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Evaluation of the Thermal Performance in External Vertical Enclosures Constituted of Metal Panels

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Abstract: Brazil has a great climatic diversity, with different demands for the adequate thermal performance of buildings, where the variables that impact it have different influences depending on the location and the type of wrapping used. When a prior study of the thermal performance of a building is not done in the design phase, the unpleasant effects for the user appear after the building is ready, and bring with them problems such as internal temperatures that are too high in the summer or too low in the winter. Therefore, the objective of this study is to provide recommendations for the application of ACM (aluminum composite material) composite panels and thermoacoustic (sandwich) tiles for external enclosure in the single-family residential sector. A high standard two-story residence with approximately 162 m^2 per floor is used as a model and through computer simulations, utilizing the Energyplus program and observing the requirements of the NBR 15.575 performance standard, the thermal performance is evaluated. The factorial experiment was applied encompassing thermal performance variables such as absorptance, natural ventilation and thermophysical properties of the "wrapping for three different climatic conditions: extreme winter climate, average climate and extreme summer climate. The results obtained show that the thermoacoustic roof tile keeps the internal temperature more stable independent of external oscillations, while the ACM panels follow the external oscillations, not meeting the expectations of thermal performance and needing passive treatments.

Key words: Metallic (wrapping), thermal performance, composite panels, thermoacoustic tiles.

1. Introduction

The aluminum composite material (ACM) is formed by two layers of aluminum and a polystyrene core, possessing durability and high fire resistance. Because of its low weight, it is indicated for the manufacturing of large panels. Its malleability is the characteristic that gives the panels of this material a great ease of conformation and assembly agility [1]. This material is widely used in architecture as a component of the ventilated façade system. The panel offers a wide variety of distinct colors and sizes, providing a great solution for residential buildings, both for new buildings and retrofits [2].

The thermoacoustic metal tile panel is characterized by two metal sheets made of galvanized steel and an inner layer of lightweight insulating material, such as Poliestileno Expandido (EPS). The use of insulating material aims at thermal and acoustic insulation, and consequently seeks to improve the internal condition of the building. The characteristic of the insulating material used is the ability to reduce heat transfer by conduction through the wrapping [3].

Elements such as walls, roofs, floors, doors and windows, for example, contribute to the increasing or decreasing of the thermal performance in a building. The lower the thermal conductivity and the higher the thermal capacity of the material used, the lower the heat exchanges through the wrapping [4]. There is a current trend to improve the thermal performance of buildings, due to the impacts in the comfort of the users and the high energy consumption of buildings [5]. In order to promote user comfort, architecture should act to ensure the best thermal performance of

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buildings and minimize the environmental impacts resulting from their energy demand, as well as favoring passive conditioning and thus reducing the use of artificial climatization systems and, consequently, the operating energy consumption of the building.

The performance standard NBR 15.575 [6] indicates the use of computer simulation to determine the thermal behavior of a building, and recommends the use of the EnergyPlus program. In order to perform the computer simulations, data presented in NBR 15.575 [6] should be used as a reference for the geographical location of some Brazilian cities and the climate data corresponding to the typical summer and winter project days of the BZs (bioclimatic zones) established in NBR 15.220 [7]. Through computer simulation, a detailed analysis of the thermal performance of an existing or planned building can be performed, and based on the obtained response, design decisions can be directed even before construction, taking into account local climate conditions.

EnergyPlus is a computer program, created from the BLAST (Building Loads Analysis and System Thermodynamics) and DOE-2 programs, developed and distributed by the U.S. Department of Energy [8], developed for thermal load simulation and energy analysis of buildings and their systems [9]. This software is a tool for modeling and evaluating building performance, which allows simulating heating, lighting and ventilation systems in order to quantify their energy consumption [10].

Point out that an important tool to define housing with adequate thermal comfort conditions is to adopt guidelines that consider the relationship between climate and humans [11] [12]. This paper evaluates the thermal performance of two metallic external closures in the single-family residential sector: ACM (aluminum composite material) composite panels and thermoacoustic sandwich tiles.

2. Methodology

The methodology is based on parametric studies obtained from computer simulations using the EnergyPlus software, making it possible to specify architectural devices to adapt the thermal performance of the building. The researched model is a high standard two-story residence, with approximately 162 m^2 per floor, with wrapping in two different types of metallic materials: ACM panels and thermal acoustic tiles (Tables 1 and 2). The building is composed of the following rooms: living/dining room integrated with the kitchen, on the first floor; a second floor with three bedrooms, one of them featuring a suite with closet, and two balconies, one in the front and the other in the back. The environments used in the study are those of prolonged stay (bedroom and living room), with the bedroom located on the second floor and the living room on the first floor (Figs. 1 and 2).

Table 3 presents the thicknesses and thermophysical properties of the materials that make up the closures, and Table 4 shows the data referring to the glass used.

The climate data from three BZs are used as reference for the computer simulations: ZB1 (city of Curitiba), ZB3 (city of São Paulo) and ZB8 (city of Manaus), representing different climatic conditions, i.e., extreme winter climate, median climate and extreme summer climate, respectively (Tables 5 and 6).

Table 1 Enclosure systems A.

Enclosure	Material
External enclosure	ACM panels (aluminum + polystyrene + aluminum)
Internal enclosure	Masonry (plaster + brick + plaster)
Rooftop	Ceramic tile and concrete (slab)
Floor	Ceramic floor on concrete
Doors	Plywood
Windows	Glass

Table 2 Enclosure systems B.

Enclosure	Material
External enclosure	Sandwich tile (steel + EPS + steel)
Internal enclosure	Masonry (plaster + brick + plaster)
Rooftop	Ceramic tile and concrete (slab)
Floor	Ceramic floor on concrete
Doors	Plywood
Windows	Glass

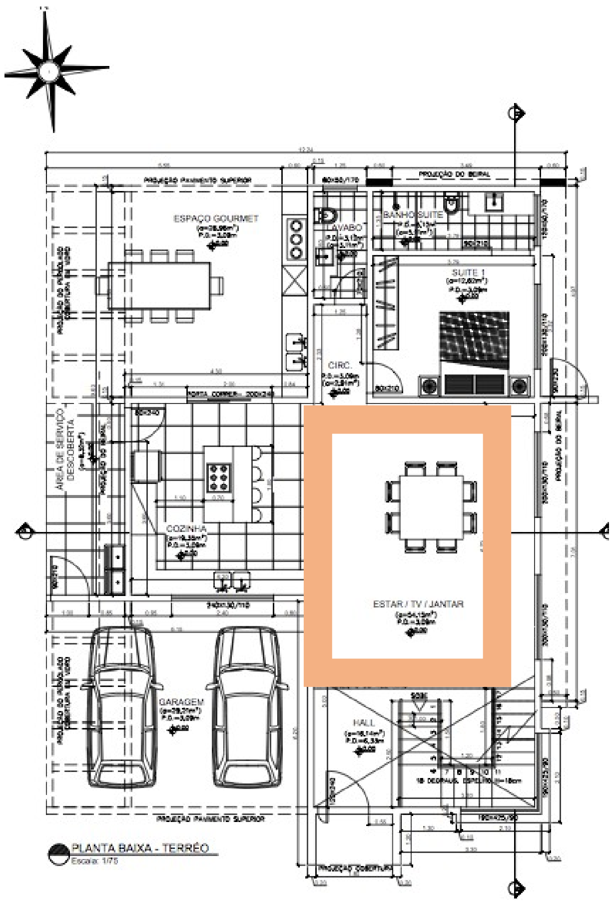

Fig. 1 Floor plan of the first floor in the studied model.
Source: own author.

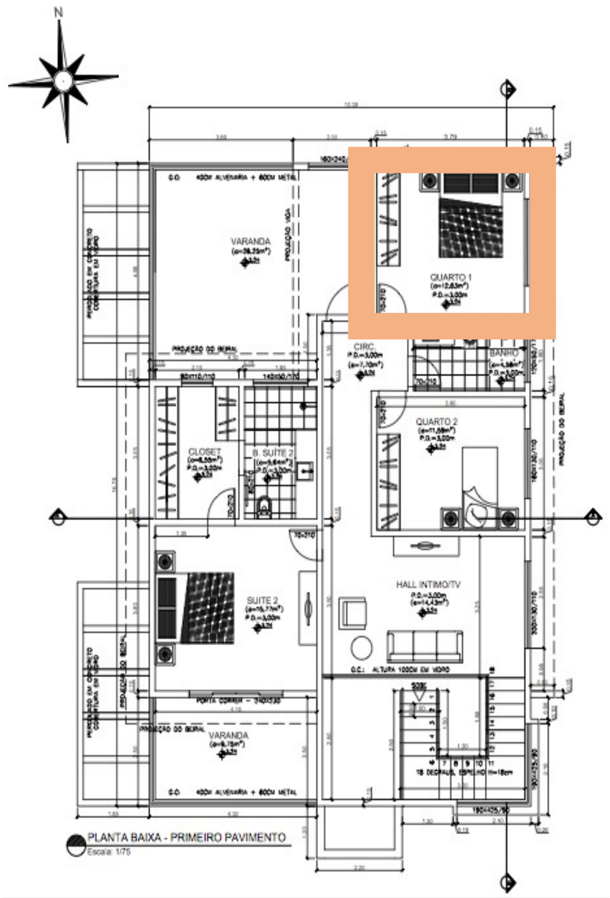

Fig. 2 Floor plan of the second floor in the studied model.
Source: own author.

The methodology can be summarized according to the flowchart presented in Fig. 3. The analysis is based on the results of the evaluation of the thermal performance in the architectural model (Figs. 1 and 2) using metallic external closures: ACM panels and thermoacoustic tiles (sandwiches). A comparative study is made of the internal temperatures of the environment in relation to compliance with thermal performance requirements according to the NBR 15.575 standard [6] and comfort in the environment.

Table 3 Thickness and thermophysical properties of the enclosed materials.

Material	Thickness (m)	Conductivity (W/mK)	Specific mass (kg/m^3)	Specific heat (J/kgK)
Concrete flooring	0.075	1.75	2.400	1.000
Ceramic floor	0.003	1.05	2.000	920
Concrete slab	0.1	1.75	2.400	1.000
Mortar	0.002	1.15	2.000	1.000
Galvanized steel	0.05	55	7.800	460
Aluminum	0.00021	230	2.700	880
Extruded polystyrene	0.00258	0.035	30	1,420
EPS	0.03	0.04	30	1,420
Plywood	0.035	0.15	550	2.300
Ceramic tile	0.001	1.05	2.000	920
Ceramic brick	0.01	1.05	2.000	920

Source: Ref. [7].

Table 4 Thickness, thermal conductivity and properties referring to glass radiation.

Material	thickness (m)	Conductivity (W/mK)	Solar Transmittance at normal incidence	Solar reflectance	Visible transmittance normal incidence	Visible reflectance at normal incidence	Hemispheric infrared emissivity
Glass	0.003	0.90	0.0837	0.075	0.898	0.081	0.84

Table 5 BZs and respective simulated cities.

BZ		Latitude	Longitude	Altitude
1	Curitiba (PR)	25°42' S	49°27' W	924 m
3	São Paulo (SP)	23°50' S	46°62' W	792 m
8	Manaus (AM)	3°13' S	60°02' W	72 m

Table 6 Data from typical summer and winter days of the simulated cities.

BZ		Daily $Te_{máx}$ (°C)	Daily temperature range (°C)	Humid Te_{bulbo} (°C)	Solar radiation (Wh/m^2)	Cloudiness (tenths)
Summer						
1	Curitiba (PR)	31.4	10.2	21.3	4.988	8
3	São Paulo (SP)	31.9	9.2	21.3	5.180	6
8	Manaus (AM)	34.9	9.1	26.4	5.177	7
Winter						
1	Curitiba (PR)	0.7	11.6	11.0	3.211	6
3	São Paulo (SP)	6.2	10.0	13.4	4.418	6
8	Manaus (AM)	21.4	7.9	25.0	4.523	7

Source: Refs. [7, 13, 14].

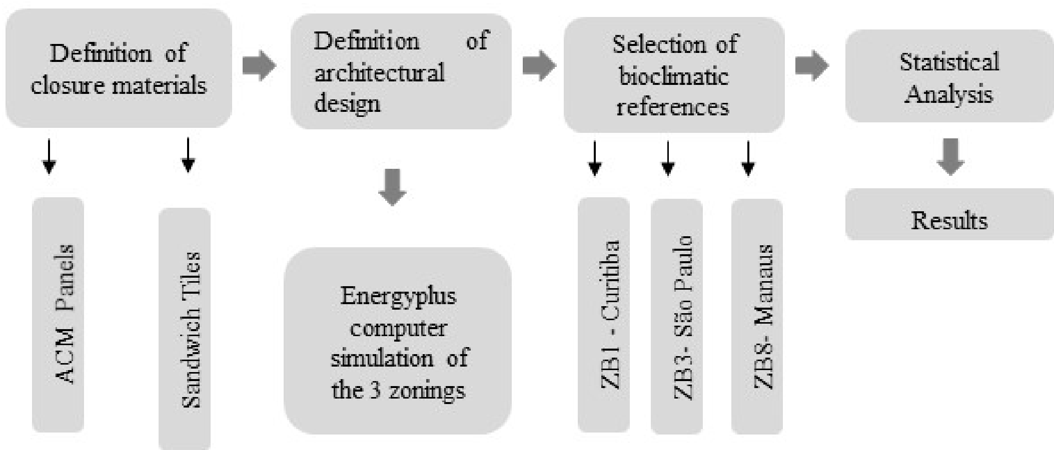

Fig. 3 Flowchart summarizing the applied methodology.

The comfort level evaluation of the environment is done using the concept of adaptive comfort, calculating the comfort temperature, according to the monthly average outside temperature, considering naturally ventilated environments through the following equation:

$$T_n = 0,31\overline{T}_e + 17,8 \quad (1)$$

where T_n is the temperature of the comfort or neutral (°C) and $\overline{T}_e$ is the average external monthly temperature (°C).

From the neutral temperature (T_n), the maximum and minimum limits for obtaining the comfort range are established. Thus, intervals are defined that guarantee the acceptability of the thermal conditions for 80% and 90% of the building occupants. By comparison to the neutral temperature equation, the comfort range limits are established for a 2.5 °C variation around the neutral temperature for 90% of the satisfied population, and for a 3.5 °C variation around the neutral temperature for 80% of the satisfied population. Thus, any occurrence of internal operating temperatures that exceed the established limits is characterized as uncomfortable hours. According to the ASHRAE Standard 55 [15] the operating temperature is the uniform temperature of an imaginary black enclosure, in which, a person would exchange the same amount of heat by radiation and convection as in the real non-uniform enclosure. With air velocity less than 0.4 m/s, it is approximately equal to the arithmetic mean of the air temperature and the average radiant temperature of the enclosure [15].

According to Addendum A of the ASHRAE 55 standard [16], the utilization of limits for 80% of the satisfied population should be used for typical applications, which is the case adopted in this study. The limits for 90% of the satisfied population should be used when a high standard of comfort is expected.

In this case study, the control variables are the absorptance, the natural ventilation rate, the thermophysical properties of the vertical closure, and the resulting internal temperature as a response variable to be compared with the requirements of the NBR 15.575 standard [6] and statistically analyzed.

From this comparative study of the internal temperatures, the influence of the absorptance, the natural ventilation rate and the thermophysical properties of the external closure used is statistically evaluated. In this research, the simple linear regression approach is used to model the action of these factors at levels that allow continuous measurement over their measurement range. It is modeled only when the absorptance is significant and when the interaction between all factors (absorptance, ventilation rate and thermophysical properties) is also significant, via analysis of variance, thus, one can predict the expected value of the response variable, from an observed value of the explanatory variable.

For the statistical confirmation, the F test or variance analysis is used [17], which aims to highlight the existence of a significant difference between the different types of factors or the interaction between them. For multiple mean comparison [18] test is used to verify the difference between the factors used and a possible grouping in equality between the means.

3. Analysis and Discussion of the Results

In Tables 7 and 8, the results for the thermal performance simulations considering the vertical closure with the ACM panel and the thermoacoustic tile closure, for the summer climatic conditions are shown.

It can be seen from the results shown in Tables 7 and Table 8 that the comfort temperature is not reached in any of the three BZs analyzed, regardless of the tile color (any absorptance value (alpha-α)) and the air renewal rate (ren/h). It is also observed by these analyses that the thermal-acoustic tile closure maintains a slightly lower internal temperature compared to that obtained with the ACM panel closure. The resulting temperatures in both cases do not meet the comfort expectations of the users and thus require passive treatments, through the proposition of adequacy strategies.

Table 7 ACM panel response for a typical summer day.

		$T_{i,\,max}$ (°C)											
		$\alpha = 0.3$				$\alpha = 0.5$				$\alpha = 0.7$			
BZ	T_n	Case 1 without shadow; 1 ren/h		Case 2 without shadow; 5 ren/h		Case 1 without shadow; 1 ren/h		Case 2 without shadow; 5 ren/h		Case 1 without shadow; 1 ren/h		Case 2 without shadow; 5 ren/h	
		Living room	Room 1	Living room	Room 1	Living room	Room 1	Living room	Room 1	Living room	Room 1	Living room	Room 1
1	25.8	28.6	30.1	28.7	30.2	28.8	30.2	29.0	30.4	29.5	30.6	29.4	30.7
3	26.2	29.4	30.7	29.4	30.7	29.9	31.0	29.9	31.0	30.4	31.4	30.4	31.3
8	27.1	33.4	34.5	33.3	34.5	34.5	35.5	34.4	35.4	35.7	36.5	35.6	36.5

Table 8 Thermoacoustic tile response for a typical summer day.

BZ	T_n	$T_{i,\ max}$ (°C)											
		$\alpha = 0.3$				$\alpha = 0.5$				$\alpha = 0.7$			
		Case 1 without shadow; 1 ren/h		Case 2 without shadow; 5 ren/h		Case 1 without shadow; 1 ren/h		Case 2 without shadow; 5 ren/h		Case 1 without shadow; 1 ren/h		Case 2 without shadow; 5 ren/h	
		Living room	Room 1	Living room	Room 1	Living room	Room 1	Living room	Room 1	Living room	Room 1	Living room	Room 1
1	25.8	27.5	29.0	27.5	29.0	27.7	29.1	27.7	29.1	27.8	29.3	27.8	29.3
3	26.2	28.2	29.3	28.2	29.3	28.4	29.5	28.4	29.5	28.5	29.6	28.5	29.6
8	27.1	31.6	32.6	31.6	32.6	32.1	33.1	32.0	33.1	32.5	33.4	32.5	33.4

Table 9 Multiple comparison tests for the closing parameter coating factor (Manaus-summer).

Test of Scott-Knott		
Treatment	Average	Position
Thermoacoustic	32.00	a1
ACM	33.04	a2

The letter "a" in the column position followed by larger numbers has a higher mean shape subsequently.

The city of Manaus representative of the ZB8 was analyzed for a typical summer day. Table 9 shows the Scott-Knott test, used for multiple comparison of means and detects that the ACM panel lining is the one that presents a higher average room temperature than the thermoacoustic tile lining.

The regression analysis models, in the case of Manaus, for the breakdowns of Alpha for each type of coating correspond:

(a) ACM panel lining: temperature = 30.44 + 3.71 × Alpha

The estimated model presents an R^2 = 99.98%, and can be interpreted in the following way: when the value of Alpha is increased, there is an expected average increase in the internal temperature room.

(b) Thermoacoustic tile covering: temperature = 31.35 + 0.93 × absorptance Alpha

The estimated model presents an R^2 = 99.83%, and can be interpreted in the following way: when the Alpha absorptance (alpha) value is increased, there is an expected average increase in the inside room internal temperature of the environment.

It is important to note that this model is only analytical, because the interaction at this level of unfolding proved to be non-significant, i.e., there is no significant difference in indoor room temperature, regardless of the (alpha) absorptance level chosen when using the thermoacoustic tile lining.

The city of Curitiba representative of the ZB1 is analyzed for a typical winter day, Tables 10-12. As can be seen in Tables 10 and 11, the only significant parameter at the 5% level, except for the period of the day when the temperature measurement is taken, is the type of closure used, all other parameters analyzed and their interactions are not significant to describe the internal room temperature.

Table 12 shows the Scott-Knott test, used for multiple comparisons of means, and detects that the closure with the ACM panel presents a lower average room temperature than the thermal-acoustic tile closure.

By the F test presented in Table 11, only the period factor was significant, i.e., different periods generate different average results in the response variable. It can also be that besides the period factor, the closure is also significant, and according to the results shown in Table 12, by the multiple comparisons test, the thermoacoustic closure presents a higher average than the ACM panel.

The city of São Paulo representative of the ZB3 is analyzed for a typical summer day and a typical winter day. It can be seen that the average indoor temperature changes significantly depending on the type of closure used, therefore, a multiple comparison test of means via Scott-Knott is performed as shown in Table 13, showing that the ACM panel closure causes a lower average temperature in winter when compared to the thermoacoustic tile closure.

Table 10 Variance analysis of the factors in Curitiba (winter).

Variation source	DL	SQ	MS	*F*-calc	*p* value
Period	3	206.81	68.93	37.54	0.00*
Renewals (Ren)	1	0.000301	0.000301	0	0.98
Absorptance(Alpha)	2	4.533149	2.266575	1.234	0.29
Closure	1	8.63266	8.63266	4.702	0.03
Ren*Alpha	2	0.131947	0.065973	0.036	0.96
Ren*Closure	1	0.0936	0.093683	0.051	0.82
Alpha*Closure	2	1.105235	0.552618	0.301	0.74
Ren*Alpha*Closure	2	0.114089	0.057045	0.031	0.97
Error	165	302.96028	1.836123		
Total	179	524.39042			

* The *p*-value demonstrates the significant factor at the 5% level.

DF = degrees of freedom; SQ = sum of squares; MS = mean squares and *F*-calc = calculated.

Table 11 Analysis table of factor variance for Curitiba (Inverno), only the significant.

Variation source	DL	SQ	MS	*F*-calc	*p* value
Period	3	206.81	68.93	37.54	0.00*
Closure	1	8.63266	8.63266	4.702	0.03*
Error	175	308.939	1.76536		
Total	179	524.39			

* The *p*-value demonstrates the significant factor at the 5% level.

DF = degrees of freedom; SQ = sum of squares; MS = mean squares and *F*-calc = calculated.

Table 12 Multiple comparison test for the closure parameter (Curitiba-winter).

Scott-Knott test		
Treatment	Mean	Position
ACM panel	7.42	a1
Thermoacoustic	7.86	a2

The letter “a” in the column position followed by larger numbers has a higher mean subsequently.

Table 13 Multiple comparison test for the closure parameter (São Paulo-winter).

Scott-Knott test		
Treatment	Mean	Position
ACM	12.87	a1
Thermoacoustic	13.15	a2

The letter “a” in the column position followed by larger numbers has a higher mean subsequently.

Table 14 Multiple comparison test for the closure parameter (São Paulo-summer).

Scott-Knott test		
Treatment	Mean	Position
ACM	28.15	a1
Thermoacoustic	28.41	a2

The letter “a” in the column position followed by larger numbers has a higher mean subsequently.

The estimated linear regression model, for São Paulo in winter, for the different levels of absorptance corresponds to: temperature = 12.25 + 1.54 × absorptance. It can be seen that there is an increase in the average inside room temperature when the absorptance levels are increased, and the proposed model presents an R^2 = 99.98%.

The same happens with the city of São Paulo on a typical summer day, as shown in Table 14; the use of ACM panel closure causes a lower average temperature when compared to the thermoacoustic tile closure.

The estimated linear regression model, for São Paulo in the summer, for the different levels of the Alpha factor corresponds to: temperature = 28.00 + 0.98 × absorptance. It can be seen that there is an increase in the average inside room temperature when the absorptance level (alpha) is increased, and the proposed model presents an R^2 = 99.97%.

4. Conclusion

This study allowed us to observe that for the warm climate cities, such as the bioclimatic 8 (ZB8), the 1st order factors that positively influence comfort were absorptance with light colors just as the simulations had already shown, making no difference in the cold climate cities (ZB1), and the ventilation showed no relevance in any of them. Under statistical analysis, the factorial experiment, for the three representative cities, obtained a high explanation capacity of the output variable from the analyzed variables. It is noticeable that the number of air renewals (ren/h) is not significant for the model, thus generating a question regarding the recommendation of the NBR 15.575 standard [6].

It is observed that the environments with longer permanence shown (bedroom and living room) present similar thermal performance, regardless of the evaluated ZB. In relation to the thermal absorptance (alpha), it is observed that light colors (α = 0.3) are more favorable to thermal performance of the building.

Regarding the ventilation rate (ren/h), it is observed that the internal temperatures are closer to the external temperature when there is a higher air renewal rate such as 5 ren/h. Thus, when the external temperature is high, ventilation should be controlled. With respect to the thermal absorptance, it is seen that light colors (α = 0.3) are more favorable to thermal performance when using the ACM panel. For the thermoacoustic tile, there was no interference in the increase or decrease of the internal temperature.

The results obtained in this statistical treatment allow a discussion about which variables are sensitive and, among them, which ones have the greatest influence on the thermal performance of the building for that city representative of the BZ. These analyses allow us to identify which are the recommendations for each type of climate. It is also observed, that compliance with normative requirements such as those suggested by the NBR 15.575 standard [6], does not guarantee thermal comfort conditions for some climatic contexts.

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