Contemporary Vernacular Architecture in The Brazilian Tropical Savana: The Case-Study of the Children's Village in the Canuana Farm, in Tocantis.

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Abstract

Completed in 2017, the building complex Moradias Infantis de Canuanã (Canuanã Children's Village) is located in the city of Formoso do Araguaia in Tocantins, in Brazil. Its architecture is strongly influenced by the local savanna climate which is characterised by distinct hot-dry and hot-mid seasons. In this study, the authors evaluated the buildings thermal conditions and the potential of natural ventilation using analytical procedures supported by computer simulations. Air movement in the transitional spaces was also simulated with CFD techniques. The findings reveal that, during the hottest periods of the year, the key habitable spaces (bedrooms) in the building have temperatures 10 oC below the outdoors. Primarily, this performance is attributed to the influence of thermal mass, combined with natural ventilation and shading. Additionally, a positive impact of natural ventilation on indoor conditions requires a combination of wind driven and buoyancy effects. In the courtyards, the distance between blocks is enough to allow perceivable air-speeds. Overall, this study has shown that the holistic design employed at the Children's Village building complex in Tocantins works well to maintain the indoor thermal environment at acceptable conditions.

Keywords -Vernacular Architecture, Tropical Savanna, Thermal Conditions, Natural Ventilation, Analytical Study.

1. Introduction

1.2 The Case Study Building: Architectural design and passive strategies

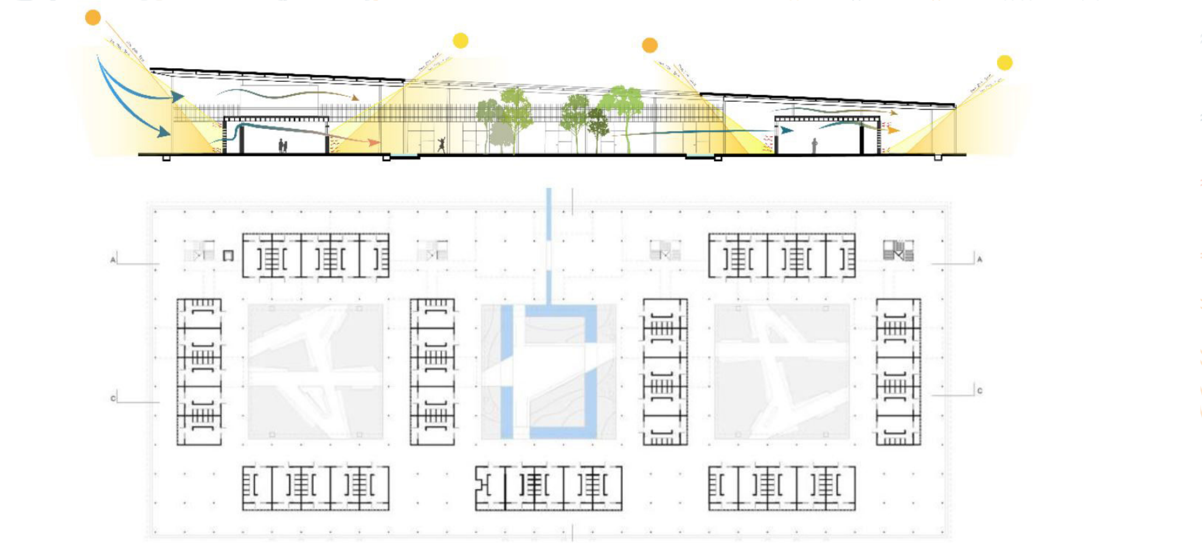
The building design of Canuanã Children's Village addresses the brief of reformulation of the spaces of the rural school of the Fazenda Canuanã, which houses 540 children (students from the Bradesco Foundation). The new building complex encompassed approximately 23,000 m^2 of built area [14]. Completed in 2016 in the city of Formoso do Araguaia, in the Brazilian state of Tocantins, the architectural design is strongly influenced by the local tropical savanna climate (tropical wet and dry - Aw), characterized by a dry and a rainy season, with peak air temperatures varying between 30°C and 40°C throughout the year and significant thermal amplitudes (mainly in dry periods), exceeding 10°C. The spaces are distributed in blocks around three rectangular patios, side by side (Figs 1 and 2), all shaded by a large roof structure made by glued laminated wood and external high-reflective metal sheets. The overarching structure acts as a second roof, shading the blocks and their roof terraces, with openings over the courtyards. The big second roof is slightly sloped to increase airflow at the roof tops. Dormitories are located at the ground floor, whilst classrooms, a library and other living spaces are on the upper level.

In the search for climatic responsive architectural solutions (the so-called passive solutions), for thermal comfort of the users throughout the year in the hot-dry and hot and humid climate of Tocantis, strategies were combined providing ample shading and natural ventilation, coupled with a high thermal capacity building fabric. The inspiration in examples from the regional construction and traditional building techniques, led to the choice of building components with low environmental impact, with emphasis on the use of raw adobe bricks, made from local soil, clay, sand and organic material for walls and floors, with the aim of adding thermal inertia to indoor environments, to deal with the high temperatures and thermal amplitudes. Precedents of analytical thermodynamic studies

Figure 1: Views of Canuanã Children's Village. One of the internal courtyards on the left and external view of the building complex, on the right [14, 5]. Architects: Aleph Zero & Rosenbaum.

for compact adobe construction environments in three hot climatic contexts showed that while the maximum external temperature occurs between 15:00 and 16:00 hrs, the temperature maximum internal temperature is registered between 19:00 and 20:00 hrs, pointing to a peak temperature delay of approximately 4 hours, accompanied by a damping between external and internal surface temperature around 12°C [8].

In Brazil, the assessment of the thermal response of brick constructions in housing was verified by measurements in loco at the Vila Butantã development in São Paulo (1998), showing that while the external temperature reaches 30°C, the internal temperature is around 24°C, given the thermal inertia combined with shading and opening control for ventilation, as applied in the Tocantins project [12]. Combined with the control of heat transfer from outdoor to indoor by means of thermal mass, perforated brick elements, known in Brazilian architecture as cobogós, are placed on the external and internal facades (in communication with the patios) of the dormitories, to induce constant air flow, which, at night, assists in the passive cooling of the internal spaces (in addition to cooling the envelope of buildings). In addition to the cobogós, dormitory windows for transitional spaces and movable wooden panels over doors and partitions have the potential to increase cross ventilation through the spaces (Fig. 2 and 3). The wooden components, including the rafters and roof slats, are made of glued laminated reforestation wood (the most local sustainable choice for the use of wood in construction). Looking at the arrangement of the building form, the courtyards facilitate cross ventilation and daylight to the internal environments, while the large double roof shades the buildings. In this way, open and transitional spaces on the ground and at roof level, where living and common areas are located, are protected against the direct impact of solar radiation throughout the year.



Figures 2a & 2b: Architectural drawings of the Canuanã Children's Village. At the top: Cross section highlighting the shading role of the double roof and the ventilation strategy through the perforated external walls. At the bottom: Ground plan of the building complex showing the three courtyards, with the bedrooms [5].

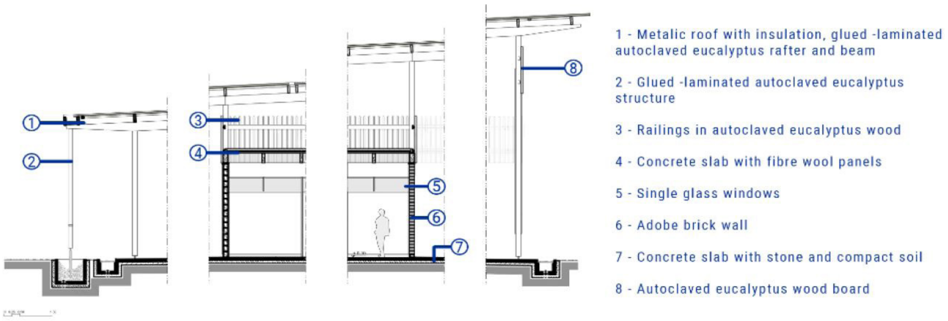


Figure 3: Detailed sections of different parts of the envelope, showing the building components and the different heights of the roof, as a result of its inclination [5].

The penetration of daylight in the dormitories occurs through the reflection of solar radiation through the external wall of the perforated elements, which shadows the area of the balcony, which, in turn, works as a transition zone for solar radiation, which is then reflected inwards. Previous analytical work showed that in addition to the meaningful reduction of solar gains, the roof worked also acts as a means to control excessive daylighting levels across the building, in locations close window openings, avoiding glare [7]. The same studies demonstrated that even without the big double roof, the occurrence of UDI in the "excessive" range is predominant in the balcony area, but does not go higher than 18%, approximately, in the worst case, being this the southwest.

In general, cross ventilation is possible by spatial communication between floors (stack effect), as well as by the continuity between same floor areas. In the dormitories, the design of the window frames allows for the complete opening of the window area. On the ground floor, open spaces in the interior and in the immediate surroundings of the buildings received a landscape treatment of native plants from the tropical savanna, qualifying the open spaces between buildings. Regarding the natural characteristics of the place, the water body close to the buildings, the Javaés River, contributes to the local microclimate, especially in the hot and dry season, increasing the relative humidity. The architectural synthesis achieved in the design Canuanã Children's Village, which explores the use of reforestation wood and earth architecture, made this design an international reference in contemporary vernacular architecture (and bioclimatic design) for hot and dry climates, awarded and published internationally. In this context, the main objective of this environmental assessment is to verify the thermal performance and the role of ventilation in the buildings complex of Canuanã Children's Village, in Tocantis, Brazil, through analytical evaluations carried out with the use of computer simulations. The analyses are focused on examining the impact of the thermal mass of the building fabric and of the large roof on the internal thermal conditions of the dormitories and their respective balconies, by quantifying the internal operative temperatures throughout the year. In addition, the resultant indoor air changes (ach) was estimated as a function of the design of the apertures and the proportions and orientations of the spaces. With respect to the outdoors, Air movement in the open and transitional spaces of the development were examined by means of simulations of computer fluid dynamics.

1.2 Climate

Located at latitude 11° 47'S, the city of Formoso do Araguaia is located in a tropical savanna region [12]. This climate is characterized by high temperatures throughout the year with a dry and a rainy season. Because of the low latitude, the northern and southern orientations receive significant amounts of solar radiation throughout the year, with the southern orientation mostly affected between January and April and from October to December (summer and spring seasons), while in the north, impinging solar radiation is significant from March to June and July to September (autumn and winter months). At this latitude, the solar path quickly reaches the most central area of the sky domo. As an example, at 12 o'clock the solar altitude reaches 77.5°on the equinoxes, 78° on the summer solstice and 55° on the winter solstice, making horizontal elements the most efficient strategy for shading. Climate data from the local meteorological station has shown that the global radiation on the horizontal surface is between 4,000Wh/m^3 and 6,000Wh/m^3, with August and October the months with the highest incidence and April the month with the lowest [12]. The drybulb temperature remains relatively constant throughout the year, with monthly averages ranging from 25°C to 30°C, with maximums exceeding 35°C and reaching close to 40°C in August and December, the hottest months. In general, the period between October and April comprises the most humid and hot months, with relative humidity rates around 80%, while the period between May and September is mostly hot and dry, with relative humidity around 40%. Because of the drop in humidity, the hottest and driest months are also those with the greatest daily temperature amplitude (ΔT), reaching 13°C in June and 18°C in September, while in the humid months this variation is about 6°C. Such values of ΔT, particularly in the hottest period of the year, point out to the advantages of thermal mass combined with night-time ventilation to moderate internal temperatures. The prevailing winds, important for wind-driven ventilation strategy, vary between the south and southeast throughout the year, with average speeds around 1.9 m/s and high speeds reaching 8.3 m/s.

2. Methods

The environmental assessment of this case-study is essentially analytical, focusing on dormitories and their respective balconies (space created between the external cobogó walls and internal facades), across three different orientations (Fig.5). For the thermal assessment, thermodynamic simulations were carried out, from which the percentages of annual hours of comfort and discomfort were calculated based on the ASHRAE adaptive thermal model [2]. In addition, aiming for a deeper understanding of the project's thermal response to the local climatic conditions, the profile of operative temperatures over two weeks of the hottest period of the year was extracted from the thermodynamic simulation, comprising the period between end of September and the beginning of October. The thermodynamic simulations were carried out with the Honeybee plugin of the Grasshopper simulation software, which makes use of the Energyplus computational calculation tools. The digital model was built with Rhinoceros 5. Tables 1 and 2 show the thermophysical properties of the building components and the internal gains and ventilation schedules used in the thermal model.

Table 1: Thermophysical specification of the construction components used in the thermal model [10, 5, 3].

Elemento	Materiais	thickness (cm)	Conductivity (W/m*K)	Density (kg/m^3)	U Value (W/m^2*K)
Floor	concrete	10	2,3	2500	2,79
	stone	40	1,3	2240	
	compact soil	10	1,28	1460	
External Wall	adobe block	14	0,37	1700	2,37
Slab	concrete	7	2,3	2500	1,60
	fibre wool	2,5	0,042	12	
Internal Wall	Concrete hollow block	15	0,48	880	1,35
	gypsum	2,5	0,22	800	
Windows	Single glass	0,3	1	2500	5,00

Table 2: Occupancy, internal thermal load and window opening regime for natural ventilation on weekdays.

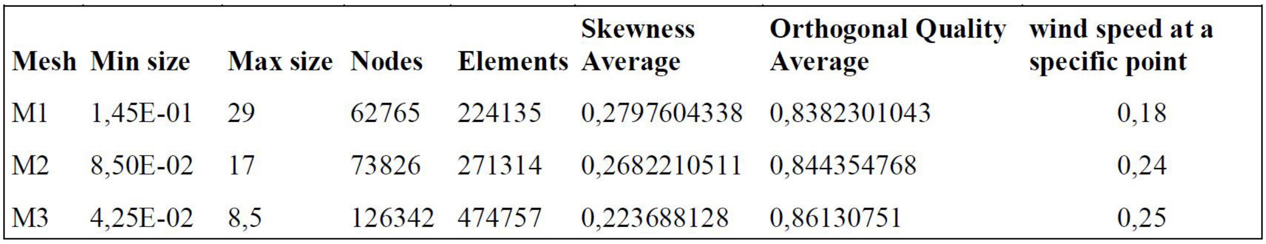
Times	People	Artificial light (W/m^2)	Equipament (W/m^2)	Natural Ventilation Schedule (% of window opening)
00:00-7:00	6	0	0	100
7:00-8:00	3	5	1	50
8:00-9:00	0	5	0	50
9:00-18:00	0	0	0	0 (infiltration = 0,28 ach)
18:00-21:00	3	2,5	2	100
21:00-23:00	6	5	2	100

To examine the potential of natural ventilation, four room scenarios were simulated with the Optivent software, an analytical tool based on the fundamental equations of air flow [4]. The scenarios included two bedrooms, one from Block B, facing southwest (leeward side) and another one from Block A, facing southeast (windward side). In both cases cross ventilation was adopted, given the possibility of using the apertures on opposite sides of the room. For each room, two scenarios were tested, one for a mild day (in June) and another one for a hot day (in October). The results were extracted in air-changes per hour (ach/hour). In all four cases the results included the contribution of stack-effect (buoyancy) only and stack-effect plus wind-driven ventilation. In order to focus on the best possible outcomes, the results presented here refer exclusively to the combined effect of stack plus wind driven ventilation. The calculation of the required air-changes assumed an internal peak temperature 2oC above the outside. It is important to mention that the natural ventilation assessment did not consider the positive impact of the thermal mass, only the shading and insulation from the building fabric.

The computer fluid dynamics (CFD) simulation was executed using the open-source software OpenFOAM [10]. For the simulations of external airflow, the simpleFOAM solver was employed for the definition of the boundary condition. The equation proposed by Hargreaves and Wright was adopted to generate an Atmospheric Boundary Layer (ABL), which best emulates the characterization of natural ventilation in an urban environment. This process facilitates the creation of an urban gradient based on parameters like roughness values, porosity, and turbulence [6]. The input data for air velocity was set at 1.9 m/s, aligning with the characteristic direction for the city in question. The simulation was carried out using the SimpleFoam calculation method within a steady, adiabatic, incompressible, and turbulent regime. Air was treated as an ideal gas at a temperature of 25°C. The methodology for the CFD simulation was divided into four stages: 1. Pre-processing; 2. Setting boundary initial values; 3.

Solving equations; and 4. Post-processing. During the Pre-processing stage, the geometry was developed using solid modeling techniques within CAD software. Meshing stands as a pivotal phase in any CFD simulation. Mesh production involves subdividing the analyzed geometry into smaller segments for analysis. The mesh was generated in an unstructured manner, focusing on creating prism elements close to the ground and buildings to better capture the detachment of the boundary layer. Additionally, tetrahedral elements were constructed to form a non-linear polymesh. A mesh independence test was conducted using three distinct meshes (Table 3).

Table 3: Data from the three meshes used in the mesh independence test.



Mesh	Min size	Max size	Nodes	Elements	Skewness Average	Orthogonal Quality Average	wind speed at a specific point
M1	1,45E-01	29	62765	224135	0,2797604338	0,8382301043	0,18
M2	8,50E-02	17	73826	271314	0,2682210511	0,844354768	0,24
M3	4,25E-02	8,5	126342	474757	0,223688128	0,86130751	0,25

The equations were repeatedly solved, with each iteration aimed at minimizing the residuals. This iterative approach stems from the differential nature of the Navier-Stokes equation, striving to converge towards values approaching zero. Beyond addressing residuals, it is imperative to ensure the physical stability of the analyzed variables. For the analysis and validation of simulation results, only simulations with residuals smaller than 10e-4 and exhibiting a physical stability variation of less than 5% across simulations were considered [9]. In addition to the examination of the internal conditions, the outcome of the CFD simulation was use to inform a qualitative interpretation of the thermal outdoor conditions in the transitional and open spaces of the building complex.

3. Results

3.1 Thermal Performance

The results of the analytical studies showed that the rooms/dormitories facing the three orientations present a high percentage of comfort hours (above 85% of the time in the dormitories and above 69% in the respective balconies) for scenarios with and without the roof. The greater exposure of the balconies to the external environment (even if well protected) results in a slightly worse thermal performance. In the case of the scenario with the big double roof, the difference between the dormitory and the balcony is around 5%. This difference goes up to 20%, approximately, in the scenario without the roof. Looking exclusively at the dormitories, as shown in Table 4, while in the scenarios with roof the heat discomfort is practically zero in all orientations, without it, the heat discomfort is between 9.19% and 11.58%, depending on the room orientation. With respect to the balconies, the difference between orientation is much greater, staying at a little less than 1%, in the best case, with the roof, and reaching almost 30% in the worst case, without the roof. Comparatively, the percentages of discomfort due to cold were low, being 4% in the worst case of dormitories facing the northeast and 7% on their respective balconies, not being a problem, per se, as a small percentage of night-time thermal discomfort can be adjusted with blankets. The small difference of annual hours of discomfort between the scenarios with and without the double roof can be attributed to the high degree of shading inherent to the external walls of perforated elements, combined with the effects of thermal mass and controlled natural ventilation.

Regarding trends of operative temperatures during the two representative weeks, the thermodynamics simulations showed that the blocks have little difference among them. Therefore, for the purpose of objectivity, Figure 4 brings the data exclusively to the dormitory and the balcony of Block B, with and without the roof, during a period of two weeks of hot and dry conditions, between September 19 and October 3. The results point to a clear thermal stability of the simulated environments, even in the scenario without the roof. However, it is worth noting that in the scenario with the roof, the air temperatures in both the dormitory and the balcony are more in the center of the comfort zone (close to the neutral temperature line). In the case of September 23, one of the hottest days of the selected period, while the outside temperature is around 38°C, the indoor temperature in the scenario with the double roof is 25.8°C, whilst without it, the temperature reaches 29°C, both still within the comfort zone. Another point to note is that only in the balcony of the scenario without the roof the upper limit of the comfort zone is exceeded during the day, presenting daily amplitudes of 12.5°C and 9.3°C, respectively, which are significant for the effectiveness of night ventilation. The operative temperature profiles prove the relevant role of the roof for the thermal comfort of the dormitories and balconies. Due to its effect, the internal temperature in the dormitory is about 3.2°C below the scenario without it.

Table 4: Annual percentage of comfort and discomfort hours, in the simulated scenarios

ASHRAE (90% acceptance)	Block A External facade: SO				Block B External facade: NO				Block C External facade: SE			
% in relation to the comfort zone	with roof		without roof		with roof		without roof		with roof		without roof	
	D*	B**	D*	B**	D*	B**	D*	B**	D*	B**	D*	B**
% Below	4.01	7.01	0.61	0.58	2.59	5.23	0.47	0.55	1.86	4.46	0.56	0.43
% Above	0.00	0.89	9.19	29.68	0.00	1.96	11.76	23.39	0.01	1.88	11.58	24.55
% Comfort	95.99	92.01	90.21	69.55	97.41	92.81	87.77	76.06	98.13	93.65	87.87	75.01

*Dormitory **Balcony

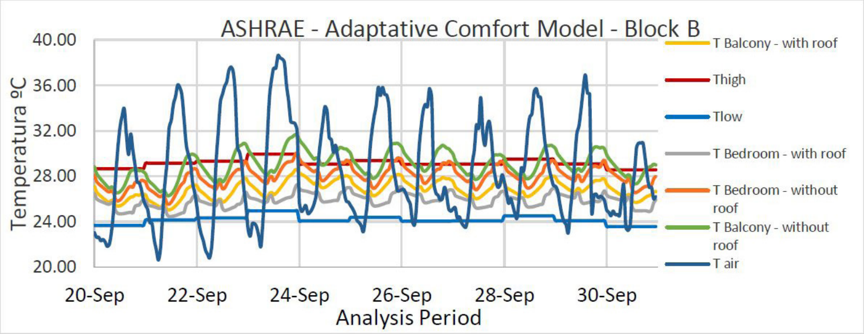


Figure 4: Profile of Operative Temperatures in the dormitory and balcony of Block B (main facade to the Southeast orientation - 208o), in the scenarios with and without the double roof, for the period between September 19 and October 3, showing the comfort zone according to the adaptive model of ASHRAE [2].

3.2. Indoor natural ventilation

Firstly, the Optivent results confirmed the need for cross ventilation if higher air change rates are required (results associated with stack effect only are not shown in this work, as they failed to provide the required air-changes in all cases). The room in the leeward direction (SW), scenarios 1 and 2, achieved more than half of the required air changes during the milder day, but stayed at less than half of the required performance on the hot day. The room on the windward orientation (SE), scenarios 3 and 4, showed a similar trend. It should be noted that, although on the leeward side, the air movement in the courtyard allows for enough wind speed to promote wind-driven cross ventilation. The insufficient air-changes found in scenarios 2 and 4 indicate the high probability of temperatures will be above the upper limit of the comfort zone during those hours.

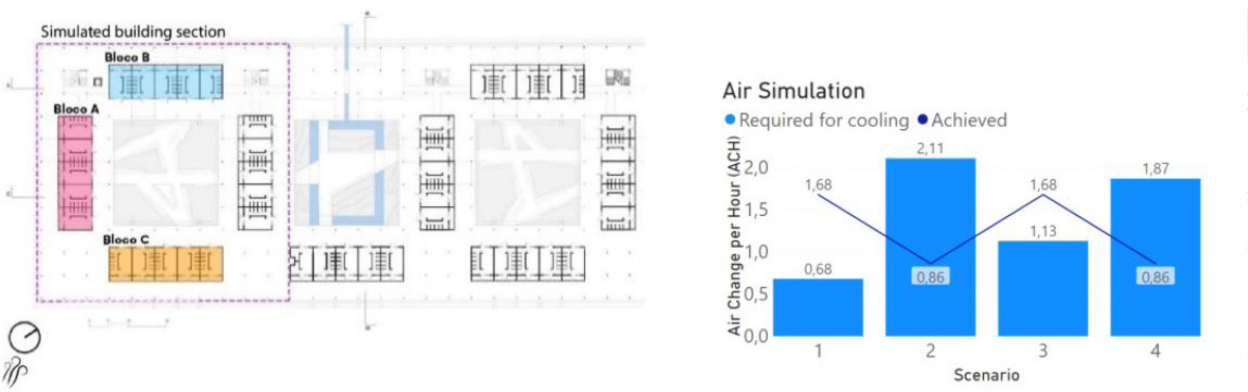


Figure 5: Comparison of air changes required and achieved in rooms A (SW) and B (SE), during the peak hour of a mild and a very hot day in Tocantis, Brazil.

3.3 Air Movement in the open and transitional

The study of air movement focused on the courtyards and respective external areas around the buildings, for the prevailing southeast wind of 1.90 m/s (Fig. 6). The result highlights a plane at 1.5m (pedestrian level), where it is possible to observe speeds of the order of 0 to 1.5m/s at some points in the open space between the buildings. Data acquisition was done for the central point of the external courtyards, where wind speeds vary between 0.24 and 0.28 m/s. It is possible to verify with this simulation that the air speed occurring inside the blocks is low, whilst natural ventilation driven by the wind should be a potential strategy to improve thermal conditions in outdoor and transition spaces. With the study of air movement, it was possible to extract the Pressure Coefficient on the facades of the buildings (Fig. 7). Figure 7 illustrates the predominantly positive pressure coefficient on facades 1 and 2, this positive Pressure Coefficient in conjunction with the predominantly negative Pressure Coefficient on facade 5 favors cross ventilation in the buildings located in row 3, however, the Pressure Coefficient predominantly Negative pressure on facades 4 and 6 adversely affects the pressure coefficient in buildings located on row 1.

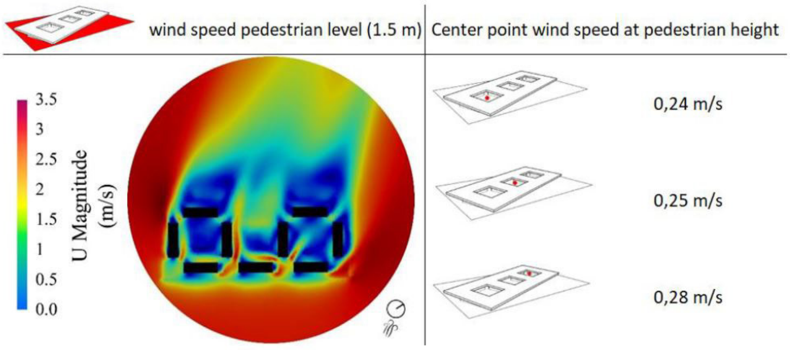


Figure 6: On the left, the ground floor plan of the buildings with the identification of the location of the simulated rooms. On the right, wind speed simulation in the open and transitional spaces, at ground level.

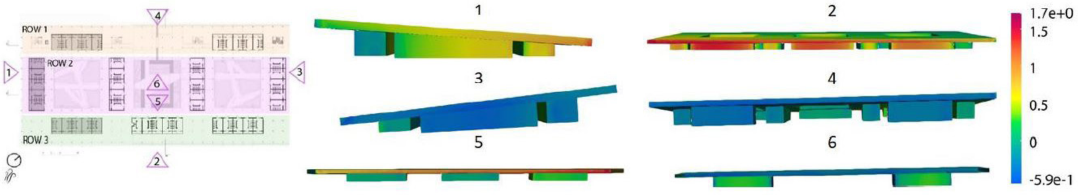


Figure 7: Pressure Coefficient on six facades that make up the Canuanã Children's Village.

4. Discussion

The thermal performance analysis of the design strategies of the Canuanã Children's Village, located in the Brazilian tropical savanna of the state of Tocantins, revealed the potential of satisfactory thermal conditions in the dormitories and their respective balconies throughout the year. As an example, for a typical week of hot and dry conditions, there were verified operative temperatures in the internal areas of the dormitories around 10oC below the outside temperatures, showing the influence of the thermal mass of the adobe walls, combined with shading. Furthermore, the overarching roof has proved to have a role in reducing solar gains, resulting in a difference of 3°C to 5°C in the dormitories, between the scenarios with and without the roof shading. Similar to the precedent studies on thermal mass [8, 11], in the Children's Village of Tocantins, internal temperatures are stable, around 25oC, while the external temperature oscillated to around 30°C. However, in general, in the dormitories operative temperatures vary within the comfort zone, even in the hypothetical scenario of the absence of the double roof, because of the shading created across all external walls by the perforated brick wall, alongside the thermal mass and the selective natural ventilation strategy, which is essential for the night-time cooling.

Commenting on the results from the indoor natural ventilation studies, the risk of thermal discomfort on the very hot day, due to the insufficient air-changes, can be dealt with by decoupling the interior spaces from the outside, but closing the ventilation openings and allowing the thermal mass to act moderating the internal peaks and the swings, as shown in thermodynamic simulations. What is also interesting to see is that, when outdoor temperatures are not so extreme, cross ventilation is sufficient to provide enough air-changes for thermal comfort. The air movement indoors and outdoors are particularly desirable during the milder period because of the higher humidity levels. Moving to the CFD simulations, reasonably low values of air speed were found in the courtyard at some positions. On this basis, the site planning of the building blocks does not always favour the air movement across the courtyards and, consequently, the cross ventilation of the internal spaces at ground level, in particular.

5. Conclusion

In conclusion, the design in question proved the possibility of achieving thermal comfort, even in extreme heat conditions (when external temperature values are around 40oC), from the joint application of passive solutions appropriate to the local climate and using techniques already known to reduce the thermal load of buildings, present in the local vernacular architecture, including shading, thermal mass, selective natural ventilation and transition zones, ultimately dismissing the use of air-conditioning. Regarding the use of passive strategies, it is particularly important to highlight the advantage of controlling (openings and closing) the apertures for cross ventilation coupled with stack effect, during the mild periods, when external air temperatures are acceptable. On the other hand, the courtyard shape blocks wind and therefore reduces the natural ventilation potential. Moreover, the refined detailed design of visually striking building components, such as the double roof structure and the cobogo walls, coupled with the flexibility of the movable wooden panels and operable windows, create a robust response to the harsh and variable conditions of the local climate, with a range of environmental adaptability to be explored by the occupants, defining the parameters of a high-quality designed of a new vernacular for the Brazilian tropical savanna.

The innovation presented here is not in the methodology of how the building was studied, but in the building itself, which opens up a new era for Brazilian locally inspired building design, featuring local (and ecological) materials and spatial quality, which can support social and environmental development.

6. Acknowledgements

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