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Thermal performance evaluation of a low-cost housing prototype made with plywood panels in Southern Brazil

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ABSTRACT

Although the Brazilian Federal Government has been increasing investments in the housing sector since 2004, there has been a significant increase in the housing deficit as well. In 2007 this deficit had already reached 7.2 million dwellings. The majority (84%) consists of families with monthly income under three minimum wages. However, none of the traditional lines of credit considers families up to that monthly income level for building their own dwellings. In 2004, a program was created to subsidize low-cost housing ("Programa de Subsídio à Habitação de Interesse Social – PSH") with a maximum subsidy of about US$ 2500 for the construction of 'do-it-yourself' units. The present research had the general purpose of conceiving, constructing and evaluating the performance of a low-cost prototype consisting of wood and plywood panels. The object of analysis in this case study was a building prototype located in Canoinhas, in the South of Brazil (26°10′38″S, altitude 765 m above sea level), which was built within the scope of a program for subsidized low-cost housing. The present paper is concerned with evaluating the thermal performance of the finished prototype by means of onsite measurements and performing computer simulations for testing improvements of the original building prototype. From obtained results, general guidelines were drawn for improving indoor comfort conditions.

1. Introduction

According to the *Ministério das Cidades* [1], in 2007 the Brazilian housing deficit encompassed 7.223 million units. The greatest part of this deficit is located in urban areas and in the northeastern and southeastern regions of the country. Over 10 million units of the existing low-cost dwellings require basic infrastructure and about 84% of the families earn up to three minimum wages (around US$ 750 monthly).

On the other hand, Brazil has a high agricultural and foresting potential. Exotic forests such as *Pinus* ssp. and *Eucalyptus* ssp. adapted well to tropical and subtropical climatic conditions, which characterize the Brazilian territory, mainly due to advanced foresting technologies. Productivity in this field may reach up to 10 times the output of temperate climates [2]. In Brazil, mainly pine and eucalyptus are grown (93% of the harvest). The southern region alone yields around 80% of the harvest.

There is a number of studies on the use of wood-based building systems for the Brazilian low-income population. Publications on the subject refer to: general construction requirements, in some cases through housing cooperatives [3,4]; supply chain analysis in wood production [5–8]; life-cycle-assessment of wood constructions [9]; energy consumption for the fabrication of wood panels in social housing [10], design and construction of wood houses for the low-income population [11–16], and, more specifically, to the wood-frame building system [17–19].

Traditionally, however, one verifies that most of the Brazilian wood constructions were built informally. Contemporary architects avoid building with wood and work rather with conventional masonry (ceramic bricks) in low-cost housing projects. This factor is related, among other factors, to the lack of skilled labor in building with wood.

1.1. Need of performance evaluations in Brazilian social housing

Delivering suitable dwellings to the low-income population in developing countries should include a whole range of issues starting with an adequate building siting, the definition of the building system itself and its construction steps and finally with the evaluation of the finished building (pre- and post-occupancy evaluations). In tropical and subtropical climates, the thermal performance evaluation of low-cost dwellings should be primarily related to the optimization of indoor comfort conditions, usually on free-running buildings. Nevertheless, from the financial point of view, the

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improvement of thermal comfort conditions in low-cost housing should not result in substantial increases in the final building costs.

There is a strong necessity to redefine new low-cost housing policies in Brazil and throughout the last decades several research projects were primarily concerned with the evaluation of building systems for the low-income sectors of the Brazilian population. Indeed, in several publications and congresses on this matter, the evaluation of low-cost housing projects, apart from technical and constructive considerations, has been taking into account the aspect of improving indoor thermal comfort conditions. Usually low-cost housing projects are implemented throughout Brazil irrespective of bioclimatic considerations. In this sense, a same building system is used in locations with very distinct climatic conditions. To correct such distortions, standards have been developed throughout the last decade within the framework of a Brazilian Thermal Performance Norm, with the aim of promoting more adequate low-cost dwellings, under the aspect of bioclimatic architecture.

One of the first contributions in Brazil with regard to thermal performance evaluations of wood-based building systems consisted of thermal simulations with the NBSLD program of wood shelters in Antarctica [20]. The authors pointed out the difficulties arising from the use of a building material with a good thermal resistance, but which presents a low heat capacity. Giglio [21] simulated wood panels used in wood-frame constructions with the French design tool COMFIE [22], compared results to the recommendations of the Brazilian Thermal Performance Norm [23] and concluded that wood-based building systems may not attend the recommendations of the Brazilian Norm in the Southern region of Brazil, although with improvements those systems may show a good thermal performance. In a comparison between different wood-based building systems in Santa Catarina State, in Southern Brazil, Bogo [24], also taking into consideration the recommendations of the Brazilian Thermal Performance Norm, showed that only 13 out of 24 building systems and partly other two would attend the proposed standards.

The Brazilian Thermal Performance Norm, i.e., the Brazilian standard for residential buildings up to five stories [23] presents an overall list of performance guidelines in order to meet occupant requirements. Within this project, performance guidelines were subdivided into three distinct groups: safety requirements, habitability requirements and sustainability requirements.

Furthermore, the Brazilian norm recommends general procedures for thermal monitoring and thermal simulations, which were followed during measurements and simulations. With regard to thermal performance evaluations, the Brazilian Thermal Performance Norm is divided in three documents:

- Terminology, symbols and units, based on definitions from several documents including the Brazilian norm NBR 12538, ASHRAE Fundamentals, ASHRAE Standard 55/1992 and ISO Standards 7726 and 7730.
- Calculation methods of thermal transmittance, thermal capacity, time-lag and solar gain factor of building elements and components, based on Calculation methods of ISO 6946.
- Brazilian bioclimatic zones and building guidelines for low-cost houses, which consists of guidelines for low-cost housing prototypes on the basis of a division of the Brazilian territory into eight bioclimatic zones, each zone with design guidelines specific of that particular region. For that purpose, Givonís Building Bioclimatic Chart was adapted [25].

This brief literature review on thermal performance evaluations in wood-based building systems in Brazil suggests the need of developing more adequate wood dwellings for the low-income population, which could guarantee comfortable levels. Wood constructions are still regarded as having low quality and as provisory dwellings. In many cases, the lack of interest with regard to wood houses are mostly related: to the unskilled construction of such dwellings; to a common prejudice of clients and civil engineers and architects, who are usually not familiar with wood constructions, in favor of conventional masonry buildings; and to legal restrictions (building codes and fire safety standards impose strict constraints with regard to wood houses). Despite this historical trend, examples of industrialized wood construction are an exception in Brazil, whereas informal wood constructions are the norm.

2. Description of the housing prototype

In 2006, the Southern Brazilian state of Santa Catarina received US$ 23 millions within the low-cost housing program PSH (*Programa de Subsídio à Habitação de Interesse Social)* for subsidizing low-cost dwellings for families with a monthly income up to US$ 420. The state of Santa Catarina then decided to subsidize do-it-yourself housing units. Municipalities would be in charge of providing the residential lots, supervising and assuming technical responsibilities for the construction of the housing units. The state has a long tradition in wood construction and is the second greatest Brazilian producer of pine forests. In association with the local housing cooperative (*Companhia Habitacional – COHAB*), the state determined the choice of pre-fabricated wood housing units for meeting the demand for low-cost dwellings. Thus, entrepreneurs linked to the Brazilian Association of Mechanically Processed Wood Industry (*Associação Brasileira da Indústria de Madeira Processada Mecanicamente – ABIMCI*) sponsored the construction of two housing prototypes, one built with massive wood boards, located in Lajes, Santa Catarina, and a second one built in Canoinhas, Santa Catarina, which resulted from the present research. The construction of such prototypes usually has commercial objectives (show house). In the case of the prototype in Canoinhas, one of the goals was to present a low-cost housing type of easy assembly for the low-income population, which could be built with unskilled labor within a self-help process.

The present paper presents the thermal performance analysis of the wood prototype, which was designed by one of the authors and built in Canoinhas, consisting of self-sustained wood panels in small dimensions, fabricated with plywood and reforestation wood. The research as a whole encompassed four stages: design and construction of the building prototype; monitoring of the quality of the building process; thermal and acoustic performance evaluation and simulations of the prototype's thermal performance for other climate types in the southern region of Brazil.

The prototype consists of small sized reforestation wood elements and double wall panels composed of plywood. A floor plan, commonly adopted in ceramic masonry units was used in the wood prototype. The basic plan was adapted to modules of 122 cm × 244 cm. Built area corresponds to 48.93 m^2. The roofing system consists of a pinewood structure covered by fiber cement tiles and a pinewood ceiling. The double walls also have a pinewood structure. Internal plywood panels have a wall thickness of 9 mm and external (façade) panels of 12 mm, which yields a wall thermal transmittance (*U*-value) of 2.17 $W\,m^{-2}\,K^{-1}$. Fig. 1 shows the prototype's floor plan.

The monitoring of the building process consisted of the management of building materials and the supervision of assembly steps. The purpose of the post-occupancy evaluation was to evaluate the thermal and acoustic performance of the building system as a whole. In this paper we focus on the thermal performance analysis.

3. Materials and methods

Subsequent to the construction of the prototype, habitability requirements have been evaluated. In the broader research, this

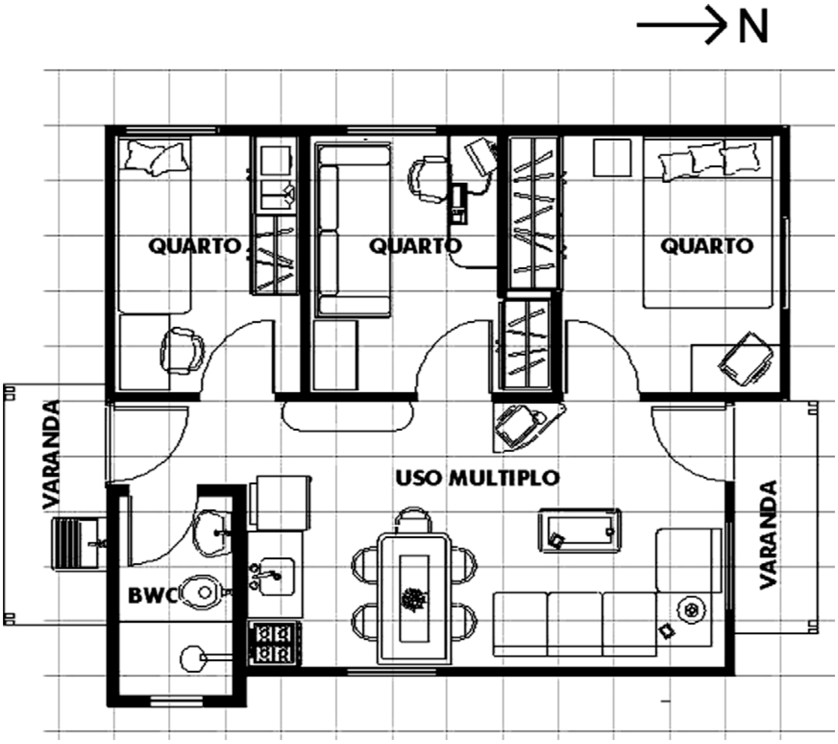

Fig. 1. Floor plan.

stage comprised of thermal and acoustic performance evaluations of the building system. In this paper we focus on the thermal performance evaluation of the prototype. The procedure adopted for the thermal performance analysis comprehended the following steps:

- On site measurements of indoor and outdoor temperatures: PT100 sensors, attached to a calibrated data logger (Lynx MCS 1000) were used to record air temperatures every minute sampled for every hour.
- Thermal simulations of the monitored building prototype were carried out with the IDA Indoor Climate and Energy (ICE) thermal simulation program (version 3.0, Build 15) [26], developed by EQUA, Sweden (http://www.equa.se) for two sets of conditions: (1) different climatic conditions and (2) different external wall panel configurations.

4. Thermal performance evaluation of the prototype: on site measurements

PT100 temperature sensors were placed in the geometric center of every room and in the living room (also at different heights to account for air temperature stratification) and the data logger was set to record data every minute. The external sensor was installed at a monitoring mast, at a two meters distance to the building and at approximately 2 m to the ground (ch#7) (Fig. 2), properly shielded against direct radiation within a small PVC cylinder approximately 15 mm in diameter and 40 mm long, which was covered by an aluminum foil. The PVC cylinder served as a naturally ventilated solar radiation shield. Temperature monitoring took place from December 6th 2006 through February 20th 2007.

Significant differences were found in temperature readings for each room as a result of the different solar exposures and internal volumes. In order to have one single, representative indoor temperature for the building, data from all sensors were averaged[1]. Fig. 3 shows both the indoor and outdoor air temperatures for 24 days in December 2006.

A great daily fluctuation can be noticed externally, reaching up to 10°C. Indoor air temperature fluctuations are much smaller and night temperatures stabilize around 20 °C.

As the building system under analysis, under normal usage, would be naturally ventilated (no HVAC systems) and its occupants would have the possibility of controlling ventilation rates by operating windows for creating a comfortable environment, the adaptive comfort method given by ASHRAE [27] was used[2]. ASHRAE Standard 55–2004 proposes an optional method for determining acceptable thermal conditions in naturally conditioned spaces. In this case, next to the control of thermal conditions through openings, mechanical cooling is not allowed, but mechanical ventilation with unconditioned air may be utilized. Occupants are engaged in near sedentary activities and are supposed to feel free to adapt their clothing to thermal (indoor/outdoor) conditions. Naturally ventilated buildings are defined as "buildings with operable windows and ceiling fans within small single or dual occupant offices that afford high degrees of adaptive opportunity" [27].

According to Linden et al. [28], user's satisfaction is directly related to thermal performance of the built environment. The adaptive approach goes under the assumption that "if a change occurs such as produce discomfort, people react in ways which tend to restore their comfort". For naturally ventilated buildings, ASHRAE Standard 55 suggests an alternative for the PMV-based method for establishing a comfort zone. Optimum comfort temperature T_{comf} is therefore calculated based on the monthly mean ambient temperature T_{out} [29]:

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[1] Since the internal mass of the building is relatively low, we chose to assume a given wall mass to the building for the computer simulations and to average measured temperatures, in order to simplify both modeling and thermal calculations.

[2] It should be stressed that during indoor temperature monitoring the building remained unoccupied and had no permanent ventilation.

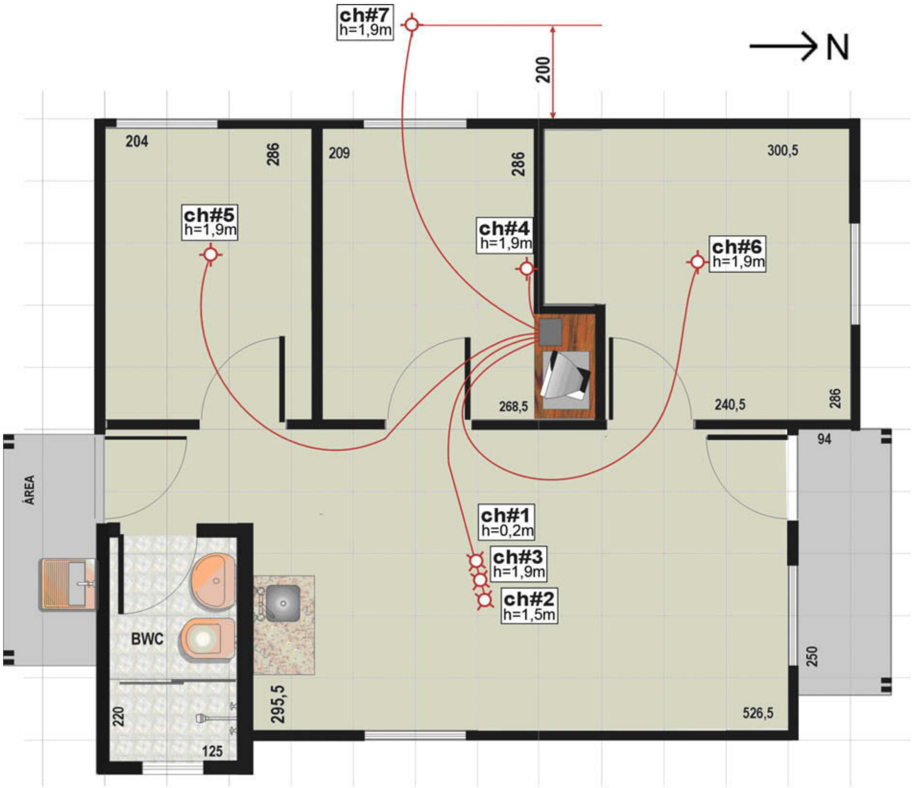

Fig. 2. Monitoring points.

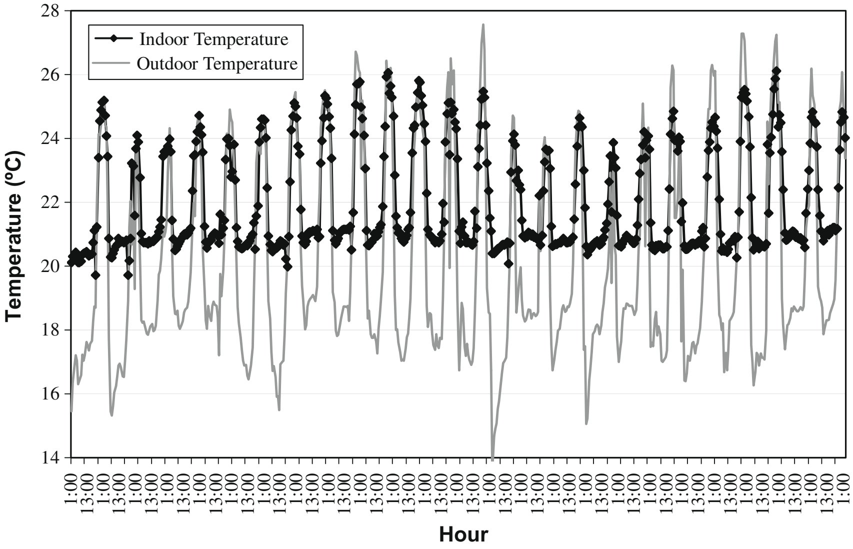

Fig. 3. Indoor and outdoor temperatures in december.

$$T_{comf} = 0.31 * T_{out} + 17.8 \quad (1)$$

The comfort range for 90% acceptability is 5 K and for 80% acceptability is 7 K. For Canoinhas, comfort temperatures are given in Table 1.

Table 2 presents a summary of the percentages of hours in cold, comfort and hot conditions, indoors and outdoors (for 80% acceptability) for each month, including the corresponding minimum, average and maximum temperatures.

Although the monitoring period consisted of summer months, over 60% of the monitoring time corresponded to a "cold" condition, i.e., below the lower adaptive comfort limit for each month (for 80% acceptability). The "hot" hours were negligible during the monitoring period, reaching a peak value of only 2% in February. Such conditions are common in Southern Brazil, where several cold fronts from the south frequently occur throughout the summer season. For these outdoor conditions, the prototype showed virtually 100% of the monitored hours in comfort.

4.1. Indoor temperature distribution

This section is concerned with the discussion of the indoor temperature distribution in the analyzed building, exemplified with sample readings within a period of five days in February 2007.

Table 1
Monthly comfort temperatures for Canoinhas.

Month	T_{out} (°C)	T_{comf} (°C)	90%		80%	
			T_{comf} min (°C)	T_{comf} max (°C)	T_{comf} min (°C)	T_{comf} max (°C)
December 2006	19.0	23.7	21.2	26.2	20.2	27.2
January 2007	18.7	23.6	21.1	26.1	20.1	27.1
February 2007	18.4	23.5	21.0	26.0	20.0	27.0

Table 2
Monitoring results – summary for Canoinhas (for 80% acceptability).

Month	Cold (%)	Comfort (%)	Heat (%)	T min (°C)	T avg (°C)	T max (°C)
Indoors – December	0	100	0	20	22	26
Outdoors – December	62	37	1	13.6	19.0	27.6
Indoors – January	0	100	0	19.8	22.2	26.1
Outdoors – January	65	35	0	14.0	18.7	27.3
Indoors – February	0	100	0	20.2	22.2	25.8
Outdoors – February	69	29	2	14.6	18.4	29.0

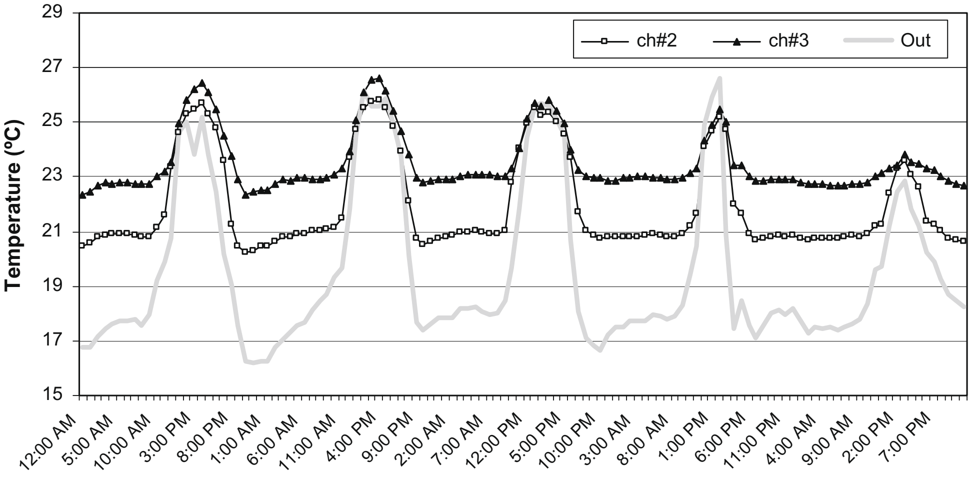

Fig. 4. Indoor temperatures, measured at three heights in the living room.

Again, it should be reminded that the building, although designed as a naturally ventilated (NV) one, remained unoccupied and had no permanent ventilation throughout indoor temperature measurements. No shadings were used for the external openings and, internally, doors remained closed between rooms. Fig. 4 presents the variability of measured temperatures at two different heights from the floor in the living room (monitoring points ch#3 and ch#2, whose temperatures were measured at 1.9 m and 1.5 m, respectively) in order to account for the effect of air temperature stratification.

The effect of air stratification is noticeable, with lower air temperatures at head height and higher temperatures, when close to the wood ceiling. The fast response of indoor temperatures with regard to outdoor fluctuations is strongly related to the low-mass characteristic of the building system.

Fig. 5 shows the distribution of indoor temperatures in four spots of the building (in the three bedrooms and in the living room, points ch#3, ch#4, ch#5 and ch#6, whose temperatures were measured at approximately the same height above floor of about 1.9 m –head height).

Except for ch#4 (denominated *Bedroom_west_center* in the graph), all indoor temperature profiles follow closely the rise of the outdoor temperature, as a consequence of the building's low thermal mass. Differences concerning the diurnal temperature swing of each monitoring point are mainly related to three aspects: the orientation of the room, the volume of the enclosed space and the exposed envelope surface regarding that particular room. As a result, ch#6 (*Bedroom_North-facing*), which has the greatest exposed surface among the three bedrooms, but a lower volume than the living room), yields lower air temperatures than ch#4 and ch#5 (*Bedroom_west_center* and *Bedroom_west_rear*). The middle bedroom (ch#4, *Bedroom_west_center*), west-facing, shows a temperature rise in the afternoon hours, which is consistent with its solar exposure, and has the lowest temperature fluctuation, which may be related to its reduced exposed surface.

Table 3 presents indoor daily minimum and maximum temperatures for the four monitoring points, as compared to outdoor data.

A comfort assessment for residential buildings, concerning recommendations for internal thermal zones is shown in Peeters et al. [30]. In the paper, reviews and adaptations are shown, in order to present acceptable temperature ranges and comfort scales for residential buildings. Based on the theoretical analysis of Maeyens et al. [31], the authors present recommended temperature guidelines for bathrooms, living rooms and bedrooms, based on user adaptiveness. The recommended neutral temperatures are given as a function of the reference external temperature, $T_{e,ref}$ (which is here calculated for the sake of simplicity as the monthly average, given in Table 1), for both evaluated conditions:

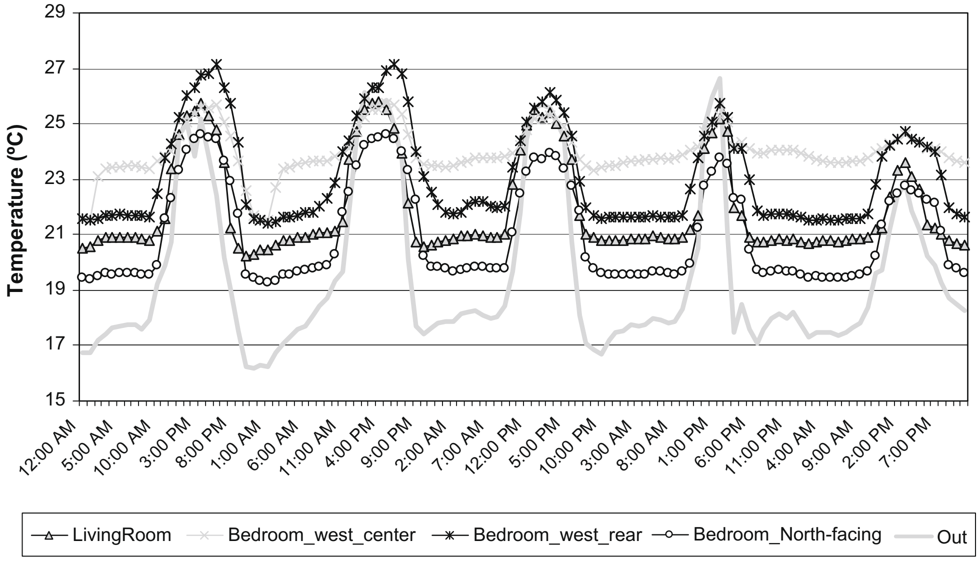

Fig. 5. Indoor temperatures distribution in the monitored building.

Table 3
Indoor and outdoor minima and maxima in February (15–19).

Date	Living room	*Bedroom_west_center*	*Bedroom_west_rear*	*Bedroom_North-facing*	Out
T min (°C)					
15/02	20.2	21.6	21.5	19.4	16.2
16/02	20.4	21.5	21.4	19.3	16.2
17/02	20.8	23.3	21.6	19.6	16.7
18/02	20.7	23.5	21.6	19.5	17.1
19/02	20.6	23.6	21.5	19.4	17.3
Average	20.6	22.7	21.5	19.4	16.7
T max (°C)					
15/02	25.7	25.7	27.1	24.6	25.2
16/02	25.8	25.7	27.1	24.6	26.2
17/02	25.5	25.3	26.1	23.9	25.7
18/02	25.2	25.3	25.7	23.7	26.6
19/02	23.6	24.6	24.7	22.8	22.8
Average	25.2	25.3	26.2	23.9	25.3

$$\text{For the bedrooms}: T_n = 0.77 * T_{e,ref} + 9.18 \quad \text{for } 12.6\,^{\circ}\mathrm{C} \leqslant T_{e,ref} < 21.8\,^{\circ}\mathrm{C} \tag{2}$$

$$\text{For the living room}: T_n = 0.36 * T_{e,ref} + 16.63 \quad \text{for } T_{e,ref} \geqslant 12.5\,^{\circ}\mathrm{C} \tag{3}$$

For the climatic conditions of Canoinhas, with a monthly average temperature of 19.5 °C in February, Eq. (2) yields T_n = 24.2 °C and Eq. (3) T_n = 23.7 °C. Average indoor temperature in the bedrooms for the five days sample lies around the recommended value, except for the biggest bedroom (*Bedroom_North-facing*). For the living room, the difference to the recommended neutral temperature is small. However, if we consider a temperature range of 5° (±2.5 °C), as used in the definition of the adaptive comfort limits, for 90% thermal acceptability) all rooms will meet the recommendations.

It should be stressed that such conclusions refer to a closed, unoccupied building. The effect of occupation may have a significant impact on the building's thermal performance. There are a number of studies relating the building thermal performance to the use of control devices, as openable windows, blinds and internal heat sources [32–35]. A field study in the NV office buildings in the UK showed that windows play a very important role in controlling the indoor climate [32]. Especially under summer conditions, cross ventilation may help improve indoor thermal conditions by means of preventing the occurrence of indoor maximum temperatures, which are higher than outdoors, as shown in Table 3 (first and last monitoring days and for almost all rooms). The effect of ventilation on indoor climate is discussed extensively in Givoni [36] and Krüger and Lamberts [37].

5. Thermal performance simulations

The main purpose of performing thermal simulations of the described building was the possibility of testing its behavior under different climatic conditions and also to evaluate the impact of design improvements. Simulations were carried out with the thermal simulation software IDA Indoor Climate and Energy (ICE Version 3.0, Build 15), developed by EQUA, Sweden (http://www.equa.se).

IDA Simulation Environment is a general-purpose modeling and simulation tool for modular systems where components are described with equations [38]. The program has a solver, which can solve non-linear algebraic problems without requiring initial guesses from the user. The application can be used for most building types for calculation of, among others: full zone heat balance; operating temperature at multiple arbitrary occupant locations,

Table 4
IDA ICE values for terrain roughness parameters.

Terrain	AO_coefficient	A_exponential
Ocean	1.3	0.1
Airport	1.0	0.15
Open country	0.85	0.2
Suburban	0.67	0.25
City center	0.47	0.35

directed operating temperature for estimation of asymmetric comfort conditions; comfort indices; daylight level at an arbitrary room location.

IDA Indoor Climate and Energy (ICE) is a program for assessing indoor climate of individual zones within a building, as well as energy consumption for the entire building. The user interface is divided into three different levels, with different support and scope for the user: the simplest level, called wizard, the standard and the advanced levels [26]. In IDA, mathematical models are described in terms of equations in a formal language, Neutral Model Format (NMF). NMF is a program independent language for modeling of dynamical systems using differential–algebraic equations [38].

IDA was validated by means of extensive comparative studies against the BRIS program [38], a heat balance program for room climate studies developed in Sweden in the early sixties. BRIS is based on detailed non-linear physical relations and has been validated against measurements in a number of studies. After several extensions, it is still widely used and well trusted by the Swedish building industry.

Further validations of IDA were carried out against measurements in the scope of IEA Task 22 [39]. The IEA tests were carried out in the spring of 1998 in a test cell. Due to existing thermal bridges in the test cell, difficulties arose in correctly assessing the results. However, after correction of thermal bridges, IDA ICE performed very well in the test.

In this study, a simulation model of the building was created in IDA ICE using as inputs its geometry and typology, the thermal properties of its constituent building materials, operation of openings and occupation patterns for a summer and a winter period.

With regard to ventilation, in IDA ICE wind flows are parameterized. For each aspect ratio, terrain roughness coefficients are used, according to typical values given in Table 4. For H/W = 0.33, terrain roughness coefficients refer to 'Open Country'; H/W = 0.66 to 'Open Suburban'; H/W = 1 to 'Suburban'; and H/W = 2 to 'City Center'.

For initial simulations, a climate file was created based on data recorded at the closest meteorological station during the monitoring period and on outdoor measurements (such as the air temperature –ch#7). The climate file was comprised of the following factors:

Time	Time (h)
TAir	Air (dry bulb) temperature (°C)
RelHum	Relative humidity (%)
WindDir	Wind direction (°) from 0 to 360; −1 if no data
WindVelRef	Wind speed (m/s)
IDirNorm	Direct normal (beam) radiation (W/m^2)
IDiffHor	Diffuse (sky) radiation on a horizontal surface (W/m^2)

When project values were uncertain, minor adjustments were made in order to calibrate the simulation model to measured data. Those adjustments included: solar reflectance of external surfaces; overall thermal wall mass inside the building; thermal properties and wall thickness.

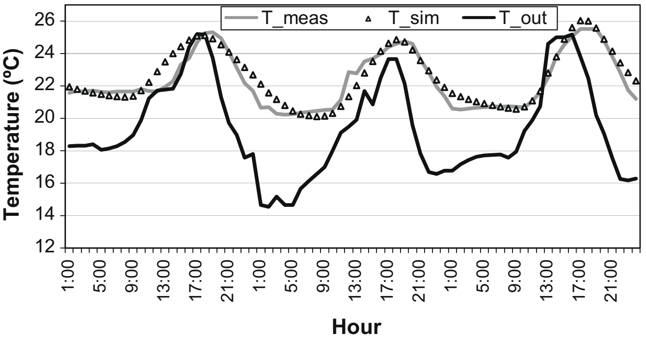

Fig. 6. Comparison between measured and simulated indoor temperatures.

5.1. Comparisons with measured data

The resulting model was found capable of realistically simulating the building's thermal behavior, correlation (R) was 0.94 after adjustments were made. Fig. 6 presents simulation results for three consecutive monitoring days.[3] Fig. 7 shows the correlation between both data sets. Table 5 presents some general statistics on that comparison, showing a small average error of 0.2°, the mean biased error, which shows the overall bias in the data and the mean square biased error, a good indicator of the overall magnitude of the errors. Results proved quite satisfactory.

5.2. Simulations with other climatic data

After a good agreement was verified between measured and simulated data, climatic data from other cities of Southern Brazil were considered for analysis: Curitiba (25°30′S, 49°20′W, 910 m above sea level); Florianópolis (27°30′S, 48°30′W, on the coast: Island of Santa Catarina); and Porto Alegre (30°S, 51°10′W, at sea level).

Curitiba has a high elevation, which is responsible for the coldest winter of all Brazilian capitals. The climate is humid subtropical and according to Koeppen's classification (IAPAR 1994) the climate type is *Cfb*. Great daily and seasonal fluctuations of the air temperature characterize Curitiba's climate.

Florianópolis is located on the Island of Santa Catarina. The climate is humid mesothermic without a dry season (*Cfb*, according to Koeppen) and is characterized by a high humidity, hot summers and mild winters.

Porto Alegre has a temperate subtropical climate, with hot summers and cold and rainy winters (for Brazilian standards). According to Koeppen's classification the climate type is *Cfa*.

For each location, the corresponding test reference year (TRY) was used (from the database available at http://www.labeee.ufsc.br). Simulations were performed for winter and summer months. In order to account for heat gains due to occupation and operation of equipments, apart from thermophysical characteristics of the envelope, thermal loads were included in the simulation model, according to a pre-defined schedule (Table 6).

Simulations were carried out for summer conditions with all windows open and unshaded during most of the day (from 7:30am to 9 pm). For winter conditions, windows were considered

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[3] The difficulties encountered for validating the software from measured data are primarily related to the availability of climatic data. Since the location has no automatic meteorological station, detailed data for Canoinhas were missing, specially with regard to solar radiation (beam and diffuse). As a result, only days with clear-sky conditions were considered, for which we used a solar radiation calculation procedure for obtaining the direct and the diffuse components, presented by Bird and Hulstrom [40]. Thus, from the total of 75 days of measurement, only a few days were considered to have complete and realistic climatic data for simulations.

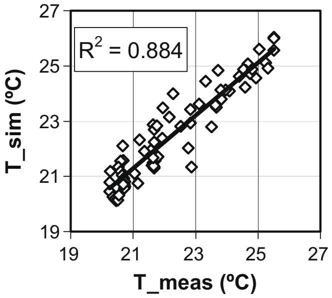

Fig. 7. Correlation between measured and simulated indoor temperatures.

Table 5
General statistics: simulated versus measured data.

Indicator	Value
Number of points	72
Observed mean	22.3
Simulated mean	22.6
Observed mean–simulated mean	−0.2
Standard deviation of observed data	1.7
Standard deviation of simulated data	1.7
Mean absolute error	0.2
Mean biased error (MBE)	0.2
Root mean square error (RMSE)	0.6
Correlation coefficient	0.94

Table 6
Thermal loads considered in the simulations.

Equipment	Load (W)	Schedule
Equipment 1	300	From 5 pm to 10 pm
Equipment 2	150	Always on
Lighting system	360	From 5 pm to 10 pm
Occupants (3)	375	From 5 pm to 8 am*
Occupant (1)	125	Always

* From Monday through Friday during working hours (8 am to 5 pm), just one dweller was considered (metabolic rate 1.2MET, which is approximately 125 W). In the evening and at night, a full occupation of four dwellers was assumed. On weekends, full occupation was assumed throughout the day.

closed for ventilation, but unshaded (allowing solar gains through the glazing).

Results were obtained in terms of indoor temperature variations for the months with the highest and lowest outdoor average temperature for Curitiba, Florianópolis and Porto Alegre (Table 7). Such months, based on TRY data, were slightly different for the three locations: for Curitiba, the months of February (hottest) and July (coldest) were chosen for analysis, and for the other two cities, January and June, respectively.

It was verified that the building system has a satisfactory thermal performance with regard to the low temperatures in winter for all three localities. Also, indoor temperatures are always higher than outdoors. This could even create problems of overheating around the period of the maximum daily temperatures, though a simple control of the building openings (by shading or ventilating) could be sufficient as a passive solution in this case.

In summer, when daily maxima can be substantially high and well above upper comfort limits, indoor temperatures can get slightly higher than outside. Such rise in the indoor temperature patterns in summer is mainly due to direct solar gains through the openings (considered unshaded for the simulations) and to high ventilation rates during the peak hours of the day.

5.3. Comfort analysis

Comfort temperatures were calculated for the months considered for analysis, for the three locations, according to the adaptive comfort method by ASHRAE [27]. Corresponding comfort ranges were obtained for 80% and 90% acceptability. Table 8 presents monthly averages, calculated comfort temperatures and ranges for Curitiba, Florianópolis and Porto Alegre, respectively.

Three configurations were taken into account for the simulations: (a) “prototype”, i.e., original configuration (roofing system composed of fiber cement tiles and pinewood ceiling, double walls with a pinewood structure, internal panels with wall thickness of 9 mm and façade panels with 12 mm, which yields a *U*-value of 2.17 W m^{-2} K^{-1}); (b) “prototype 1”, i.e., internal panels with a pinewood structure and thickness of 12 mm and façade panels with 15 mm, yielding a *U*-value of 1.81 W m^{-2} K^{-1}; (c) “prototype 2”, i.e., with thermal insulation (rock wool 7.5 cm thick) between

Table 7
Indoor and outdoor temperatures for curitiba, florianópolis and Porto Alegre – averages for the daily minima and maxima.

Location	Situation	Winter			Summer		
		T min (°C)	*T* avg (°C)	*T* max (°C)	*T* min (°C)	*T* avg (°C)	*T* max (°C)
Curitiba	Indoors	14.9	19.2	23.2	20.0	23.8	27.3
	Outdoors	7.5	12.5	19.1	17.1	20.7	26.3
Florianópolis	Indoors	20.7	23.2	26.2	24.6	27.3	30.2
	Outdoors	12.7	17.0	22.5	21.7	24.8	29.3
Porto Alegre	Indoors	20.1	22.6	25.3	23.3	27.9	31.8
	Outdoors	11.7	14.9	19.1	19.6	24.6	30.5

Table 8
Monthly averages and comfort ranges for curitiba, florianópolis and Porto Alegre.

Location	Month	T_{out} (°C)	T_{comf} (°C)	90%		80%	
				T_{comf} min (°C)	T_{comf} max (°C)	T_{comf} min (°C)	T_{comf} max (°C)
Curitiba	February	20.7	24.2	21.7	26.7	20.7	27.7
	July	12.5	21.7	19.2	24.2	18.2	25.2
Florianópolis	January	24.8	25.5	23	28	22	29
	June	17	23.1	20.6	25.6	19.6	26.6
Porto Alegre	January	24.6	25.4	22.9	27.9	21.9	28.9
	June	14.9	22.4	19.9	24.9	18.9	25.9

internal and external panels (9 mm and 12 mm thick, respectively), yielding a *U*-value of 0.42 W m^{-2} K^{-1}.

Figs. 8 and 9 present the indoor and outdoor minimum, average and maximum temperatures for summer and winter in Curitiba as an example of the varying thermal performance of the building under the three configurations described above (prototype, prototype 1, and prototype 2).

Fig. 8 shows results for winter (January) in Curitiba, where a typical high daily fluctuation of the outdoor air temperatures can be noticed, which are greatly affected by cold fronts from the south. In winter, daily temperatures lie usually below the adaptive comfort range, except for the times around the daily maxima on a few days. The variations of the indoor temperatures resulting from

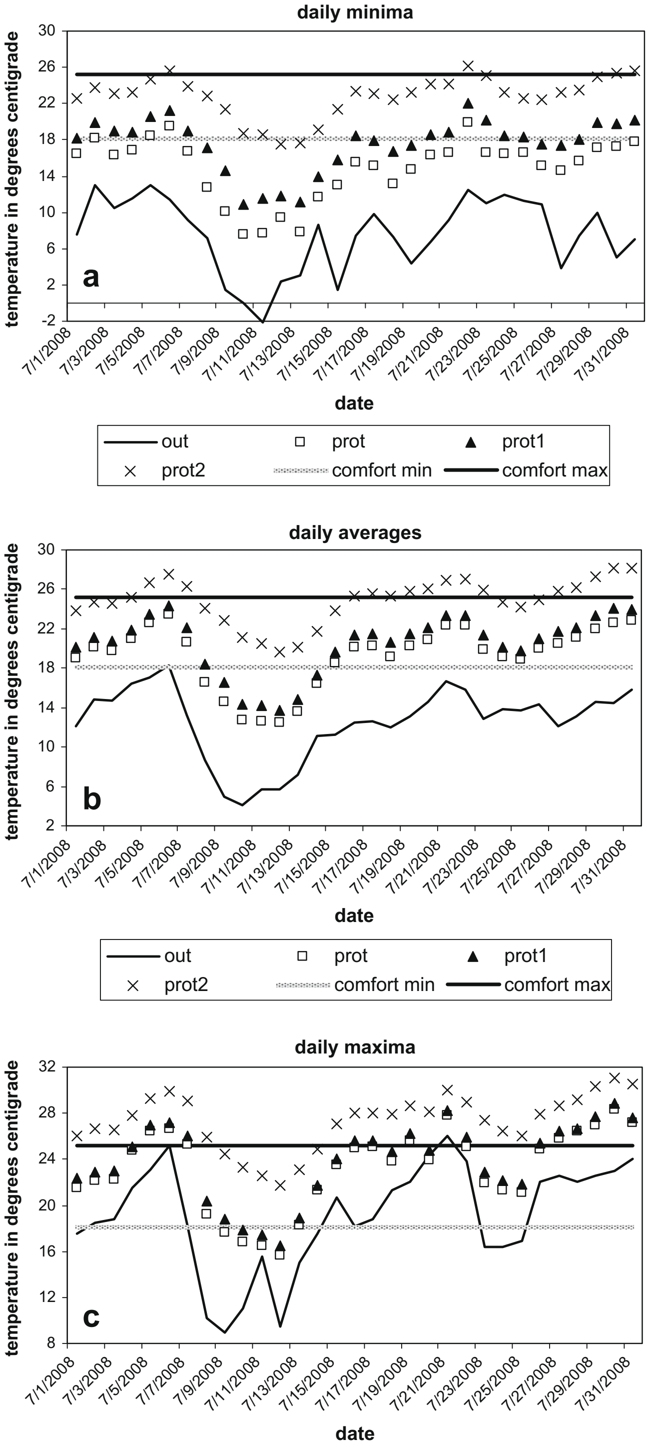

Fig. 8. Minimum (a), average (b) and maximum (c) indoor and outdoor temperatures in winter for curitiba.

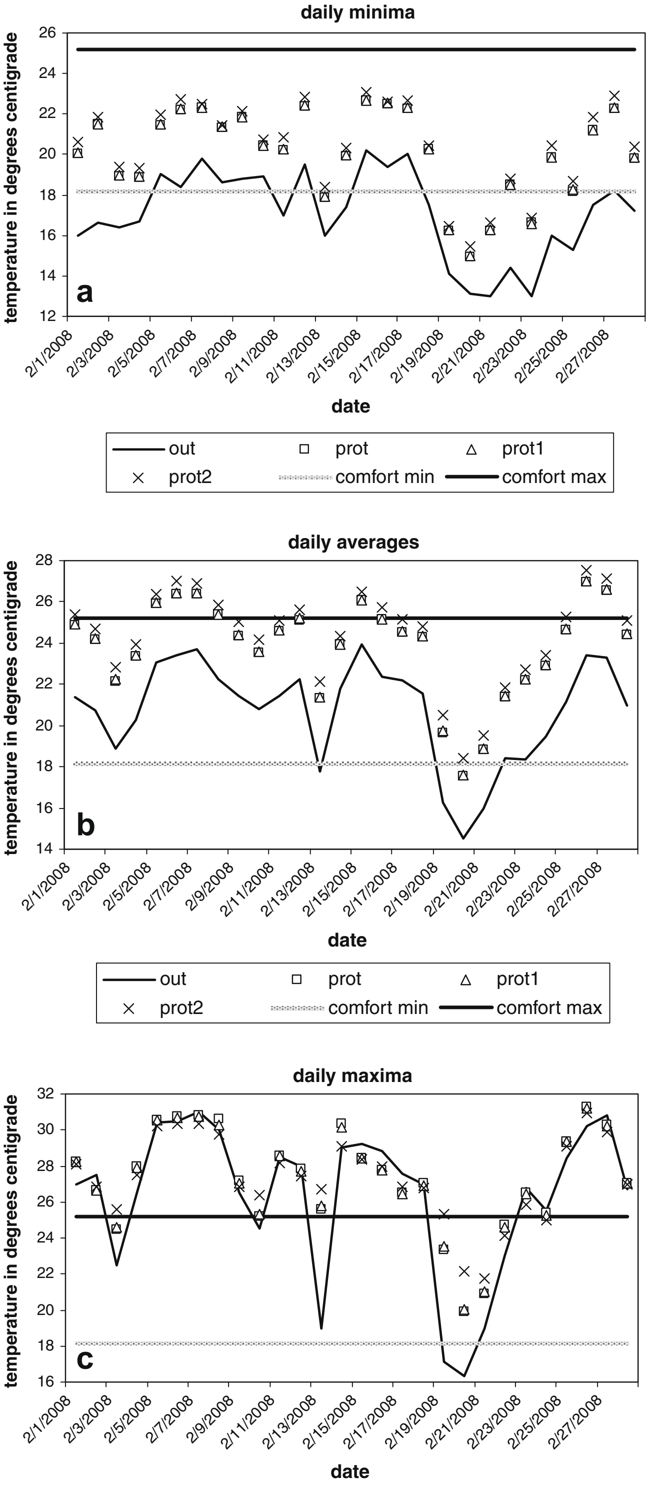

Fig. 9. Minimum (a), average (b) and maximum (c) indoor and outdoor temperatures in summer for curitiba.

Table 9
Summary – summer and winter.

Location	Configuration	Cold (%)	Comfort (%)	Heat (%)	Tmin (°C)	Tavg (°C)	Tmax (°C)	Heating/cooling degree–hours
Curitiba – summer (February)	*Prototype*	17	75	8	20.1	23.8	27.3	79
	Prototype 1	16	75	9	20.1	23.9	27.2	76
	Prototype 2	13	76	11	20.4	24.4	27.3	79
	Outdoors	**50**	**5**	**45**	**17.1**	**20.7**	**26.3**	**54**
Curitiba – winter (July)	*Prototype*	36	57	7	14.9	19.2	23.2	863
	Prototype 1	23	67	10	17.5	20.4	23.9	493
	Prototype 2	1	53	46	22.8	24.8	27.3	4
	Outdoors	**85**	**15**	**0**	**7.5**	**12.5**	**19.1**	**4604**
Florianópolis – summer (January)	*Prototype*	2	72	26	24.6	27.3	30.2	327
	Prototype 1	2	71	27	24.6	27.4	30.1	331
	Prototype 2	2	68	30	24.6	27.7	30.2	386
	Outdoors	**18**	**70**	**12**	**21.7**	**24.8**	**29.3**	**205**
Florianópolis – winter (June)	*Prototype*	11	78	11	20.7	23.2	26.2	92
	Prototype 1	0	38	62	24.6	27.4	30.2	0
	Prototype 2	0	31	69	24.8	27.8	30.2	0
	Outdoors	**75**	**25**	**0**	**12.7**	**17**	**22.5**	**2317**
Porto Alegre – summer (January)	*Prototype*	4	58	38	23.3	27.9	31.8	749
	Prototype 1	4	58	38	23.3	27.9	31.7	761
	Prototype 2	4	52	44	23.8	28.4	31.6	846
	Outdoors	**31**	**50**	**19**	**19.6**	**24.6**	**30.5**	**428**
Porto Alegre – winter (June)	*Prototype*	5	87	8	20.1	22.6	25.3	60
	Prototype 1	0	31	69	23.2	27.9	31.8	2
	Prototype 2	0	24	76	23.7	28.3	31.6	0
	Outdoors	**89**	**10**	**1**	**11.7**	**14.9**	**19.1**	**3078**

enhancing the panels' thickness (prototype 1) are more verified in the daily indoor minimum temperatures (a), as solar gains through the openings tend to minimize such differences during daytime. The addition of insulation (prototype 2) will have a strong effect on the indoor temperatures, raising the daily averages, in some cases, above the upper adaptive comfort limit for winter. As in Brazilian low-income sector its is not common the use of insulating shutters (mostly Venetian blinds with virtually no insulating effect are adopted), the addition of an insulating layer within the panels may be a recommended strategy. It should also be stressed that the use of artificial heating is not frequent in such dwellings.

Fig. 9 shows the varying thermal behavior of the three configurations in summer. A similar pattern of the indoor temperatures is verified for all configurations, as a result of employing cross ventilation from all openings throughout the day. Under such conditions, changes in the panels will not play a major role in indoor thermal conditions.

Table 9 shows summer and winter results for the three locations. It can be verified that in the coldest month Porto Alegre presents the highest percentage of hours of cold, followed by Curitiba and Florianópolis. However, Curitiba has the most extreme minimum temperature in this period (the minimum for July in Curitiba was -2.1 °C and for Porto Alegre in June was 2.5 °C). In summer, Porto Alegre shows the highest maximum temperature (maximum temperature for the period was 36.5 °C, against 31 °C in Curitiba and 36 °C in Florianópolis) of all three locations, presenting the highest percentage of hours of heat.

In the comfort analysis, the original prototype shows in general a good performance in summer, suggesting that any modification in the wall panels would prove unnecessary. On the other hand, in winter, the introduction of insulation can be quite important, as the plywood building system has a low thermal mass.

In general, the addition of an insulating layer between wall panels may contribute to raise indoor temperatures in winter. However, the rise of the indoor temperatures may lead to thermal discomfort due to overheating. Such an improvement may not be justified according to the location: in Curitiba thermal insulation may be appropriate, such measure may even improve comfort conditions in summer, whereas in Florianópolis and Porto Alegre this may prove unnecessary. In Florianópolis, enhancing the panels' thickness (prototype 1) may be interesting for reducing thermal discomfort due to cold, whereas in Porto Alegre differences with regard to comfort levels by changing panel configuration are not note-worthy.

5.4. Heating and cooling degree–hours

The degree–hours procedure is a simplified, practical method for determining cumulative temperatures over the course of a season. Originally designed to evaluate energy demand and consumption, degree–hours are based on how far the average temperature departs from a pre-defined comfort level (Tb or base temperature). The sum of degree–hours accumulated in a day is proportional to the amount of heating/cooling to keep a building within comfort conditions.

In summer, Tb was assumed to be the upper limit of the comfort range according to the adaptive comfort method and in winter, the lowest limit was considered, both for 80% acceptability.

Table 9 also presents the sum of heating (winter) and cooling (summer) degree–hours obtained for Curitiba, Florianópolis and Porto Alegre, for the three aforementioned configurations ("prototype", "prototype 1" and "prototype 2").

According to the degree–hour method, Curitiba presents the most critical condition in winter and Porto Alegre in summer. The totals for winter and summer suggest that the three southern locations (subtropical) are mostly characterized by cold and not by heat, differing from the most common condition in Brazil (tropical). Correspondingly, the heating load for Curitiba is the highest for the first prototype configuration, which may be neutralized by adding insulation to the wall panels. Analogously, the highest cooling load is for Porto Alegre, but no improvements can be noticed by changing the wall panel configuration.

In all locations, the cooling degree–hours is higher indoors than outdoors. As mentioned before, under hot conditions (summer) it is more important in low-mass buildings to have a correct management of the building openings than to perform substantial (and, in some cases, cost-intensive) changes in the building envelope.

Table 10
Summary – heating and cooling degree–hours, percentage of hours of discomfort and degree–hours ratio for the original configuration of the prototype.

Location/month	Summer					Winter				
	Cooling degree–hours		Hours of discomfort (heat)		Cooling degree–hours ratio	Heating degree–hours		Hours of discomfort (cold)		Heating degree–hours ratio
	In	Out	In	Out	In/out	In	Out	In	Out	In/out
Canoinhas (December 2006) – *Monitored*	0	1	0	6	0	–	–	–	–	–
Curitiba (February and July) simulated	79	54	54	302	1.46	863	4604	268	632	0.19
Florianópolis (January and June) simulated	327	205	118	193	1,60	92	2317	79	540	0.04
Porto Alegre (January and June) simulated	749	428	283	141	1.75	60	3078	36	640	0.02

5.5. Summary of thermal evaluations of the building prototype

Table 10 shows a summary of all calculated parameters: heating/cooling degree–hours, hours of discomfort and the ratio between indoor and outdoor heating/cooling degree–hours. For the latter, a low ratio stands for a high thermal performance.

For the original prototype configuration, the best performance in terms of the degree–hour factor under summer conditions is identified for Curitiba and the worst for Porto Alegre. For the three simulated locations, this factor was higher than 1, meaning that indoor thermal comfort conditions tend to be worse than outdoors.

In winter, the best performance is verified for Porto Alegre and the worst for Curitiba. The factor, lower than 1, indicates that indoor conditions are better than outdoors. As mentioned before, a suggested improvement for Curitiba would be to use an insulating layer between wall panels. In this case, the degree–hours factor would drop to zero (virtually 0.001).

6. Final considerations

In the last decade, investments from the Brazilian Federal Government in the Housing Sector have been implemented by means of different lines of credit. However, existent credit lines are usually not offered to the low-income population. Notwithstanding, there is a strong market of wood products in Brazil, which benefits from the country's high agricultural and foresting potential. Considering the huge demand for new homes, wood houses may be a viable and interesting alternative. It was the purpose of this study to present a thermal comfort evaluation of a wood-based building system, which was designed and built by one of the authors.

Results of the thermal monitoring of the wood prototype, built in Canoinhas, Southern Brazil, which took place in summer, showed that the prototype had all monitoring hours in thermal comfort for 80% acceptability.

Those measurements served: (1) to evaluate the thermal behavior of the prototype by means of a 45 days on site thermal monitoring and (2) to provide sufficient data for calibrating a thermal simulation model using IDA ICE. With that model, simulations were run for different climatic conditions and locations, in order to test the applicability of the prototype in the southern region of Brazil. Also, improvements were tested by means of computer simulation of the original project.

With regard to thermal simulations, the issue of using a thermal simulation program developed in Sweden (cold climate) for Brazilian climatic conditions could be raised. It should be pointed out that validations of the IDA program took place in France and the procedure described for such validations indicates a temperature range around 12–25 °C for the test runs [39]. As the locations chosen for analysis are subtropical, high temperatures are not common. Indeed, Table 7 shows outdoor average temperatures for the three locations, which lie around 12–17 °C in winter and 23–27 °C in summer.

Most of the limitations regarding the calibration procedure refer mainly to the difficulties to collect reliable climatic data for the region where the prototype was built, Canoinhas. Data used as simulation input were gathered in Curitiba, which shows similar climatic conditions and elevation. However, under particular sky conditions (overcast sky and partially cloudy days) solar radiation data did not correspond to local conditions.

Simulations of the original prototype showed that, with regard to its thermal performance, it may be adequate to other locations in the south of the country without greater improvements in the original project. In colder locations, such as Curitiba as well as other cities with high elevation in the south of Brazil, simulations results suggest that the air cavity between external and internal panels may be filled with insulating materials.

The study had the purpose of presenting a wood-based prototype and testing its thermal performance with in situ measurements and by means of computer simulations. Results show that such buildings may be suitable to local climatic conditions with small adaptations of the original project. The detailed data analysis contributes to the spreading of this type of construction, which is nowadays not properly considered as an alternative for the low-cost housing sector in Brazil.

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