The Thermal Behaviour of Educational Buildings in the Tropical Andes. A Case Study of the Millennium Educational Units of Ecuador

María Isabel Vivanco-Villavicencio and Maureen Trebilcock-Kelly

Abstract Studies show that children are more vulnerable than adults to the effects of low and high temperatures. They spend a lot of time every day in educational buildings, making it essential to take steps to mitigate health and comfort risks in school classrooms. In this context, this chapter addresses the thermal behaviour and comfort of school buildings located in the tropical Andes. The case study is the "Millennium Educational Units" (Unidad Educativa Milenio-UEM) school typology, which has been built in different climates throughout Ecuador. An evaluation was made of three UEM cases, which integrated passive strategies, considering the different climates found in the country. The methodology was based on an analysis of UEMs and their occupants, using observation and evaluating thermal behaviour. The database used for the analysis was obtained from climate files; the calculation of the adaptive comfort range and thermal simulation, based on domestic and international standards. This study demonstrates the importance of including sustainable passive strategies in educational buildings and thereby contributes to improving the comfort and performance of its occupants.

Keywords Environmental comfort · Educational buildings · Tropical Andes

1 Introduction

People spend 80–90% of their lives inside buildings [1], hence the relevance of studying environmental comfort as an important factor for health. In Latin America,

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Fig. 1 UEM Bernardo Valdivieso de Loja Millennium Educational Unit

67.5% of buildings are uncomfortable [1], so there is a need to improve design processes, construction standards and regulations, as well as to guide their users so that comfortable and healthy indoor environments can be achieved.

However, studies have shown that children are more vulnerable than adults to the effects of low and high temperatures. They spend a lot of time every day in educational buildings, making it essential to take steps to mitigate health and comfort risks in school classrooms [2]. Studies recommend that standards consider the impact of both temperature and CO_2 levels on perceived indoor environmental quality, as these affect children's overall comfort and fatigue levels.

Since 2012, Ecuador has established a public policy to provide school infrastructure to all the country's regions. The Ministry of Education and the Undersecretariat of School Administration—the entity in charge of planning and improving educational infrastructure—promoted a standardized infrastructure called Millennium Educational Units (Unidad Educativa Milenio—UEM) (see Fig. 1), to offset the lack of educational infrastructure in underdeveloped sectors. The aim was to improve educational quality and equity. The UEM typology consists of a classroom block that has been built across the country with little variation in terms of design and building properties. It has been located in different climatic regions of Ecuador, without properly assessing its ability to provide thermal comfort to students.

The typologies are based on different education levels with four variants: a Major Educational Unit with a capacity of 1140 students per day; a Minor Educational Unit with a capacity of 570 students per day; Multi-teacher Exception Infrastructure and Two-Teacher Exception Infrastructure [3, 4]. To face the increasing student demand, the Ecuadorian Ministry of Education built 65 UEMs until 2016, from a total of 324 UEMs planned throughout the country. According to Ponce and Drouet [5], the investment in standardized public infrastructure is significant. Each major UEM benefits 1140 students at a cost of around US$6.3 million, while every minor UEM benefits 570 students at a cost of around US$4 million. The planning process includes specific urban planning consultations to determine requirements for services and urban infrastructure. However, it does not consider aspects of thermal comfort and climate adaptation.

This paper aims to assess the integration of passive design strategies to improve the thermal performance of the UEM classroom block prototype for three natural regions in Ecuador's zone 7: El Oro, Loja, and Zamora Chimchipe. It is expected that this study can contribute to the future development of UEMs with quality standards that consider indoor environmental quality and student comfort.

2 Methodology

To achieve the goal outlined, the methodology consisted of making thermal simulations of three case studies of Millennium Educational Units and proposing appropriate passive design strategies for each case/climate.

2.1 Case Studies

Continental Ecuador is located on the northwestern coast of South America and is divided into four natural regions: the Coast Lowlands (Región Costa), Andean Highlands (Región Sierra), the Amazon Rainforest (Región Amazónica) and the Island Region (Región Insular), which in this chapter will be referred to as the Coast, Sierra, Amazon and Insular regions. Several factors such as altitude, the equatorial line and the Andes mean the country has a variety of climates and microclimates throughout each of its regions, where temperatures can exceed 38 °C and reach as low as 2 °C. The three case studies are located in administrative zone 7 in southern Ecuador, comprising the provinces of El Oro, Loja, and Zamora Chinchipe. This zone is the only one that covers three natural regions—Coast, Sierra and Amazon—with short distances between them. The UEMs are not heated or cooled, so thermal behaviour depends purely on architectural design and occupant behaviour (see Fig. 2 and Table 1). To evaluate the case study, the calculation of comfort range limits is made based on the ASHRAE 55 adaptive model, considering average outdoor temperatures [6]. It is important to note that in these tropical climates there is no temperature variation throughout the year, so the annual average temperature determines the adaptive comfort range (see Table 2).

2.2 Thermal Simulation

With the data obtained from the comfort range limits and the classroom block's technical parameters, a thermal simulation analysis was carried out using the TAS "Thermal Analysis Simulation" software, which allowed diagnosing the thermal behaviour of each UEM classroom block. Each block has 12 classrooms of 70 m^2

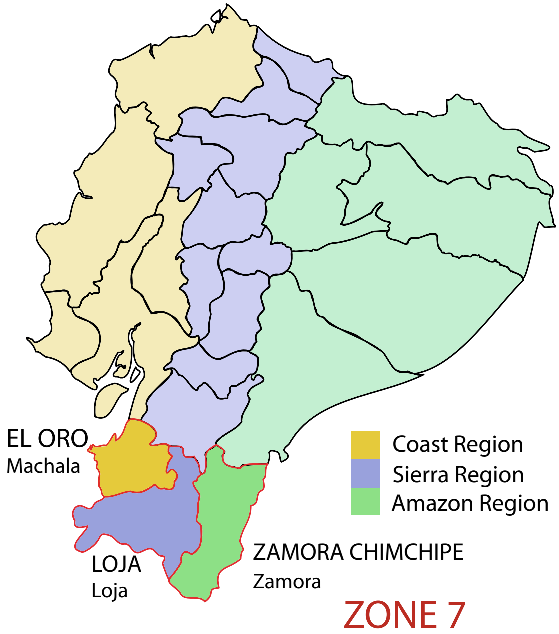


Fig. 2 Location of the case studies in three climatic regions of Ecuador's zone 7

Table 1 Location of the case studies

Case study	City	Natural region	Admin zone	Climate zone (NEC 2011)	Climate zone (NEC 2018)
UEM 9 de Octubre	Machala	Coast	El Oro	ZT6	1
UEM Bernardo Valdivieso	Loja	Sierra	Loja	ZT3	2
UEM Arutam	El Pangui	Amazon	Zamora Chinchipe	ZT5	3

NEC 2011: NEC-11 Chapter 13, 2011 [7]. NEC 2018: NEC-HS-EE, 2018 [8]

that are 4 m high. Each classroom is used by 40 students and 1 teacher in three shifts. The thermal simulation parameters for each case are detailed in Table 3.

2.3 *Passive Design Strategies*

The last stage of the methodology consisted of developing a passive design strategies matrix to improve the typology considering the specific characteristics of each climatic region. The strategies comprised the thermal protection of the envelope (roof,

Table 2 Climatic data and calculation of comfort range

NATURAL REGION/City/Case	Alt. (masl)	T_{min} (°C)	T_{aver} (°C)	T_{max} (°C)	$T_{Comfmin}$ (°C)	$T_{Comfmax}$ (°C)
COAST/Machala/UEM 9 de Octubre	5	19.00	25.21	29.15	22.12	29.12
SIERRA/Loja/UEM Bernardo Valdivieso	2145	11.50	16.35	21.4	19.37	26.37
AMAZON/El Pangui/UEM Arutam	775	17.10	22.80	28.15	21.37	28.37

Note: Data obtained from the National Meteorology and Hydrography Institute—INAMHI
T_{min}: minimum outdoor temperature
T_{aver}: average outdoor temperature
T_{max}: maximum outdoor temperature
$T_{Comfmin}$: minimum comfort temperature
$T_{Comfmax}$: maximum comfort temperature

Table 3 Parameters for thermal simulation

Location of the UEMs	Coast Region Machala	Sierra Region Loja	Amazon Region El Pangui
Ventilation systems	Natural	Natural	Natural
Average wind speed (m/s)	0.31	0.83	0.56
Metabolic rate (MET)	1.30	1.30	1.30
Clothing (CLO)	0.50	1	0.50
Occupancy	Monday to Friday (07:00 to 22:30)	Monday to Friday (07:00 to 22:30)	Monday to Friday (07:30 to 20:30)
Window-to-wall ratio (%)	32.4	32.4	32.4
Floor area (m^2)	70	70	70
Wall area (m^2)	40	40	40
Window area (m^2)	12.9	12.9	12.9

Note: Data obtained from the 2015 Technical Standards for the Design of Educational Environments

wall, floors and windows), passive solar energy and natural ventilation. This was developed based on domestic and international regulations.

Using the TAS software tool, the thermal behaviour of the improved educational units was evaluated and analysed based on the strategies proposed in the matrix, determining indoor temperatures.

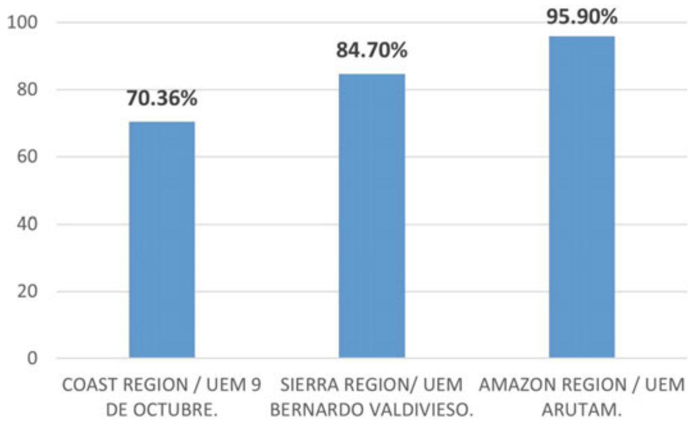


Fig. 3 Percentage of time within the adaptive comfort range

3 Results

The results of the first thermal simulation of the three cases are shown in Fig. 3. The percentage of time that the indoor temperature remains within the comfort range established by the adaptive method [6] for each climate shows important differences between the three cases. The UEM Arutam case in the Amazon Region has the best thermal performance with 95.9% of the occupancy time within the 21.37–28.37 °C range. In contrast, UEM 9 de Octubre, located in the Coast Region, has the worst thermal performance with 70.36% of the occupancy time within the 22.12–29.12 °C range.

According to the simulation, the UEM located in the Coast Region, with indoor temperatures reaching 38 °C, does not adequately reach thermal comfort for its occupants, while the UEMs in the Sierra and Amazon require some improvements. The application of passive strategies that look to improve the thermal comfort of school classrooms is key. Passive strategies were proposed based on domestic and international studies and regulations: Ecuadorian Construction Standard [7], Chilean Thermal Regulation Standard [9], Energy Efficiency Guide for Educational Establishments [10] and the Manual for Passive Design and Energy Efficiency in Public Buildings [11].

A set of different strategies was foreseen, including solar shading, cross ventilation, improved thermal transmittance and ventilated walls. The best strategies for each case are highlighted in Fig. 4.

The results of the thermal simulation are shown in Fig. 5, which compares the base case against the improved case with passive strategies. The UEM in the Coast Region, with a comfort range between 22.12 and 29.12 °C, showed an improvement

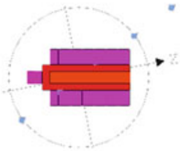
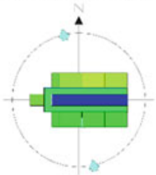
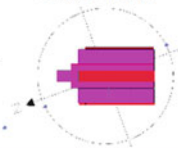
	Orientation	Thermal transmittance U-value (W/m^2K)	Glazing properties
COAST REGION			
BASE CASE	EAST-WEST	U roof: 1.59 U wall: 2.76 U floor: 3.83	SINGLE TS: 0.69 U: 5.7
NEC-11 Ch. 13		U roof: 0.74 U wall: 2.76 U floor: 2.84	SINGLE TS: 0.69 U: 5.7
NRTC		U roof: 0.82 U wall: 2.76 U floor: 2.07	DOUBLE TS: 0.05 U: 3.46
STRATEGY 2 (Solar shading and cross ventilation)		U roof: 1.59 U wall: 2.76 U floor: 3.83	SINGLE TS: 0.69 U: 5.7
STRATEGY 2+3+6 (Solar shading, cross ventilation, U value, and ventilated walls)		U roof: 0.21 U wall: 0.43 U floor: 3.83	SINGLE TS: 0.05 U: 6.39
SIERRA REGION			
BASE CASE	NORTH-SOUTH	U roof: 1.59 U wall: 2.76 U floor: 3.83	SINGLE TS: 0.69 U: 5.7
NEC-11 Ch. 13		U roof: 1.59 U wall: 1.53 U floor: 1.44	SINGLE TS: 0.69 U: 5.7
NRTC		U roof: 0.56 U wall: 2.76 U floor: 0.88	DOUBLE TS: 0.19 U: 2.13
STRATEGY 3 (Thermal transmittance)		U roof: 0.56 U wall: 0.52 U floor: 3.83	DOUBLE TS: 0.19 U: 2.13
AMAZON REGION			
BASE CASE	EAST-WEST 	U roof: 1.59 U wall: 2.76 U floor: 3.83	SINGLE TS: 0.69 U: 5.7
STRATEGY 2 (Solar shading and cross ventilation)		U roof: 1.59 U wall: 2.76 U floor: 3.83	SINGLE TS: 0.69 U: 5.7
STRATEGY 2+6 (Solar shading, cross ventilation, and ventilated walls)		U roof: 1.59 U wall: 0.58 U floor: 3.83	SINGLE TS: 0.69 U: 5.7

Fig. 4 Passive strategies matrix for each region

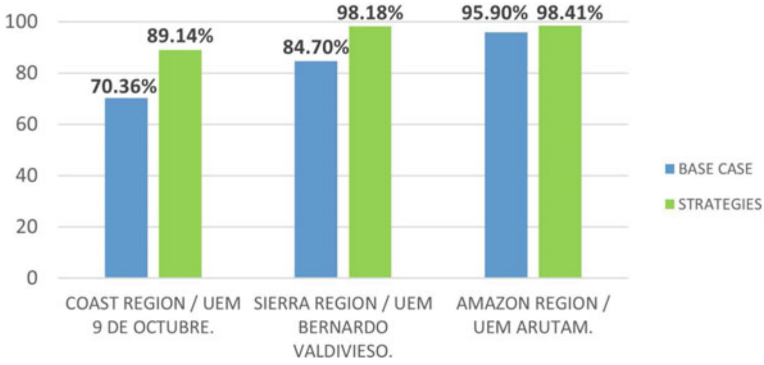


Fig. 5 Percentage of time within the adaptive comfort range

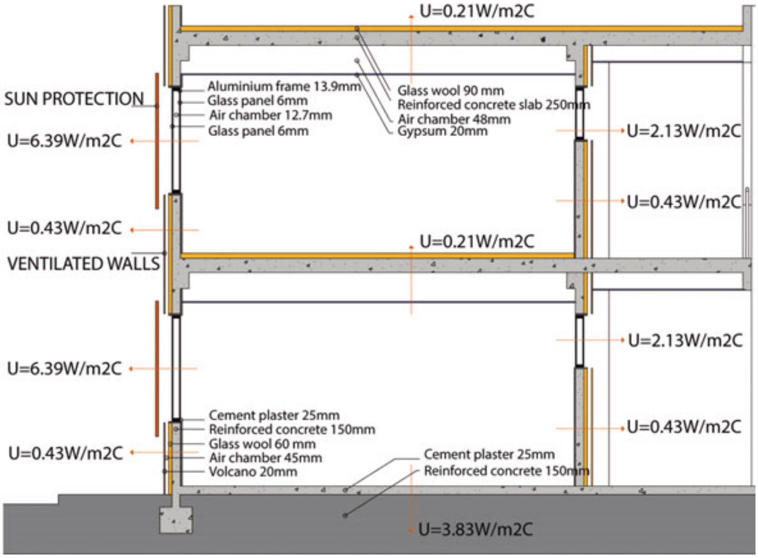


Fig. 6 Passive improvement strategies for the Coast Region classroom block

of 18.78%, while the maximum temperature dropped from 35 to 29 °C. The UEM in the Sierra Region, with a comfort range between 19.37 and 26.37 °C, improved by 13.48%, and was nearly all the time within the comfort range, while the minimum temperature increased from 14 to 19 °C. Finally, the UEM in the Amazon Region, had a comfort range between 21.37 and 28.37 °C, the percentages increased by 2.51% and the temperature decreased from 28 to 25 °C.

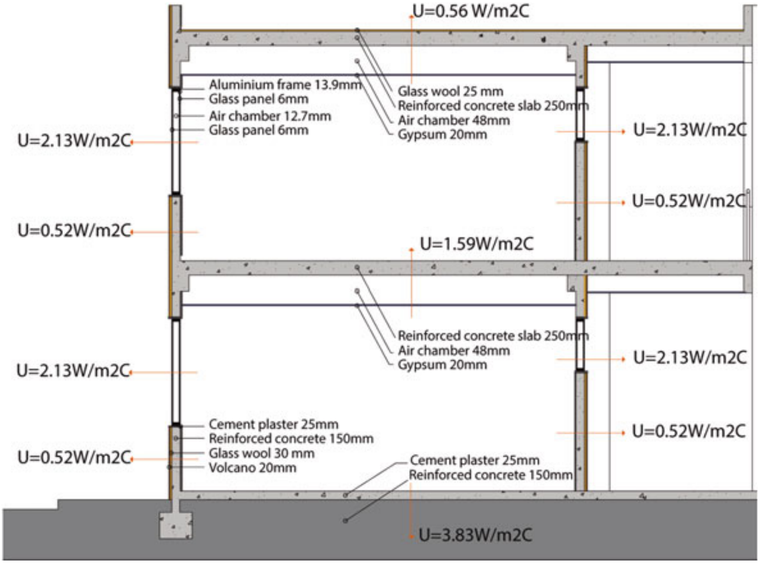


Fig. 7 Passive improvement strategies for the Sierra Region classroom block

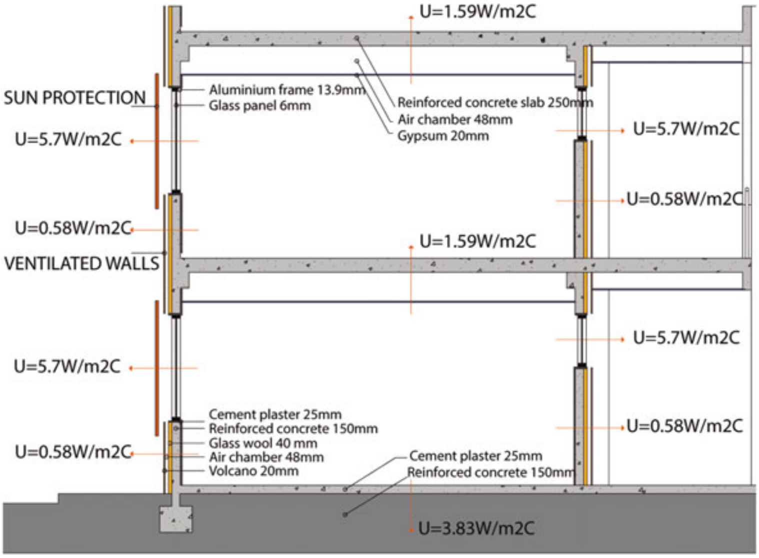


Fig. 8 Passive improvement strategies for the Amazon Region classroom block

Regarding the recommendations to improve the thermal performance of UEMs, Fig. 6 shows that in the Coast Region, STRATEGY 2+3+6, which includes solar shading, cross ventilation, improved thermal transmittance and ventilated walls, ensures comfortable temperature conditions and indoor air renewal, and, therefore, improves student performance and comfort.

In the Sierra Region, STRATEGY 3, which includes improved thermal transmittance (See Fig. 7), allows increasing the percentage of time that children would be within the comfort range, avoiding the phenomenon of cold walls, and reducing air movements.

Figure 8 shows the strategies proposed for the Amazon Region (STRATEGY 2 + 6) that include solar shading and ventilated walls and would allow reducing relative humidity conditions, which is an important factor in this region.

4 Conclusions

Considering the locations of the study, chosen based on their most extreme climates, altitude and humidity of the three natural regions of Zone 7, it is concluded that the UEM typology performs better in the Amazon Region and worse in the Coast Region. The application of passive design strategies such as solar shading, cross ventilation, thermal transmittance and ventilated walls allows improving the thermal performance of UEMs by 18.78% in the Coast Region. Therefore, the application of passive improvement strategies should be considered, which will serve as a guide for future standardized UEM construction in Ecuador.

In this context and considering that children are more vulnerable than adults to high- and low-temperature conditions, it is not appropriate to standardize the construction of UEMs in Ecuador, since the climatic conditions are different for each natural region; therefore, there must be a specific design that takes into consideration aspects such as context and climate and can meet the comfort requirements inside the classroom.

Finally, this research can contribute as a guide for the applicability of similar studies for public infrastructure standards of other state entities in the country or other similar contexts that allow removing environmental comfort barriers.

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