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Benefits of the use of thermal insulation in a naturally ventilated residential building in Brazilian temperate climate

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ABSTRACT
The use of thermal insulation is not a common practice in civil construction in Brazil. The national standard for thermal performance and the energy efficiency labeling program do not require the use of thermal insulation in the building envelope, even for the hottest and for the coldest regions of the country. Brazil has a temperate climate region that covers 7.2% of its territory and contains important and populous cities. This paper explores the benefits of the use of thermal insulation in dwellings located in that climate. A heat balance analysis was conducted in the computational model of a naturally ventilated single-family residential building. The simulation task was carried out in the EnergyPlus software with the use of weather files of three cities, classified as temperate climates. The main sources of heat transfer through the building envelope were identified and subjected to a sensitivity analysis, seeking for the building performance optimization. Simulation results shows that thermal insulation can be applied on building walls, roof and floor, with benefits measured as a reduction in the heating degree hours along the year. Increase in cooling degree hours during the summer could be overcome with strategies to control the solar heat gain on windows.
***Keywords*–**building simulation, temperate climate, thermal insulation, residential building

I. INTRODUCTION

The first version of the Brazilian standard for overall performance of residential buildings was published in 2013 [1]. One of its sections defines requirements of thermal performance for the building envelope regarding minimum U-values and heat capacity of exterior walls and roofs. However, no thermal insulation is required for any Brazilian climate zone, even for the extreme hot (northern Brazil) or extreme cold (southern Brazil) regions.

Southern Brazil presents warm and maritime temperate climates classified as Cfa and Cfb according to Köppen classification [2]. The main characteristics of the temperate climate is the occurrence of dry winters and rainy summers. Designing a residential building with passive conditioning strategies to satisfy both conditions of cooling and heating needs is a challenge.

Thermal insulation increases the thermal resistance of the building envelope and, thus, difficults the heat transfer by conduction due to difference of temperature. Consequently, the energy consumption for heating and cooling can be reduced.

North-American standards, like ASHRAE Standard 90.2 [3] and International Energy Conservation Code (IECC) 2012 [14 define envelope requirements for energy efficient buildings for each climate zone based on cooling and heating degree-days (Table 1). The Brazilian standard of performance for residential buildings [1] divides the country into eight climate zones, according to average temperature and humidity. Nevertheless, it is possible to identify some Brazilian cities located in zones 3A (warm – humid) and 3C (warm – marine) applying the same criteria of classification of American standards. For these zones, ASHRAE Standard 90.2 and IECC 2012 recommend the use of thermal insulation, but the Brazilian standard does not recognize the use of thermal insulation as beneficial in any portion of the country.

While the American regulation establishes 1.48 W/m².K as maximum U-value for walls in buildings located in climate zone 3, Brazilian standard limitsvalue at 2.50 W/m².K for minimum thermal performance in equivalent climate zones. Requirements for roof are even more different when comparing standard for both countries, as shown in Table 2. The Brazilian labeling program of the level of energy efficiency of residential buildings [5, 6] adopts the same requisites of U-values for the building envelope presented in Table 2 for those buildings intended to be level “A” of energy efficiency (most efficient).

Table 1 – International climate zone classification as a function of cooling and heating degree-days (ASHRAE, 2007)

Climate zone	Name	Thermal Criteria (SI Units)
1	Very Hot - Humid (1A), Dry (1B)	5000 < CDD10°C
2	Hot - Humid (2A), Dry (2B)	3500 < CDD10°C ≤ 5000
3A and 3B	Warm - Humid (3A), Dry (3B)	2500 < CDD10°C ≤ 3500
3C	Warm - Marine	CDD10°C ≤ 2500 and HDD18°C ≤ 2000
4A and 4B	Mixed-Humid (4A), Dry (4B)	CDD10°C≤2500 and 2000<HDD18°C≤3000
4C	Mixed Marine	2000<HDD18°C≤3000
5A, 5B and 5C	Cool-Humid (5A), Dry (5B), Marine (5C)	3000<HDD18°C≤4000
6A and 6B	Cold-Humid (6A), Dry (6B)	4000<HDD18°C≤5000
7	Very Cold	5000<HDD18°C≤7000
8	Subartic	7000<HDD18°C

Table 2 – Comparison of constructive requirements of ASHRAE Standard 90.2-2007, IECC-2012 and Brazilian standard of performance.

Maximum U-value (W/m^2 K)	ANSI/ASHRAE Standard 90.2 - 2007	IECC 2012	Brazilian Standard 2013
Wall	1.48	0.94 (zone 2); 0.56 (zone 3)	2.50
Roof	0.20	0.17(zones 2 and 3)	2.30
Floor	-	0.36 (zone 2); 0.20 (zone 3)	-

The need for thermal insulation is evident for climates with extreme temperatures, i.e., excessively hot or cold. European Directives constantly updates its requirements to more restrictive values, in order to promote more energy efficient buildings [7]. However, the use of thermal insulation in temperate climates still raises questions, mainly due to the possibility of overheating in summer.

In this regard, recent studies suggest highly insulated and airtight building envelope for warmer countries than cold climates of Europe. Researches in Portugal [7, 8], Italia [9, 10]; Turkey [11]; China [12, 13]; Thailand [14] and Chile [15, 16] indicate the feasibility of application of thermal insulation for warmer climates. In this way, adjustment for the Passive Haus standard is also under investigation by the Passive-on project, funded by the European Commission [17]. Schnieders et al. [18] suggest limits for U-value of the opaque envelope ranging from 0.30 to 0.40W/m²K for buildings located in the south and the southeast of Brazil.

Ballarini and Corrado [8] conducted a sensitivity analysis to investigate the effect of thermal insulation in summer conditions of residential buildings in Rome (cool, humid winters and hot, dry summers). They found limited influence of opaque assemblies in the energy needs for cooling and in the maximum cooling loads, suggesting more attention to transparent envelope in order to minimize energy needs in summer. Stazi et al. [10] performed experimental comparison between different wall constructions, also in Mediterranean climate. They found that the high thermal insulation of a residential building envelope causes problems of overheating when coupled with high thermal mass (solid brick masonry). However, a stratified envelope (unfilled brick-block cavity wall) provides better performance for both seasons, summer and winter, with external insulation being preferable.

Yilmaz [1] recommends lightweight and insulated construction as a good strategy for temperate climate because the long period of winter. In the other way, the use of thermal mass is more suitable for the hot and dry climate.

In this context, this paper explores the use of thermal insulation in a naturally ventilated dwelling in Brazilian temperate climate.

II. METHODOLOGY

Computer simulation with the EnergyPlus software was carried out over a virtual model of a single-family residential building. The study was conducted in four steps described as follows:

1. Selection of representative cities of temperate climate in Brazil;
2. Definition of the baseline model;
3. Heat balance analysis;
4. Sensitivity analysis.

2.1. Cities

The cities selected to run the analysis satisfy three criteria:

1. to be listed in the National Standard for Thermal Performance [19];
2. to be classified in Brazilian climate zones 1 or 2 (colder climate zones in the country); and
3. to have weather files available in EPW format (for EnergyPlus simulation).

Three cities were selected in order to have three different scenarios in terms of how many and how cold are the days along the year. The city of São Joaquim, in the state of Santa Catarina, is one of the coldest cities in the country, mainly due to its high altitude (1410 m). Curitiba, in the state of Paraná, and Santa Maria, in the state of Rio Grande do Sul, are the most studied and representative cities of climate zones 1 and 2, respectively. Among the three cities chosen, Santa Maria is the one with records of highest temperatures in the summer. Figure 1 shows the location of each city in Brazilian territory. The three cities are located in southern region.

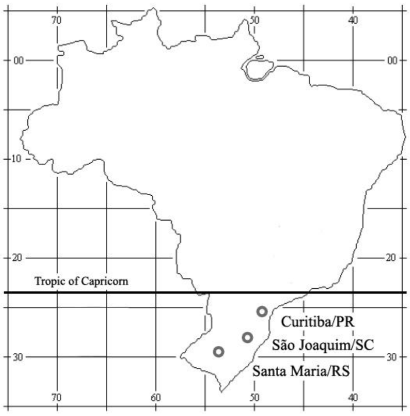

Figure 1 – Location of cities selected for the study.

Figure 2 presents the climate zoning defined in the Brazilian Standard for Thermal Performance of Buildings [19]. This classification was established based mainly on the pattern of occurrence of maximum and minimum average temperatures in each region, despite the average relative humidity has been also considered in the classification, as a secondary parameter. According to standard NBR 15220 [19], Brazil is characterized by eight climate zones, being the Zone 1 the coldest one and the Zone 8 the hottest one. The last includes the Amazon rainforest and almost the entire coast side of the country. The Zones 1 and 2 contains the three cities considered in this study and covers approximately 7.2% of the country, with an area of 613,135 km² [20], that is equivalent, for example, to territorial areas of Spain (504,030km²) and Portugal (92,389km²) together.

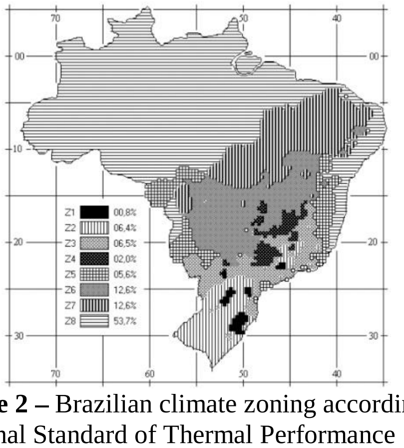

Figure 2 – Brazilian climate zoning according to National Standard of Thermal Performance [17].

Table 3 presents geographical location of each city; the extreme and average values of annual dry bulb temperature; the heating degree-hours for the base temperature of 18°C (HDH18) and cooling degree-hours for the base temperature of 23°C (CDH23). These levels of temperature were chosen to represent the amount of discomfort of the outside air according to the set point of air-conditioning systems recommended by the Brazilian standard for design and installation of HVAC systems [20]. Temperature data presented in Table 3 were obtained from the weather files used in the computer simulation. In this research, heating degree-hours at base 18°C were calculated as defined in Equation 1, and cooling degree-hours at base 23°C follows calculation procedure described in Equation 2. In the equations, *h* is the hour of the year and T_{exth} is the outdoor dry bulb temperature at hour *h*.

Table 3 – Summary of description data of the three cities.

City / Estate	São Joaquim/SC	Curitiba/PR	Santa Maria/RS
Latitude	-28.28	-25.43	-29.68
Longitude	-49.93	-49.27	-53.81
Elevation (m)	1410	924	95
Annual Lowest Temp (°C)	-4.1	-0.1	-0.2
Annual Mean Temp (°C)	13.2	17.3	18.9
Annual Highest Temp (°C)	26.5	31.7	38.3
HDH18	45055	19294	18164
CDH23	113	2531	4357

$$HDH18 = \sum_{h=1}^{8760}(18 - Text_h)[\text{If } T_{exth}<18] \quad (1)$$
$$CDH23 = \sum_{h=1}^{8760}(Text_h - 23) \quad [\text{If } T_{exth}>23] \quad (2)$$

2.2. Baseline Model

The baseline model is a single-family dwelling with 57.75 m² of floor area containing two bedrooms, two bathrooms, living room, kitchen and laundry area. The floor plan is presented in Figure 3 and the isometric view of the simulation model can be seen in Figure 4.

The building has masonry walls with clay blocks; floor and ceiling of concrete slab 120mm thick and a roof with ceramic tiles and thermal insulation underneath composed by expanded polyethylene foam (5mm) with metallized faces. Due to small thickness of the insulation foam, the increment on thermal resistance of the roof is provided more by the air-layer than the insulation itself.

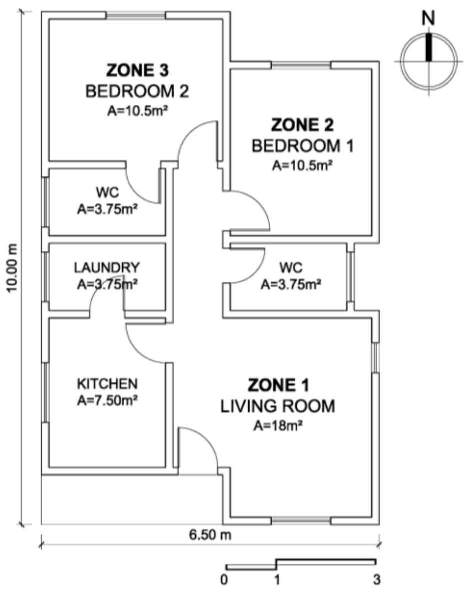

Figure 3 – Floor plan of the baseline model.

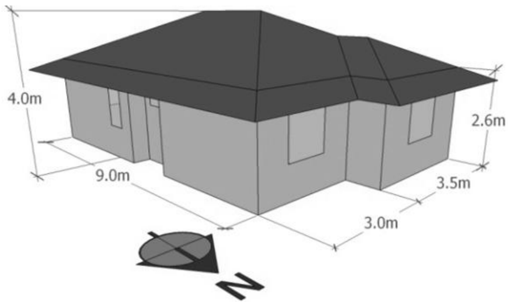

Figure 4 – Isometric view of the baseline model.

The analysis of thermal comfort accounted only for zones with more hours of occupancy, i.e., living room and bedrooms. The bedrooms have 10.5 sqm of area with a window faced to the north orientation each. The living room has 18.0 sqm with windows faced to the south and east orientations. Windows were modeled with 3 mm clear glass, without any shading device. There is no air conditioning in the model. Natural ventilation strategy was simulated during all day as an ideal condition, considering that the house could have venetian blinds on windows or even a portion of the window could be opened in order to seek satisfactory comfort conditions, even at night. Such operation routine is in accordance with the Brazilian Energy Efficiency Labelling Program for Residential Buildings [5, 6]. There is an attic space over the ceiling. The roof is tilted to 30% with eaves of 800mm depth.

The window-to-floor ratio (WFR) for dormitories and living room was set according to Brazilian regulation [19]. In the baseline model, a ratio of 12% was setup for living room and 14% for bedrooms, according to data presented in Table 4.

Table 4 – Dimensions of thermal zones under analysis.

Zone	1	2	3
Use	Living room	Bedroom 1	Bedroom 2
Area [m²]	18	10.5	10.5
Volume [m³]	46.8	27.3	27.3
Window Area [m²]	2.16	1.44	1.44
WFR	12%	14%	14%

The Brazilianthermal performance standard defines maximum U-values for exterior walls and roofs. The limits for climate zones 1 and 2 are 2.50 W/m²K and 2.30 W/m²K, respectively, considering a solar absorptance less than 0.6 in the exterior face. The U-value of the constructions of the baseline model are 2.38 W/m² for walls and 2.30 W/m².K for the roof. Table 5 presents a summary of thermal performance data of the constructions of the baseline model.

Table 5 – Thermal performance data of constructions of the baseline model.

Construction	U-Factor [W/m²K]	Reflectance
Wall	2.38	0.5
Floor	4.04	0.5
Ceiling	3.34	0.5
Roof	2.30	0.5
	Glass U-Factor [W/m²K]	Glass SHGC
Window	5.89	0.87

2.3. Internal loads and schedules

Internal loads densities and schedules of the baseline model were defined according to the same rules adopted in the simulation procedure described in the Brazilian Energy Efficiency Labelling Program for Residential Buildings [5, 6].

Figure 5 shows the pattern of occupancy for weekdays and weekends modeled in the baseline for the bedrooms and the living room. A maximum of two people were assumed to be present in each bedrooms and four people represent the 100% of occupancy in the living room. Metabolic rate of 108 W (60 W/m² of skin area and 1.8 m² of body surface) were considered for people in the living room (sitting sedentary activity) and 81 W (45 W/m² of skin area) were considered for people in the bedrooms (sleeping condition).

Schedules of operation of the lighting system is presented in Figure 6. Artificial lights are on in some periods of the day in the living room, when probably there is no sufficient daylight level. In the bedrooms, the light bulbs are switched on two hours before sleep time and one hour after. Bedrooms are equipped with 5W/m² of light power density and the living room was modeled with 6W/m². Other plug loads were considered as 1.5W/m² only in the living room, with operation 24 h/day.

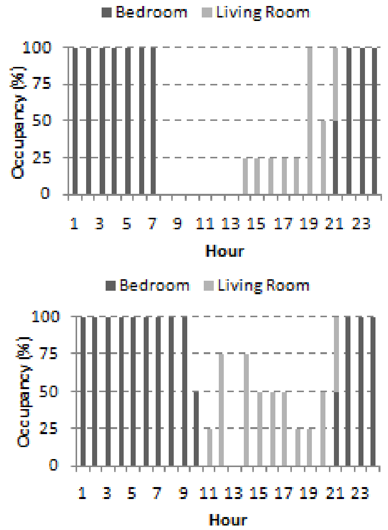

Figure 5 – Schedules for occupancy of the baseline model: weekdays (left) and weekend (right).

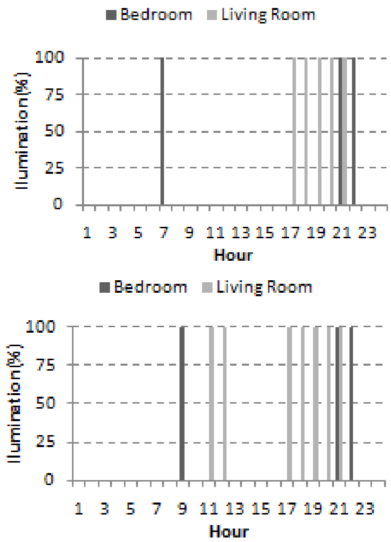

Figure 6 – Schedules for lighting system operation: weekdays (left) and weekend (right).

Table 4 – Monthly ground temperature profiles for the three cities, in degrees Celsius.

City	São Joaquim	Curitiba	Santa Maria
Jan	19.4	20.0	20.8
Feb	19.2	19.8	20.5
Mar	18.3	18.9	19.3
Apr	17.1	17.8	18.0
Mai	15.0	15.7	16.0
Jun	13.6	14.5	14.7
Jul	13.4	14.2	14.1
Aug	13.8	14.6	14.5
Sep	14.7	15.5	15.6
Oct	16.1	17.0	17.3
Nov	17.7	18.5	19.0
Dec	18.9	19.6	20.0

As the baseline model is a single floor building, with direct contact to the ground, the influence of ground temperature in the thermal performance of the building is significant. Therefore, monthly mean temperature for the ground was calculated through the Slab program routine, available in the EnergyPlus software package. This program uses the mean internal temperature of the building, the outdoor monthly mean temperature, thermal properties of soil and building geometry to generate the annual profile of ground temperature variation in a monthly basis. Values generated for the three cities are presented in Table 6.

2.4. Heat balance analysis

The heat balance analysis allows to identify components of cooling and heating loads that should receive more attention to optimize the thermal performance of the building. The analysis covered envelope sources of heat transfer, internal heat gains, air infiltration and ventilation.

Hourly reports of heat gains and losses were extracted from EnergyPlus simulation and treated in spreadsheets. The analysis was developed for the typical week in the summer, i.e., that sequence of 7 days that registered the average outdoor dry bulb temperature similar to the average of summer outdoor air temperature for the city under analysis. That same analysis was carried out to the winter typical week.

Heat gains and losses were calculated at each hour and identified according to their sources: exterior walls; interior walls (from adjacent rooms); floors; ceiling; windows, infiltration and internal gains (people, lights and plug loads). Those sources of heat transfer with major impact on cooling and heating loads were the focus of the next step of the study, the sensitivity analysis.

2.5. Sensitivity analysis

Important sources of heat gain or losses identified in the heat balance analysis were submitted to sensitivity analysis. The influence of thermal insulation of the building envelope was assessed in an iterative way.

Lam and Hui [22] present different forms of sensitivity coefficient. At general, the measure of sensitivity consists on quantify the changes in the output with the changes in the input.

In the present work, a simple approach of sensitivity analysis was applied. As variations in the input comprise alternatives representing technical feasible options of construction or architectural design, input parameters were not changed in a continuous scale. Output variations were related to a baseline condition and assessed as a Performance Improvement Index (PII), according to Equation 3, where OP_n represents the output value of an alternative case n; and OP_{base} is the output of the baseline case.

$$PII = \frac{OP_n - OP_{base}}{OP_{base}} \quad (3)$$

As output indicator, heating degree hours at base 18°C (Eq. 1) and cooling degree hours (Eq. 2) at base 23°C were calculated for the interior operative temperature of the building.

In temperate climate, some strategies applied to minimize heat loss in winter may increase hot discomfort in summer. Therefore, a sensitivity analysis was conducted to identify components with major influence in heating and cooling loads. Alterations on building envelope were focused on these components. Sensitivity analysis and building envelope improvements were conducted in an iterative way, divided into four steps. At each step, the analysis indicates the main sources of heat gains or losses; alterations are made to these sources and another sensitivity analysis is carried out to indicate the next set of parameters with significant influence on building loads.

III. RESULTS AND DISCUSSION

3.1. Heat balance analysis results

In order to save space and avoid data repetition, this paper presents only the results for the thermal zone 2 (bedroom 1), analyzed for winter in the coldest city (São Joaquim) and for summer in the hottest city (Santa Maria).

Figure 7 presents heat gains and losses at each hour of the day with the lowest outdoor dry bulb temperature extracted from the typical winter week for the baseline model simulated with weather file of São Joaquim, July 25th. Bars with positive values indicate heat added to the room from the respective source. Bars with negative values represent heat losses. Data presented in curves are outdoor and indoor dry bulb temperatures.

The most significant heat gain during nighttime is internal heat loads, due mainly to people metabolic rate. During the day, the window contributes with the major portion of heat gain. Heat losses through walls, exterior and interior, is equivalent to a half part of the total heat gain during the night. Another important source of heat loss in that period is the window. These results indicates that the thermal insulation of the building envelope could avoid the excessive loss of the heat generated internally in the building during the period that the bedroom is being occupied (sleeping time). In the period presented in the graph of Figure 7 the interior air temperature of thermal zone 2 achieves a minimum of 12^{o}C while in the outdoor registered 1^{o}C minimum. The maximum temperature was 14^{o}C inside the building and 9^{o}C at the outside.

Figure 8 presents the heat balance in the thermal zone 2 for the day with the highest temperature extracted from the typical summer week in the hottest city, Januray 24th in Santa Maria. In this condition, the heat gains from exterior and interior walls during the nighttime are significant, together with the internal loads. In this period, the natural ventilation, indicated in the graph as "infiltration", provides the heat loss. During the occupancy time at night, from 8.00p.m. to 7.00a.m., internal temperature achieved 28^{o}C maximum and 26^{o}C minimum, while the outdoor dry bulb temperature oscillates between 24^{o}C to 34^{o}C. Probably the heat gain through walls occurs due to the heat storage from solar radiation incident on exterior surfaces during the day, as the outdoor temperature is not so high, compared to indoor temperature in the night. During the day, the window represents the major portion of the heat gain, and the floor is the key source of heat loss.

From the analysis of the summer day, it may expected that the thermal insulation of walls could avoid significant heat gain to the room during the night.

Figure 9 presents heat gains aggregated for the entire winter extreme day under analysis for São Joaquim city and for the entire summer extreme day for Santa Maria. Positive values represent heat added to indoor space and negative values correspond to heat loss from indoor environment.

In both situations internal loads are the most representative source of heat gain. In winter, the window is the second source of heat gain and walls are the main source of heat loss. In summer, walls are the third source of heat gain, followed by internal loads and window. Air infiltration (i.e., natural ventilation) is the main source of heat loss.

Data obtained from the heat balance analysis will be helpful to conduct the next step of the study that is the sensitivity analysis of building envelope parameters and design optimization, with focus on thermal insulation. The analysis over the main sources of heat gains and losses indicates that thermal insulation of walls, floor and window may contributes to avoid excessive heat gain in summer and excessive heat loss in winter. The challenge is to define if the solution for one situation does not compromises the performance in the another condition. Therefore, an ideal or average solution can be set up.

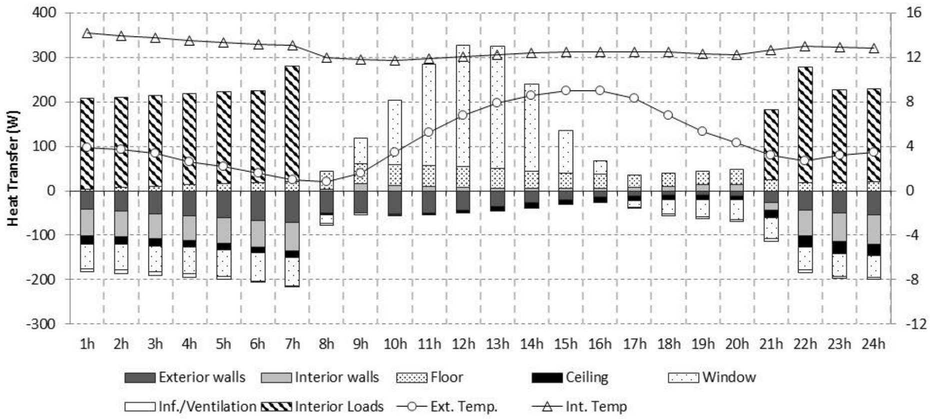

Figure 7 – Heat balance analysis of the zone 2 for the winter day with lowest temperature, July 25th, in São Joaquim city.

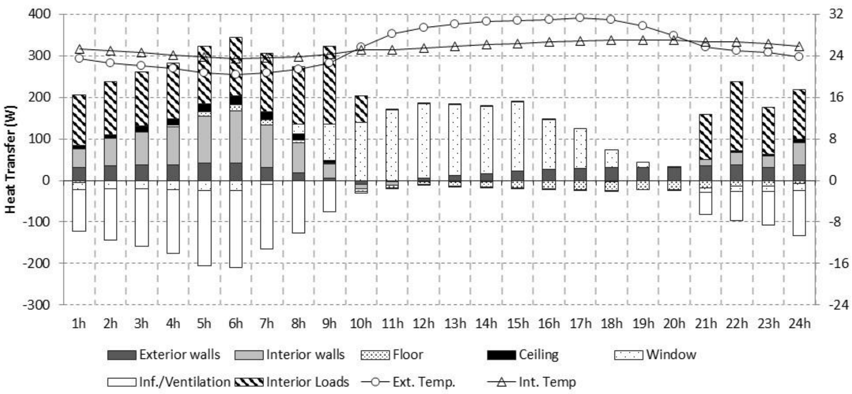

Figure 8 – Heat balance analysis for the summer day with highest temperature, January 24th, in Santa Maria city.

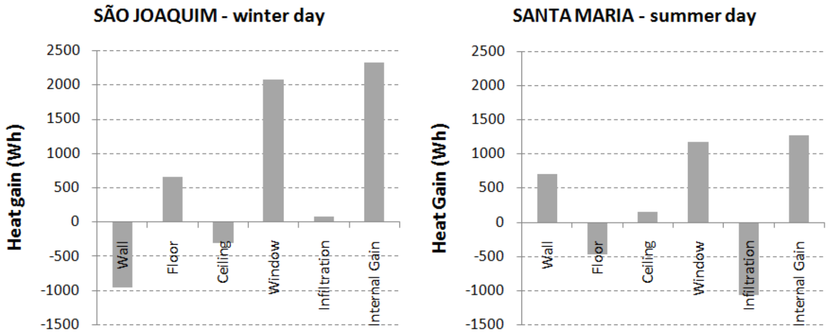

Figure 9 – Total heat gain aggregated for each source in the extreme winter day in São Joaquim city and in the extreme summer day in Santa Maria city.

3.2. Sensitivity analysis results

The heat balance analysis has supported the definition of strategies to improve thermal performance of the building envelope. Strategies selected to assessment in the sensitivity analysis task are as follows:

1. The increase of window area to promote heat gain in winter, taking advantage of envelope thermal mass as energy storage;
2. Addition of thermal insulation in the outside face of exterior walls, in order to avoid heat loss in winter and minimize the heat gain from solar radiation in summer;
3. Addition of thermal insulation in the roof to decrease the heat gain in summer;
4. Installation of thermal insulation on the floor.

3.2.1. First step of sensitivity analysis

The first strategy submitted to the sensitivity analysis task was changing window area. The heat balance analysis showed a need for increase the internal heat gain in winter. Promoting higher solar radiation gain, coupled with high thermal mass – acting as energy storage – in the envelope can help to rise the room internal temperature, even at night. In summer, high window area can promote high rates of air changes per hour, but the increase in the solar heat gain can be prejudicial. Thus, the ideal window area must be seek in conjunction with other strategies to improve thermal performance of the envelope.

Table 7 shows three values of window area simulated from the baseline model. The first window-to-floor ratio (WFR_1) represents 50% of increase in the window area of the baseline. Model WFR_2 increases window area in 150% and WFR_3 has 200% more opening area than the baseline model.

Table 7 – Values of window area simulated in the first step of sensitivity analysis for the thermal zone 2 – bedroom.

Model	Window Area [m²]	WFR [%]
Baseline	1.44	14
WFR_1	2.16	21
WFR_2	3.60	34
WFR_3	4.32	41

3.2.2. Second step of sensitivity analysis

The second step of sensitivity analysis consisted on application of thermal insulation on the outside face of exterior walls of the baseline and the three models with changes in window area. Table 8 presents the U-value of exterior walls of the baseline and the three options of thermal insulation thickness: 25, 50 and 100mm.

Table 9 shows the results obtained in the first two steps of sensitivity analysis for the three cities. The table presents values of heating degree-hours at base 18°C (HDH18) and cooling degree-hours at base 23°C (CDH23). The Performance Improvement Index (PII), in percentage values, is presented to HDH18 and CDH23 for each case, considering that the baseline model is that one with WFR 14% and no thermal insulation (the upper left cell of the table for each city). Negative values of PII means that the alternative is worse than the baseline.

Table 8 – Thermal insulation thickness and U-values of walls simulated in the sensitivity analysis.

Wall Type	U-Value [W/m²-K]
Masonry with clay blocks (150mm) and no insulation	2.378
Masonry with clay blocks + thermal insulation 25mm	1.025
Masonry with clay blocks + thermal insulation 50mm	0.653
Masonry with clay blocks + thermal insulation 100mm	0.378

Table 9 – Cooling degree-hours and heating degree-hours optimization for cases simulated in the sensitivity analysis task when window area and thermal insulation were changed.

	HDH18 / PII (%)								
	Thermal Insulation (mm)								
	WFR	0		25		50		100	
SÃO JOAQUIM	14%	20457	-	18301	11%	17451	15%	16706	18%
	21%	20022	2%	17838	13%	16994	17%	16186	21%
	34%	19415	5%	17260	16%	16452	20%	15754	23%
	41%	18907	8%	16740	18%	15935	22%	15242	25%
CURITIBA	14%	7301	-	6852	6%	6575	10%	6395	12%
	21%	7136	2%	6582	10%	6365	13%	6175	15%
	34%	6843	6%	6244	14%	6012	18%	5809	20%
	41%	6617	9%	5997	18%	5758	21%	5550	24%
SANTA MARIA	14%	7013	-	6295	10%	6025	14%	5800	17%
	21%	6909	1%	6187	12%	5917	16%	5689	19%
	34%	6727	4%	6007	14%	5740	18%	5517	21%
	41%	6576	6%	5859	16%	5593	20%	5373	23%

	CDH23 / PII (%)								
	Thermal Insulation (mm)								
	WFR	0		25		50		100	
SÃO JOAQUIM	14%	0	-	0	-	0	-	0	-
	21%	0	-	0	-	0	-	0	-
	34%	0	-	0	-	0	-	0	-
	41%	0	-	0	-	0	-	0	-
CURITIBA	14%	38	-	0	100%	0	100%	0	100%
	21%	61	-61%	5	87%	2	96%	0	99%
	34%	117	-206%	26	33%	17	55%	13	66%
	41%	170	-345%	57	-50%	44	-15%	37	4%
SANTA MARIA	14%	4357	-	3608	17%	3416	22%	3276	25%
	21%	4633	-6%	3944	9%	3769	13%	3641	16%
	34%	4879	-12%	4290	2%	4152	5%	4052	7%
	41%	5193	-19%	4657	-7%	4542	-4%	4460	-2%

Changes on window size decreased the HDH18 up to 9% in Curitiba and 6% in Santa Maria for models without thermal insulation. Nevertheless, the increment on CDH23 was significant. In Santa Maria, the model with the highest window area presented CDH23 19% superior than baseline. In this case, the benefits with the higher solar radiation gain in winter is much lower than the decrement on thermal comfort in summer.

In Curitiba, despite high values of PII in cooling degree-hours, absolute values are very low and could be negligible. São Joaquim was the city that did not show any increment on CDH23 with the simulated strategies. For this city, the increase on window size and the installation of thermal insulation has proved to be beneficial for the bedroom, as they minimize HDH18 up to 25% (WFR of 41% and 100mm of thermal insulation) with no damage to thermal comfort conditions on cooling season.

For the baseline window area (WFR 14%), the increase on thermal insulation thickness to 100mm promoted reduction of 18% on HDH18 in São Joaquim, 12% in Curitiba and 17% in Santa Maria. The impact of thermal insulation thickness has not shown to be linearly related to HDH18 in each city. Probably its influence is also governed by the pattern of variation on daily temperature profiles, which cannot be well expressed through degree-hours.

At general, the first two steps of sensitivity analysis have shown that:

1. increasing the window area can help to minimize heating degree hours for the three cities;
2. the thermal insulation on walls can reduce heating degree hours at base 18ºC;
3. higher benefits on heating degree hours were verified in the coldest city, São Joaquim;
4. in São Joaquim, city with the lowest value of cooling degree hours (almost null), the impact of thermal insulation on this parameter was insignificant;
5. in Santa Maria, city with the highest value of cooling degree hours, the increase on window area has resulted in poor performance in cooling season. However, the increase on thermal insulation thickness has shown to be valuable in that condition.

3.2.3. Third step of sensitivity analysis

The third step of sensitivity analysis focused over those cases with best performance in heating season: highest window area and high thermal insulation thickness. In this step, roof and floor received one additional layer of thermal insulation, as describe in Table 10.

Figure 10 shows the decreasing of the HDH18 from the baseline with the increase in window area and insulation thickness on walls simultaneously (cases 1 to 4). Case 5 represents the simulation of the best model from previous set, plus thermal insulation on the floor. Case 6 represents the addition of thermal insulation on the roof of case 5.

Adding thermal insulation on floor and roof decreased significantly heating degree-hours of the bedroom in the three cities. The increment on cooling degree-hours in São Joaquim and Curitiba was null or negligible. Nevertheless, in Santa Maria, CDH23 has increased almost 50% with the thermal insulation of these building components.

Table 5 – U-value of roofs and floors simulated in the third step of sensitivity analysis.

Model	Floor Type	U-Factor [W/m²K]
Baseline	Concrete slab (no insulation)	4.037
Alterna-tive	Concrete slab + thermal insulation 15mm	1.705
Model	Roof Type	U-Factor [W/m²K]
Baseline	Ceramic roof tiles + thermal insulation 5mm + concrete roof slab	2.313
Alterna-tive	Ceramic roof tiles + thermal insulation 25mm + concrete roof slab	1.127

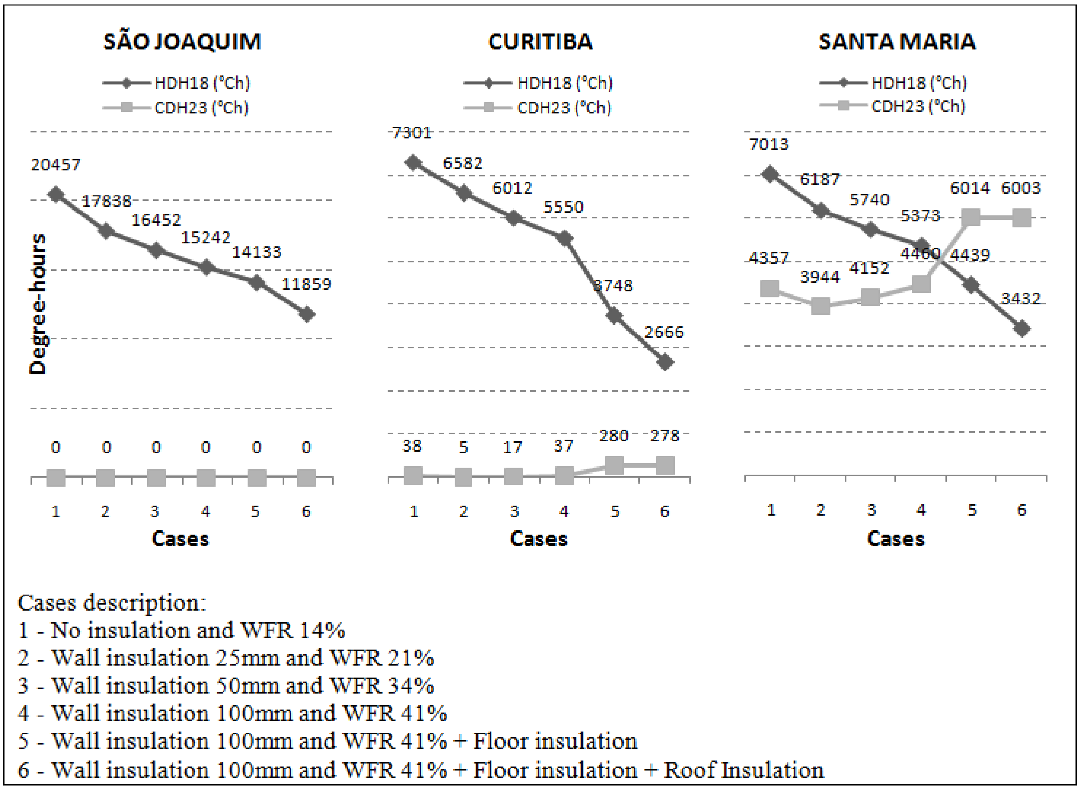

Figure 2 – Modeling optimization results from the third step of sensitivity analysis.

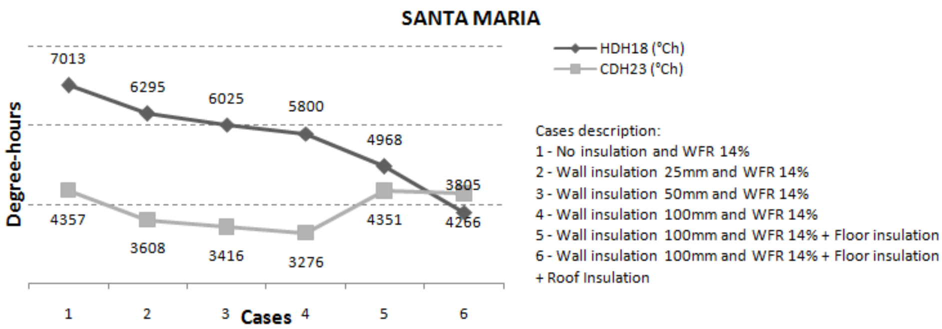

Figure 3 – Results for the fourth sensitivity analysis step for Santa Maria city.

3.2.4. Fourth step sensitivity analysis results

As the thermal performance of the model decreased in Santa Maria for the cooling season, a fourth sensitivity analysis was performed for this city. In this case, application of thermal insulation in roof and floor was made over the model with the lowest window area (WFR 14%), instead of the highest window area (WFR 41%). Figure 11 shows results obtained in this step. Significant increment was achieved for HDH18, maintaining the same performance of the baseline for CDH23.

IV. CONCLUSION

The main objective of this study was to analyze the improvement of thermal performance of a naturally ventilated Brazilian dwelling with the use of thermal insulation in temperate climate.

The heat balance analysis confirmed the strategies recommended to temperate climates: the need for increasing heat gain in winter, coupled with high thermal mass; but with some caution in solar heat gain to avoid overheating during summer. Thermal insulation on walls could be applied to avoid heat loss during the night.

From these main conclusions, a sensitivity analysis was carried out seeking for thermal performance improvement in the building envelope. First, the window area was increased, and heating degree hours was significantly decreased, with differences up to 8% and 9% in two cities under analysis. Second, thermal insulation was applied on the outer face of exterior walls, which resulted in reduction up to 25% in heating degree hours, with little reduction in cooling degree hours (4%), even in the models with high window area.

The third step of the sensitivity analysis considered thermal insulation on floor and roof. Heating degree hours was significantly decreased for the three cities, but overheating was registered for the city with hottest summer. In this case, a fourth step of sensitivity analysis was conducted showing that benefits with the use of thermal insulation can be achieved with moderate window area, i.e., controlling the heat gain from solar radiation.

At general, the study has proved that more stringent limits of U-values could be explored in Brazilian standards for thermal performance of residential buildings in order to promote more control over operative temperature in temperate climates. The overheating in summer can be avoided with adequate window area or shading strategies to minimize heat gain from solar radiation. This confirms that strategies for passive conditioning of buildings have to be assessed in an integrative way. Heat balance and sensitivity analysis with the use of computer simulation can help to find adequate solutions for each climate, building typology and use.

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