Energy Conversion and Management: X 20 (2023) 100494

Contents lists available at ScienceDirect

Energy Conversion and Management: X

journal homepage: www.sciencedirect.com/journal/energy-conversion-and-management-x

Natural lighting performance of vernacular architecture, case study oldtown Pasa, Ecuador

Darío Bustán-Gaona [a], Manuel Ayala-Chauvin [b,*], Jorge Buele [c], Patricia Jara-Garzón [a], Genís Riba-Sanmartí [d]

[a] Carrera de Arquitectura, Facultad de Arquitectura y Construcción, Universidad Indoamérica, Ambato 180103, Ecuador
[b] Centro de Investigación en Ciencias Humanas y Educación (CICHE), Universidad Indoamérica, Ambato 180103, Ecuador
[c] Carrea de Ingeniería Industrial, Facultad de Ingeniería, Industrial y Producción, Universidad Indoamérica, Ambato 180103, Ecuador
[d] Centro de Diseño de Equipos Industriales (CDEI), Universidad Politécnica de Cataluña, Llorens Artigas, Barcelona, Spain

ARTICLE INFO

Keywords:
Vernacular architecture
Domestic energy consumption
Natural lighting levels

ABSTRACT

Vernacular architecture is an architectural style that reflects the traditions and cultural aspects of a particular region or community. It is characterized by the use of local materials and traditional construction techniques, adapting to the climatic, geographical, and cultural conditions of the place. Despite extensive research on the benefits of natural lighting in modern architecture, there is limited understanding of how vernacular architecture integrates natural lighting principles in various climatic conditions, mainly due to restrictions in intervention and concerns about structural integrity. In today's world, energy efficiency and conservation are crucial aspects of building design. Therefore, this study aims to analyze the effectiveness of natural lighting in the indoor spaces of vernacular architecture. The research includes measurements taken in traditional buildings in the parish of Pasa, Ambato, Ecuador, as well as simulations to evaluate the behavior of sunlight. The findings reveal that, with new construction technologies, lighting levels in the interior spaces of these buildings can be improved. To address this issue, a proposed solution is presented to optimize the use of natural light, resulting in an increase from 30 to 100 lx. This improvement could pave the way for the implementation of policies that enhance the quality of life for users.

Introduction

In the field of sustainable architecture and construction, natural lighting and its impact on building performance are crucial aspects in achieving more habitable, efficient, and environmentally friendly spaces [1]. The quest for solutions to improve the penetration of natural light in buildings is a topic of great interest among researchers and professionals in the field. In this context, various research works have been taken as a basis to explore different aspects related to natural lighting, energy efficiency, and the quality of life of occupants.

In the first group of research, relevant works have applied diverse strategies to optimize natural lighting in buildings. Ruggiero et al., [2] used a multi-objective optimization method to design various daylight shelf configurations in a student house undergoing deep energy renovation. The objective is to achieve nearly zero-energy building with improved daylight penetration and thermal comfort. On the other hand, Xue et al., [3] proposed a method to optimize natural light quality in commercial atria in cold regions like Jinan, China, aiming to enhance building energy efficiency and interior comfort. Similarly, Pan et al., [4] investigated the impact of urban design factors on exterior natural lighting in urban neighborhoods in Shenzhen, highlighting the importance of urban morphological features in optimizing exterior natural lighting and energy use in urban design. Also, in this group, Aguilera-Benito et al., [5] conducted an experimental analysis of passive strategies in glass-façade buildings to utilize natural light, concluding that passive elements such as solar control films and overhangs improve interior illuminance. Lim et al., [6], on the other hand, evaluated the performance of solar shading devices in residential buildings in South Korea, finding that the egg crate type of shading was the most effective in achieving greater energy savings in cooling and lighting.

In the second group of research, emphasis has been placed on energy efficiency and performance of artificial lighting in buildings. Durmus

* Corresponding author.
E-mail addresses: dariobustan@uti.edu.ec (D. Bustán-Gaona), mayala@uti.edu.ec, mayala5@indoamerica.edu.ec (M. Ayala-Chauvin), jorgebuele@uti.edu.ec (J. Buele), patriciajara@uti.edu.ec (P. Jara-Garzón), genis.riba@upc.edu (G. Riba-Sanmartí).

https://doi.org/10.1016/j.ecmx.2023.100494
Received 31 January 2023; Received in revised form 14 November 2023; Accepted 16 November 2023
Available online 20 November 2023

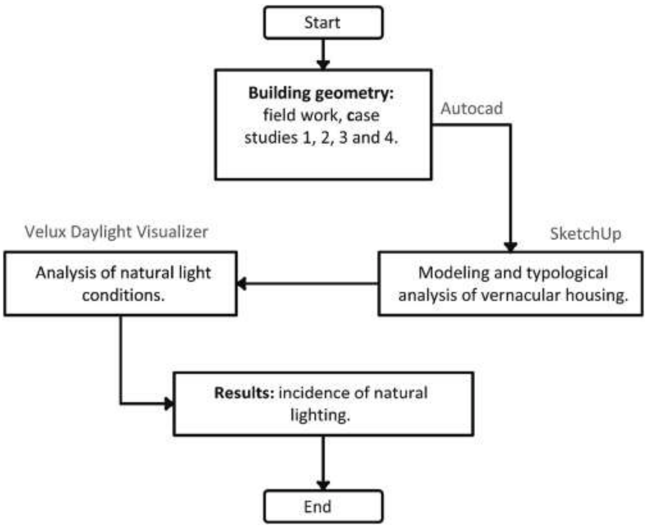

Fig. 1. Flowchart 1of the used methodology.

et al., [7] presented a new framework called Lighting Application Efficiency (LAE), which provides a more comprehensive and accurate measure of lighting efficiency in architectural spaces, considering the entire process of light generation, emission, travel, and visual perception. Furthermore, Albatayneh et al., [8] examined the impact of improving the efficiency of the lighting system on the optimal window-to-wall ratio in residential buildings in Jordan, suggesting that buildings with efficient artificial lighting will have a lower WWR compared to those relying on daylight.

In the third group of research, the relationship between home lighting and occupant health has been addressed. The systematic review by Osibona et al., [9] analyzed the quality of lighting in housing and its importance for visual performance and physiological functions, but also pointed out the need for more research in specific domains. Bellia et al., [10] focused on the impact of light on circadian rhythms, highlighting the crucial role of architecture in shaping the characteristics of light that affect these rhythms. Additionally, Aguilar-Carrasco et al., [11] proposed a methodology to evaluate the combination of natural and electric lighting in office spaces, ensuring adequate circadian stimulation and benefiting occupant health while promoting energy conservation. Similarly, the research by Muñoz-González et al., [12] and Cabeza-Lainez et al., [13] have presented approaches to improve natural lighting levels in historic buildings and the Egebjerg school in Denmark, aiming to achieve healthier and more comfortable spaces.

In the fourth group of research, the performance and optimization of lighting systems and energy efficiency in buildings have been explored. Eaton et al., [14] investigated the availability of natural light in skyscraper farms using climate-based daylighting models, indicating that skyscraper farms require more lighting than greenhouses. On the other hand, Al-Ghaili et al., [15] conducted a review on lighting system designs applied to different building types to achieve greater energy savings, emphasizing the importance of efficient lighting systems in reducing energy consumption. Thongtha et al., [16] evaluated the integration of natural lighting in buildings using cylindrical glass in a test model, finding that certain configurations allow for electrical energy savings in cooling and lighting. Additionally, the research by Amoruso et al., [17] and Zhou et al., [18] addressed energy efficiency and lighting performance in building renovations, presenting proposals to improve light quality and reduce energy consumption in residential and office spaces.

These research works have been fundamental in advancing knowledge on natural and artificial lighting in buildings, as well as their impact on building performance and occupants' quality of life. The optimization studies on natural lighting, such as those by [2] and [3], have provided innovative strategies to improve energy efficiency and thermal comfort in buildings, resulting in lower energy consumption and reduced environmental footprint. On the other hand, research on energy efficiency and performance of artificial lighting, like that of [7] and [8], has emphasized the importance of considering both natural and artificial light in architectural space design, aiming to achieve a balance between daylight utilization and energy consumption reduction.

Regarding health and indoor lighting quality, the research by [9,12,10,11], and others has contributed evidence on the influence of light on circadian rhythms and occupants' well-being. These studies have highlighted the need to design spaces that promote the health and comfort of individuals, especially in contexts like the present, where indoor environmental quality is particularly relevant due to the pandemic.

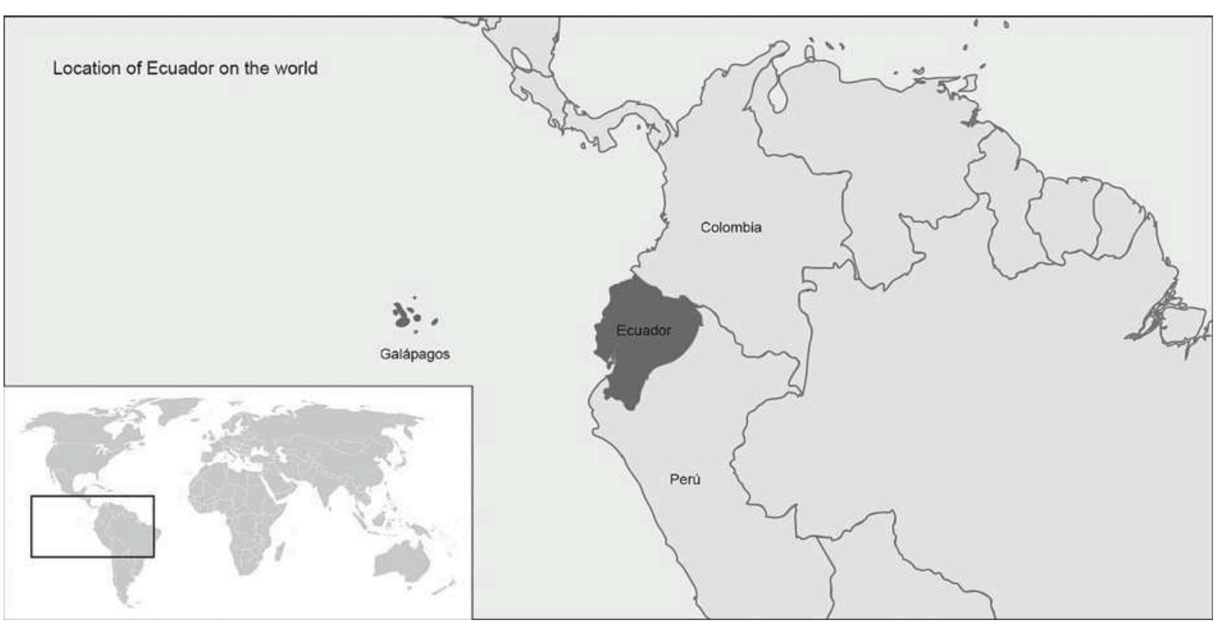

Fig. 2. Location of Ecuador on the world, .
Source [28]

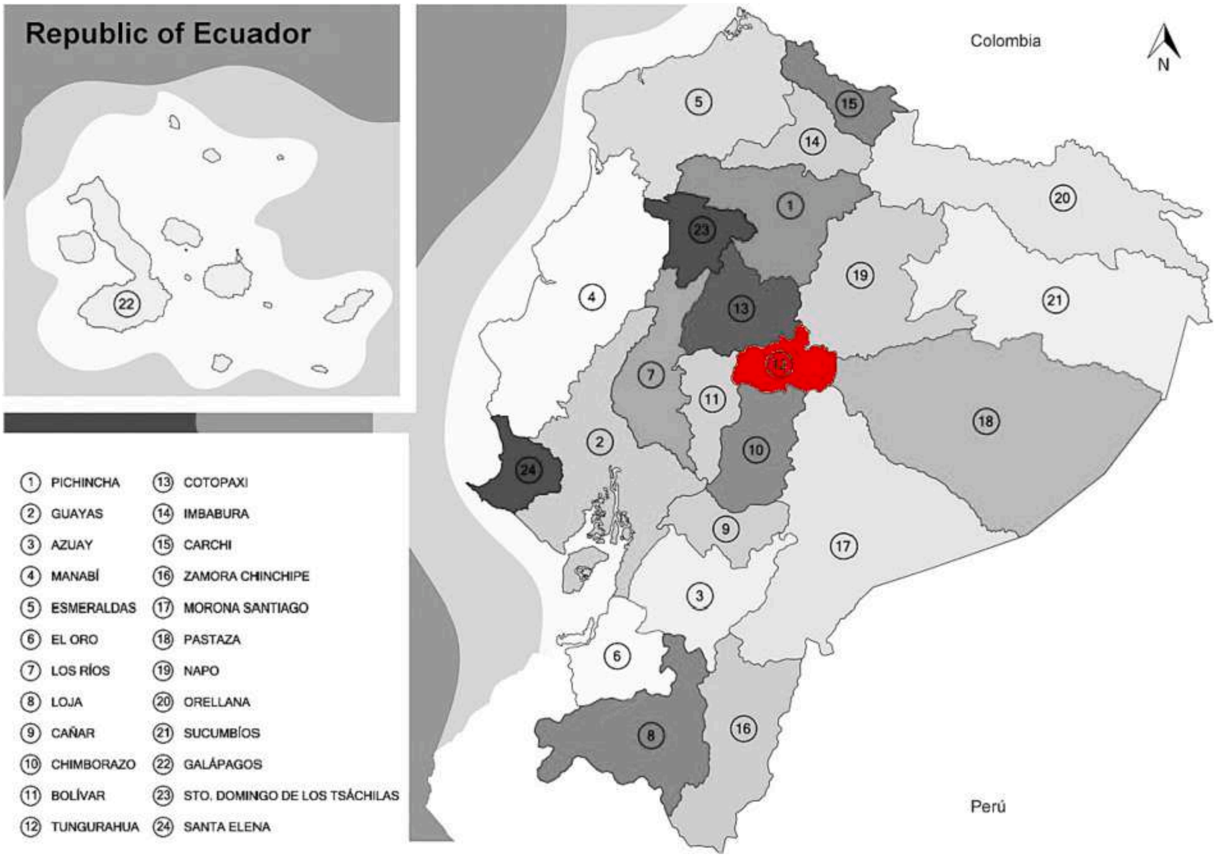

Fig. 3. Tungurahua, Ecuador.

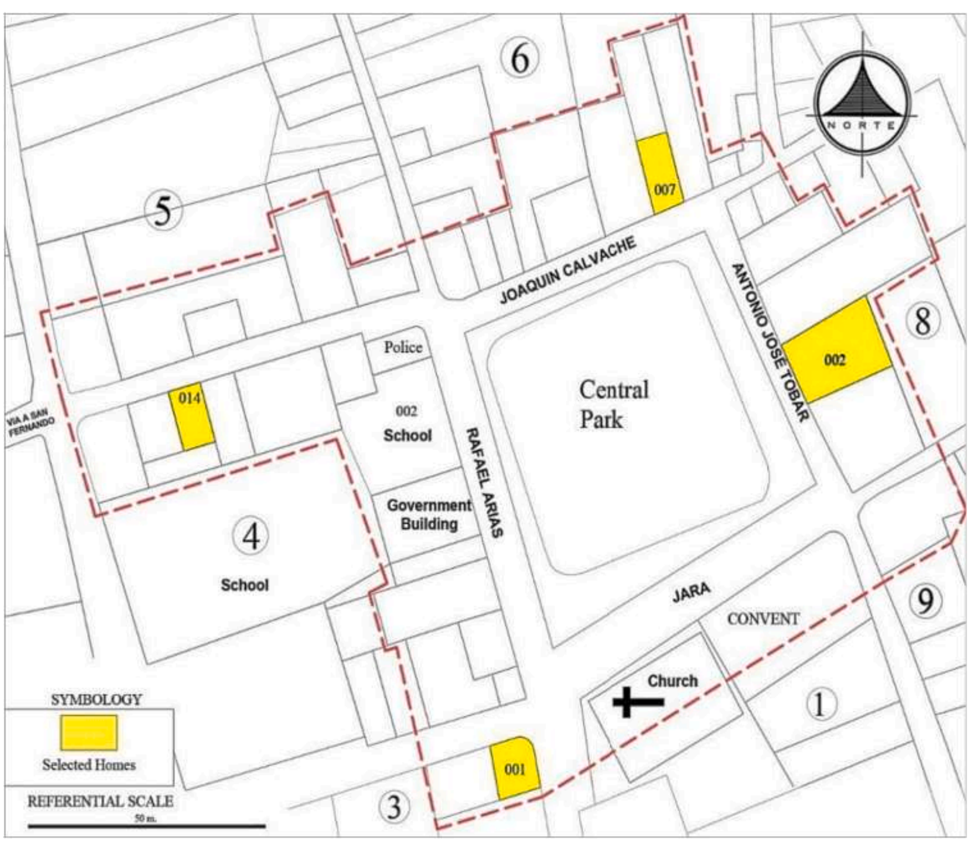

Fig. 4. Map of the study area with highlighted buildings for analysis.

Fig. 5. Study cases.

Fig. 6. Measurements from the case studies.

In the field of energy efficiency and lighting system performance, the research by [19,14,15,16,13,17], and [18] has provided valuable information to improve lighting efficiency and usage in buildings, thus reducing energy consumption and contributing to the sustainability of the built environment.

Despite the advances in the field of natural and artificial lighting in buildings, there are still knowledge gaps that require further research. Michael et al., [20] studied urban vernacular architecture in the Mediterranean region and found that the dense urban fabric and introverted character of the buildings limited lighting levels in indoor spaces on the ground floor. Maria et al., [21] focused on heritage school buildings and found that the daylight penetrating into the classrooms was below standard levels, leading to the use of artificial lighting as a supplement. Specifically, a better understanding is needed regarding the influence of natural lighting in different climatic and geographical contexts. Further investigation is also necessary on the effects of indoor lighting on occupant health and well-being, particularly in times of a pandemic where indoor environmental quality has become even more relevant.

In the realm of architectural and sustainability research, a notable gap in knowledge persists concerning the adaptability of vernacular architecture to emerging sanitation and lighting standards. Despite extensive investigations into the advantages of daylighting in contemporary architectural practices, a deficiency exists in comprehensive studies that systematically scrutinize historical vernacular styles, examining their daylighting strategies across diverse regions and material compositions. Works by [22] and [23] for instance, predominantly concentrate on the general bioclimatic conditions of structures, with an emphasis on thermal comfort measurement, resulting in a limited grasp of natural lighting principles in heritage residences across varied geographical conditions and the potential for future interventions.

A profound understanding of the interplay among apertures (windows), natural illumination, and regional idiosyncrasies in façade design is imperative for contemporary architects. This comprehension enables the development of sustainable and contextually fitting solutions, all while preserving heritage architecture and mitigating an increase in energy consumption, as highlighted by [24], given the scarcity of architectural discourse in this domain. Closing these knowledge gaps is indispensable for advancing the comprehension of architectural heritage and fostering the application of sustainable design principles across diverse cultural and environmental settings.

In the realm of architectural and sustainability research, a critical knowledge gap persists concerning the nuanced natural lighting strategies inherent in vernacular architecture. Despite extensive research on the benefits of natural lighting in modern architecture, there is a lack of comprehensive studies systematically analyzing vernacular styles and their associated natural lighting across diverse regions. Limited understanding exists on how vernacular architecture effectively integrates natural lighting principles in various climatic conditions. Recognizing regional and cultural nuances in vernacular design is crucial for contemporary architects to develop sustainable and contextually relevant solutions. Furthermore, literature gaps exist regarding challenges and opportunities in integrating vernacular design principles into modern practices and their contribution to broader sustainability goals. Addressing these gaps through meticulous research not only preserves traditional architectural wisdom but also informs contemporary practices, fostering the development of sustainable and contextually sensitive architecture. Bridging these knowledge gaps is essential for advancing the understanding of architectural heritage and promoting sustainable design principles across diverse cultural and environmental contexts.

Based on the previous studies conducted by the mentioned authors, it is hypothesized that the optimization of natural lighting and energy efficiency in buildings will contribute to the creation of more sustainable and healthy spaces for occupants. It is expected that future research in this field will continue to explore innovative strategies to improve natural and artificial lighting in buildings, with a focus on energy efficiency, occupant quality of life, and environmental preservation. The objective of this research is to advance knowledge about natural lighting and its impact on building performance, as well as energy efficiency and occupants' well-being.

Table 1
On-site data measurements.

Building code	Ground floor Illuminance (lux) June	Ground floor Illuminance (lux) December	Upper floor Illuminance (lux) June	Upper floor Illuminance (lux) December
Mz.3-viv.001	76.80	66.50	230.4	178.0
Mz.4-viv.004	202.4	191.6	294.0	304.7
Mz.4-viv.005	225.7	221.3	231.8	168.2
Mz.4-viv.006	282.6	291.2	307.3	285.0
Mz.4-viv.007	146.1	184.5	99.50	139.3
Mz.4-viv.013	191.9	163.3	169.2	172.5
Mz.4-viv.014	243.2	251.2	135.0	153.1
Mz.4-viv.017	41.90	33.50	17.50	17.20
Mz.5-viv.004	146.1	135.0	13.40	11.30
Mz.6-viv.004	180.6	176.0	50.40	49.90
Mz.6-viv.006	166.5	158.0	158.4	152.0
Mz.6-viv.007	69.6	68.8	133.2	150.7
Mz.6-viv.008	135.0	119.9	51.40	49.50
Mz.6-viv.009	195.4	190.0	113.6	108.0
Mz.6-viv.010	164.8	147.4	320.0	312.5
Mz.8-viv.002	148.5	133.3	81.2	83.2
Mz.8-viv.003	23.40	25.6	79.30	73.90
Mz.8-viv.006	112.2	116.2	71.90	65.50
Mz.9-viv.001	123.0	115.2	144.3	132.4

Table 2
Summary of the application of the t–Student statistic.

Place	Period	t	df	p-value
Ground floor	June-December	1,775	18	0,093
Upstairs	June-December	1,143	18	0,268
Ground floor - trade	June	−23,463	18	0,000
Ground floor - trade	December	−23,469	18	0,000
Upstairs - living room	June	−7,229	18	0,000
Upstairs - living room	December	−7,978	18	0,000
Upstairs - bedroom	June	−0,617	18	0,545
Upstairs - bedroom	December	−0,934	18	0,363

Note: "t" is the value of the statistic used; "df" are the degrees of freedom and "p-value" is the non-arbitrary minimum level of significance at which we can reject the null hypothesis.

Method

Multiple studies have explored the lighting performance of various building types, emphasizing the significance of visual comfort in indoor environments. They have assessed the daylight properties of different existing building envelopes under diverse climatic conditions, utilizing illuminance levels as a key analytical tool [25].

The method presented for the Natural lighting performance of vernacular architecture is based on a multidisciplinary approach that combines on-site measurements and simulations.

First, a review of literature, research articles, and books related to natural lighting in vernacular architecture was conducted. This provided a foundation of existing knowledge and identified key concepts, theories, and research gaps in this area. Additionally, several case studies of vernacular architecture from a city were selected based on their orientation, allowing for the interpretation of the behavior of natural light and its impact on various arrangements.

Data and information were collected for each selected case study, focusing on aspects of natural lighting such as orientation, size, and location of windows, as well as shading devices and material selection. Data on natural light levels, spatial organization, building form, and materiality were collected in relation to the performance of natural lighting. The collected data were analyzed using qualitative and quantitative methods. The relationship between different architectural elements and their impact on the quality of natural lighting was examined.

Common patterns, strategies, and design principles employed in vernacular architecture to optimize natural lighting were identified. A comparative analysis of the case studies was conducted, identifying similarities, differences, and variations in natural lighting strategies. Any recurring themes or principles emerging in different building types were identified. The effectiveness of natural lighting strategies in vernacular architecture was evaluated in terms of interior lighting quality, energy efficiency, and occupant well-being. The potential application of these strategies in contemporary architectural design and their implications for sustainability were assessed.

Based on the findings and analysis, recommendations were developed for architects and designers seeking to incorporate natural lighting strategies in contemporary buildings. Possible challenges and opportunities associated with integrating vernacular design principles into modern design practices were examined. The key findings of the research were summarized, emphasizing their implications for sustainable architectural design and heritage preservation initiatives. Finally, the study's limitations were discussed, and areas for future research were suggested.

Study phases

Firstly, measurements were taken in traditional buildings located in the city of Ambato, Ecuador. These measurements provided accurate data on the quantity and quality of natural light entering the interior spaces of the houses. These data are obtained at three different times of the day: 10:00, 12:00 and 15:00, with a latitude of −1.26667 and longitude of −78.7333.

Subsequently, computational simulations were conducted to evaluate the behavior of sunlight in these spaces. These simulations were performed using specialized software such as Velux Daylight Visualizer and SketchUp. With the help of these programs, different scenarios and lighting conditions could be analyzed, allowing the identification of areas with light deficiencies and possible solutions to improve natural lighting in the interiors.

The method also considered the typology of the buildings, such as window arrangements, the distribution of interior spaces, and the orientation of the facades. These factors play a crucial role in the amount of natural light that can enter the spaces and were therefore taken into account in the simulations. This multidisciplinary approach offers a solid foundation for developing effective strategies that optimize natural lighting in these spaces, thereby contributing to sustainability, occupant well-being, and the preservation of traditional architectural heritage.

In summary, the method used in this research combines real data obtained through on-site measurements with computational simulations to provide a comprehensive understanding of the performance of natural lighting in Ecuador's vernacular architecture.

In Fig. 1, show the flowchart of the method is presented. The method employed in this study consists of three primary steps: 1) Selection of buildings; 2) Geometric characterization of buildings; 3) Creation of a 3D model of the studied houses; 4) Simulation of natural sunlight variables; and 5) Presentation of results.

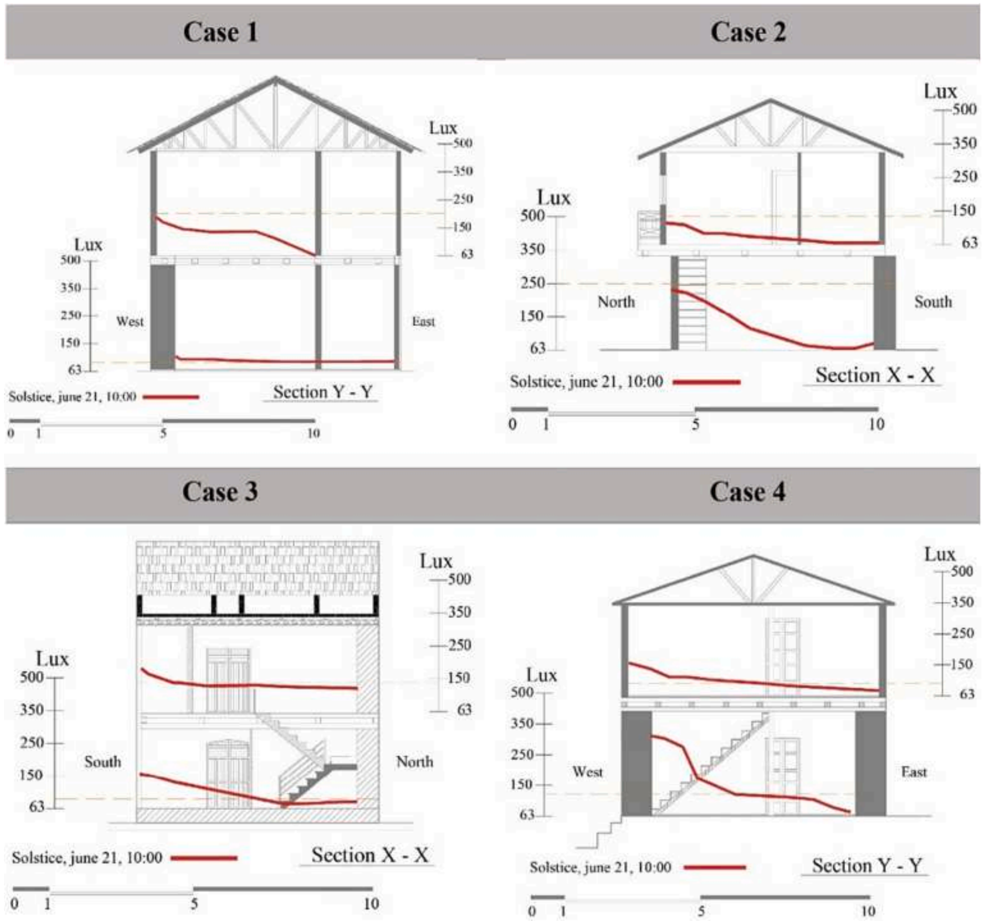

Fig. 7. Sections with a projection of luminous intensity.

The method of the *t*-test was employed using SPSS version 26 software to analyze the variation in incident radiation in households over the course of months. The Shapiro-Wilk test was applied to check the normality of the data. The Velux software was used to predict natural lighting and its implications in the buildings studied to analyze the energy process, as Ahmad et al., did [26].

Results

The research on the performance of natural lighting in vernacular architecture has revealed traditional design strategies and their impact on the quality of natural illumination. Through an examination of factors such as building orientation, window characteristics, shading mechanisms, and material choices, this research seeks to interpret the complex relationship between architectural elements and the efficiency of natural lighting. The results provide insights into specific design principles employed in vernacular architecture, showcasing patterns and strategies that optimize the use of natural light. The following paragraphs delve into the detailed results, highlighting recurring themes, effective strategies, and the potential applicability of these findings in the realm of sustainable architectural design.

Case study

Ecuador, a country located in the western part of South America (see Fig. 2), boasts a diverse and varied landscape. Bordered by the Pacific Ocean to the west, Colombia to the north, and Peru to the southeast, it lies within the coordinates of 81.03° W to 75.16° W longitude and 1.48° N to 5.04° S latitude [27].

In Fig. 3 show, the parish of Pasa is located in Tungurahua, Ecuador, with a latitude of 1° 26′ S and a longitude of 78° 73′ W. Being close to the equator, the path of the sun is the same in summer and winter and the amount of light is similar throughout the year. The situation produces a direct incidence of the sun's rays, with greater intensity and heat, unlike other geographical locations. From the socio-economic point of view, this population has as main activities agriculture, the development of handicrafts and the sale of textiles.

The studied houses are considered vernacular architecture since they were built in the late 19th and early 20th century, maintaining strong tendency of a colonial and republican tradition. In general, its simple construction of square and rectangular plans, using traditional and artisanal materials. As for its construction system, the main feature is the traditional construction of the Ecuadorian Andean Sierra, load-bearing walls with mixed use of mud blocks; that is why the thickness of its walls is approximately 60 cm. In addition, the use of a bahareque construction system, which is based on the use guadua wood and mud, relieves the load and is usually used on the upper floors. As far as its materiality, there is a use of local materials that have to do with sustainability and location, like adobe, bahareque, rammed earth, hand wall, cangahua stone, pishilata stone, wood, iron (not very regular) and a tile roof [29]. In this sense, thick and heavy walls have hight thermal inertia that acts as a thermal regulator contributing to stabilise indoor temperatures, and small windows can lead to lighting deficiencies. On the other hand, the intervention in these traditional homes can jeopardize the conservation of heritage due to several intrinsic and extrinsic factors. Therefore, it is necessary to analyze their current state and propose changes without compromising their cultural characteristics.

Fig. 4 illustrates the location and orientation of each building under study. The first house (case 1) is situated in a corner position with a northeast orientation. It has three facades, and the main openings are

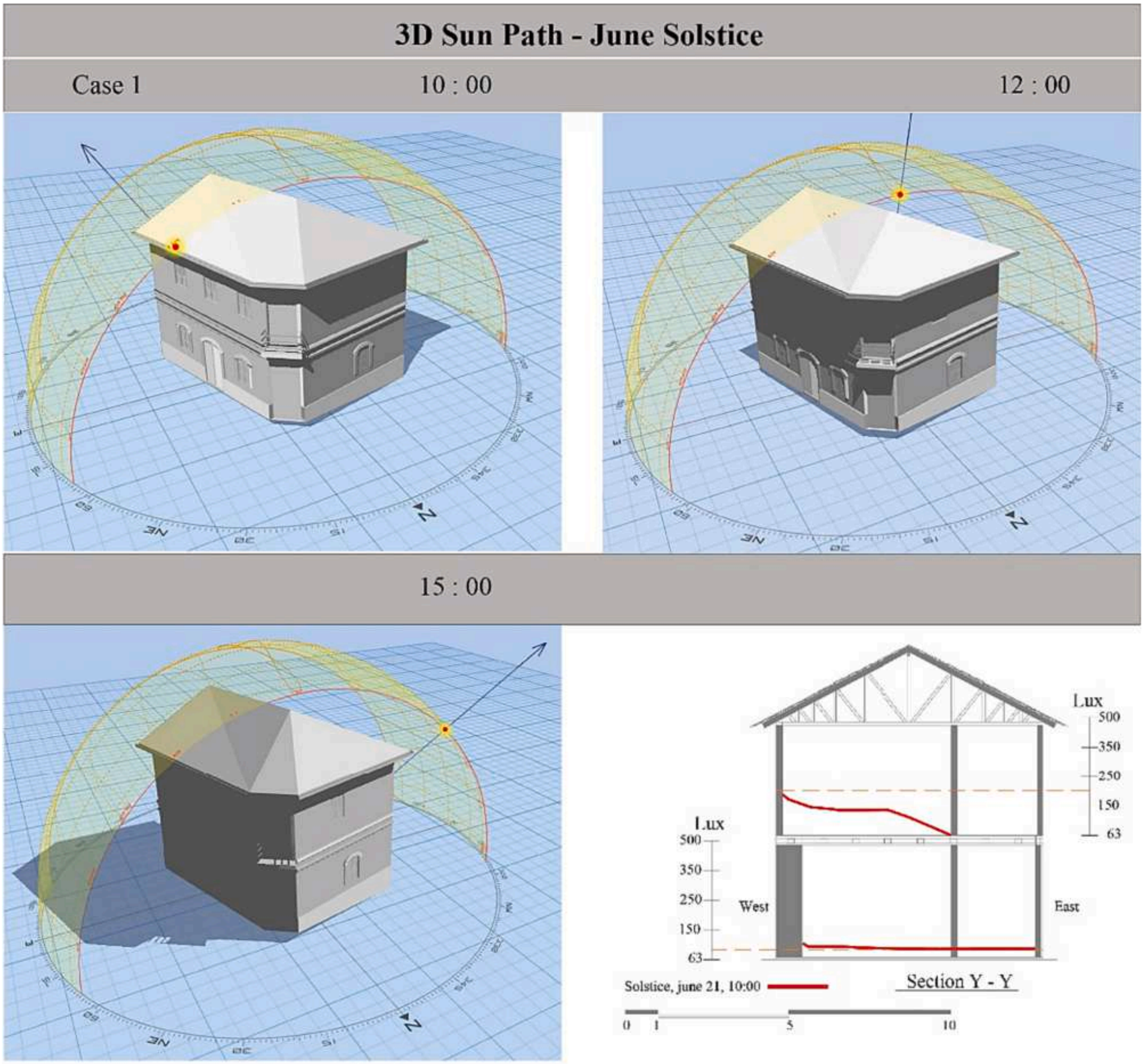

Fig. 8. Simulation of the June solstice in a dwelling (case 1).

located on the northeast facade. The second unit (case 2) is compact with a northeast orientation and follows a townhouse typology. The main openings are positioned on the north facade. The third house (case 3) consists of two building bodies, with the study focusing on the one facing the main street. It has a south orientation and features a compact front with a townhouse type layout. The main openings are located on the south facade. Lastly, the fourth house (case 4) is a compact dwelling with a west-facing balcony and a dividing wall. The main openings are situated on the main west facade.

The orientation of the main facades and the number and size of openings play a crucial role since they are the sole means through which natural light enters these spaces. Therefore, understanding the specific location and orientation of each building is fundamental to comprehending the impact of natural lighting within their interiors. In Fig. 5, photos of the 4 case studies are shown.

Information collection

For data collection, two observation sheets were applied, which constitute the research instruments. The first one collected the general elements of the drawing and measurement survey of each of the houses. In Fig. 6, the measurements of the case studies are displayed.

Table 1 shows the illuminance values obtained in the in-situ measurements, for the ground floor and the upper floor of the 19 traditional buildings. Two measurements were made in the year, which correspond to the months of June and December.

The results obtained from the measurements and simulations revealed that some interior spaces had insufficient levels of natural lighting, especially those with a compact typology and few openings to the exterior. For the ground floor with measurements in June and December, a significance of 0.093 is obtained and therefore higher than 0.05, so the null hypothesis that establishes that there is no significant difference between the measurements is accepted. For the measurement of the upper floor in the same months, there is a significance of 0.268 that in the same way, accepts the null hypothesis. In this way, it can be concluded that the existing illuminance in these homes does not have variations in different months of the year.

Based on the NTE INEN 1152 standard, the reference table of the quantity of luxe per environment is considered: commercial area = 500 lx, bedroom = 150 lx, room = 300 lx. In these houses, on the ground

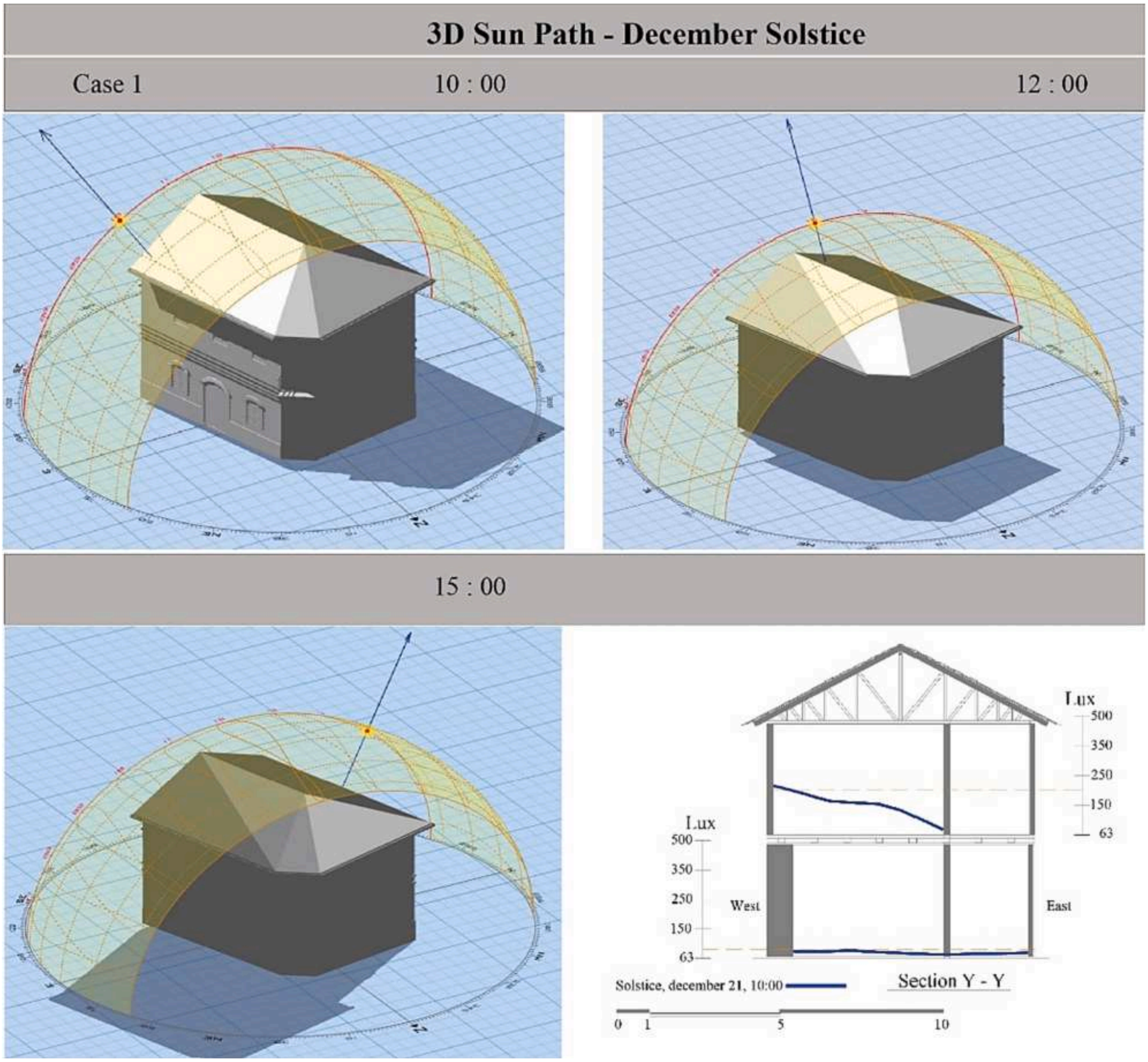

Fig. 9. Simulation of the December solstice in a dwelling (case 1).

floor are located the commercial premises, while on the upper floor both the living room and the bedrooms. The same statistical analysis above is applied and it is obtained that there is a significant difference between the samples of the ground floor in June and December, and the data of the norm a commercial space. Similarly, the samples from the upper floor also present a difference when compared to what is required by the standard for a room. While in the analysis of the samples of the upper floor in June and December there is no significant difference compared to the standard measure of a bedroom. Table 2 presents the summary of what was obtained, with an error of 5 %. This concludes that the spaces examined could not be used as a room or as a place of commerce and the use of artificial lighting is justified.

The aforementioned information is corroborated with the cross sections generated by housing, where the volume of the space (length and width) and the projection of the luminous intensity generated by the source of natural light is evidenced. This crosses the vertical opening of the main facade until it reaches the surface, thus generating the corresponding level of illumination. In all four cases, there are similar values, with levels between 60——250 lx, as shown in Fig. 7. It can be inferred that the typology of the buildings is compact, having mostly openings in the main facade and there is its only source of light.

In the initial phase of analyzing the properties, a meticulous selection process was undertaken, focusing on the ingress of natural light based on different orientations and the encompassing variations. Alongside this, meticulous attention was paid to the percentages of the daylight factor penetrating the interior spaces. This evaluation centered on specific points within these spaces, they considered the percentages of the daylight factor entering the spaces which are in the range of 0.5 % to 1.5 %. Similarly, the percentages of illuminance infiltrating the spaces were taken into account. These values were found to lie within the approximate range of 42 to 250 lx.

It's important to note that this evaluation was conducted for both the summer and winter solstices. This is especially noteworthy as the equatorial region experiences only two discernible seasons. The outcomes of this rigorous analysis are visually presented in Fig. 8 and Fig. 9, offering a graphical representation of the results obtained from the data.

With the information collected, the project strategies for the intervention are put together, which has to do with spatial planning for the execution of the proposal. Figure presents the schemes of the implementation of the pipeline system in the selected case studies. As it can be seen in the illustrations, the contrast is notorious, in which the colour on the surfaces changes with the application of the solar tubes compared to

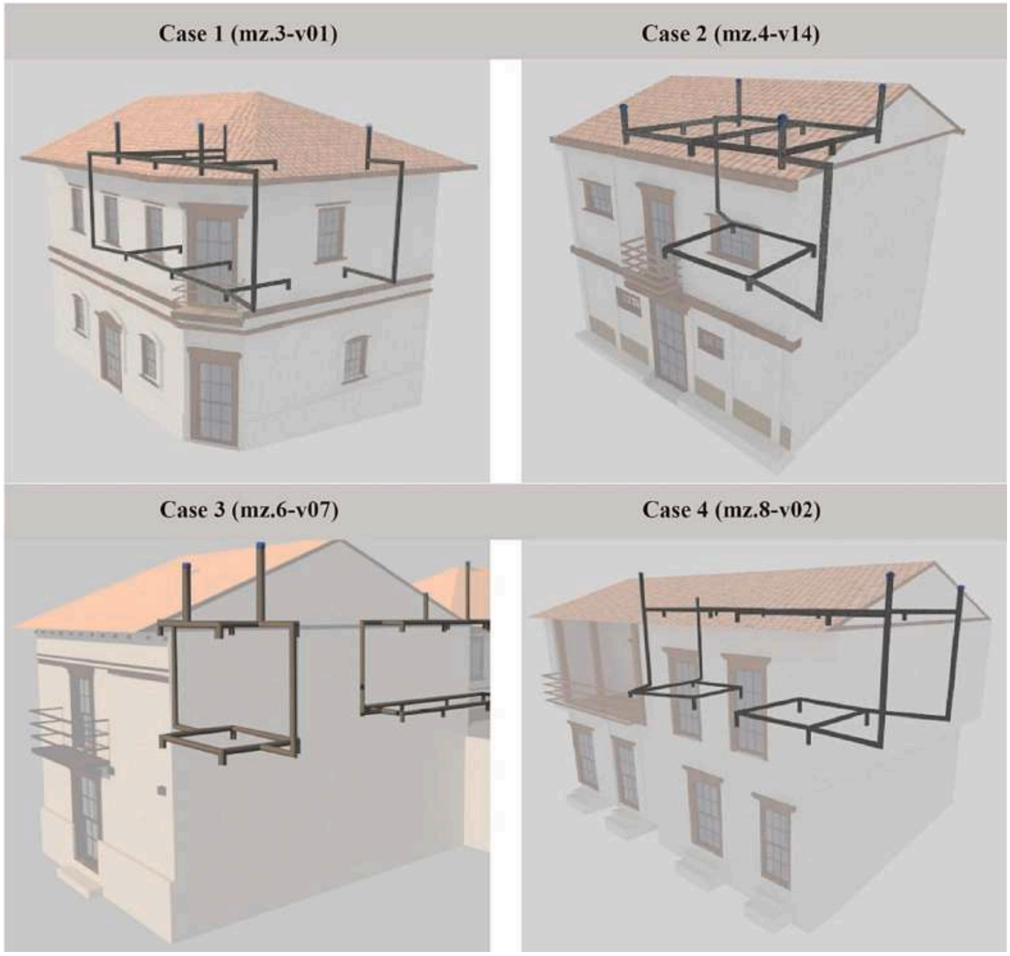

Fig. 10. Pipeline system in case studies.

Table 3
Daylight factor of the four houses.

Case	Ground floor Current (%)	Intervention (%)	Difference (%)	Upper floor Current (%)	Intervention (%)	Difference (%)
1	0,5	0,7	0,2	0,6	1,3	0,7
2	1	2,5	1,5	0,3	2,1	1,8
3	0,5	1,6	1,1	0,1	1,8	1,7
4	0,7	1,3	0,6	1,3	3,5	2,2

the current state; it is also important to mention that the application of this system is in the same structure of the house, that is, the structural or formal part is not altered, mainly in the facade.

The specific parameters featured in Fig. 10 depicting the pipeline system encompass pipe diameters of approximately 15 cm, accompanied by path lengths varying from 6 to 8 m. These specific configurations were thoughtfully selected to maximize the capture of natural light and optimize its even distribution throughout the interior spaces.

After establishing the existing conditions and defining the intervention, we employ the VELUX software to generate a series of graphs that provide percentages of the daylight factor, categorized by floors. Simultaneously, data is extracted from images to quantify illuminance contrasts during both the summer and winter solstices. These measurements are conducted within the same selected interior space on a per-floor basis, mirroring the current scenario.

a) Daylight factor analysis

In the first analysis of the representation of the daylight factor, using isolux curves, there is an improvement of the percentage levels of interior illuminance in the selected spaces, under the same sky conditions and on the same dates (summer and winter). Table 3 describes the percentages of initial lighting and those achieved with the proposal, as well as their difference. In all four cases, an increase in the percentages of natural lighting can be observed, being cases 2 and 3 where there is a uniformity of both floors. However, as a trend, it is identified that the upper floor is the one that presents the greatest use. This is related to what is expected since the proposal allows the entry of light through the roof of the home. For better appreciation, the corresponding illuminance contrast is arranged in Fig. 11, Fig. 12, Fig. 13 and Fig. 14.

In the simulations, the interior surfaces were characterized with an average reflectance value of approximately 0.7, reflecting the typical properties of materials commonly used in local constructions.

Table 3 presents the Daylight Factor (DLF) values for the four houses under study, comparing the current conditions with the proposed

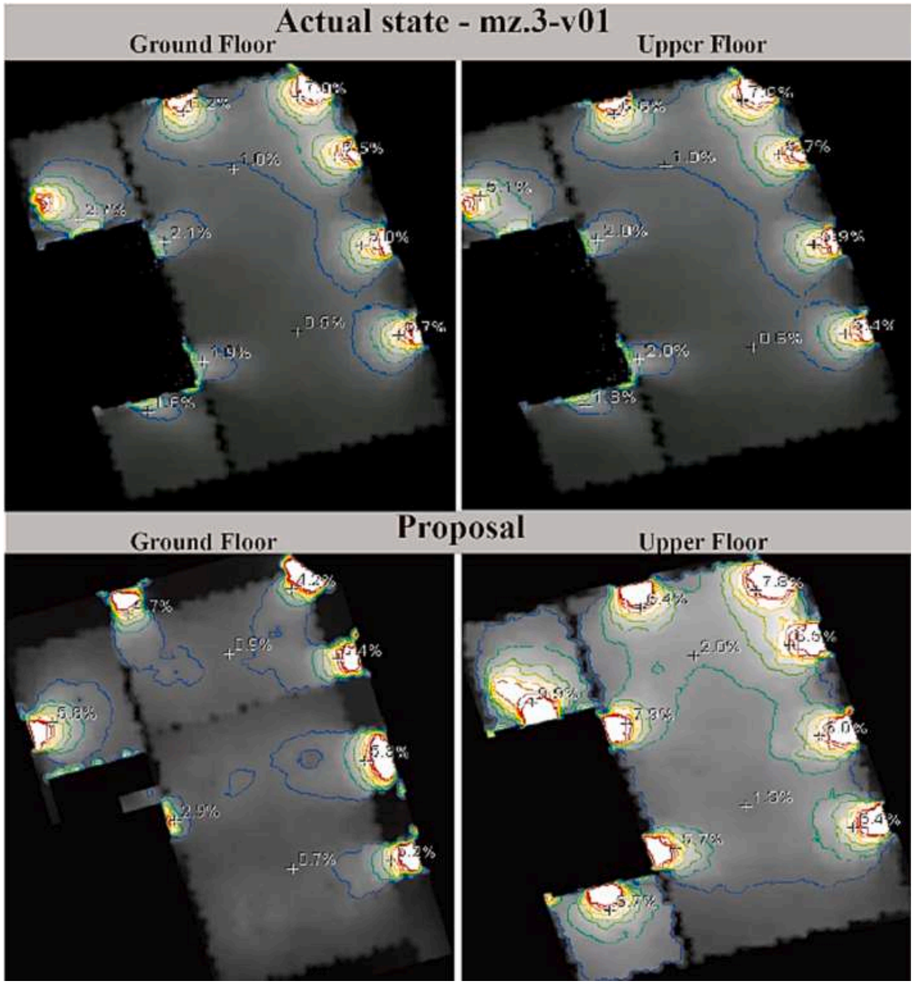

Fig. 11. Contrast of illuminances (isolines) of the four dwellings: case 1.

intervention. The DLF is a measure of the amount of natural daylight that reaches the interior of a space.

For Case 1, (Fig. 11) on the ground floor, the current DLF is 0.5 %, which increases to 0.7 % after the intervention, resulting in a difference of 0.2 %. On the upper floor, the current DLF is 0.6 %, rising to 1.3 % after the intervention, indicating a difference of 0.7 %.

In Case 2, (Fig. 12) the ground floor experiences an increase from 1 % to 2.5 % in DLF after the intervention, a difference of 1.5 %. On the upper floor, the current DLF is 0.3 %, which notably improves to 2.1 % post-intervention, representing a significant difference of 1.8 %.

Case 3, (Fig. 13) demonstrates a similar pattern. The ground floor's DLF shifts from 0.5 % to 1.6 % after the intervention, leading to a difference of 1.1 %. Meanwhile, the upper floor witnesses a transition from 0.1 % to 1.8 % DLF, resulting in a substantial difference of 1.7 %.

Lastly, Case 4 (Fig. 14) displays an increase in DLF for both floors. On the ground floor, the current DLF of 0.7 % advances to 1.3 % after the intervention, yielding a difference of 0.6 %. On the upper floor, the DLF escalates from 1.3 % to 3.5 % post-intervention, presenting a remarkable difference of 2.2 %.

b) Contrast of illuminances (lux)

The second analysis corresponds to the measurement of the luminous flux given by the lux illuminances and which was measured in the same spaces as the analysis of the current state. Therefore, it is the ratio of the luminous flux per unit area, this being the amount of light on a given surface. Below is the analysis with the respective variations for the verification of the light values obtained. For the ground floor of the four cases, the information is provided in Table 4 and their respective contrast of illuminances in Fig. 15, Fig. 16, Fig. 17 and Fig. 18. The results show that there is a considerable increase, especially in the fourth house, where it is more than double of the initial percentage. In general, it can be observed that following what is expected during the summer solstice, the values obtained with the developed proposal are enhanced.

Table 4 displays illuminance values in lux on the ground floor of the four houses during the summer solstice and winter solstice, both in current conditions and after the proposed intervention.

In Case 1, (Fig. 15) during the summer solstice, the current illuminance on the ground floor is 76.8 lx, which increases to 99.8 lx after the intervention, resulting in a difference of 23.0 lx. During the winter solstice, the current illuminance is 66.5 lx, which rises to 100.4 lx after the intervention, indicating a difference of 33.9 lx.

For Case 2, (Fig. 16) during the summer solstice, the current illuminance on the ground floor is 243.2 lx, which escalates to 284.2 lx after the intervention, yielding a difference of 41.0 lx. During the winter solstice, the current illuminance is 251.2 lx, which increases to 290.6 lx after the intervention, reflecting a difference of 39.4 lx.

In Case 3, (Fig. 17) during the summer solstice, the current illuminance on the ground floor is 133.2 lx, which advances to 222.7 lx after the intervention, resulting in a difference of 94.5 lx. During the winter solstice, the current illuminance is 150.7 lx, which rises to 205.5 lx after the intervention, indicating a difference of 54.8 lx.

Lastly, in Case 4, (Fig. 18) during the summer solstice, the current illuminance on the ground floor is 97.6 lx, which increases to 236.4 lx

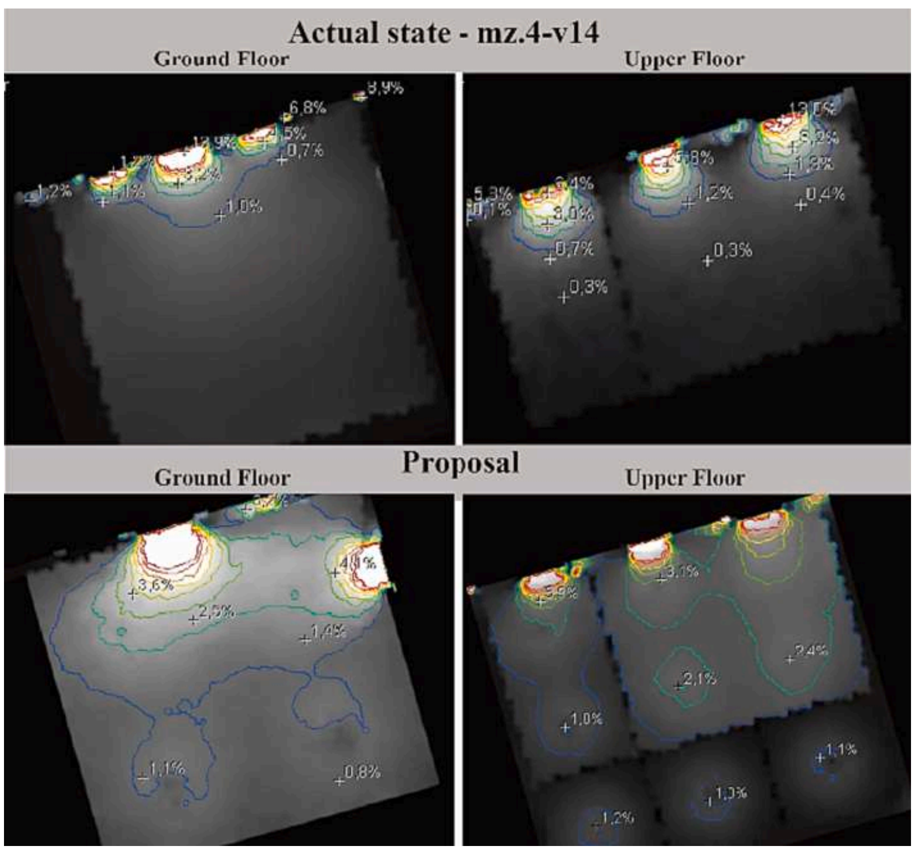

Fig. 12. Contrast of illuminances (isolines) of the four dwellings: case 2.

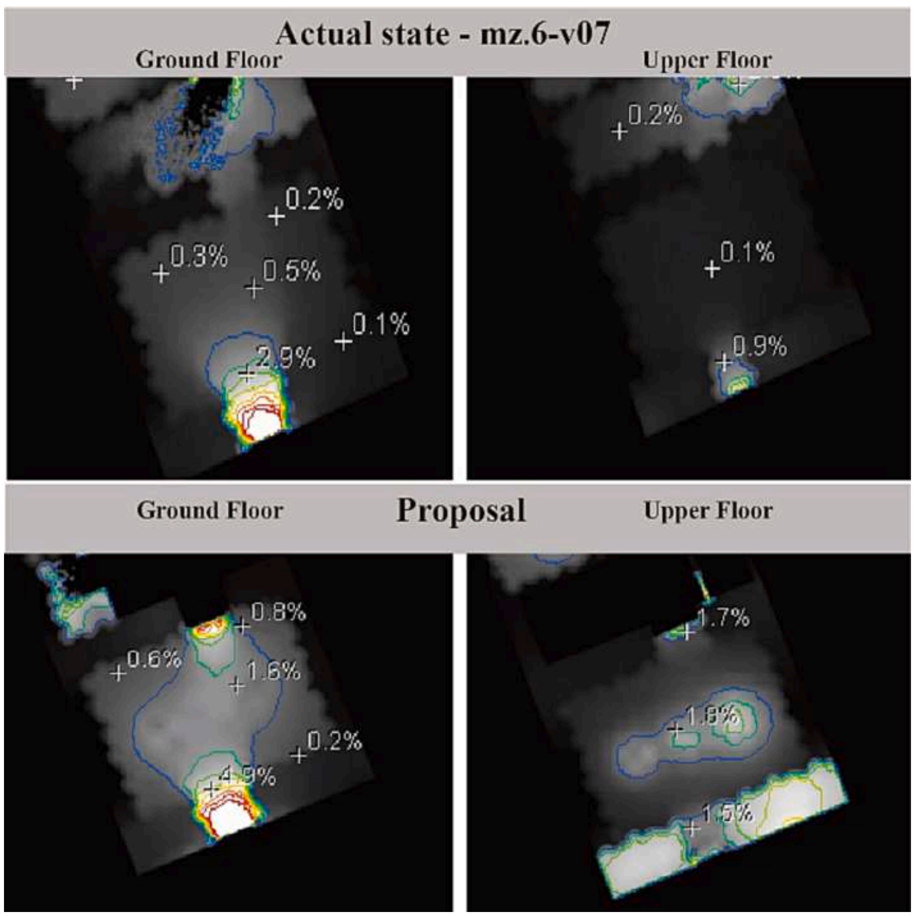

Fig. 13. Contrast of illuminances (isolines) of the four dwellings: case 3.

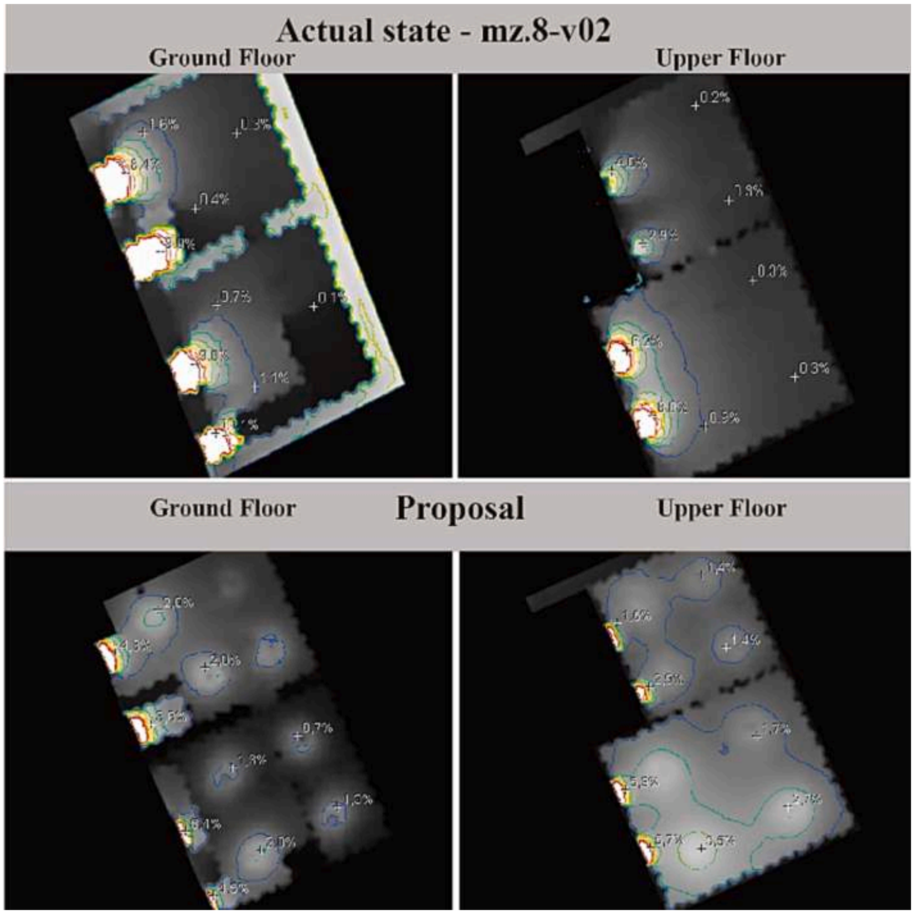

Fig. 14. Contrast of illuminances (isolines) of the four dwellings: case 4.

Table 4
Illuminances of the ground floor of the four houses.

Case	Summer Solstice Current (lux)	Intervention (lux)	Difference (lux)	Winter Solstice Current (lux)	Intervention (lux)	Difference (lux)
1	76,8	99,8	23,0	66,5	100,4	33,9
2	243,2	284,2	41,0	251,2	290,6	39,4
3	133,2	222,7	94,5	150,7	205,5	54,8
4	97,6	236,4	138,8	99,1	203,3	104,2

after the intervention, leading to a difference of 138.8 lx. During the winter solstice, the current illuminance is 99.1 lx, which rises to 203.3 lx after the intervention, presenting a difference of 104.2 lx.

Something similar was done for the analysis of the upper floor in each of the houses, which is shown in Table 5, Fig. 19, Fig. 20, Fig. 21 and Fig. 22. Based on the results, it is established that in cases 1 and 2 there is a higher percentage of increase during the summer solstice, compared to the winter solstice. While in cases 3 and 4 the values remain similar in both cases and with a slightly higher difference during the winter solstice.

Table 5 illustrates illuminance values in lux on the upper floor of the four houses during the summer solstice and winter solstice, both in their existing state and following the proposed intervention.

In Case 1, (Fig. 19) during the summer solstice, the current illuminance on the upper floor is 230.4 lx, which increases substantially to 351.5 lx after the intervention, resulting in a significant difference of 121.1 lx. During the winter solstice, the current illuminance is 178.1 lx, which rises to 231.1 lx after the intervention, indicating a difference of 53.0 lx.

For Case 2, (Fig. 20) during the summer solstice, the current illuminance on the upper floor is 135 lx, which experiences a remarkable escalation to 277.6 lx after the intervention, generating a substantial difference of 142.6 lx. During the winter solstice, the current illuminance is 153.1 lx, which significantly increases to 273.8 lx after the intervention, revealing a difference of 120.7 lx.

In Case 3, (Fig. 21) during the summer solstice, the current illuminance on the upper floor is 38.8 lx, which rises considerably to 112.2 lx after the intervention, yielding a notable difference of 73.4 lx. During the winter solstice, the current illuminance is 49.7 lx, which significantly improves to 134.4 lx after the intervention, reflecting a difference of 84.7 lx.

Lastly, in Case 4, (Fig. 22) during the summer solstice, the current illuminance on the upper floor is 48.0 lx, which experiences a substantial increase to 162.2 lx after the intervention, resulting in a notable

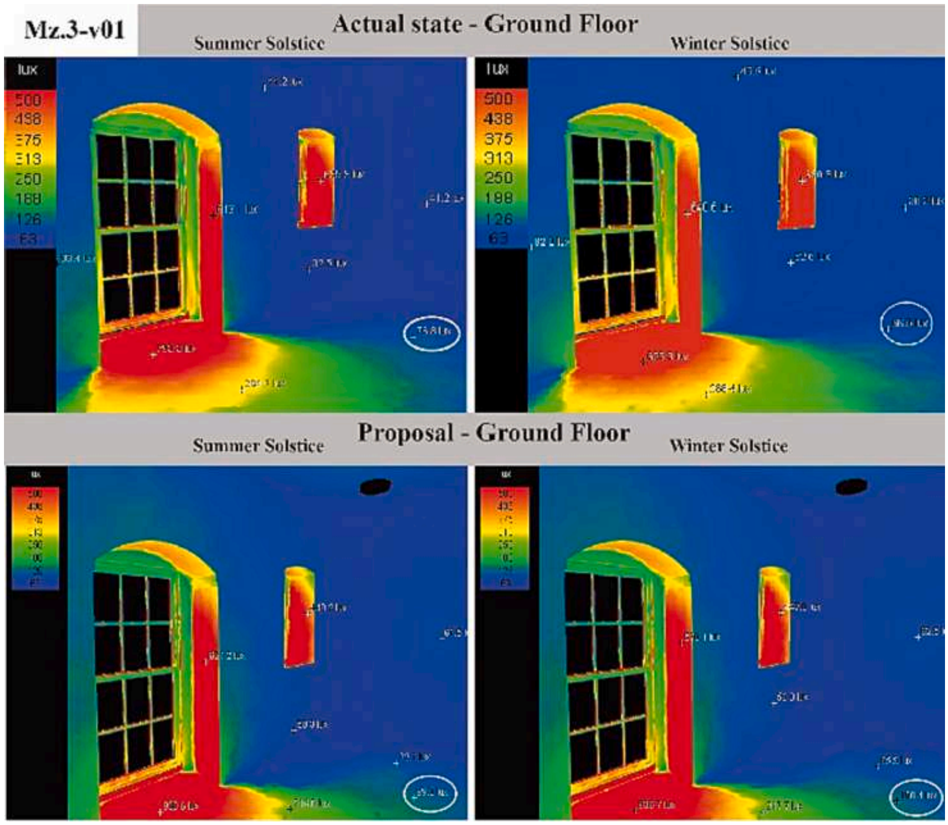

Fig. 15. The contrast of illuminances (lux) of the ground floor of the four houses: case 1.

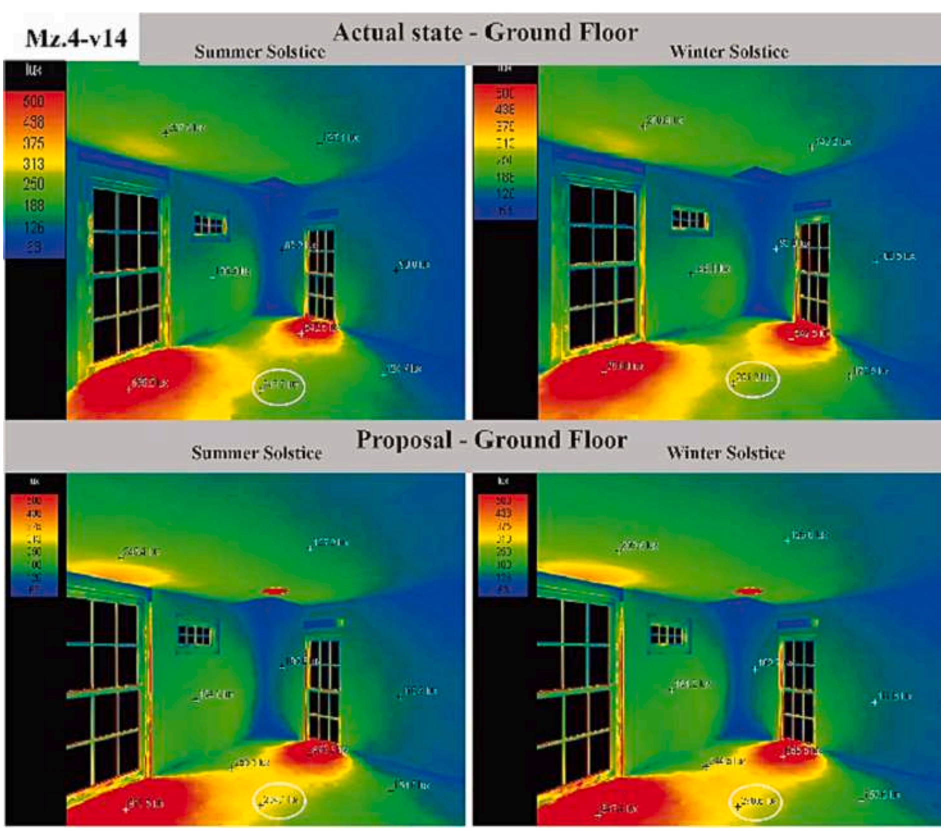

Fig. 16. The contrast of illuminances (lux) of the ground floor of the four houses: case 2.

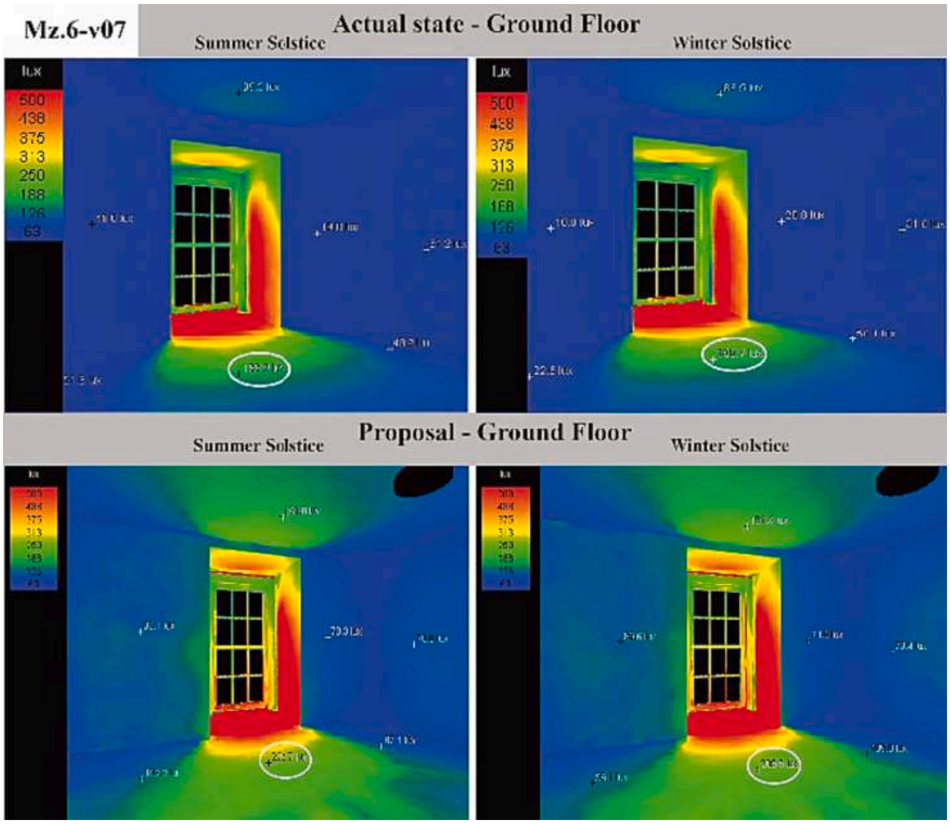

Fig. 17. The contrast of illuminances (lux) of the ground floor of the four houses: case 3.

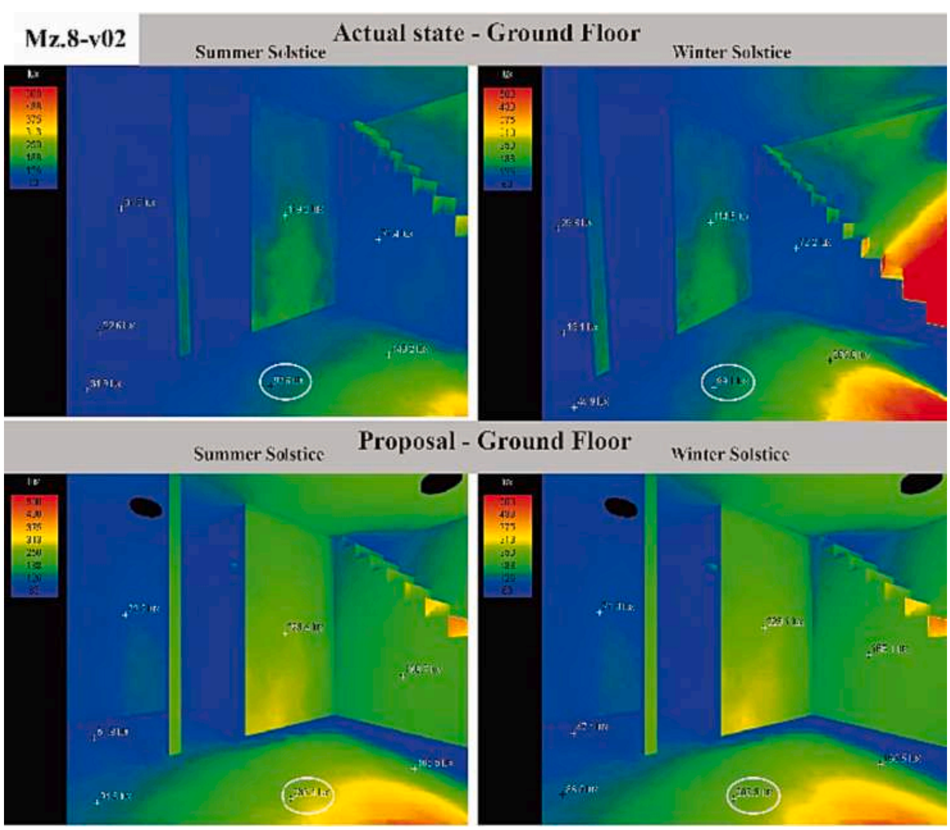

Fig. 18. The contrast of illuminances (lux) of the ground floor of the four houses: case 4.

Table 5
Illuminances of the upper floor of the four houses.

Case	Summer Solstice Current (lux)	Intervention (lux)	Difference (lux)	Winter Solstice Current (lux)	Intervention (lux)	Difference (lux)
1	230,4	351,5	121,1	178,1	231,1	53,0
2	135	277,6	142,6	153,1	273,8	120,7
3	38,8	112,2	73,4	49,7	134,4	84,7
4	48,0	162,2	114,2	42,9	159,1	116,2

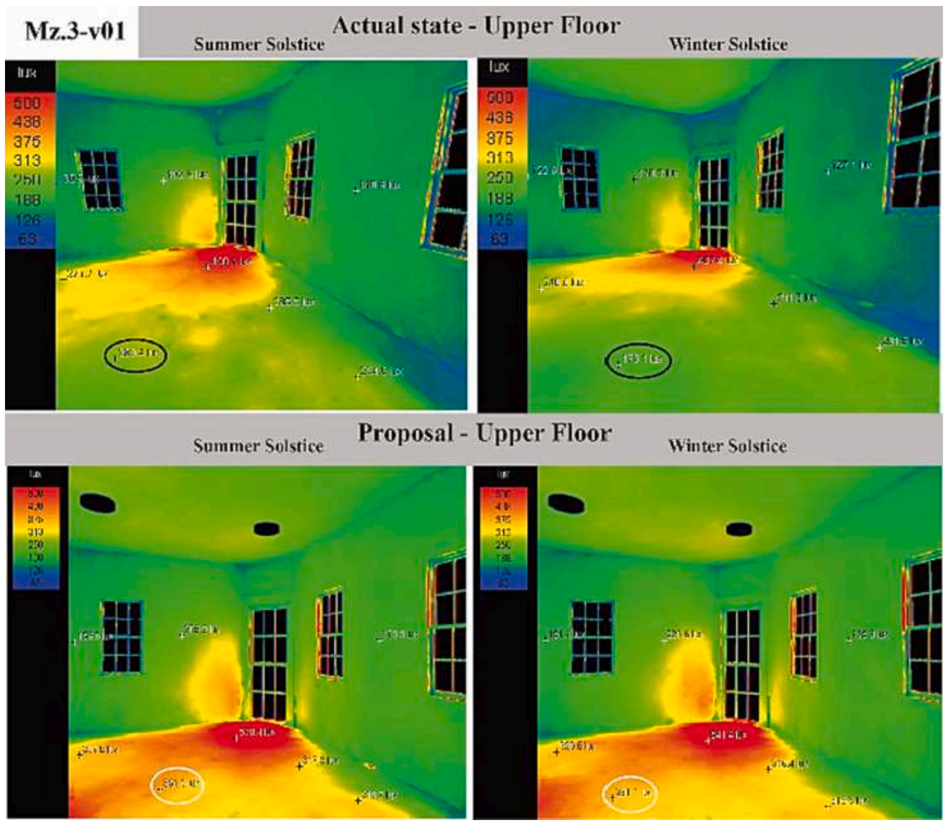

Fig. 19. The contrast of illuminances (lux) of the upper floor of the four houses: case 1.

difference of 114.2 lx. During the winter solstice, the current illuminance is 42.9 lx, which significantly improves to 159.1 lx after the intervention, demonstrating a difference of 116.2 lx.

Discussion

The Pasa parish preserves its historic buildings. However, the lighting conditions in the selected houses often fall short of adequacy. The initial analysis revealed that the daylight illumination of both the ground and upper floors of the 19 houses exhibited minimal variation between the solstices. This is attributed to the scarcity of natural light sources, which limits potential variations. These findings parallel studies on Ecuadorian vernacular architecture [29] and [30], which commonly feature few and small windows on the ground floor, leading to insufficient illumination in these areas. Local regulations indicate non-compliance, particularly on the ground floor used for commercial establishments. Similarly, on the upper floor, typically hosting rooms, meetings, and activities necessitating substantial lighting presence, compliance remains an issue.

Ecuador's proximity to the equator ensures uniform solar incidence throughout the day. The analysis of radiation variations across months found statistically insignificant differences.

In terms of physical characteristics, simulations aligned with the chosen strategy indicated substantial increases in the Daylight Factor (DLF) within the four studied houses. These improvements were prominent on both ground and upper floors, with a more pronounced effect on the latter due to shorter light pathways through the roof entry point. Notably, House number 4 demonstrated the most significant changes, potentially negating the need for artificial lighting on the second floor. Despite minor annual radiation variation, illuminance values generally increased during the summer solstice. While values differed for houses 3 and 4 in the upper floor analyses and for the ground floor analysis of house 1. Crucially, the proposed intervention requires no major structural changes.

Contrasting with some multifaceted studies our research solely focused on lighting, underpinned by well-preserved structures and durable materials. This approach aligns with the common emphasis on lighting enhancement within this housing type, as reiterated in the review by Galatioto and Beccali [31].

Lastly, socio-cultural identity emerges as a pivotal consideration. Research [32,33] and [34] underscores the intangible value of Ecuadorian geoheritage, necessitating safeguarding. Traditions in the Andean region, only transferable through tangible forms like handicrafts or housing, exemplify the indigenous peoples' resource-efficient home-building ability.

Traditional architecture possesses many valuable and relevant features in both construction and form. Today, from a sustainability perspective and in the study of its relationship with the environment,

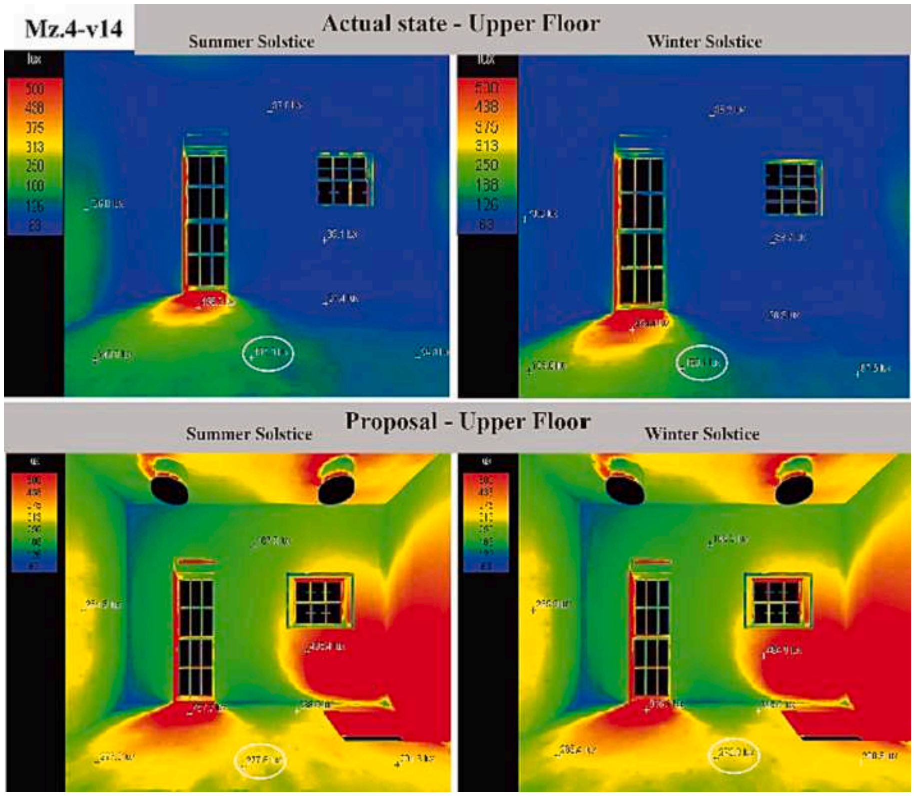

Fig. 20. The contrast of illuminances (lux) of the upper floor of the four houses: case 2.

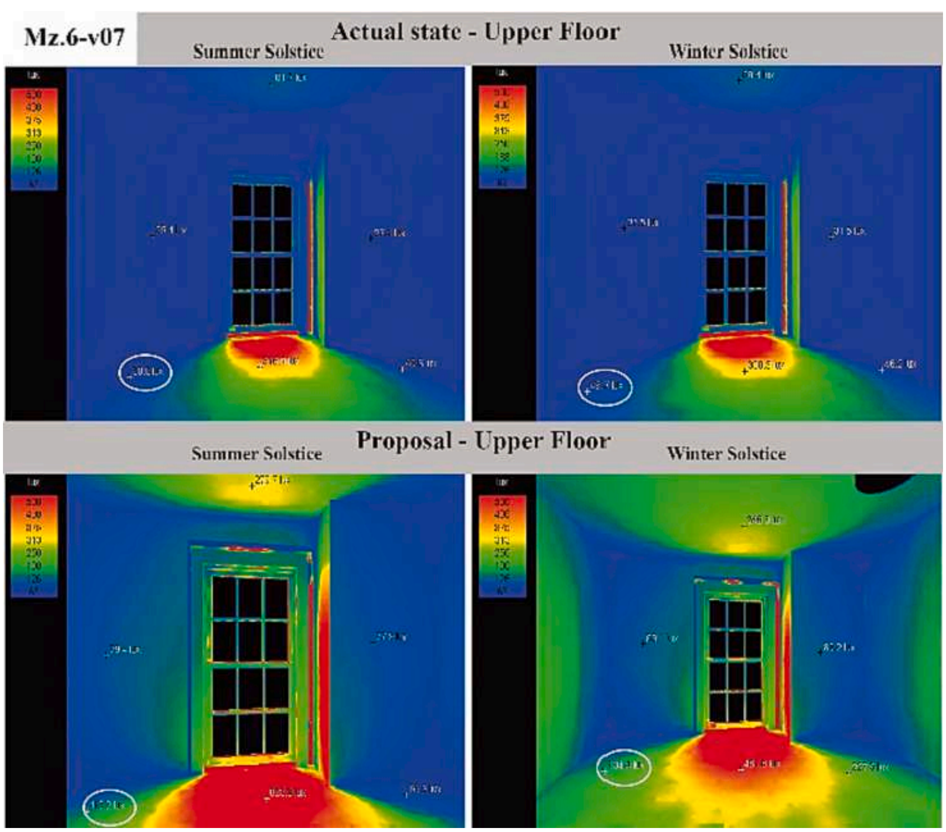

Fig. 21. The contrast of illuminances (lux) of the upper floor of the four houses: case 3.

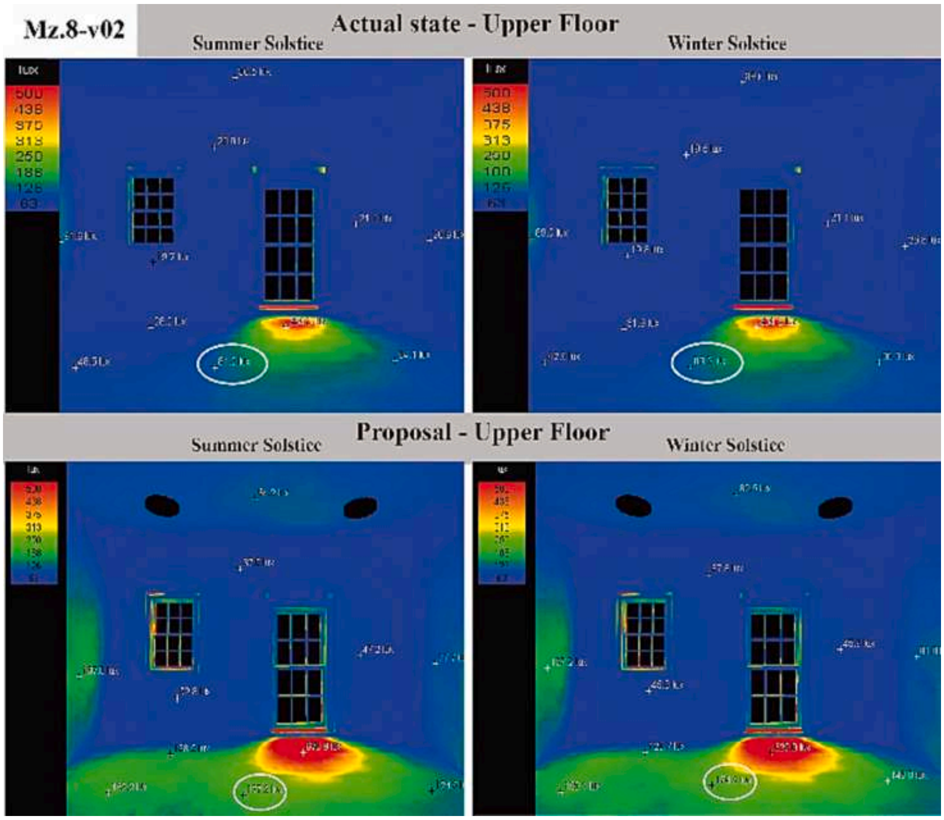

Fig. 22. The contrast of illuminances (lux) of the upper floor of the four houses: case 4.

this architecture is being reevaluated, even though the way of life it once represented has become obsolete. Valuing traditional architecture involves integrating the needs of new lifestyles, which highlights deficiencies that were not significant at the time or couldn't be easily addressed. Natural ventilation and lighting levels are often insufficient in these structures due to the size of openings (windows), which were constrained by the construction system and available materials. Earth construction requires mass to ensure structural support, leading to a much smaller proportion of openings compared to solid components. This reduced size of openings persisted over time due to limited access to materials like glass, which allows windows to let in light while protecting against rain or wind.

Today, changes in the use of buildings are common, and their adaptation to new needs is necessary. In places like the Pasa canton in the Tungurahua province of Ecuador, the occupancy patterns of buildings have evolved. Despite being located in rural areas; new activities have been incorporated into the village. The ground floors of buildings are adapted for commercial purposes, and modifications are made to the upper floors to accommodate one or more residences. This involves incorporating other spaces like kitchens and bathrooms and dividing the originally large rooms to suit larger families. These functional changes in buildings and housing reevaluate the comfort levels of both natural and artificial lighting and ventilation in old buildings. Therefore, it makes sense to improve the quality of lighting in these buildings constructed in different times and with different principles.

It's important to note that interventions to adapt artificial lighting in heritage buildings can pose challenges, as they require balancing the incorporation of new elements with the preservation of elements with architectural value. However, with careful planning and the use of techniques that maximize the utilization of natural lighting with minimal interventions to the buildings, it's possible to achieve a successful rehabilitation of vernacular buildings considered as heritage. These techniques may include restoring original windows or incorporating skylights and natural lighting systems that respect the morphology and integrity of the building.

Conclusions

Vernacular architecture adapts the design of both interior spaces and facades to local climatic conditions, using bioclimatic approaches. This study evaluates the natural lighting conditions of 19 traditional homes in the parish of Pasa, Ecuador. Furthermore, four representative buildings of the study, were chosen based on their orientation. Both simulations and in situ measurements show the relationship of the lighting of the different areas and their social use. Ground floor space tends to show insufficient lighting level and is therefore relegated to secondary functional roles. The findings of this study point to some possible interventions to improve design principles and patterns to offer a more diverse and efficient use of all living spaces in the area.

The findings also show that vernacular buildings are nor proportional to current living standards. Since the use of natural light is not a priority in the design of these houses, the lighting levels of many spaces are below regulation. This has an impact on the behavior of the occupants, who must limit the development of certain activities in these areas. Therefore, owners and tenants have opted for the use of electric lighting even during the day, which affects their economy and quality of life. This study was developed to prove that important improvements can be obtained, combining ancestral design and contemporary techniques.

The in situ measurements validated the simulations in different seasons and the results provide technical information on possible interventions to improve the lighting conditions of the houses without harming their state of conservation. The use of natural light in interior spaces is proposed, as an architectural asset to be considered in the design process. However, for a more complete approach, periodic measurements are needed to generate time series. Therefore, it is proposed as future work to carry out an investigation with longitudinal cut, which allows to have a greater amount of information. These complete sets of data can be used in conjunction with advanced methods such as artificial intelligence to predict new scenarios. The findings of this and other studies point to the need to implement policies to improve lighting conditions in traditional dwellings, in line with contemporary theories on Indoor Environment Quality [35].

Local government encourages this behavior with direct incentives and in other cases tax cuts. However, conservation policies do not contemplate lighting improvement schemes since natural light is not considered as a resource to improve habitability. The proposed approach has sustainable validity, since it takes advantage of a free and natural resource, considering that there are people sensitive to artificial lighting, which improves their quality of life. The optimization of resources allows it to be used to promote economic development and investment in other basic services less accessible. The conservation of these spaces is also a boost to sustainable tourism, which motivates internal and external tourists, boosting trade. Another important aspect Environmental protection that is obtained by reducing electricity consumption and other related resources.

Funding

This work was supported by the Universidad Indoamérica [project "Estudio de confort térmico y estrategias pasivas en viviendas del sector rural del Cantón Ambato", 2022].

CRediT authorship contribution statement

Darío Bustán-Gaona: Conceptualization, Methodology, Software, Visualization, Investigation, Validation. **Manuel Ayala-Chauvin:** Data curation, Methodology, Writing – original draft, Investigation. **Jorge Buele:** Writing – review & editing. **Patricia Jara-Garzón:** Writing – review & editing. **Genís Riba-Sanmartí:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

[1] Akram MW, Hasanuzzaman M, Cuce E, Cuce PM. Global technological advancement and challenges of glazed window, facade system and vertical greenery-based energy savings in buildings: A comprehensive review. Energy Built Environ 2023;4:206–26.
[2] Ruggiero S, Iannantuono M, Fotopoulou A, Papadaki D, Assimakopoulos MN, De Masi RF, et al. Multi-Objective Optimization for Cooling and Interior Natural Lighting in Buildings for Sustainable Renovation. Sustain 2022;14. https://doi.org/10.3390/su14138001.
[3] Xue Y, Liu W. A Study on Parametric Design Method for Optimization of Daylight in Commercial Building's Atrium in Cold Regions. Sustain 2022;14. https://doi.org/10.3390/su14137667.
[4] Pan W, Du J. Effects of neighbourhood morphological characteristics on outdoor daylight and insights for sustainable urban design. J Asian Archit Build Eng 2022;21:342–67. https://doi.org/10.1080/13467581.2020.1870472.
[5] Aguilera-Benito P, Piña-Ramírez C, Varela-Lujan S. Experimental analysis of passive strategies in houses with glass façades for the use of natural light. Sustain 2021;13. https://doi.org/10.3390/su13158652.
[6] Lim T, Yim WS, Kim DD. Evaluation of daylight and cooling performance of shading devices in residential buildings in South Korea. Energies 2020;13. https://doi.org/10.3390/en13184749.
[7] Durmus D, Hu W, Davis W. Lighting application efficacy: A framework for holistically measuring lighting use in buildings. Front Built Environ 2022;8:1–5. https://doi.org/10.3389/fbuil.2022.986961.
[8] Albatayneh A, Atieh H, Jaradat M, Al-Omary M, Zaquot M, Juaidi A, et al. The impact of modern artificial lighting on the optimum window-to-wall ratio of residential buildings in jordan. Appl Sci 2021;11. https://doi.org/10.3390/app11135888.
[9] Osibona O, Solomon BD, Fecht D. Lighting in the home and health: A systematic review. Int J Environ Res Public Health 2021;18:1–20. https://doi.org/10.3390/ijerph18020609.
[10] Bellia L, Fragliasso F. Good Places to Live and Sleep Well: A Literature Review About the Role of Architecture in Determining Non-Visual Effects of Light. Int J Environ Res Public Health 2021;18. https://doi.org/10.3390/ijerph18031002.
[11] Aguilar-Carrasco MT, Domínguez-Amarillo S, Acosta I, Sendra JJ. Indoor lighting design for healthier workplaces: natural and electric light assessment for suitable circadian stimulus. Opt Express 2021;29:29899–917. https://doi.org/10.1364/OE.430747.
[12] Muñoz-González C, Ruiz-Jaramillo J, Cuerdo-Vilches T, Joyanes-Díaz MD, Vega LM, Cano-Martos V, et al. Natural lighting in historic houses during times of pandemic. The case of housing in the mediterranean climate. Int J Environ Res Public Health 2021;18. https://doi.org/10.3390/ijerph18147264.
[13] Cabeza-Lainez J, Almodovar-Melendo JM, Dominguez I. Daylight and architectural simulation of the Egebjerg School (Denmark): Sustainable features of a new type of skylight. Sustain 2019;11. https://doi.org/10.3390/su11215878.
[14] Eaton M, Harbick K, Shelford T, Mattson N. Modeling natural light availability in skyscraper farms. Agronomy 2021;11:1–13. https://doi.org/10.3390/agronomy11091684.
[15] Al-Ghaili AM, Kasim H, Al-Hada NM, Othman M, Saleh MA. A Review: Buildings Energy Savings - Lighting Systems Performance. IEEE Access 2020;8:76108–19. https://doi.org/10.1109/ACCESS.2020.2989237.
[16] Thongtha A, Boontham P. Experimental investigation of natural lighting systems using cylindrical glass for energy saving in buildings. Energies 2020;13. https://doi.org/10.3390/en13102528.
[17] Amoruso FM, Dietrich U, Schuetze T. Integrated BIM-parametric workflow-based analysis of daylight improvement for sustainable renovation of an exemplary apartment in Seoul, Korea. Sustain 2019;11. https://doi.org/10.3390/su11092699.
[18] Zhou J, Mohd Nazi WIW, Wang Y, Roskilly A. Investigating the impact of building's facade on the building's energy performance – a case study. Energy Procedia 2019;158:3144–51. https://doi.org/10.1016/j.egypro.2019.01.1016.
[19] Valetti L, Floris F, Pellegrino A. Renovation of public lighting systems in cultural landscapes: Lighting and energy performance and their impact on nightscapes. Energies 2021;14. https://doi.org/10.3390/en14020509.
[20] Michael A, Heracleous C, Thravalou S, Philokyprou M. Lighting performance of urban vernacular architecture in the East-Mediterranean area: Field study and simulation analysis. Indoor Built Environ 2015;26:471–87. https://doi.org/10.1177/1420326X15621613.
[21] Maria YS, Prihatmanti R. Daylight characterisation of classrooms in heritage school buildings. Plan MALAYSIA 2017;15. https://doi.org/10.21837/pm.v15i1.236.
[22] Philokyprou M, Michael A. Evaluation of the Envrionmental Features of Vernacular Architecture. A Case Study in Cyprus. Int J Herit Digit Era 2012;1:349–54. https://doi.org/10.1260/2047-4970.1.0.349.
[23] Chandel SS, Sharma V, Marwah BM. Review of energy efficient features in vernacular architecture for improving indoor thermal comfort conditions. Renew Sustain Energy Rev 2016;65:459–77. https://doi.org/10.1016/j.rser.2016.07.038.
[24] Gürani Y. Examination of natural lighting in vernacular architecture in the context of sustainability. Çukurova Üniversitesi Sos Bilim Enstitüsü Derg 2022;31:359–67. https://doi.org/10.35379/cusosbil.1023065.
[25] Michael A, Heracleous C, Thravalou S, Philokyprou M. Lighting performance of urban vernacular architecture in the East-Mediterranean area: Field study and simulation analysis. Indoor Built Environ 2017;26:471–87. https://doi.org/10.1177/1420326X15621613.
[26] Ahmad A, Kumar A, Prakash O, Aman A. Daylight availability assessment and the application of energy simulation software – A literature review. Mater Sci Energy Technol 2020;3:679–89. https://doi.org/10.1016/j.mset.2020.07.002.
[27] Solano JC, Montaño T, Maldonado-Correa J, Ordóñez A, Pesantez M. Correlation between the wind speed and the elevation to evaluate the wind potential in the southern region of Ecuador. Energy Rep 2021;7:259–68. https://doi.org/10.1016/j.egyr.2021.06.044.
[28] Ayala-Chauvin M, Riba Sanmartí G, Riba C, Lara P. Evaluation of the energy autonomy of urban areas as an instrument to promote the energy transition. *Energy Sources, Part B Econ. Plan.* Policy 2022. https://doi.org/10.1080/15567249.2022.2053897.
[29] Cárdenas-Haro X, Todisco L, León J, Jurado C, Vergara E. Geometry and Proportions of Adobe Vernacular Buildings in Cuenca, Ecuador. Int J Archit Herit 2021;1–19. https://doi.org/10.1080/15583058.2021.1879312.
[30] Tenze A, Cardoso F, Achig MC. Experiences of social participation in the recovery of vernacular heritage in southern Ecuador. Int Arch Photogramm Remote Sens Spat Inf Sci - ISPRS Arch 2020;54:603–10. https://doi.org/10.5194/isprs-archives-XLIV-M-1-2020-603-2020.

[31] Galatioto A, Beccali M. Aspects and issues of daylighting assessment: A review study. Renew Sustain Energy Rev 2016;66:852–60. https://doi.org/10.1016/j.rser.2016.08.018.

[32] Sánchez-Cortez JL. Conservation of geoheritage in Ecuador: Situation and perspectives. Int J Geoheritage Park 2019;7:91–101. https://doi.org/10.1016/j.ijgeop.2019.06.002.

[33] Hayes M. The coloniality of UNESCO's heritage urban landscapes: Heritage process and transnational gentrification in Cuenca. Ecuador *Urban Stud* 2020;57:3060–77. https://doi.org/10.1177/0042098019888441.

[34] Garcia G, Vandesande A, van Balen K. Place attachment and challenges of historic cities: A qualitative empirical study on heritage values in Cuenca. Ecuador *J Cult Herit Manag Sustain Dev* 2018;8:387–99. https://doi.org/10.1108/JCHMSD-08-2017-0054.

[35] Guillén-Mena V, Quesada F. Assessment model of energy performance in housing of Cuenca. Ecuador *Ain Shams Eng J* 2019;10:897–905. https://doi.org/10.1016/j.asej.2019.03.010.