cost electricity	0.092 $/kWh	0.092 $/kWh	0.092 $/kWh	0.092 $/kWh
Cost Gas	0.016 $/kWh	0.016 $/kWh	0.016 $/kWh	0.016 $/kWh

Table 3 Construction and energy characteristics of the case studies. Values taken from Climabox tool.

The construction characteristics of the facade walls are described below. Case A uses gypsum mortar, cement plaster, hollow concrete block, cement plaster and gypsum mortar. Case B uses exterior plaster, concrete block, expanded polyurethane, exterior plaster. Case C uses fiber cement board, gypsum board, steel structure and insulating glass wool. These first three cases have a U-value close to 1.66 W/m^{2}K. In case D, the envelope is characterized by the glazed surface that makes up 85% of the total surface of the envelope with a Solar Heat Gain Coefficient (SHGC) factor of 0.66, while the remaining 15% corresponds to the surface of the concrete wall. This last case has a U-value close to 3.5 W/m^{2}K. The U-values were used according to the low and regular ranges established in the Climabox tool. Moreover, official information was considered for emissions values from the International Renewable Energy Agency (IREA, 2021) and cost per energy consumption from the Latin American Energy Organization (OLADE, 2021).

2.7 CLIMABOX AND DIALUX VALIDATION

The methodology consists of using Climabox as web tool developed to facilitate the design of energy-efficient, low-carbon, naturally ventilated and mixed-mode hybrid buildings. It has been developed with the Massachusetts Institute of Technology (MIT) Energy Initiative.

The Climabox model has been thoroughly validated in the Arsano (2022) study, which compares Climabox against Energy Plus. Mentioned work, performed the validation for both model input and output parameters using the direct comparison method based on ASHRAE 140, as well as a pairwise comparison, a new approach specifically designed for this validation analysis. Moreover, previous work, regarding the input parameters of the Climabox approach, it is concluded that the hourly loads of lighting, equipment and occupants are similar with a standard deviation of the residual values (RMSE 0.02) if schedules similar to those of EnergyPlus are used.

On the other hand, DiaLUX is a software used in the validation of daylighting design (Reda et al., 2021) as well as artificial lighting in relation to visual comfort and energy consumption (Suriansyah et al., 2020).

3. RESULTS

3.1 TEMPERATURE AND HUMIDITY

Differentiated temperature profiles were observed, indicating minimum temperatures in the morning hours of up to 16°C, while maximum temperatures close to midday reached up to 22°C (Figure 4a). In addition, a thermal difference of up to 3°C was observed in the morning hours between cases B and C, whereas a similar thermal difference was observed between cases B and D at midday. For its part, relative humidity reached a maximum value in the morning of up to 70%, while at midday it reached minimum values of up to 40% (Figure 4b).The wind speed values are not indicated because they are insignificant within the apartments.

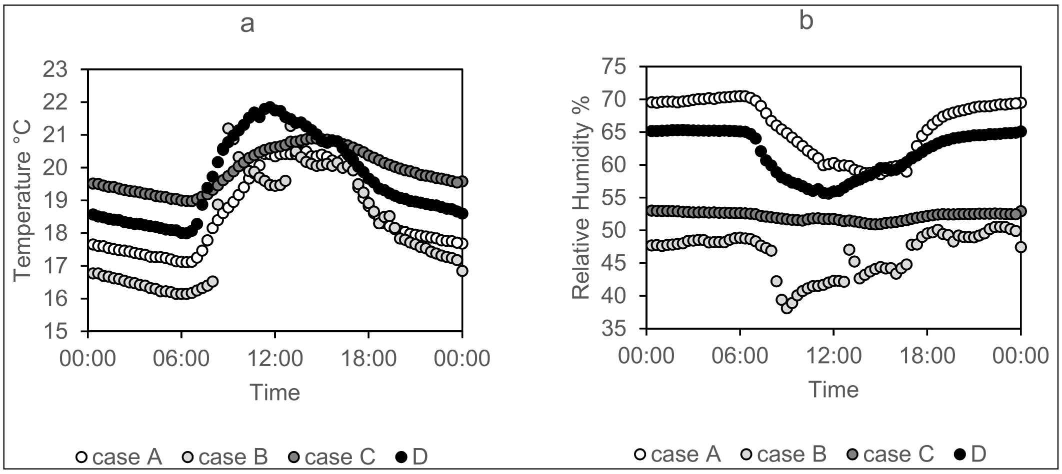

Figure 4 Mean values recorded by the anemometer in the different case studies. **a)** Temperature, and **b)** Relative Humidity.

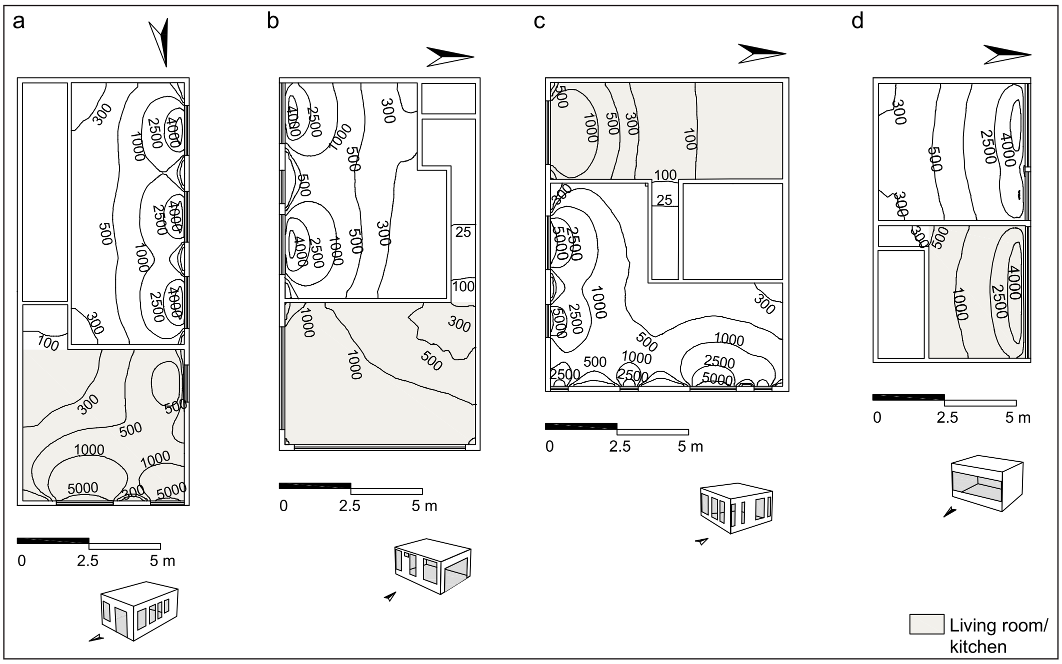

Figure 5 Daylight analysis performed in DIALux for case studies: **a)** case A, **b)** case B, **c)** case C, and **d)** case D.

3.2 ABSORBANCE AND REFLECTANCE

Surfaces with neutral reflectance and absorbance values were evaluated. The PAR calculation only considered exterior surfaces that generally used light colors and similar textures. The first three apartments (A, B, and C) have both surfaces exposed, whereas case D has only one surface exposed to the exterior. The PAR value result was defined by the solid surfaces for which strategies were applied in relation to the percentage of glass. After applying the PAR equation, the following values are obtained: Case A (PAR = 78%), case B (PAR = 67%), case C (PAR = 78%), and Case D (PAR = 67%).

3.3 DAYLIGHT

The DIALUX evo program allowed the simulation of the lighting curves and DLF values for the case studies (Figure 5). The standard (INEN 1 152-1984-05) indicates that the minimum indices (DLF) for the living room and kitchen are 0.625 and 2.5, respectively. The following values were obtained from the simulations (DLF): case A (3.10), case B (7.17), case C (2.01), and case D (8.43). Moreover, according to INEN 1 152-1984-05, the minimum lighting values for the living room and kitchen are 50 and 200 lx, respectively. From the simulations, average values of illumination in the horizontal plane were obtained for the open space (living room and kitchen): case A (795 lx), case B (1651 lx), case C (515 lx), and case D (1791 lx).

3.4 THERMAL COMFORT

In Climabox tool, simplified models of apartments were entered that considered geometric dimensions, WWR factor and orientation (Figure 6). The models entered the properties of the construction and energy consumption values. Hourly values of indoor temperature and indoor temperature frequency were obtained at more than the total number of hours of discomfort due to high and low temperatures.

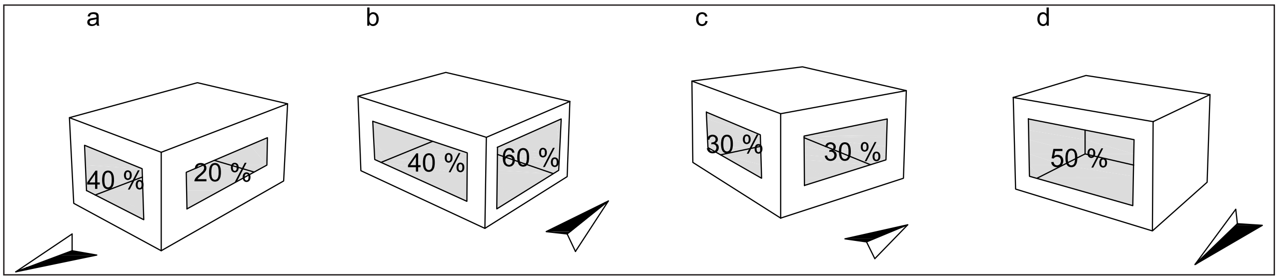

Figure 6 Simulation model used in Climabox for the case studies: **a)** case A, **b)** case B, **c)** case C, and **d)** case D.

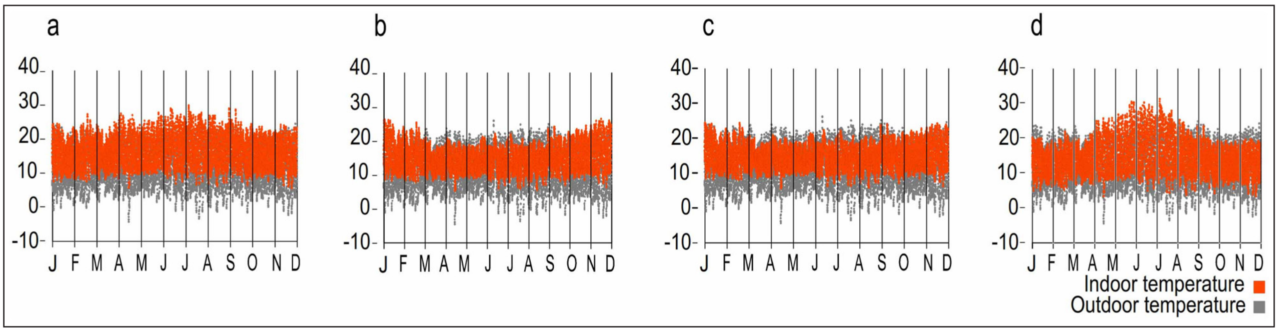

Figure 7 Indoor temperature hourly in study cases: **a)** case A, **b)** case B, **c)** case C, and **d)** case D. Obtained from Climabox simulation.

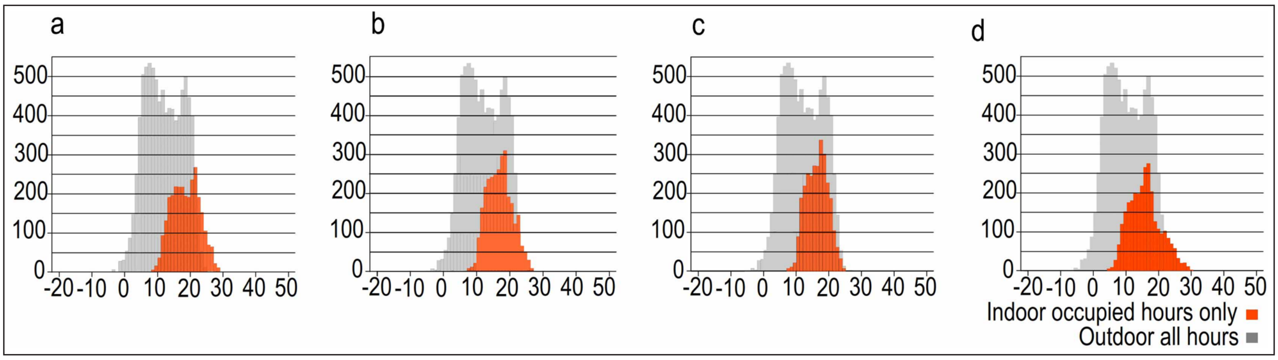

Figure 8 Indoor temperature frequency in study cases: **a)** case A, **b)** case B, **c)** case C, and **d)** case D. Obtained from Climabox simulation.

The monthly indoor temperature of the cases reached values between 10 and 30°C (Figure 7). However, the behavior differed according to window orientation. Cases B and C obtained minimum temperatures between March and August (Figure 7b and 7c), while cases A and D with northward openings reached maximum temperatures between the same months (Figure 7a and 7d). Finally, case D obtains the highest temperatures, not only due to the larger window size, but also due to the exterior wall with low U (Figure 7d).

Graph frequency showed that the four study cases recorded indoor temperatures between 10 and 30°C; however, the maximum frequencies (hours per year) vary as follows. Case A reached a temperature of 22°C for 270 h, case B reached a temperature of 19°C for 320 h, case C reached a temperature of 18°C for 380 h, and case D reached a temperature of 17°C for 280 h (Figure 8). Results show a higher frequency of indoor temperature between 17°C and 22°C. This range is similar to the hourly profile obtained from on site measurements, with values from 16°C to 22°C (Figure 4).

The study cases identified that of the total annual hours (8640), less than 100 h were due to discomfort due to high temperatures, while from 1300 to 1800 h were due to discomfort due to low temperatures (Figure 9). This indicates that approximately 20% of hours throughout the year are in discomfort due to low temperatures.

3.5 COMPARISON OF ENERGY USE WITH SCENARIOS WITHOUT IMPROVEMENTS

This part includes compared real cases (eco-efficiency) and cases with the same geometry but without improvements in the constructive characteristics of the envelope and energy efficiency. The Climabox tool allowed the estimation of Energy Use Intensity (EUI), CO_2 emissions and operational cost.

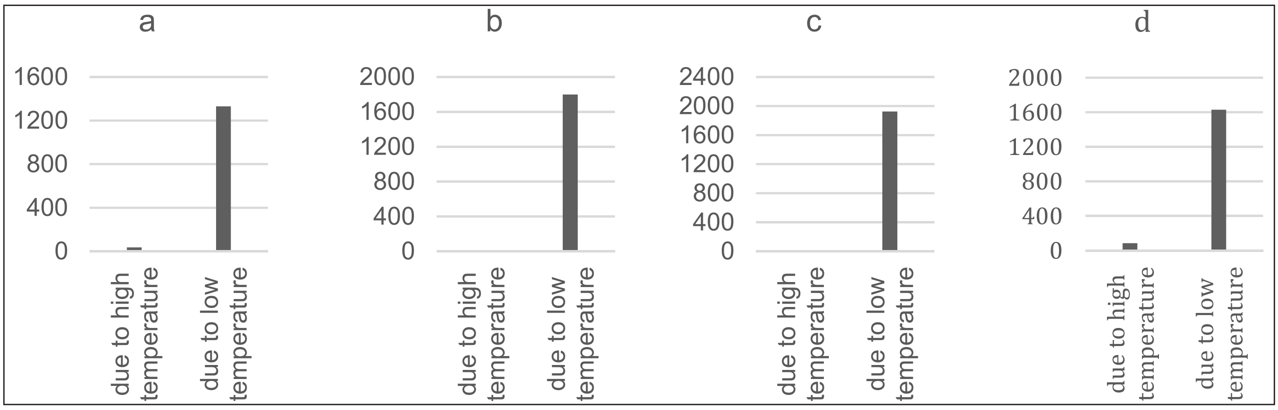

Figure 9 Discomfort hours in study cases: **a)** case A, **b)** case B, **c)** case C, and **d)** case D. Obtained from Climabox simulation.

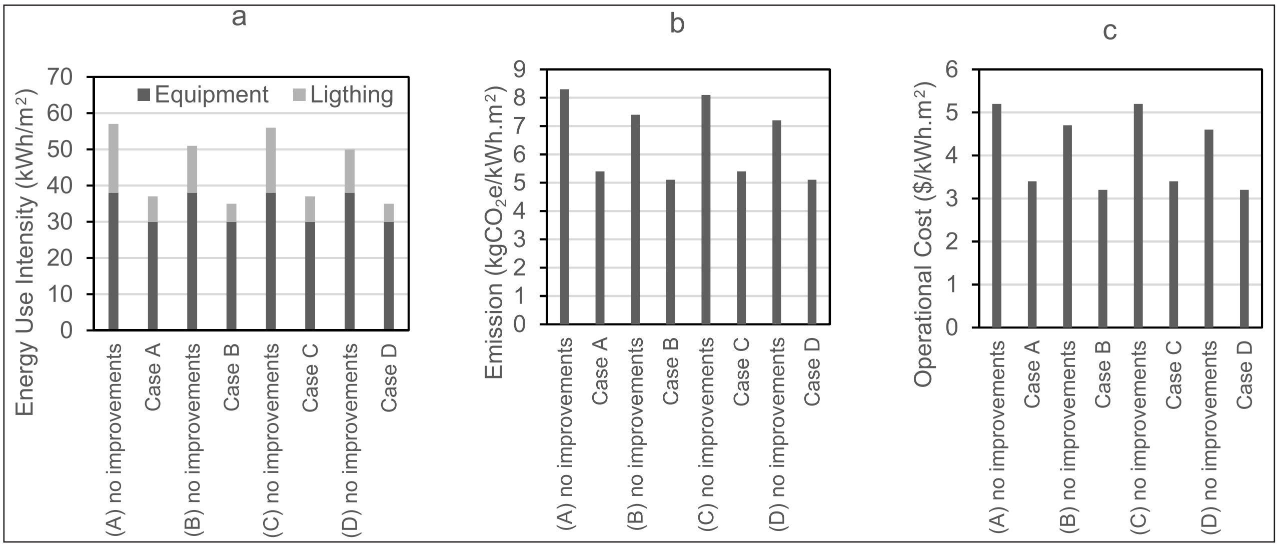

Figure 10 EUI, emissions, and operational costs. Case studies and cases without improvements. Obtained from Climabox simulation.

In general, the cases studied obtained an EUI value between 30 and 40 kWh/m^2, whereas the same cases without efficiency improvements reached values between 50 and 60 kWh/m^2 (Figure 10a). This shows that cases (eco-efficiency matrix) consume an average of 33% less energy than the same cases without improvements.

In the research, a value for lighting energy consumption of 4 W/m^2 was considered, compared to a conventional system close to 10 W/m^2. Part of this efficient proposal is due to complements to the lighting system that automate consumption and save energy, and this improvement in energy consumption is also due to the WWR ratio that allows better natural lighting. On the other hand, the improved proposal uses a reference energy value in equipment of 8 W/m^2, compared to a less efficient system with a value of 10 W/m^2. The implementation of efficient equipment is another strategy to mitigate energy consumption. Among the energy categories analyzed, the energy demand for equipment is twice as high as the demand for lighting. In addition, eco-efficiency cases implemented efficient luminaries that allowed an energy reduction of 61%, whereas the implementation of efficient equipment allowed a reduction of 21% of energy (Figure 10a).

Based on the energy results, the amount of pollution and the operational cost were determined. Eco-efficiency cases obtained emissions of 5.25 kgCO$_2$e/kWh.m^2 on average, while the cases without improvements obtained an average of emissions of 7.75 kgCO$_2$e/kWh.m^2, so the eco-efficiency cases polluted 32% less (Figure 10b). Finally, eco-efficiency cases obtained an operational cost average of \$3.3/kWh.m^2, while the cases without improvements obtained an operational cost average of \$4.93/kWh.m^2, so the eco-efficiency cases spend 33% less (Figure 10c).

4. DISCUSSION

Records taken on site showed that most of the time, the naturally conditioned apartments reached an acceptable operating temperature according to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2004). However, values below 18°C were recorded and were concentrated in the hours of dawn. This behavior was confirmed in the simulations of ClimaPlus, where the results showed more hours of discomfort due to low temperatures. It should be noted that the temperature results were achieved only with passive strategies.

PAR is a variable that depends on the exterior finishes, and this study presents neutral values of reflectance and absorbance. The facades of the apartments reach an average PAR value of 73%. The SRI value may vary because of the current conditions of the coatings and the presence of radiation, dust, and rain (Nutakki & Kazim, 2022). This relationship is limited in explaining why SRI not only affects indoor comfort but also externally influences heat island mitigation. In this sense, when designing a building, it is necessary to understand the requirement of solar radiation that some surfaces need to absorb, while others need to reflect (Boujelbene et al., 2023).

Natural lighting was analyzed in the living room and kitchen spaces, and all cases reached permitted values according to the INEN 1 152-1984-05 standard. The kitchen and living room are in the same area; however, the window area is closer to the living room and achieves higher lighting values. Thus, larger window openings allow better use of natural light.

The city of Quito is located in the tropics and at an altitude of 2850 meters above sea level, which conditions the thermal gradient. From the data taken at the site, it was found that in hours with less solar gains, temperatures of up to 16°C were reached, while in hours of solar gains, temperatures of 22°C were reached. Solar gains are directly conditioned by the WWR ratio. In warm climates, the north, east, and west facades must use a WWR value between 30% and 45% to avoid increases in total energy use (Goia, 2016). The case studies used the mentioned WWR ranges, so the WWR ratio can be considered the inherent geometric characteristic of the building (Ma, Ma & Long, 2023). The cases studied apply strategies that avoid the accumulation of heat and excessive radiation; however, WWR ratios greater than 50% lose heat easily.

The cases studied obtained EUI values between 30 and 40 kWh/m^2, compared with the cases without strategies that obtained values between 50 and 60 kWh/m^2. This data is relevant in comparison to a similar study of simulations in departments, but in Northern Europe, which may require double or triple the energy due to air conditioning, or even the value obtained in Quito may be lower than the energy demand of an nZEB building (nearly Zero Energy Building) which primary energy is below 100 kWh/m^2 (Pikas et al., 2015). On the other hand, in the present study, the highest percentage of EUI corresponds to the demand for equipment use, which remains the dominant demand, even in apartment buildings with extremely hot and humid climates (Kamal et al., 2023).

Cases B and C used insulation (expanded polyurethane and glass wool) in the wall construction. However, this was implemented in parts of the building, so the U-value for the enclosure cannot be generalized. All proposals with bioclimatic design have a similar construction system (U-value 1.66 W/m^{2}K) with better performance compared to a conventional construction system (U-value 3.5 W/m^{2}K or worse insulation). Therefore, the strategy of improving the wall construction can mitigate the overall energy consumption. Similarly, to achieve a low/zero carbon building, improvements in the construction system can be considered. For example, the incorporation of novel insulation plaster reached a U-value of 2.86 W/m^{2}K (Cuce et al., 2023), or even with better insulation (PUR), U-values of 0.23 W/m^{2}K can be achieved (Cuce et al., 2024).

This research determines CO_2 emissions and operational cost based on energy consumption; however, in addition to the energy performance of the building, an analysis of macroeconomic policies is suggested focused on the impact of income, the price of energy, and political proposal to reduce the impact of the external climate (Mata et al., 2021). On the other hand, with the use of passive strategies, potential reductions in pollution and costs can be obtained (Xue, Wang & Chen, 2022). The cases with bioclimatic strategies resulted to be more efficient, less polluting and require less operational cost. The orientation of the windows, the sizing of windows, the use of efficient fixtures, the use of efficient luminaires, constitute basic but viable strategies to obtain significant results in reducing energy consumption.

This study analyzed case studies by housing unit (apartment) using simplified simulation models, which through the DIALux evo software allowed defining the degree of natural lighting, and through the ClimaPlus software allowed defining the thermal and energy behavior. Energy consumption per housing unit (KWh/m^2) was analyzed, rather than the overall consumption of buildings. This study did not use complex calculation models and did not significantly affect the calculation of energy demand (Pomianowski, Hu & Larsen, 2023). Finally, the use of the eco-efficiency matrix, as a local tool, constitutes a government policy that promotes innovation and, at the same time, the development of energy efficiency (Zakari et al. 2022).

5. CONCLUSIONS

In the present work, the thermal and energy performance of apartment units that applied bioclimatic design strategies according to an eco-efficiency matrix were compared with cases of the same geometry but without energy strategies or improvements. In this sense, a hybrid methodology was used based on the analysis of real cases, on site measurements, and analysis in computer simulation programs.

Thus, it is concluded that buildings that apply the eco-efficiency matrix offer better energy performance, which is achieved through a bioclimatic design proposal.

At the same time, improvements in energy performance can vary significantly according to the design proposals and strategies for each case, in such a way that it affects energy performance from parameters such as absorbance, reflectance, lighting comfort and thermal comfort. The thermal comfort variable was the most relevant in the study because it is affected by the other bioclimatic design parameters. According to the results, the outputs of this research are represented as follows:

- Based on the indoor measurements, it was observed that the cases studied obtain a similar thermal profile, and that in most cases they are in a thermal range from 16°C to 22°C. This range is similar to that obtained in the Clilmabox software simulations according to the indoor temperature frequency graph.
- According to the DIAlux simulations, it was observed that in most cases the minimum illumination values (50 to 200 lx) established in the national standard INEN 1 152-1984-05 are reached. These results are due to the orientation and dimension of the windows, which are directly related to the WWR relation. The results obtained were analyzed for WWR values between 30 and 50%.
- The study showed that of the total hours per year, discomfort due to low temperatures reaches 1800 hours in the most unfavorable case. Therefore, strategies to mitigate discomfort due to low temperatures should be proposed in Iñaquito.
- When designing an efficient building, one of the effective measures to improve efficiency is the implementation of lighting fixtures that can enable a 61% reduction in energy consumption compared to non-efficient proposals.
- Finally, it is concluded these results were achieved through passive strategies and without air conditioning. In this sense buildings with bioclimatic criteria and energy efficiency reduce energy consumption by 33%, reduce CO_2 emissions by 32%, and reduce operational cost by 33%.

COMPETING INTERESTS

The author has no competing interests to declare.

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REFERENCES

Arsano, AY. 2022. Climate-carbon-equity Making sustainable design concepts accessible for all. PhD Thesis. Massachusetts Institute of Technology.

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). 2004. Thermal Environmental Conditions for Human Occupancy (ANSI/ASHRAE Standard 55-2004).

Ashrafian, T and **Moazzen, N.** 2019. The impact of glazing ratio and window configuration on occupants' comfort and energy demand: The case study of a school building in Eskisehir, Turkey. *Sustainable Cities and Society*, 47. May 2019. DOI: https://doi.org/10.1016/j.scs.2019.101483

Behrens, R. 2013. Análisis de desempeño Térmico y Lumínico en edificios de oficina a partir de monitoreo experimental. Master Thesis. *Universidad Internacional de Andalucia.* Available at: http://hdl.handle.net/10334/2599

Boujelbene, M, Boukholda, I, Guesmi, T, Amara, M and **Khalilpoor, N.** 2023. Solar reflection and effect of roof surfaces material characteristics in heat island mitigation: toward green building and urban sustainability in Ha'il, SaudiArabia. *International Journal of Low-Carbon Technologies*, 18: 1039–1047. DOI: https://orcid.org/0000-0001-9864-8152

Boukli, M and **Chabane, N.** 2020. Energy efficient design optimization of a bioclimatic house. *Indoor and Built Environment*, 29(2): 270–285. DOI: https://doi.org/10.1177/1420326X19856668

Cao, Y, Xu, C, Kamaruzzaman, SN and **Aziz, NM.** 2022. A Systematic Review of Green Building Development in China: Advantages, Challenges and Future Directions. *Sustainability*, 14(19). DOI: https://doi.org/10.3390/su141912293

Cheong, KH, Teo, YH, Koh, JM and **Acharya, U.** 2020. A simulation-aided approach in improving thermal-visual comfort and power efficiency in buildings. *Journal of Building Egineering*, 27. January 2020. DOI: https://doi.org/10.1016/j.jobe.2019.100936

(CIE) The International Commission on Illumination. 1994. Spatial Distribution of Daylight – Luminance Distributions of Various Reference Skies (CIE 110.1-1995).

Couvelas, A. 2020. Bioclimatic building design theory and application. In: Lagaros, N, Abdalla, K, Marano, G, Phocas M and Rousan, R (eds.), *1st International Conference on Optimization-Driven Architectural Design (OPTARCH 2019). Procedia Manufacturing*, 44: 326–333. DOI: https://doi.org/10.1016/j.promfg.2020.02.238

Cubillos-González, RA and **Tiberio, G.** 2020. Clean Technology Transfer and Innovation in Social Housing Production in Brazil and Colombia. *A Framework from a Systematic Review. Sustainability*, 12(4). DOI: https://doi.org/10.3390/su12041335

Cuce, E, Cuce, PM, Alvur, E, Yilmaza, YN, Saboor, S, Ustabas, I, Linul, E and **Asif, M.** 2023. Experimental performance assessment of a novel insulation plaster as an energy-efficient retrofit solution for external walls: A key building material towards low/zero carbon buildings. *Case Studies in Thermal Engineering*, 49. DOI: https://doi.org/10.1016/j.csite.2023.103350

Cuce, E, Cuce, PM, Wood, C, Gillott, M and **Riffat, S.** 2024. Experimental Investigation of Internal Aerogel Insulation Towards Low/Zero Carbon Buildings: A Comprehensive Thermal Analysis for a UK Building. *Sustainable and Clean Buildings*, 1(1). DOI: https://doi.org/10.37256/scb.1120244072

Elshafei, G, Vilcekova, S, Zelenakova, M and **Negm, A.** 2021. Towards an Adaptation of Efficient Passive Design for Thermal Comfort Buildings. *Sustainability*, 13(17). DOI: https://doi.org/10.3390/su13179570

Goia, F. 2016. Search for the optimal window-to-wall ratio in office buildings in different European climates and the implications on total energy saving potential. *Solar Energy*, 132. July 2016. 167–492. DOI: https://doi.org/10.1016/j.solener.2016.03.031

Heidari, A and **Olivieri, F.** 2023. Qualitative and Quantitative Scientometric Analysis of Bioclimatic Retrofitting in Commercial Buildings from 2008 to 2022. *Buildings*, 13(9). DOI: https://doi.org/10.3390/buildings13092177

(INEN) Instituto Ecuatoriano de Normalización. 1984. Iluminación Natural en Edificios (INEN 1 152-1984-05).

(IREA) International Renewable Energy Agency. 2021. Energy Profile Ecuador.

Kamal, A, Kadam, ST, Hou, D, Hassan, IG, Wang, L, Sezer, N and **Rahman, M.** 2023. Detailed profiling of high-rise building energy consumption in extremely hot and humid climate. *Cleaner Energy Systems*, 4. April 2023. DOI: https://doi.org/10.1016/j.cles.2023.100060

Karakounos, I, Dimoudi, A and **Zoras, S.** 2018. The influence of bioclimatic urban redevelopment on outdoor thermal comfort. *Energy Buildings*, 158. January 2018. 1266–1274. DOI: https://doi.org/10.1016/j.enbuild.2017.11.035

Lakhdari, K, Sriti, L and **Painter, B.** 2021. Parametric optimization of daylight, thermal and energy performance of middle school classrooms, case of hot and dry regions. *Building and Environment*, 204. October 2021. DOI: https://doi.org/10.1016/j.buildenv.2021.108173

Liberalesso, T, Oliveira, C, Matos, S and **Manso, M.** 2020. Green infrastructure and public policies: An international review of green roofs and green walls incentives. *Land use policy*, 96. July 2020. DOI: https://doi.org/10.1016/j.landusepol.2020.104693

Li, Q, Zhang, L, Zhang, L and **Wu, X.** 2021. Optimizing energy efficiency and thermal comfort in building green retrofit. *Energy*, 237. December 2021. DOI: https://doi.org/10.1016/j.energy.2021.121509

Ma, R, Ma, R and **Long, E.** 2023. Analysis of the rule of window-to-wall ratio on energy demand of residential buildings in different locations in China. *Heliyon*, 9(1). DOI: https://doi.org/10.1016/j.heliyon.2023.e12803

Mata, E, Wanemark, J, Cheng, SH, Broin, EO, Hennlock, M and **Sandvall, A.** 2021. Systematic map of determinants of buildings' energy demand and CO_2 emissions shows need for decoupling. *Environmental Research Letters*, 16. DOI: https://doi.org/10.1088/1748-9326/abe5d7

Mebarki, C, Djakab, E, Mejedoub, A, Amrane, Y and **Derradji, L.** 2021. Improvement of Daylight Factor Model for Window Size Optimization and Energy Efficient Building Envelope Design. *Journal of Daylighting*, 8: 204–221. DOI: https://doi.org/10.15627/jd.2021.17

Mercado, U. 2020. Sustainability Assessment in Housing Building Organizations for the Design of Strategies against Climate Change. *HighTech and Innovation Journal*, 1(4): 136–147. DOI: https://doi.org/10.28991/HIJ-2020-01-04-01

Municipality of the Metropolitan District of Quito. 2019. Regulation No. 003. https://www7.quito.gob.ec/mdmq_ordenanzas/Ordenanzas/ORDENANZAS%20MUNICIPALES%202019/.

Nutakki, TU and **Kazim, W.** 2022. Effects of Natural Weathering on the Performance of High Solar Reflective Index Paint Surfaces Exposed in Harsh Climatic Conditions of United Arab Emirates. *Buildings*, 12(7). DOI: https://doi.org/10.3390/buildings12071002

(OLADE) Organización Latinoamericana de Energía. 2021. Precios de la Energía en América Latina y el Caribe. Informe Anual Abril 2021.

Omer, MAB and **Noguchi, T.** 2020. A conceptual framework for understanding the contribution of building materials in the achievement of Sustainable Development Goals (SDGs). *Sustainable Cities and Society*, 52. January 2020. DOI: https://doi.org/10.1016/j.scs.2019.101869

Osuizugbo, C, Oyeyipo, O, Lahanmi, A, Morakinyo, A and **Olaniyi, O.** 2020. Barriers to the Adoption of Sustainable Construction. *European Journal of Sustainable Development*, 9(2): 150–162. DOI: https://doi.org/10.14207/ejsd.2020.v9n2p150

Pan, BTC and **Kao, JJ.** 2021. Comparison of indices for evaluating building green values based on greenhouse gas emission reductions. *Ecological Indicators*, 122. March 2021. DOI: https://doi.org/10.1016/j.ecolind.2020.107228

Pikas, E, Thalfeldt, M, Kurnitski, J and **Liias, R.** 2015. Extra cost analyses of two apartment buildings for achieving nearly zero and low energy buildings. *Energy*. 84: 623–633. DOI: https://doi.org/10.1016/j.energy.2015.03.026

Pomianowski, MZ, Hu, Y and **Larsen, OK.** 2023. Model simplification of geometry and facilities, for energy and indoor environment towards more reliable energy labelling. *Journal of Physics: Conference Series*, 2600. DOI: https://doi.org/10.1088/1742-6596/2600/3/032010

Rahmah, L and **Jurizat, A.** 2022. The effect of window orientation on the amount of light in the inner space over year using DIALux Evo application simulation. *IOP Conference Series: Earth and Environmental Science*, 1058. DOI: https://doi.org/10.1088/1755-1315/1058/1/012001

Reda, I, Elzefzafy, H and **Al-Rawi, OY.** 2021. Effect of Luminaries' Arrangement and Type on Visual Comfort and Energy Consumption. *Information Sciences Letters*, 10(3): 417–426. DOI: https://doi.org/10.18576/isl/100304

Shrestha, A and **Shimizu, T.** 2021. Evaluation of the suppressive effects on solar radiation for a building façade covered with green layers in the Kathmandu valley. *Environmental Challenges*, 5. DOI: https://doi.org/10.1016/j.envc.2021.100246

(STHV) Secretary of Territory, Habitat and **Housing of the Metropolitan District of Quito.** 2017. Resolución No. STHV-14–2017. https://www.quito.gob.ec/documents/SHTV/Resolucion-No-STHV-014-2017_INCREMENTO_EDIFICABILIDAD_ECOEFICIENCIA.pdf.

Sun, Y, Liu, X, Qu, W, Cao, G and **Zou, N.** 2020. Analysis of daylight glare and optimal lighting design for comfortable office lighting. *Optik*, 206. March 2020. DOI: https://doi.org/10.1016/j.ijleo.2020.164291

Suriansyah, Y, Sutandi, AC and **Kusliansjah, K.** 2020. The Potential of Natural Daylight Utilization for the Visual Comfort of Occupants in Two Units of Service Apartments Certified as Green Buildings in Kuala Lumpur, Malaysia. *International Journal of Integrated Engineering*, 12(4): 276–289. Available at: http://penerbit.uthm.edu.my/ojs/index.php/ijie

Xue, Q, Wang, Z and **Chen, Q.** 2022. Multi-objective optimization of building design for life cycle cost and CO_2 emissions: A case study of a low-energy residential building in a severe cold climate. *Building Simulation*, 15: 83–98. DOI: https://doi.org/10.1007/s12273-021-0796-5

Zakari, A, Khan, I, Tan, D, Alvarado, R and **Dagar, V.** 2022. Energy efficiency and sustainable development goals (SDGs). *Energy*, 239. Part E. DOI: https://doi.org/10.1016/j.energy.2021.122365

Zepeda-Gil, C and **Natarajan, S.** 2020. A Review of "Green Building" Regulations, Laws, and Standards in Latin America. *Buildings*, 10(10). DOI: https://doi.org/10.3390/buildings10100188

Zhang, Y, Wang, H, Gao, W, Wang, F, Zhou, N, Kammen, DM and **Ying, X.** 2019. A Survey of the Status and Challenges of Green Building Development in Various Countries. *Sustainability*, 11(19). DOI: https://doi.org/10.3390/su11195385

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