Simulation experiences for the thermal performance improvement of naturally ventilated classroom in the tropics of Costa Rica

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Abstract

In tropical developing countries, the considerations of energy efficiency and quality of school buildings are minimal, compromising the minimum internal comfort. This paper explores the effects on thermal comfort and energy generated by performing parametric variations on the typical configuration of naturally ventilated classrooms in tropical Costa Rica. Using dynamic simulations by the software Design Builder, weather data and surveys of comfort, classrooms with the same design pattern in three locations prone to overheating were analysed. Effects on energy demand and the operative temperature of the enclosure by varying bioclimatic parameters of passive cooling and solar control were reviewed.

The results indicate that certain configurations can optimize the performance of the typology of the cases studied, generating the possibility of applying these design parameters to new configurations of classrooms to be built in the area.

The impact of choosing appropriate design considerations and the use of simulation tools to verify building performance is demonstrated. In addition the combined potential of using passive cooling and solar control to achieve favourable thermal conditions for the user and to solve an energy demand improvement of school buildings was proved.

1. Introduction

In countries with tropical climates, where environmental conditions are hot and humid, a key challenge for the design and construction is proposed to balance the pulse asset utilization and air conditioning systems in order to have less impact on the economy, operating costs in the long term, cultural conditions and resource efficiency. (Sosa Griffin and Siem 2004) The phenomenon of adaptive comfort, studied and defined by (de Dear and Brager 2001), and incorporated in ASHRAE 55 promotes the concept that people in naturally ventilated buildings (passive system) can feel comfortable in higher internal temperatures.

The buildings designed under the concept of natural ventilation have the potential to improve the work environments in relation to energy consumption and interior comfort compared with mechanically controlled systems. (Bordass et al. 2001; Givoni 2011; Rajapaksha and Hyde 2012)

The natural ventilation combined with other aspects related to architectural design and spatial configuration patterns can improve the internal airflow. (Prianto and Depecker 2003)

In addition, the user adaptation by exposure to a weather condition plays an important role in defining the spatial designs. An adequate knowledge of these aspects may potentiate the adjustments in the conditioning means, depending on the type of building, to reduce energy costs without limiting user comfort.

School buildings are the focus of this study. Authors like (Corgnati, Filippi, and Viazzo 2007; Liang, Lin, and Hwang 2012; Wargocki and Wyon 2007) have demonstrated the importance of the quality of the physical environment and environmental comfort (thermal comfort, ventilation, acoustics, lighting and air quality) is established for students. According to the above, the thermal comfort and ventilation are essential aspects to determine the quality of space, and the health of students that routinely remain in studio spaces for an extended period. (Hwang et al. 2009)

In the tropical region of Latin America, the development of educational infrastructure has gone through very similar processes of evolution and typology. The design of school buildings under the same pattern, spatial distribution and materials has been predominant and this has been repeated throughout the countries.

This use of the same typology has caused unsuitable internal conditions in the classrooms for every climatic zone. Moreover, many of these designs were imported. The use of foreign construction typologies that are not appropriate for the weather conditions, the cultural reality and the space requirements in the tropics compromise the thermal comfort. (Sosa Griffin and Siem 2004)

In Costa Rica, 43% of 4,071 existing schools have been designed using prefabricated industrial systems. For the next five years an increase of 3% of the infrastructure under a unique typology of construction with the same standards has already been planned. This led us to seek an improvement in the current typology to optimize its thermal and energy performance in different localities where new school buildings are going to be developed.

87% of schools are outside the metropolitan area. They are mostly divided among three central-coastal sectors with high rates of overheating in the dry season, with temperatures between 28°C and 36°C. It is possible to improve the thermal and energy behaviour of the current type of classroom if the influence of the shape, material and other micro-climatic variables in classroom performance is established.

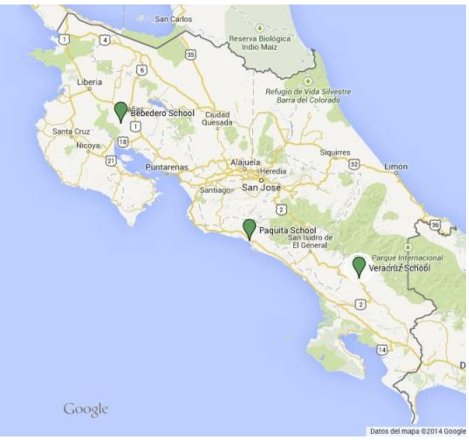


Fig. 1 – Location of schools utilized as case studies. Costa Rica map provided by Google Maps and modified by the author.

The aim of this study is to explore the effects on thermal comfort and energy performance generated by the change of architectural parameters (design) and configuration of typical classrooms in the Costa Rican tropics. Specifically, a review of the consequences is to be realized by applied passive cooling strategies (solar control, heat decrease and heat dissipate) and the possibility to improve the basic typology will be demonstrated.

2. Case studies: Bebedero, Paquita and Buenos Aires Cities.

The case studies are found in the hot-humid tropical zone of Costa Rica, located between the area of the Tropic of Cancer and the Equator. The framework of microclimates is dominated by a non-seasonal climate with a rainy season from May to November and a dry season with little or no rain during the months of December to April.

Field studies were conducted for six (6) naturally ventilated classrooms, in three (3) different locations of Costa Rica's Pacific coast. The school buildings studied are located in Bebedero - Cañas (10°22'10.21 "N / 85°11'37.86" W and 12 m above sea level), Paquita - Puntarenas (09° 27'40.57 "N / 84°10'50.81 "W and 10 m above sea level) and Veracruz - Buenos Aires (09°09'45.44"N / 84°19'26.35 "W and 385 m above sea level). Fig. 1 shows the location of each school on the map of Costa Rica.

The selected case studies based on existing constructions permit us to improve their performance through the use of thermal and energy simulation. Verification strategies can then be applied to new buildings to be constructed in areas with increased risk of overheating. These zones have ranges of average outdoor air temperatures between 25.4°C and 29.7°C, with a maximum of 34.4°C and a minimum of 19.1°C.

The elementary classrooms are occupied mainly by children between 9 and 13 years for academic activities. The average metabolic rate corresponds to 1.2 metabolic rate in accordance with the provisions of the ISO 7730: 1994 and ASHRAE 55: 2004. Within these spaces, operable windows on opposite sides (cross ventilation) and ceiling fans are the main sources of natural ventilation, plus the teachers are given the freedom to operate the windows to change the indoor environment with respect to airflow rate.

2.1 Description of the classroom typology

The investigated classrooms use a unique model of classroom that was designed under the normative of the Compendium of Standards and Recommendations for the Construction of Buildings for Education with a series of minimum requirements. The rooms have internal dimensions of 50.50 m^2 of area and 2.50 / 2.70 m of height, built with a precast concrete system. Each one has a maximum occupancy of 34 students but the mean occupancy is 20 students. It is recommended to use the natural light from the north so that the orientation of the windows should respect this condition. The minimum size of the windows on facades is equivalent to a fifth of the floor surface; that corresponds to 10.1 m^2 of windows (single glazing), a 20% relative glazed / surface area; and are protected by external eaves. Fig. 2 shows the floor plan and the classroom configuration.

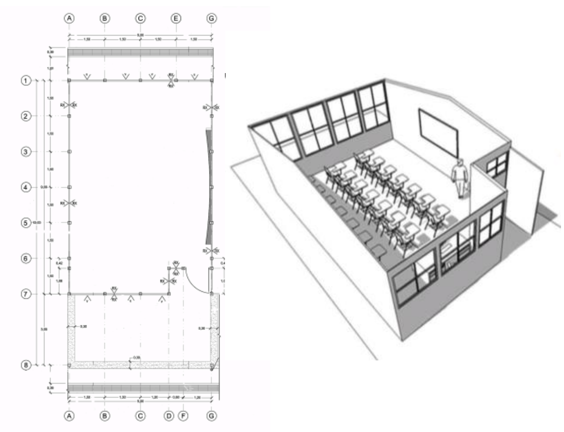


Fig. 2 – Floor plan and sketch 3D view of the classroom model. Source: Plans by DIEE- Ministry of Education- Costa Rica

2.2 Thermal conditions

During the dry season a survey was performed according to ISO 10551 - ISO 7730 and applied to 105 elementary students between 9 and 13 years of age. Furthermore, experimental measurements (dry bulb temperatures -interior and exterior-, relative humidity, wet bulb temperatures, wind speed, CO_2) were carried out in order to evaluate the internal conditions and correlated to models of comfort. Results with respect to the Thermal Sensation Scale show that 67% of the students reported feeling comfortable or close to comfort (with scales between 1 and -1) with internal average temperatures near 30°C and relative humidity between 50 and 62%. The responses were obtained in a range of Tbs (dry bulb temperature) between 30.4°C and 33.1°C. 21.5% of students surveyed indicated feel neutral thermal condition (neither cold nor hot), with comfort index equal to 0. This confirms the statement by (Bravo and González 2001) in a study of the city of Maracaibo, Venezuela. They found that people who remain in environments subjected to free variation of temperature in unmanipulated environments acquire greater status adaptation and tolerance to high temperature and humidity. This is compared to people in other localities or people who are exposed to controlled conditions, especially in warm and tropical climates.

The results of the surveys and measurements were compared with simple adaptive models to find the perception of the user to overheating. In this case the formula adaptive comfort for buildings with passive operation (no mechanical systems) developed by (Humphreys, Nicol, and Raja 2007) was applied. (1)

$$Tc = 12.9 + (Tavg * 0.54) \quad (1)$$

Table 1 – Comparative table of comfort temperature ranges for the case of Bebedero City.

Case Bebedero -Dry Season					
	Dec	**Jan**	**Feb**	**Mar**	**Apr**
Tº (1)				30,4ºC	30,7ºC
Tº (2)	28,4ºC	28,6ºC	29,1ºC	29,6ºC	29,7ºC
Tº(3)	30,4ºC	30,6ºC	31,1ºC	31,7ºC	30,9ºC
Tº(4)	26,4ºC	26,6ºC	27,1ºC	27,7ºC	27,7ºC

(1) Comfort Temperature perceived for the students.
(2) Comfort Temperature by simple adaptive model comfort
(3) Upper Limit Comfort Zone by simple adaptive model.
(4) Lower Limit Comfort Zone by simple adaptive model.

Table 1 shows an example of the data obtained for the Case of Bebedero with respect to the simple model of comfort for the dry season. Comfort temperature perceived by the user is within the limits established by the model, but closer to the upper limit. These data were taken into account in the simulation process to evaluate the comfort achieved through optimization processes. The lower limit of comfort is around 27ºC in the three cities, which was set as the operating temperature to be reached in the simulations that use mechanical support by fans.

3. Definition of the simulation model

3.1 Parameters for simulation models of energy and comfort.

Dynamic simulations for a typical classroom model were realized using the software 'Design Builder' as an interface of 'Energy Plus' (version 8.0), and climate databases generated by 'Meteonorm 7.0'. The workflow of Design-Builder (Fig.3) starts with the selection of a location and the corresponding weather through a weather file (.EPW) followed by the creation of specific thermal building model geometry with the integrated CAD interface. Lists of definable parameters include internal loads (with occupancy patterns/activities), construction types, openings (windows and doors), lighting, and HVAC systems (if applied). Once the definition of all input parameters is complete, one can perform design day and/or annual simulations.

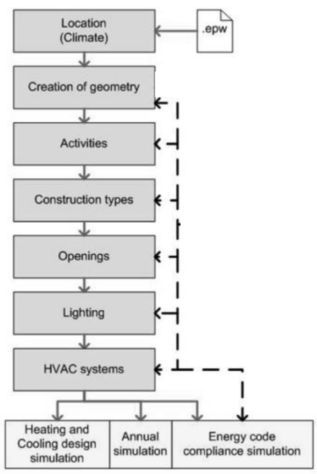


Fig. 3 – Definition of parameters in Design Builder. Source: (Rallapalli 2010) -edited by the author.

Two simulation models were performed. The first calculates the demand for cooling when setting a minimum operating temperature at the inner enclosure. The simulations are performed in order to evaluate the energy demand of ceiling fans in the actual configuration, and using technical solution proposals to improve the efficiency of the system.

The second model is free running (no mechanical constraints to achieve comfort), where the results show internal operating temperatures obtained with the variations realized in the pattern of simulation.

Calibration of the model with fixed parameters.

The simulation model is calibrated according to general design data classrooms defined in paragraph 2.1. These 'fixed parameters' are used for both the base case simulation (real current performance) and for optimization solutions raised in the calculation models of energy demand and comfort conditions.

The fixed parameters included internal loads, ventilation mode, and some physical characteristics.

- Internal loads (only during the occupation period) calculated according to ASHRAE: students with light study work 66 W; adults standing / walking 108 W; artificial lighting 300 lux classrooms – 11.25 W/m^2; not considering the use of computers in the classroom; average occupational density of twenty (20) students per classroom and a teacher (0.39 persons/ m^2).
- Occupation Period: Monday to Friday, from 8:00 to 12:00 and 13:00 to 17:00.
- Holiday periods: Half year, from 30 June to 11 July; and vacation season, from December 15 to February 10.
- Operating temperatures during the period of occupation: (This information was defined for the simulation model that calculates demand for cooling) 23°C minimum, 27°C average and 30°C maximum. In unoccupied periods, there is no limit temperature.
- Ventilation: simulations with 2 ac/h were performed on period occupation minimum. It was also considered to simulate the free additional ventilation by opening windows

when the temperature inside exceeds 23°C, from Monday to Friday between 8:00 and 17:00.

- Surfaces: the 3 schools studied have the same model classroom with a unique materiality. External walls in concrete tile (1% reinforced concrete steel) and a thickness of 0.038 m, with U-value of 5.36 W/m²-K. Roof of enamelled steel sheet of 0.44 mm thick with thermal insulation EPS (expanded polystyrene) of 5 mm thick. Over a frame of black iron metal of 15 cm, 1.5 mm thick with U-value of 3.773 W/m²-K. Ceiling suspended in plasterboard 1 cm thick with U-value of 2.229 W/m²-K. Floor compound by 10 cm thick slab with ceramic tile of 13 mm thick with U-value of 2.803 W/m²-K. Windows of two types: fixed window of 3 mm thick, aluminium frame and window blinds glass of 3 mm thick (opening percentage 95%) with aluminium frame. With a U-value of 5.894 W/m²-K.
- The exterior walls were considered adiabatic, except those with windows (to the outside and into the hall).

Variable parameters using in optimization solutions

Of the variable parameters, only those related to building orientation, ventilation rate and use /operation of windows to promote passive cooling strategies were considered for this study.

Variable parameters are based on design rules allowed for the type of building, according to paragraph 2.1 of this article, and intend to observe how it influences the change in ventilation management and use of the site on their performance. These are shown underlined in Table 2, which summarizes all possible combinations of variables for simulation.

Table 2 – Summary of simulations parameters

Parameters		**Nº of variables**
Orientation	North, South, East, West, Northeast, Northwest, Southeast, Southwest	8
Occupation (p/m²)	Average (20), Max (34)	2
Glass Thickness	3 mm	1
Glazed Area / m²	20% Minimum, 30% Current	2
Solar Control	Yes (Eaves)	1
Window Operating	Only hours of lessons, Day and Night (Dry Season), All the year.	3
% Of Operate Windows	90% Open-10% closed; All Opened	2
Envelope	Current material (wall, floor and roof)	1
	TOTAL	192 POSSIBILITIES

Note: Underlined parameters correspond to the options that were varied within the simulation settings.

According to the parameters used, 192 possible combinations (Table 2) were obtained per city. Probabilistic analysis was used to identify the possibilities with better performance. Of the 192 possibilities, twelve (12) cases simulated represent significant improvements. The study was bounded to five (5) solutions per city that demonstrated the highest reductions. The strategies aim to avoid thermal and solar gains and promote natural ventilation.

The five (5) different solutions were analyzed and compared with the current situation (base case):

- Case_1: The orientation of windows according to utilization of the wind direction is adjusted. The air changes set in 2 ac/h at the base are left free and the period of operation by keeping windows open stretches during the day and night in days of the dry season (the period of overheating)

- Case_2: Based on the case_1, the operation window for all operating days expands during the day and night.
- Case_3: Based on the case_1, window operation is extended to every day of the year without restriction.
- Case_4: Based on the case_3, the area of operating windows is expanded from 90% to 100%.
- Case_5: Based on the above improvement (case_4) the glazed area decreased from 30% to 20% of the classroom. This continues to maintain the required percentage of natural light and reduces heat gains generated by glazed surfaces.

Only the Case_5 proposes changes in the components of the envelope of the classroom. The other solutions demonstrate passive strategies to reduce heat gains and improve ventilation strategies.
The variables used in cases with a better performance are composed of two or more parameters simultaneously, demonstrating the need for a combination of strategies.

4. Simulation results

4.1 Energy performance

Different scenarios were simulated for each locality. The evaluation of the advantages achieved with regard to energy efficiency was performed for each proposal based of annual demand.
The simulation model was performed using mechanical ventilation and cooling by fans in the ceiling, supported with the use of natural ventilation. The highest energy savings occur in warm periods, especially between the months of December to April.
The combination of reduced heat gains for glazed area, a constant flow of ventilation and 100% operable windows (Case_5), shows the best performance. Fig.4 illustrated the results of the different cases for the Bebedero School and the decrease in the annual demand.
The individual parameter that influences mostly in energy saving corresponds to the amount of air changes / infiltrations by 30.6%. The appropriate use and control of air changes, natural ventilation and orientation of windows led to a decrease in energy demand for the base cases of between 25% and 40%.
The second significant parameter (but on a smaller scale) is the orientation with 2.05%, predominantly with a better performance from the spaces oriented to the North.
The glass surface is a parameter with media influence but produces a higher incidence in cities with higher daily thermal oscillation; its impact is a 1.42% decrease in demand. Reducing average demand in the three (3) cases is between 30% and 40% annually. Table 3 shows the percentage of energy saving for the cities.

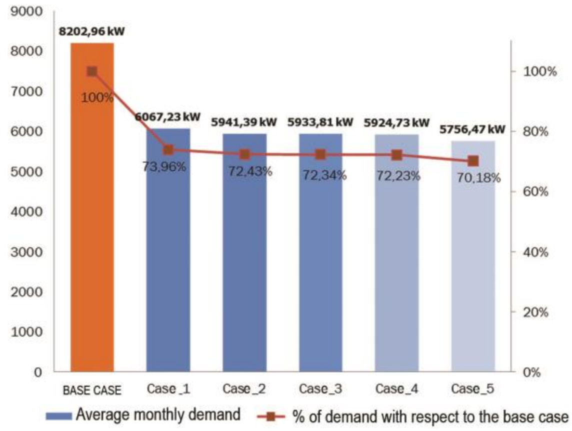


Fig. 3 – Decrease in annual demand by case. Analysis for the Bebedero School.

Table 3 – Energy saving (%) for solutions proposals respect to the annual demand of the base case.

Base Case		Energy Saving (%) Solutions				
Cities	AD	C_1	C_2	C_3	C.4	C_5
Bebedero	8202,96 kWh	27,57	27,66	27,65	27,77	**29,82**
Veracruz	3448,75 kWh	39,12	38,96	38,97	**43,25**	42,21
Paquita	6886,59 kWh	25,72	24,46	24,46	25,52	**27,46**

Note: The percentages in bold show the cases with better performance for each locality.
C_1 (Case 1), C_2 (Case 2), C_3 (Case 3), C_4 (Case 4), C_5 (Case 5), AD (Annual Cooling Demand)

4.2 Comfort conditions

The current configuration of the classroom takes into account the use of ceiling fans. The ability to save on the use of the cooling system is demonstrated in the previous section. However, the design of classrooms should be improved from models without the use of mechanical systems.

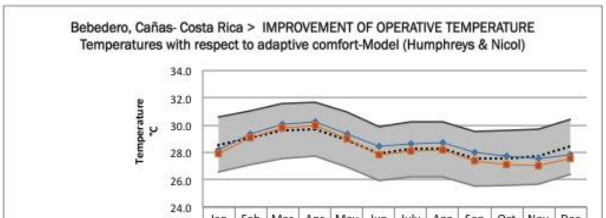
Free running scenarios for the five (5) cases were simulated per city in order to achieve improvements in internal operating temperatures to implement variations in ventilation conditions and emplacement.

The overall results showed an improvement of between 6% and 27% in the internal operating temperature that are within the comfort zone according to the adaptive comfort model explained in section 2.2.

All operating temperatures calculated are among the upper and lower limit of the comfort zone indicated by the model, but closer to the lower area and the average of 27ºC, which could be achieved with the support of a mechanical system.

Improvements include up to a decrease of 1°C in the operating temperature in the critical months.

Fig.4 shows the results of the base case operating temperatures and operating temperatures achieved for the Bebedero School.



	Jan	Feb	Mar	Apr	May	Jun	July	Ago	Sep	Oct	Nov	Dec
Diference	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Zone -Lower limit	26.6	27.1	27.6	27.7	26.9	25.9	26.2	26.2	25.5	25.6	25.7	26.4
Comfort Temperature	28.6	29.1	29.6	29.7	28.9	27.9	28.2	28.2	27.5	27.6	27.7	28.4
Zone -Upper limit	30.6	31.1	31.6	31.7	30.9	29.9	30.2	30.2	29.5	29.6	29.7	30.4
Zone -Lower limit	26.6	27.1	27.6	27.7	26.9	25.9	26.2	26.2	25.5	25.6	25.7	26.4
Operative T° Base Case	28.18	29.33	30.06	30.26	29.35	28.48	28.63	28.74	27.98	27.72	27.52	27.79
Operative T° Case_5 Best Performance	27.94	29.03	29.79	30	28.94	27.81	28.08	28.2	27.32	27.14	27.03	27.54

Fig. 4 – Improvement of operative temperature for the Bebedero case.

5. Conclusion

The thermal and energetic analysis of the three (3) case studies in the simulation tool allowed us to consider the performance of the current typology in addition to achieving the factors that have a positive impact in terms of indoor comfort and energy efficiency (reduced cooling demand). through parametric comparison.

The simulations showed patterns known within the current architectural design of the classroom, such as the improved performance of the north facing classrooms and the effect of height and glazed in the thermal quality of the building area.

The possibility of enhancing air changes through natural ventilation and controlling the operation and heat gains proved to be key to slowing demand in refrigeration, for example with the use of mechanical ventilators or HVAC systems.

A cooling system with ceiling fans in one school (Bebedero) can reduce the annual consumption of 15,120 kWh to 10,584 kWh, a decrease of 30% in the annual cost of service. If we think of the 4,070 schools that exist in the country, this is a considerable number of savings in energy production and in the education budget, especially in rural areas where the budget is very limited.

The opportunity to use dynamic scenarios and validation with field studies allows us to define future parameters to use in the design to achieve an improvement in the actual performance of this type of buildings.

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7. Nomenclature

Symbols

Tc	Comfort temperature
Tavg	Average exterior temperature
W	Watts
kWh	Kilowatt hour
° C	Celsius Degrees
lux	Luxes
ac/h	Air changes per hour
Tbs	Dry Bulb Temperatures

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