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Investigation of Passive Solutions of Thermal Comfort in Housing Aiming to Reduce Energy Consumption

Josiane R. Pires, Marco A. S. González, Bruna L. Brenner, Luciana S. Roos

Abstract**—**The concern with sustainability brought the need for optimization of the buildings to reduce consumption of natural resources. Almost 1/3 of energy demanded by Brazilian housings is used to provide thermal solutions. AEC sector may contribute applying bioclimatic strategies on building design. The aim of this research is to investigate the viability of applying some alternative solutions in residential buildings. The research was developed with computational simulation on single family social housing, examining envelope type, absorptance, and insolation. The analysis of the thermal performance applied both Brazilian standard NBR 15575 and degree-hour method, in the scenery of Porto Alegre, a southern Brazilian city. We used BIM modeling through Revit/Autodesk and used Energy Plus to thermal simulation. The payback of the investment was calculated comparing energy savings and building costs, in a period of 50 years. The results shown that with the increment of envelope's insulation there is thermal comfort improvement and energy economy, with a pay-back period of 24 to 36 years, in some cases.

Keywords**—**Civil construction, design, thermal performance, energy, economic analysis.

I. INTRODUCTION

ENERGY consumption in housing represents an important share of total demand for electricity in Brazil. The country faces some difficulties in the sector, having suffered periods of energy "blackout" few years ago. To increase energy generation have some drawbacks. The construction of hydroelectric plants causes many environmental impacts, with flooding of large areas and environment changes. In some cities energy is generated in power plants based on coil or oil, with CO_2 and other emissions. Reducing energy consumption is beneficial to society [1], [2].

Thermal comfort in Brazilian buildings has often been obtained through artificial based conditioning. It's supposed that 32% of the electricity consumed in housings is to provide thermal comfort [1], [3]. In this sense, residential sector has good potential to improve energy efficiency. One of the simplest ways to clear this scene is to reduce the energy consumption required for thermal conditioning of buildings using bioclimatic strategies. Cunha et al. [4] and Roméro [5] point out that bioclimatology seeks to satisfy the requirements of thermal comfort by identifying the environmental conditions - natural and built environments - and also aspects of place, history and culture, for later use in architectural design, selecting the most appropriate solutions.

The thermal efficiency of the building envelope (set of systems of external seals and roofing of buildings) is a key strategy in the housing design and construction aimed at reducing the use of artificial conditioning [6]. According Lamberts and Triana [7] the characteristics of the building envelope and systems employed determine the thermal performance of the building. Several variables influence, such as the types and colors of materials used, the use or not of thermal insulation, solar orientation, area and type of windows, internal thermal loads and the use or not of bioclimatic strategies.

The Brazilian standard that addresses performance of buildings, NBR 15575, reviews the adequacy of a building and its systems, regardless of the technical solution adopted. Regarding the thermal performance, this can be classified qualitatively and should be included in the project. Evaluation is based on internal temperature, looking for maximum temperature in summer and minimum in winter. The standard presents three procedures for assessing the adequacy of buildings: simplified procedure, simulation and measurement (through measurements in actual buildings or prototypes). It also establishes three levels of performance: minimum (M), intermediate (I) and superior (S) [8].

Briefly, the requirements for the performance of buildings by NBR 15575 are simple. Housing need to present thermal conditions better than or equal to the external environment for typical days of summer and winter. The maximum temperature of the air inside the building in the summer in prolonged-use rooms, without the presence of internal heat sources, must be less than or equal to the maximum external temperature. On winter, the minimum temperature of indoor air in prolonged-use rooms need be greater than or equal to the minimum external temperature plus 3°C [8].

In addition to the simulation method of NBR 15575, can be addressed alternative methods for thermal evaluation of buildings and building systems. Barbosa [9] developed a method of discomfort hours ("Degree-hour"). This method applies in social housing, using the comfort zone of Givoni [10] and to verify the number of hours of discomfort, both the cold as heat, the building presents for an entire year. Results are the sum of the difference in air temperature that exceeds a stipulated base temperature. The sum of Degree-hours is the amount of hours that the environment was outside the comfort range as in (1) [11], [12]:

J. R. Pires and B. L. Brenner are with the Universidade do Vale do Rio dos Sinos (UNISINOS), Av. Unisinos, 950, São Leopoldo, RS 93022-000 Brazil.

M. A. S. González is with the Universidade do Vale do Rio dos Sinos (UNISINOS), Av. Unisinos, 950, São Leopoldo, RS 93022-000 Brazil (corresponding author; phone: 5551-35911122; e-mail: mgonzalez@unisinos.br).

L. S. Roos is an independent Architect.

$$DH = \sum (T_b - T_h) \qquad (1)$$

where: DH: degree-hour index; Tb: base temperature, and, Th: hourly temperature.

The analysis of the cost of apply strategies for thermal performance can determine whether or not these projects are justifiable as based as reducing the cost of energy and other costs involved, or for help in choosing the strategy that has the best benefit/cost [6]. The pay-back period (2) is a technique that allows calculating the time required to recover an investment [13].

$$\text{Payback (years)} = \text{Initial investment} / \text{annual savings} \qquad (2)$$

Given this context, the aim of this work is to investigate the technical and economic feasibility of reducing electricity consumption in horizontal residential buildings, based on the climatic conditions of Porto Alegre, city on southern Brazil. We considered changes on transmittance and thermal absorptance in the building envelope, with analysis using Autodesk Revit as BIM system and thermal simulation by EnergyPlus.

II. METHODOLOGY AND DATA

The study is based on the method of computer simulation using EnergyPlus program, with an emphasis on energy efficiency and thermal analysis. Both cases based on typical project in the region of study. Case 1 is a single-family, terraced and detached house, composed by two bedrooms and floor area of 34.07 m² (Figs. 1 and 2). The ceiling height is 2.5m, and each house is supposed be occupied by four people. The Case 2 is based on a two-story detached house's design, with three bedrooms and total floor area of 79.89 m² (Figs. 3 and 4). In this case, ceiling height is 2.8m and we supposed five inhabitants per unit. Simulations are based on climate data from Porto Alegre, located in the bioclimatic zone ZB3 (after [14]). Design and specifications were inserted into BIM, adopting the Autodesk Revit platform.

Fig. 1 Case 1 - Perspective of terraced houses

Fig. 2 Case 1 - floor design

Fig. 3 Case 2 - Perspective of two story houses

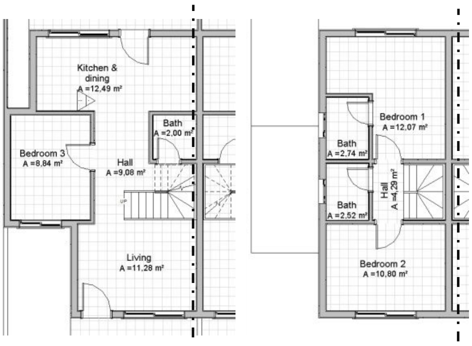

Fig. 4 Case 2 - Floor design: left-ground story; right-second story

Porto Alegre has a humid subtropical climate, with occurrences of well-distributed rainfall, average relative humidity of 76% and average temperatures max/min of 31ºC/9ºC. The bioclimatic chart of Porto Alegre is in Fig. 5. This chart was generated using AnalysisBio (software developed by LabEEE - Laboratory for Energy Efficiency in Buildings - http://www.labeee.ufsc.br/). We used a climatic hourly file (.try file) prepared by Roriz, following hourly data recorded in INMET (National Institute of Meteorology - http://www.inmet.gov.br/portal) climatological station between the years 2000 and 2010 [15]. A bioclimatic chart to developing countries was developed by Givoni, being divided into 12 zones. Each zone represents a bioclimatic strategy, including thermal comfort [10]. A bioclimatic chart uses a psychometric diagram, connecting air temperature with relative humidity.

TABLE I
BUILDING SYSTEMS AND DESIGN PARAMETERS

Code	Description	U [W/(m²K)]	CT [KJ/m²K]	φ [h]	α	FCS
R0	Concrete slab e=3cm, air layer (≥ 5cm) and painted asbestos-cement roofing e=7mm.	2.25	77	2.6	0.2 0.4 0.8	1.8 3.6 7.2
R1	Concrete slab e=10cm, air layer (≥ 5cm) and painted asbestos-cement roofing e=7mm.	2.06	233	4.0	0.2 0.4 0.8	1.64 3.28 6.56
R2	Precast concrete slab e=12cm, air layer (≥ 5cm) and painted asbestos-cement roofing e=7mm.	1.93	106	3.6	0.2 0.4 0.8	1.54 3.09 6.18
W0	Grouted, painted masonry (6' holes ceramic bricks, 2.5 cm mortar and acrylic painting in both sides) Total thickness = 19cm	2.02	192	4.5	0.2 0.4 0.8	1.62 3.23 6.46
W2	Grouted, painted masonry (2' holes ceramic bricks, 2.5 cm mortar and acrylic painting in both sides) Total thickness = 19cm	2.45	203	4.0	0.2 0.4 0.8	1.96 3.92 7.84
W1	Grouted, painted masonry (8' holes ceramic bricks, 2.5 cm mortar and acrylic painting in both sides) Total thickness = 24cm	1.80	231	5.5	0.2 0.4 0.8	1.44 2.88 5.76
W3	Grouted, painted masonry (ceramic bricks, 2.5 cm mortar and acrylic painting in both sides) Total thickness = 26cm	2.30	430	6.6	0.2 0.4 0.8	1.80 3.70 7.40
G1	Inner walls - Grouted, painted masonry (6' holes ceramic bricks, 2.5 cm mortar and acrylic painting in both sides); Total thickness = 14cm	2.48	159	3.3	0.2	1.98
G2	Intermediate slabs and floor finishing - Precast concrete slab e=12cm, mortar and ceramic floor e=1cm; Total thickness = 13cm	2.58	-	-	0.7	7.22

[a] Codes R0-C3: Roofs; W0-W3: Walls; G1-G2: General; Source: [14] (except FCS, calculated by the authors)

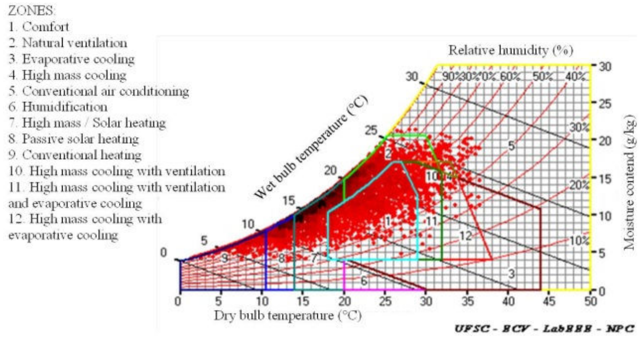

Fig. 5 Psychometric chart to Porto Alegre, Brazil (Source: [16])

Extracting the percentage of each zone in Fig. 5, it was found that in 22.4% of the time there are comfort and in 77.6% of the time there are thermal discomfort (those 51.7% caused by cold and 25.9% caused by heat). It appears, therefore, that the climate is more comfortable in the summer, but there is need to improve thermal performance of the building for both periods. The main strategies to be adopted to provide thermal comfort are: (i) shading in 45.3% of the time, (ii) high thermal inertia in 33.8%, (iii) cross ventilation in 23.33%, (iv) passive solar heating in 11.8%, and (v) artificial heating and cooling in 6.07% and 1.35% of the time, respectively.

Using as reference the recommendations of NBR 15575-4 and NBR 15575-5 [18], [19] we identified some building systems for use in thermal simulations. According to these standards, the thermal transmittance of the roofing must be equal to or less than 2.30 W/m².K and thermal delay equal to or less than 3.3 hours. Walls must have thermal transmittance less than or equal to 3.60 W/m².K and thermal delay equal to or less than 4.3 hours. After all, we tested three compositions to roofing (R0-R2 in Table I) and four compositions to external walls (W0-W3 in Table I).

For the absorptance values we tested 0.2 (light colored paint), 0.4 (medium colored painting) and 0.8 (dark colored paint). For the simulations were kept constant the specifications of intermediate slabs, floor finishes, interior walls (G1-G2 in Table I), and shading (external shutters with the closing setpoint on 29ºC) to windows in bedrooms and living rooms, using glass parameters presented in Table II.

TABLE II
TRANSPARENT GLASS THERMAL PROPERTIES

e [m]	Ts	Rs	Rs	Tv	Rv	Rv	Tir	ε	k [W/m.K]
0.003	0.837	0.075	0.075	0.898	0.081	0.081	0	0.84	0.9

[17], *apud* [20]

Simulations were performed initially using a reference system. The base system has external walls type W0 with absortance of 0.2 (identified as W0/0.2) and coverage type R0, also with absorptance of 0.2 (R0/0.2). Subsequently, the proposed strategies have been simulated in order to improve the internal temperature through different alternatives to envelope. Simulations to walls were carried out only with the coverage which had the best results among covertures.

Simulations were performed to analyze thermal performance the considering natural ventilation. In the energy efficiency analysis simulations used air conditioning system in prolonged-used room. The modeling of air conditioning system held the thermostat temperature at 20°C for heating and 24°C to cooling. It was defined 0.7 to continuous fan efficiency and 0.9 to engine efficiency. The rate of air flow per person was 0.00944 m³/sec, and the ratio between the energy consumed by device and heat removed was 3.0 W/W. For the heat supplied to the environment we adopted 2.75 W/W. Finally, the capacity of these systems has been automatically sized by EnergyPlus.

For the classification of the thermal performance of buildings we used the Brazilian performance standard proposed by NBR 15575-1 [8]. Its application is intended for prolonged-used rooms and the values of the internal temperature resulting from the simulations are compared with the outside temperature. The difference between them is compared with the maximum to summer and minimum to winter, as presented in Table III.

TABLE III
CRITERIA FOR EVALUATION OF THERMAL PERFORMANCE - FOR ZB3

Performance Level	Summer	Winter
Minimum (M)	$T_{i,Max} \leq T_{e,Max}$	$T_{i,Min} \geq T_{e,Min}$ +3°C)
Intermediate (I)	$T_{i,Max} \leq$ ($T_{e,Max}$ -2°C)	$T_{i,Min} \leq$ ($T_{e,Min}$ +5°C)
Superior (S)	$T_{i,Max} \leq$ ($T_{e,Max}$ -4°C)	$T_{i,Min} \leq$ ($T_{e,Min}$ +7°C)

Source: [14]

Simulations were carried out for a time period of one year, for better comparison of the results with the method of degrees hour. For the evaluation of the data using this method, the base temperature was defined using comfort zone after [10] for developing countries, with temperatures ranging between 18°C and 29°C.

Finally, as a way to economically evaluate construction systems, we used the period of return on investment (Payback), calculated from the comparison between the investments to change the design and annual savings achieved in energy consumption. Bioclimatic interventions reduce the operating cost of the building, however, generally increase the initial cost (cost of construction). Payback indicates the time elapsed between the completion of the initial investment and the return on this investment. It was calculated from the ratio between the extra cost for adoption of each solution and annual cash flow of energy savings with this alternative. Building costs were estimated through the price system SINAPI (calculated by Brazilian Federal Bank "Caixa"), for the region, with values for September, 2013. The quantities of materials were calculated directly from BIM models.

TABLE IV
CASE 1 - THERMAL PERFORMANCE LEVELS OBTAINED ON ROOFINGS

Code	α	$Ti_{máx}$ [°C]	Ti_{min} [°C]	Summer	Winter
R0/0.2	0.2	31.5	9.7	I	DM
R0/0.4	0.4	33.7	10.1	I	DM
R0/0.8	0.8	37.8	10.7	M	DM
R1/0.2	0.2	30.4	10.8	S	DM
R1/0.4	0.4	32.0	11.2	I	DM
R1/0.8	0.8	35.1	12.0	I	DM
R2/0.2	0.2	31.1	10.3	S	DM
R2/0.4	0.4	32.9	10.7	I	DM
R2/0.8	0.8	36.4	11.3	M	DM

*S:Superior; I:Intermediate; M: Minimum; DM: does not meet.

The annual energy consumption considered is the amount of energy required to maintain the temperature desired (from 18°C to 29°C) on the prolonged-used rooms (bedrooms and living rooms), as calculated by EnergyPlus. The annual cost for electricity was calculated based on the energy costs at US$0.25/kWh, a common value for social housing in the region. Finally, calculated savings represents the difference between the energy expenditure on reference building system and the expenses on alternative systems. With this annual savings is calculated the payback of the initial investment.

TABLE V
CASE 1 - THERMAL PERFORMANCE LEVELS OBTAINED ON EXTERNAL WALLS

Code	α	$Ti_{máx}$ [°C]	Ti_{min} [°C]	Summer	Winter
W0/0.2	0.2	30.2	12.6	S	M
W0/0.4	0.4	30.9	12.9	S	M
W0/0.8	0.8	32.3	13.4	I	M
W1/0.2	0.2	30.3	12.1	S	DM
W1/0.4	0.4	31.2	12.4	S	M
W1/0.8	0.8	32.8	13.0	I	M
W2/0.2	0.2	29.9	13.1	S	M
W2/0.4	0.4	30.5	13.4	S	M
W2/0.8	0.8	31.7	14.0	S	M
W3/0.2	0.2	29.2	15.0	S	M
W3/0.4	0.4	29.5	15.3	S	M
W3/0.8	0.8	30.0	15.9	S	M

*S:Superior; I:Intermediate; M: Minimum; DM: does not meet.

III. RESULTS AND DISCUSSION

A. Results from Case 1 - Terraced House

1. Thermal Analysis

Using analysis of hourly data obtained by the simulations, and the adoption of limits corresponding to the bioclimatic zone 3 (Table III) are presented in this item the values of thermal performance of coverage systems (Table IV) and external walls systems (Table V). In Table IV we show the levels of thermal performance obtained by the base coverage system (R0/0.2) and the other simulated systems. The base system attained the intermediate level for the summer but the minimum level of thermal performance was not met for the winter. In relation to performance in the summer, it increases with the use of materials with higher mass in the slab and decreases with increasing absorptance. Thus, the systems R1 and R2 have the top level in summer, but it does not occur in winter in which kept the same result in all simulations (does not meet, DM). It is noticed that the maximum and minimum temperatures of each alternative studied are extreme and are outside the limit of thermal comfort established. None of the systems studied presented $Ti_{máx}$ below 30°C or Ti_{min} above 12°C and the highest figures were obtained by R0/0.8 system as 37.8°C and lower Ti_{min} at 9.7°C, in the R0/0.2 building system. Thus, the coverage system R2/0.2 was used for the remaining simulations.

Table V shows the thermal performance levels achieved to different external walls. At this stage of the construction system based simulations (W0/0.2) presented higher in summer and lower in winter. With changing construction system these levels remain unchanged, however with the change of absorbance to higher values in W0 and W1 systems level in summer passes superior to intermediate. We also observe that, despite the increased level of thermal performance, internal temperatures are extreme, especially in winter, where the lower Ti_{min} was 12.1°C (W1/0.2) and the highest of 15.9°C (W3/0.8). In the summer, the building systems showed temperatures closer to the limit of 29°C, although they are still high.

The evaluation of the time data by the method of degree-hours is shown in Figs. 6 and 7. It is observed that the thermal performance increases gradually with use of absorptances and thermal mass of the building systems, despite the increase in thermal discomfort caused by heat.

The base coverage system (R0/0.2) showed 27% of the hours in discomfort caused by cold (2337 hours), 1% of the hours in discomfort heat (126 hours) and 72% of the hours in thermal comfort (6296 hours) , and the system with the highest number of hours of discomfort from cold (Fig. 6). With absorbance of 0.8 (R0/0.8), had the highest number of hours of discomfort in the heat of 9% (814 hours). The use of building systems R1 and R2 presented a subtle increase in thermal comfort, 3% points, comparing the systems and R1/0.2 R2/0.2 with the base system. The building system with the highest number of hours in thermal comfort, among the alternatives simulated roofing, was R1/0.8, with 80% (6971 hours).

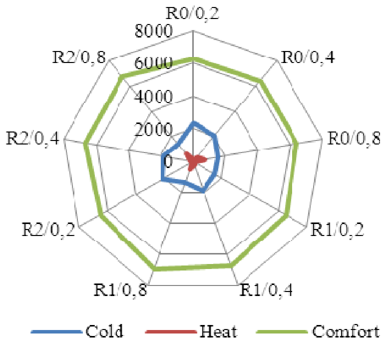

Fig. 6 Case 1 - Degree-hours to different roofs (in hours)

Fig. 7 shows the results of degree-hours to different wall systems. The system of external wall base (W0/0.2) showed 86% of thermal comfort hours (7536 hours), the cold thermal discomfort caused by corresponds to 13% of the hours (1178 hours) and 1% caused by heat (46 hours). The increase in absorbance increased by 3% points (237 hours) thermal comfort, despite the increased discomfort heat 2% points. Systems W0, W1 and W2 were the ones with the greatest hours of thermal discomfort from cold and heat, with 1358 hours (W1/0.2) and 272 hours (W1/0.8), respectively. Moreover, the system W3/0.8 presented 9 points (829 hours) more in thermal comfort, the highest number of hours of thermal comfort.

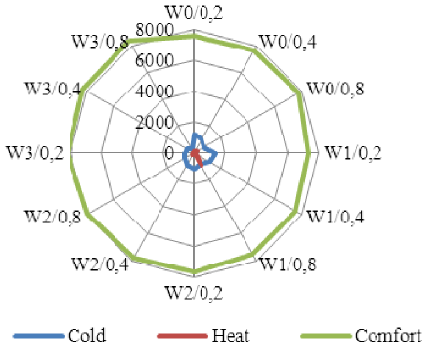

Fig. 7 Case 1 - Degree-hours to different external walls (in hours)

2. Economic Analysis

Payback was used for the economic analysis of building systems, estimating the cost of the base system and simulated alternatives and the difference in cost of these investments. To calculate the payback period for the coverage we calculated the cost of a pavement. In Tables VI and VII shows the comparative cost in annual electricity for Case 1, with savings achieved and the payback period of the investment.

TABLE VI
CASE 1 - SIMULATION ON ROOFING - COSTS, SAVINGS AND PAYBACK PERIOD

Code	α	Building costs [US$]	Investment (Cost C_x-R0) [US$]	Annual energy consumption [kWh]	Annual electric energy costs [US$]	Annual savings (Cost $C_{x,\alpha}$-R$0_{0.2}$) [US$]	Payback [years]
R0/0.2	0.2	39,792.32	NA	3,917.43	945.62	NA	NA
R0/0.4	0.4	39,792.32	NA	4,035.17	974.04	-28.42	NA
R0/0.8	0.8	39,792.32	NA	4,340.25	1,047.68	-102.06	NA
R1/0.2	0.2	43,042.71	3.250.39	3,697.24	892.47	53.15	61
R1/0.4	0.4	43,042.71	3.250.39	3,762.90	908.31	37.30	87
R1/0.8	0.8	43,042.71	3.250.39	4,004.07	966.53	-20.91	-
R2/0.2	0.2	43,350.95	3.558.63	3,728.21	899.94	45.68	78
R2/0.4	0.4	43,350.95	3.558.63	3,823.33	922.90	22.71	157
R2/0.8	0.8	43,350.95	3.558.63	4,072.61	983.07	-37.46	-

NA: Not applicable

There was a reduction in operating costs and increased starting with improved thermal performance. Table VI presents the results of simulated construction systems coverage. The coverage showed similar costs, with gradual increase of the cost depending on the type of slab used. Although the cost of operating systems R1 and R2 were much lower than in the base system, the construction cost was higher and less non-return to 50.

TABLE VII
CASE 1 - SIMULATION ON EXTERNAL WALLS - COSTS, SAVINGS AND PAYBACK PERIOD

Code	α	Building costs [US$]	Investment (Cost C_x-R0) [US$]	Annual energy consumption [kWh]	Annual electric energy costs [US$]	Annual savings (Cost $C_{x,\alpha}$-R$0_{0.2}$) [US$]	Payback [years]
W0/0.2	0.2	114,808.89	NA	5,626.12	1,358.07	NA	NA
W0/0.4	0.4			5,677.09	1,370.37	-12.30	NA
W0/0.8	0.8			5,852.85	1,412.80	-54.73	NA
W1/0.2	0.2	111,943.09	-	5,761.08	1,390.65	-32.58	-
W1/0.4	0.4			5,820.98	1,405.11	-47.04	-
W1/0.8	0.8			6,001.72	1,448.74	-90.66	-
W2/0.2	0.2	116,241.79	-1,432.90	5,408.06	1,305.43	52.64	27
W2/0.4	0.4			5,461.04	1,318.22	39.85	36
W2/0.8	0.8			5,607.26	1,353.52	4.55	315
W3/0.2	0.2	135,729.23	-20,920.34	5,107.57	1,232.90	125.17	167
W3/0.4	0.4			5,154.47	1,244.22	113.85	184
W3/0.8	0.8			5,285,76	1,275.91	82.16	255

NA: Not applicable

This finding confirms that found by the method of degree-hours, in which one realizes that there is a subtle increase in the thermal performance of the building and that this improvement is mainly through the change of absorbance. You can also confirm the reduction in spending power with increasing absorbance, comparing the absorptances in the same constructive system.

Table VII shows the alternatives for external walls. These systems have the cost of building higher and lower operating costs than the systems coverage. Only one system (W2) presented payback period less than the life cycle of the building under study (50 years), due to lower investment cost reduction and greater spending electric, compatible with the cost of construction. Already the system W3/0.2 showed the greatest reduction in electrical consumption, US$ 69.45, however, due to the high construction cost, the payback period of this investment is greater than the life cycle of the building.

TABLE VIII
CASE 2 - THERMAL PERFORMANCE LEVELS OBTAINED ON ROOFINGS

Code	α	$Ti_{máx}$ [°C]	Ti_{min} [°C]	Summer	Winter
R0/0.2	0.2	30.5	10.6	S	M
R0/0.4	0.4	31.7	11.0	S	M
R0/0.8	0.8	34.0	11.6	I	M
R1/0.2	0.2	30.0	11.3	S	M
R1/0.4	0.4	30.9	11.7	S	M
R1/0.8	0.8	32.6	12.4	S	M
R2/0.2	0.2	30.3	11.1	S	M
R2/0.4	0.4	31.3	11.4	S	M
R2/0.8	0.8	33.2	12.0	S	M

*S: Superior; I: Intermediate; M: Minimum; DM: does not meet.

B. Results from Case 2- Two-story detached house

1. Thermal Analysis

Data analysis limits the light corresponding to the climatic zone 3 (Table III) allowed the examination of the performance level of the building to different simulated alternatives presented in Tables VIII and IX.

According to Table X, the construction system based coverage presented for the summer and the upper level for the winter the minimum level of thermal performance. Regarding performance in the summer, this remains constant, except in R0/0.8 system, where it reduces to intermediate level. In winter, the level of thermal performance remains constant, even with the change of absorbance and thermal mass. It is noticed that the maximum and minimum temperature extremes and remain outside the limit established thermal comfort. The highest values was obtained by system R0/0.8 with a $Ti_{máx}$ 34.0°C and Ti_{min} lower than 10.6°C, with the constructive system R0/0.2

Table IX shows the levels of thermal performance obtained in the simulations of exterior wall building systems. At this stage, the base building system (W0/0.2) showed higher level at least in summer and winter. With changing construction system for systems W2 and W3, this level in winter is modified to an intermediate level. Despite the increased level, internal temperatures are extreme. In winter the lower Ti_{min} was 13°C (W0/0.2). In the summer, the building systems had internal temperatures near the limit of 29°C, although they are still high, up to 31.9°C (W0/0.8).

The evaluation of the data using the degree-hours is shown in Figs. 8 and 9. Through this method, note that the alternatives presented similar results, with increasing comfort by increasing the absorptance and the thermal mass of the building systems, up to 3% points in thermal discomfort proved by heat.

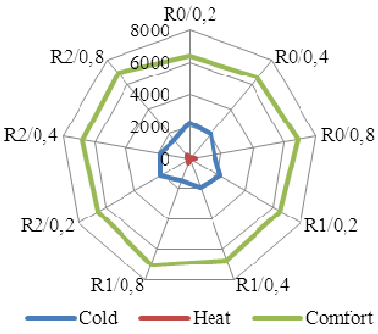

Fig. 8 Case 2 - Degree-hours to different roofs (in hours)

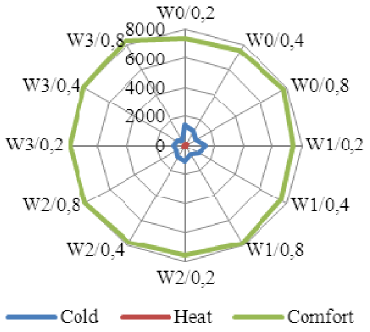

Fig. 9 Case 2 - Degree-hours to different external walls (in hours)

TABLE IX
CASE 2 - THERMAL PERFORMANCE LEVELS OBTAINED ON EXTERNAL WALLS

Code	α	$Ti_{máx}$ [°C]	Ti_{min} [°C]	Summer	Winter
W0/0.2	0.2	30.1	13.0	S	M
W0/0.4	0.4	30.7	13.5	S	M
W0/0.8	0.8	31.9	14.2	S	M
W1/0.2	0.2	30.0	13.2	S	M
W1/0.4	0.4	30.6	13.6	S	M
W1/0.8	0.8	31.8	14.4	S	M
W2/0.2	0.2	29.8	13.8	S	M
W2/0.4	0.4	30.3	14.2	S	I
W2/0.8	0.8	31.2	14.9	S	M
W3/0.2	0.2	29.5	15.4	S	I
W3/0.4	0.4	29.8	15.7	S	I
W3/0.8	0.8	30.3	16.3	S	I

*S: Superior; I: Intermediate; M: Minimum; DM: does not meet.

As seen on Fig. 8, the base coverage system (R0/0.2) presented 73% of the hours in thermal comfort (6418 hours), 26% of the hours in discomfort caused by cold (2283 hours) and discomfort caused by heat during the year is 1% (60 hours). The system R0/0.2 had the highest number of hours in discomfort due to the cold, and when the absorbance with 0.8, heat (370 hours). The level of thermal comfort increases mainly with increasing absorbance. With the construction systems of higher thermal mass, R1 and R2, there was a subtle increase in comfort, up 2% point (137 hours more than the base system). The building system that presented the best comfort was R1/0.8 with 80% of the hours in thermal comfort (7019 hours).

The level of thermal performance of the external walls is presented in Fig. 9. The base system showed 84% of thermal comfort hours (7326 hours), 15% thermal discomfort caused by cold (1387 hours) and 1% due to heat (47 hours). The system W1/0.8 had the highest number of hours of discomfort caused by heat, 2% of hours (178 hours). The increased number of hours of discomfort caused by cold was the base system. Walls of building systems that showed the best results, the system W3/0.8 presented 94% of the hours in thermal comfort (8276 hours).

2. Economic Analysis

Table X shows the comparative cost in annual electricity for Case 2, with savings achieved and the payback period of the investment. Just as in Case 1, there are a higher initial cost of the building and reduce operational costs with increased thermal performance.

As in Table VI, roofing alternatives presented gradual increase in initial cost and operational cost reduction. It is confirmed, therefore, the reduction in energy expenditure with increased absorbance and thermal mass. Despite the increased thermal performance of the building and the lower operation cost systems R1 and R2, the construction cost was higher in this way; none of the simulated return period has less than 50 years.

TABLE X
CASE 2 - SIMULATION ON ROOFING - COSTS, SAVINGS AND PAYBACK PERIOD

Code	α	Building costs [US$]	Investment (Cost C_x-R0) [US$]	Annual energy consumption [kWh]	Annual electric energy costs [US$]	Annual savings (Cost $C_{x,\alpha}$-$R0_{0.2}$) [US$]	Payback [years]
R0/0.2	0.2	64,322.35	NA	6,379.15	1,539.84	NA	NA
R0/0.4	0.4	64,322.35	NA	6,389.47	1,542.33	-2.49	NA
R0/0.8	0.8	64,322.35	NA	6,453.88	1,557.88	-18.04	NA
R1/0.2	0.2	68,669.00	4,346.65	6,220.15	1,501.46	38.38	113
R1/0.4	0.4	68,669.00	4,346.65	6,236.77	1,505.47	34.37	126
R1/0.8	0.8	68,669.00	4,346.65	6,339.49	1,530.27	9.57	454
R2/0.2	0.2	69,081.20	4,758.85	6,205.12	1,497.83	42.01	113
R2/0.4	0.4	69,081.20	4,758.85	6,222.17	1,501.95	37.89	126
R2/0.8	0.8	69,081.20	4,758.85	6,290.25	1,518.38	21.46	222

NA: Not applicable

Table XI shows the results of the different walls. These systems have the construction cost and reduction in power consumption higher than the coverage. Only one system (W2) presented payback period less than the life cycle of the building under study, 27 and 36, and the alternatives W2/0.2 W2/0.4 respectively. The system W3/0.2 showed the greatest savings in electrical consumption, US$ 125.17, but with a return period greater than 50 years.

C. Discussion to Cases 1 and 2

Construction systems simulated in Case 1 showed an increase in thermal performance, presenting alternatives outside walls with results above 7760 hours in thermal performance. Thus, there was an increase of up to 36% in thermal performance. By the method of performance of NBR 15575 all simulated systems presented in the winter and the minimum level to the upper level in the summer.

TABLE XI
CASE 2 - SIMULATION ON EXTERNAL WALLS - COSTS, SAVINGS AND PAYBACK PERIOD

Code	α	Building costs [US$]	Investment (Cost C_x-R0) [US$]	Annual energy consumption [kWh]	Annual electric energy costs [US$]	Annual savings (Cost $C_{x,\alpha}$-$R0_{0.2}$) [US$]	Payback [years]
W0/0.2	0.2	114,808.89	NA	5,626.12	1,358.07	NA	NA
W0/0.4	0.4			5,677.09	1,370.37	-12.30	NA
W0/0.8	0.8			5,852.85	1,412.80	-54.73	NA
W1/0.2	0.2	111,943.09	-	5,761.08	1,390.65	-32.58	-
W1/0.4	0.4			5,820.98	1,405.11	-47.04	-
W1/0.8	0.8			6,001.72	1,448.74	-90.66	-
W2/0.2	0.2	116,241.79	-1,432.90	5,408.06	1,305.43	52.64	27
W2/0.4	0.4			5,461.04	1,318.22	39.85	36
W2/0.8	0.8			5,607.26	1,353.52	4.55	315
W3/0.2	0.2	135,729.23	-20,920.34	5,107.57	1,232.90	125.17	167
W3/0.4	0.4			5,154.47	1,244.22	113.85	184
W3/0.8	0.8			5,285,76	1,275.91	82.16	255

NA: Not applicable

Already the Case 2 obtained by the method of NBR 15575, performance level in summer top and middle winter. On the analyzed building systems, some of the external wall systems showed results within the limit of 1000 hours of discomfort. This structure also presented an increase of the thermal comfort of 31%.

Data presented by the method of Degree-hour (Procel/NBR 15575) and corroborate each other and indicate that in cold period no greater amount of thermal discomfort. According to the presented results, we can conclude that with the increase in thermal mass (thermal and delay), and therefore a greater thermal resistance is improved thermal performance of the building. This system accumulates and stores amounts of heat in its interior (bulk) and then directs them to the surface, supplying the thermal demand of the building. However, this may result in increased energy consumption for cooling, because it is difficult to heat loss from the environment. This occurs both in roofing systems as systems of external walls.

The results confirm also the results obtained by the program Bio Analysis, for the climate of Porto Alegre. According to the bioclimatic chart, Porto Alegre has 51.6% of the hours for thermal discomfort caused by cold, and in 25.9% of the hours the thermal discomfort is caused by heat. Also confirms the strategies to be adopted indicated by the letter (high thermal mass, passive solar heating, shading, cross ventilation) and shown that despite the increased thermal performance and reduced power consumption for conditioning air, there is still need for artificial heating and cooling of buildings in the surroundings.

There is also the absorptance 0.2 had the best thermal performance for both methods. At high absorptances is increased by heat thermal discomfort even with the closing of the shutters when the outside temperature reaches 29°C. This can be improved with a promotion shading of frames (brise soleils), or shading at lower temperatures than stipulated, and the promotion of cross ventilation controlled in coverage, enabling shading and ventilation in warm periods.

Already the results of analyzes of the costs in the life cycle of Cases 1 and 2 demonstrate that the building systems coverage had greater influence in reducing the power consumption. However, few of these systems showed return on investment before the life cycle of the building. It is noticed that the increase in hours of thermal comfort with increased mass and absorptance has impact on costs in the life cycle of the buildings studied. Have thus correlation between building systems with higher cost efficiency and thermal performance of these.

However, in some systems analyzed, this saving in electricity consumption was insufficient to return the cost of investment in these buildings. Thus, in relation to the economic impact study of the systems used, despite the greater thermal mass systems have higher operating reducing the high cost makes constructive investment economically impractical. Thus, systems that had a low investment cost combined with a smaller reduction in the cost of electricity obtained payback periods shorter than 50 years.

IV. CONCLUSIONS

Based on buildings studied, it can be concluded that the best solution in terms of thermal performance did not produce the same results in economic performance. Among the alternatives studied can be considered that, for the city of Porto Alegre, the use of appropriate materials for composite climates in walls and roofs improve the thermal performance of the building because the city has a large thermal variation with energy required for both warming as cooling the building. The use of ventilation and shading the facade can enhance the thermal performance of buildings located in this climate, the warm periods of the year.

Alternatives easily implemented in the design process with little / no increase in cost, for example, the absorbance (color of the walls) and specifying different walls, influence on thermal performance. The payback period of the investment minimum was 24 years. The study demonstrates that, although some differences were subtle through projective planned alternative can decrease the use of artificial air-conditioning.

It is noteworthy that, although some constructive simulation systems have achieved good results among the systems, there is room for improvement. This can be obtained through the study of other building systems, solar orientation, and type of area frames, controlled cross-ventilation, shading, the use of facades for bioclimatic strategies that allow its use in climates compounds, like the city studied.

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