Thermal comfort analysis of a representative multi-story social housing unit with wood as an alternative construction material in Brazil

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Abstract. This research intends to link thermal comfort as an important part of achieving energy efficiency in the operational phase of a building with the use of wood as a low embodied energy and carbon efficient construction material. The thermal performance of a representative multi-story social housing unit with common construction materials is evaluated in contrast to wood-based construction systems in Brazil. A project located in São Carlos, Brazil was selected. The construction system for walls consists of concrete blocks while roofs are composed of a fiber cement sheet and a concrete slab ceiling. As alternative wood-based wall systems, plywood panels with an air chamber or three different insulation materials (expanded polystyrene, cellulose and mineralized wood fiber) were tested while two alternative roof systems were analyzed (plywood lining with air chamber or insulation material). The project with common construction materials as well as the wood-based alternatives were evaluated through the Brazilian standard NBR 15575 and the European Standard ISO 13786. Furthermore, a transient simulation was conducted following the procedure established by NBR 15575 and using the adaptive comfort model ASHRAE 55-2013. The analysis evidenced the neglect of the recommended passive design strategies according to the Brazilian Standard 15220 and the psychometric chart of Givoni. In regard to the wood-based constructions, results showed that insulation of mineralized wood fiber in panels performed better than cellulose and expanded polystyrene. The transient simulation also demonstrated better thermal comfort conditions with a hybrid wood-based model compared to the construction typology of the representative project.

1. Introduction
The use of wood in buildings brings many environmental benefits; it is renewable, recyclable, represents a permanent carbon deposit and requires low energy in its manufacturing process for construction. In spite of having the second largest forest reserves on the planet, wood-based building components are not commonly used in the construction sector in Brazil [1].

In less than 50 years, Brazil increased its urbanization rate from 50% to 85% [2]. As a response to this rapid urbanization, in 2009 the Brazilian government launched the program “Minha Casa, Minha Vida” - MCMV (“My house, My Life”), as a strategy to address the housing deficit in the country [3]. Previous researchers have pointed out the great financial interest of the main actors involved in the production of social housing and the low concern regarding design quality [4].
The selected project is Spazio Mont Royal (SMR) located in the city of São Carlos, Brazil. SMR presents characteristics of social housing developments being currently built in Brazil, including construction system, building arrangement, and space distribution [5]. In addition, the project takes part in MCMV program and has been used as a reference for other research [4]. SMR has 602 housing units distributed in 36 buildings of 5 stories with 20 apartments each. The building units have a symmetrical floor plan with central circulation and are arranged as symmetrical twin blocks (see figure 1).

![Distribution plan of residential complex SMR (left) and typical floor plan of building units in SMR (right).](image)

The apartment unit has a total internal area of 37.65 m² with two bedrooms, a living room, a bathroom, a kitchen, and a service area. The construction system for walls consists of concrete blocks of 9 cm with external and internal plaster. The roof is composed of a fiber cement sheet with metal structure and a 10 cm concrete slab ceiling. The composition of the intermediate floors is 10 cm concrete slab with ceramic tiles.

Due to the high degree of prefabrication and benefits in terms of costs and quality, a platform wood-frame construction technique was assumed for the selection of wood-based alternative systems. The basic concept of the wall system is a sandwich panel with air chamber or insulation layer encased between two skins of plywood boards. Three insulation materials are tested; expanded polystyrene EPS, cellulose, and mineralized wood fiber. The construction system of the roof consists of repetitive wood joists sheathed internally with plywood panels and fiber cement sheets on the external surface. Two roof alternatives were tested; air cavity and insulation material (EPS). The floor system consists of repetitive wood beams at a prescribed spacing encased with wood boards or panels (see figure 2).

![Alternative wood-based construction systems considered for the evaluation.](image)

2. Methods of assessment of climate, comfort and constructions; first conclusions for passive optimized buildings

2.1. Assessment of climate and comfort

The city of São Carlos is situated in the center of the state of São Paulo in Brazil. It has a temperate-warm climate with rains throughout the year [6]. The temperature in summer ranges from 14 °C to 30 °C while in winter from 8 °C to 26 °C. Relative humidity (RH) is high for most of the year and remains around 70% on average. Prevailing winds in São Carlos come from east throughout the year with important variations ranging from northeast to southeast.
The software Climate Consultant 6.0 [7] makes use of the Psychrometric Chart developed by Givoni [8]. It relates the air temperature and the relative humidity of the environment with design strategies to achieve thermal comfort conditions. According to this chart and applying the ASHRAE 55 comfort model [9] and the EnergyPlus weather file (EPW) of São Carlos [10], the city has a very mild climate with comfort in 23.3% of the hours along the year (see figure 3). The main design strategies in buildings are internal heat gain thermal (41.7%) and natural ventilation (25.3%). With these design strategies, the predicted number of hours in discomfort is reduced from 76.7% to 9.7%, a significant reduction with only passive design strategies.

In respect to the assessment of climate, the Brazilian standard of thermal performance in buildings NBR 15220 [11] divides the Brazilian territory into eight relatively homogeneous zones called bioclimatic zones (BZ). It offers passive design strategies for each BZ to optimize the thermal performance of housing. São Carlos forms part of the BZ 4. For this BZ the standard recommends evaporative cooling, thermal inertia for cooling and cross ventilation. Good natural ventilation is achieved when windows are oriented to prevailing breezes and with openings located on opposite sides of building. The building units in SMR present openings in opposite facades, but prevailing winds (from east) and external obstacles were not considered to define the arrangement (see figure 1). In winter, solar heating and heavy internal walls are recommended. The purpose is to receive and store the heat from the sun during the day and to release it during the night for a comfortable temperature while sleeping. In this regard, the optimal orientation of long-stay areas (rooms where residents spend most of the time) is north since this facade has a long-day sun exposure in winter. However, the layout of the representative project is symmetrical, with long-stay areas in opposite facades (see figure 1).

For the assessment of climate, the adaptive model ASHRAE 55 was considered. It is frequently used for the analysis of the thermal performance in the context of thermal comfort research in Brazil [12]. The ASHRAE 55 adaptive model assumes that occupants adapt to thermal conditions through the opening of windows and clothing. This comfort model applies only in naturally ventilated buildings without heating, ventilation and air conditioning systems (HVAC), as it is in the case of SMR. As result of the calculation proposed by ASHRAE 55-2013 adaptive model [9], figure 4 shows the comfort range for indoor operative temperatures in comparison with the outdoor temperatures considering the EPW file of São Carlos.
The quantification of discomfort of the operative temperature in the building was carried out using the degree-hours method (DH). This method is used to classify the thermal performance of residential buildings by the Brazilian Energy Labeling methodology RTQ-R [13]. The degree-hour method allows the quantification of degrees out of the thermal comfort range every hour in the period of interest. The quantification of degree-hours is divided into discomfort by heat (upper limit) and discomfort by cold (lower limit). With the assumption of the outdoor temperature as indoor temperature and the comfort model ASHRAE 55-2013, 625 DH by heat and 16,393 by cold, for a total of 17,018 DH of discomfort are found out of the comfort range. This shows the potential of passive optimization; with only few hours of discomfort by heat, comfort can be widely reached with natural ventilation while the hours of discomfort by cold can be lifted into the comfort range by using internal and solar heat gains. In addition, a medium thermal storage mass would help in both periods.

2.2. Assessment of constructions.

At present, Brazil has one mandatory standard of thermal performance of housing: NBR 15575 [14]. This standard offers minimum pre-requisites regarding thermal properties of building components to meet thermal comfort performance in different BZ. Both, construction of external walls and roof of the representative project meet the requirements of thermal transmittance U (W/m²K), thermal capacity CT (kJ/m²K) and solar absorptance (α) according to NBR 15575 (table 1). The solar absorptance for walls was assumed to be 0.33 (“pérola” color) and 0.514 (“amarelo-antigo” color) in roof according to the existing characteristics of SMR and the common paints used in Brazil [15].

| Table 1. Compliance of SMR against minimal requirements by NBR 15575. |
|---------------------------------------------------------------|
| **Thermal Transmittance U (W/m² K)** | **Thermal Capacity (kJ/m² K)** |
| Required | SMR | Compliance | Required | SMR | Compliance |
| Wall ≤ 3.7 | 2.78 | ☒ | ≥ 130 | 209 | ☒ |
| Roof ≤ 2.3 | 2.06 | ☒ | - | 233 | - |

Regarding the wood-based alternatives, all wall systems were considered deficient for the requirement of thermal capacity (kJ/m2K) according to NBR 15575. The highest number was obtained by the system with mineralized wood fiber W2C (see table 2). Low values of thermal capacity mean low thermal mass, reducing the thermal inertia against daily temperature fluctuations. The influence of these values will be investigated and assessed through simulation in section 3.
Table 2. Compliance of wood-based alternatives against minimal requirements of NBR 15575 in BZ 4.

|         | Thermal Transmittance U (W/m² K) | Thermal Capacity (kJ/m² K) |
|---------|----------------------------------|----------------------------|
|         | Required α ≤ 0.6 | WBA | Compliance | Required | WBA | Compliance |
| Wall    |                    |     |            |          |     |            |
| W1      | ≤ 3.7              | 1.43 | ✓          | ≥ 130    | 40.48 | ✓          |
| W2A     | ≤ 3.7              | 0.56 | ✓          | ≥ 130    | 42.25 | ✓          |
| W2B     | ≤ 3.7              | 0.55 | ✓          | ≥ 130    | 47.48 | ✓          |
| W2C     | ≤ 3.7              | 0.76 | ✓          | ≥ 130    | 88.45 | ✓          |
| W3      | ≤ 3.7              | 0.76 | ✓          | ≥ 130    | 73.6  | ✓          |
| Roof    |                    |     |            |          |     |            |
| R1      | ≤ 2.3              | 1.96 | ✓          | -        | 23.98 | -          |
| R2      | ≤ 2.3              | 0.35 | ✓          | -        | 27.53 | -          |

To predict the thermal comfort conditions in a building, the behavior of the construction system should be considered dynamical. The European standard EN ISO 13786 [16] describes the calculation method of the dynamic behavior of constructions. Important results are decrement delay and temperature-amplitude-damping TAD. The decrement delay is the time shift between the amplitudes of external and internal temperature and it is determined by the thermal properties of the material, including density, conductivity, heat capacity and thickness of the construction system. TAD refers to the temperature attenuation of the amplitudes of exterior temperature and internal surface temperature. The external surface of a wall can heat up remarkably under solar radiation. That high temperature is transferred to the interior surface of the wall. If the attenuation of the amplitude is very small, a high amount of the corresponding heat flow will be transferred to the interior and heat up the room. Values for TAD under 15 can be regarded as critical, below 10 as very critical (strong risk of overheating). When TAD is in critical range, the decrement delay plays further an important role. A short decrement delay (less than 6 hours) implies that the heat is transferred already during the day increasing the overheating effect by direct solar heat gains. When the time shift is about 8 to 12 hours, the heat transfer occurs during night hours, with the possibility to ventilate the space with cooler night air (night cooling).

Table 3 shows the TAD and decrement delay values of the wood-based alternatives. Regarding TAD, all wall systems showed a risk of overheating, while system W1 (plywood boards and air cavity) has a strong risk of overheating. The roof construction R2 (roof with insulation) was the only system with a recommended value for TAD. Regarding the decrement delay, all constructions have a short shift time. The range goes from 5 hours for the wall with mineralized wood fiber W2C to less than one hour for the roof system with air cavity R1. This means that heat transfer occurs during the day. These effects will be investigated in section 3.

Table 3. Evaluation of TAD and decrement delay of wood-based alternatives according to EN ISO 13786.

|         | TAD dynamical | Decrement delay (hours) |
|---------|---------------|-------------------------|
|         | Value Assessment | Value Assessment          |
| Wall    |                |                         |
| W1      | 5.51 Very critical, strong risk of overheating | 1.39 Short shift time, heat transfer during day |
| W2A     | 14.37 Critical, contributes to overheating | 1.92 Short shift time, heat transfer during day |
| W2B     | 14.90 Critical, contributes to overheating | 2.46 Short shift time, heat transfer during day |
| W2C     | 13.65 Critical, contributes to overheating | 4.94 Short shift time, heat transfer during day |
| W3      | 12.08 Critical, contributes to overheating | 4.08 Short shift time, heat transfer during day |
| Roof    |                |                         |
| R1      | 4.46 Very critical, strong risk of overheating | 0.90 Short shift time, heat transfer during day |
| R2      | 22.99 Recommended value | 1.81 Short time shift, heat transfer during day |
To summarize, all the wood-based alternatives for walls comply with the limit values for thermal transmittance (U-value) but were considered as deficient for the requirement of thermal capacity according to the mandatory Brazilian standard NBR 15575. Regarding temperature-amplitude-damping, all wall systems showed a risk of overheating. It is important to ensure a minimal quality in thermal insulation (U-value) to keep higher indoor temperatures in cold periods while a minimal quality for dynamic properties of the constructions to avoid quick heat transfer through constructions during hot periods.

3. Transient simulation of thermal comfort: comparison of representative model and wood-based model

3.1. General assumptions
The program adopted in this research is EnergyPlus, version 8.3.0 [17]. Since almost 80% of the building units are oriented on the axis Northwest-Southwest to maximize the number of building units (longest facades towards Northeast and Southwest), these conditions were assumed for the simulation model. The ground, intermediate and top stories were modeled with internal thermal zones per long-stay room (living room/kitchen, bedroom 1 and bedroom 2) since only these three floors will be considered for the analysis (see figure 5). In order to consider the thermal influence of the 2nd and 4th story, these apartments were considered as a single thermal zone with windows and without internal walls. For the analysis of the simulation results, the DH of discomfort per apartment represents the sum of the three long-stay areas based on the adaptive comfort model ASHRAE 55, while the DH of discomfort in the building wing is the sum of the DH of the apartments located in the ground, intermediate and top story on that side of the building unit. A-wing represents the facade facing southwest while B-wing faces northeast.

A shading surface was modeled in parallel to the biggest facades to consider the shading effect of adjacent buildings. The apartment unit has two types of windows - 2 sashes horizontal slide in the living room, kitchen and bedrooms and 4 blades louver window in the bathroom. The windows in bedrooms (largest facade) have an internal aluminum screen in one of the sashes, avoiding direct solar infiltration. This condition was also modeled and considered for the simulation. The glazing type assigned to the model is single glass of 4 mm similar to the existing conditions of SMR. All doors in the three fully-modeled stories were included. As recommended in the evaluation procedure through simulations proposed by NBR 15575 [14], one air change per hour (ACPH) was assumed for the simulation during the day and year. Heat gains from internal loads (e.g., people, lights, and equipment) and schedules followed the recommended values stated on the Brazilian Standard NBR 15575.

3.2. Representative model
As showed in figure 6, the representative model with common construction systems presented a significantly higher level of discomfort by cold (147,884 DH, 97%) than by heat (4,029 DH, 3%). B-wing had slightly more DH of discomfort by heat than A-wing, while A-wing has much more DH of discomfort by cold than B-wing. This is directly related to the orientation and solar exposure of the
building wings; the northeast facade (B-wing) has a day-long sun exposure in winter and half-day incidence during summer. In total, A-wing presents 19% more DH of discomfort than B-wing. This different comfort qualities shows the lack of passive design strategies addressed on the representative project.

The intermediate story showed a better thermal performance compared to the ground and top story. As expected, the top story has a higher DH of discomfort by heat, due to external exposure through the roof and the high transfer of absorbed solar radiation. The ground story has the highest total level of discomfort from the three stories, caused mostly by cold. The apartments on this level have almost no direct solar exposure due to the proximity of adjacent buildings.

According to the simulation results, apartment B501 has the highest discomfort level by heat (512 DH, 7%), while A502 has the highest by cold (8,549 DH, 95%). A502 is the least comfortable apartment with a total 8,955 DH of discomfort. The best thermal conditions are found in B304, located on the third floor of B-wing. This apartment unit showed a total of 3,311 DH of discomfort with 2% produced by heat and 98% by cold. The reduced surface exposed to outdoors and the higher sun exposure of that facade in winter offer these conditions.

Figure 6. Total degree-hours of discomfort in the building per apartment in representative model.

3.3. Wood-based model

All construction systems with roof type R2 resulted in less DH of discomfort by heat and cold than the alternatives with roof type R1 (see figure 7). This represents the positive effect of the addition of an insulation layer to the roof system. The better thermal behavior of R2 was predicted by the TAD calculation of EN ISO 13786.

Compared to the representative model, the wood-based alternatives showed a more even proportion of discomfort by cold and heat. The proportion of discomfort by heat ranges from 28% to 40% in the wood-based models. Due to the climate conditions of São Carlos, it is expected to see discomfort by cold remaining with a bigger portion than the discomfort by heat in all simulated models. All the tested models presented a significantly higher DH of discomfort by heat than the reference outdoor temperature of the weather file EPW, indicating an overheating effect in the apartment units. On the other side, all alternatives have a reduction of more than 50% of DH of discomfort by cold from the outdoor
temperature assumption. The strategy now is to reduce discomfort by heat, since it represents higher discomfort and therefore the need of air conditioning.

Among the three insulation options, mineralized wood fiber W2C showed less total discomfort level, followed by cellulose W2B. The model R1W1 resulted in a very high degree of discomfort by cold and heat, signifying the need of replacing the air gap with another material in external walls and roofs.

After the alternatives with wall system W2C (with mineralized wood fiber), W3 with three air gaps showed a better performance than the others, even better than the systems with cellulose W2B and EPS insulation W2A.

From all the tested wood-based models, R2W2C showed the best performance. This model resulted in 11% less DH of discomfort by cold than the representative model. On the other hand, the discomfort by heat is around 15 times more than the model of the representative project. The combination of these construction systems resulted in 27% more DH of the total discomfort than the representative model. These wood-based constructions behave well in cold periods (better U-values), but the tendency to overheat in hot periods increases. Following NBR 15575, W2C has the highest thermal capacity value (88.45 kJ/m²K) but below the recommendation (130 kJ/m²K) (see table 2). According to EN ISO 13786, the dynamical thermal behavior of the roof construction R2 is good while the wall construction W2C is nearly in the recommended range (13.65, recommended is >=15), thus both constructions behave better than the others and the transfer of heat through the construction is minimized. This shows the potential for improving this model accomplished with the reduction of the DH of discomfort by heat through optimizing the model increasing the thermal storage mass and against the overheating effect.

![Figure 7](image_url)

**Figure 7.** Total number of DH of discomfort for the whole building in representative model and with wood-based constructions.

3.3.1. Optimization of wood-based model. Five other alternatives were simulated based on the fact that R2W2C was the construction system that showed the best performance. All alternatives include the wall system W2C. W2C-1 considers the roof system R2 but replaces the layer of EPS with mineralized wood fiber. W2C-2 presents the same layers of roof system R2 but increases the thickness of the insulation layer of mineralized wood fiber from 10 cm to 15 cm. W2C-3 represents a hybrid construction with a roof system similar to the one used in the representative project. W2C-4 includes a green roof of 10 cm on top of a sandwich wooden panel with mineralized wood fiber as insulation. W2C-5 proposes a wood-based roof system similar to the one in W2C-1 (R2 system with mineralized wood fiber as insulation).

In this alternative, internal floors are made of concrete slabs of 10 cm similar to the one in the representative project. This represents a second hybrid construction.

All alternatives resulted in a lower level of discomfort by cold than the representative building, with the exception of W2C-4 (see figure 8). On the other hand, the discomfort by heat remains significantly high for most of the construction systems, the hybrid model W2C-5 being the one with the lowest. The
construction system with the green roof W2C-4 was the only model with a higher DH of discomfort by heat than if considering the outdoor temperature, indicating a high overheating effect. The increase of 5 cm in the thickness of the insulation layer with mineralized wood fiber (W2C-2) lead to a reduction of 6% of DH of discomfort compared to the roof system with 10 cm of the same material (W2C-1).

When summing the annual DH of discomfort by cold and heat, W2C-5 resulted in a reduction of nearly 50% of the total DH of discomfort of the representative building on a yearly basis. The addition of a concrete slab in the interior floors in W2C-5 represents an increase of the internal thermal mass, hence improving the thermal performance of the building. The model W2C-5 resulted in a higher DH of discomfort by cold (62,539 DH, 88%) than by heat (8,943, 12%) in the sum of the DH in long-stay areas of the apartment units in the ground, intermediate and top story in a year.

![Figure 8. Total number of DH for the whole building in optimized models with wood-based alternatives.](image)

4. Final discussion

The arrangement and the characteristics of the building units in the representative project seem to respond to the maximization of the number of units accommodated in the complex, disregarding the thermal comfort performance in the apartment units. The orientation and the proximity of the units causes high solar exposure in summer and low exposure in winter for many units. As expected, the total discomfort is mainly by cold, with the apartments in lower stories showing a higher discomfort level.

Thermal comfort standards are required to establish limits for the building thermal performance, improve comfort conditions and reduce the energy consumption for heating and air conditioning systems. The present mandatory Brazilian standard NBR 15575 could predict with simplified calculation methods the positive/negative thermal behavior of the building. However, it is important to consider not only external elements but also internal components for the overall thermal performance (e.g. internal floor and internal walls), especially in multi-story buildings. The calculation of TAD and decrement delay in EN ISO 13786 is an alternative for the Brazilian standards to have a better and more detailed prediction of the dynamic behavior of building components. The dynamic behavior of construction has great importance in many climates in Brazil where thermal mass plays an important role as a passive design strategy.

Regarding the thermal performance of wood-based models, insulation of mineralized wood fiber in wood-based constructions performed better than cellulose and EPS. This insulation material showed the highest value of thermal wave shift, as other studies have also pointed out [18]. In addition, this material is produced from wood waste and has low embodied energy and climate change potential compared to other insulation materials on the market such as EPS [19]. Insulation materials with higher density (e.g. 500 kg/m³ for mineralized wood fiber) show a better overall thermal performance due to the thermal storage effect, even when their conductivity is lower than other insulation materials.

The computer simulation showed the existing risk of overheating when considering wood-based components in a building, especially with air cavity. However, with the optimization of these systems
through the careful selection of the insulation material and the substitution of some components by “heavier” materials (such as concrete), the risk is significantly minimized. This study demonstrates, through a computer simulation, that better thermal comfort conditions are reachable with a hybrid wood-based model (wood panels with mineralized wood fiber and concrete floors) compared to the representative type of construction in social housing in Brazil. Hybrid models represent a way to increase the use of wood in buildings, without negatively affecting the overall thermal performance in certain Brazilian climates, as it is the case of São Carlos.

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