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Influence of the Coating System on the Acoustic, Thermal and Luminous Performance of Brazilian Buildings

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Received: 5 August 2020; Accepted: 4 September 2020; Published: 8 September 2020

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Abstract: This work presents an extensive numerical simulation to analyze the influence of the coating layers on the performance of construction systems, in order to make the constructions projects feasible, not only economically but also technically. Through numerical simulations based on a defined reference model, the present work studied the influence of different layers of floor, roof and internal and external wall systems, on the acoustic, thermal, and luminous performance of buildings in Brazil. The results showed the materials and elements with the greatest influence on: lighting performance are the internal finishes of the environment and the type of glass used in the external windows. On thermal performance, all elements of the roofing system and façades, especially an absence of external cladding and the use of thermal blankets on the roof, have greater influence. The acoustic performance of the façade function on the external windows and acoustic performance of the floor system are mainly influenced by the thickness of the structural element and the use of a ceiling and acoustic blanket; acoustic performance of internal walls is affected by typology of the structured element of the wall and thickness.

Keywords: building performance; acoustic performance; thermal performance; luminous performance; coatings; numerical simulations

1. Introduction

The relation between man and construction, especially housing construction, is remote and intertwined with the evolutionary history of humanity and society itself. The establishment of functional requirements for buildings and their parts stems from the obvious premise that buildings, being indispensable to the life and activity of man, must have characteristics that correspond to and meet human needs. In other words, the establishment of functional requirements for buildings is a performance prescription [1].

The word performance is widely used throughout society and has quite broad meaning. It is used for hardware evaluation, professional analysis business and sports, for example. It is common to use performance to compare professionals and equipment; in general, a desirable standard is defined, often informally, for comparison with the performance delivered. A more modern view of performance began to be structured in the 20th century, where studies were proposed by the National Bureau of Sciences (NBS) during the 1920s. In the 1930s and 1940s, the first performance standards were developed and the English expression performance requirements emerged [2].

After the Second World War and the consequent need to build large-scale buildings in the reconstruction movement, especially in Europe, the application of innovative construction technologies and systems at the time caused the incidence of high cases of pathological manifestations, generating high economic and social burdens. Given this scenario, the need for a more careful analysis of the performance of the construction systems used proved to be very relevant. From the end of the 1960s, the USA and some European countries devoted themselves to deepening their studies and striving to solidify the application of the concept of performance to buildings. In the past few years, there has been an increase in public awareness about the effects of the indoor environment on people's comfort and health. Besides the thermal environment, the indoor environment also includes indoor air quality, as well as acoustic and luminous environments [3,4].

For example, related to temperature and relative humidity, the thermal environment affects occupants' sensation and is considered to be the environmental factor most valorized by the occupants. Extensive studies have been conducted on thermal comfort, resulting in many thermal comfort equations. The PMV (Predicted Mean Vote) and PPD (Predicted Percentage Dissatisfied) based on Fanger's comfort equation are widely used in design guides and standards [5,6].

To establish an acceptable indoor environment, all these factors should be considered [7]. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standards 55 and 62 address different environmental factors. More recently, the equivalence of the discomfort caused by different physical qualities was examined. An equivalence of acoustic sensation to thermal sensation for short-term exposure was established. Specifically, a change in temperature of 1 °C had the same effect as a change in noise of 2.6 dB [8]. Physical environmental parameters are all interrelated, and the feeling of comfort is a composite state involving an occupant's sensations of all these factors [8–11].

Published in 1984, ISO 6241 [12] is still a valid and important reference for defining the performance requirements of buildings, and perhaps its main gap in relation to contemporary requirements is sustainability, considering that, at the time, the theme did not have the current relevance. As in the European post-war period (1970s and 1980s), in Brazil, the construction of large-scale buildings induced the use of new techniques and constructive technologies. During this period the productivity was prioritized, without clear technical criteria for evaluating the innovations adopted to enable this productivity. As an example of this process of technological innovations without a more detailed performance analysis, is the cases of the "coffin buildings" built in the Metropolitan Region of Recife.

In 2000, a Study Committee and Working Groups were created with the objective of coordinating the discussion on the performance of buildings in the technical environment, seeking consensus for the development of a Brazilian standard NBR 15575 [13–16], within the scope of ABNT (Brazilian Association of Technical Standards). In Brazil, the popular standard NBR 15575 [13–16] "Housing Buildings—Performance", is under review in order to be published, in 2020, a new version. According to NBR 15575-1 [13], the building performance is the "behavior in use of a building and its systems". This definition makes clear the concept of scope for all housing buildings, regardless of the construction systems, elements and components used, because the object of the standard is the user behavior in the building and its parts. This bias is different from most ABNT technical standards related to civil construction, which focuses on the prescription of methods of sizing and execution of specific components, elements and construction systems. The requirement does not express values, being naturally qualitative.

The main objective of NBR 15575 [13–16] is to establish the requirements and performance criteria applicable to housing buildings as an integrated whole, as well as to be evaluated in insulation for one or more specific systems, represented by each part of the standard. The definition of the performance requirements of NBR 15575 [13–16] represents the user's requirements.

It is important to highlight that Brazil has continental dimensions, with a total area that corresponds to about 80% of the entire territory of Europe. As a result, in addition to climate issues, there is a great diversity of customs and cultures, which forces designers to decide on different finishing solutions for the façades, namely types and sizes of materials, predominant colors, etc.; depending on the region where the building will be constructed. However, when it is governed by the same regulation (NBR 15575 [13–16]) to be used throughout the country, it is very important to know the difference in performance between the various solutions available on the market so that it is possible to ensure, both for the designers and for the users, the expected technical and aesthetic result.

2. Building's Performance and Requirements

2.1. Acoustic Performance of Housing Buildings

Analyzing the standard NBR 15575-1 [13], it is possible to divide the acoustic performance requirement into four groups: (a) Insulation of external walls to air noise; (b) Insulation of internal walls to overhead noise; (c) Insulation of floor systems from overhead noise; and (d) Insulation of floor systems to impact noises. The standard recommends three procedures for acoustic performance evaluation: precision method performed in the laboratory (the result obtained is the weighted sound reduction index, R_w), engineering method carried out in-field (the results obtained are the weighted standardized level difference, $D_{nT,w}$, the standardized level difference measured 2 m away from the façade, $D_{2m,nT,w}$, and the weighted standardized impact sound pressure level, $L'_{nT,w}$) and simplified in-field method (without normative values).

Table 1 presents the criteria for insulation of external walls (façades), according to the surrounding noise class.

Table 1. Minimum values of $D_{2m,nT,w}$, for bedrooms [15].

Noise Class	Housing Location	$D_{2m,nT,w}$ (dB)
I	Housing located far away sources of intense noise	≥20
II	Housing located in areas subject to non-fit noise situations in Class I or III	≥25
III	Housing subject to intense noise from transports and others, since that it complies with the legislation	≥30
For external walls of rooms, kitchens, laundries, and bathrooms, there are no specific requirements. In regions of airports, stadiums, sporting event venues, highways, and railways, there is a need for specific studies.		

Taking into account the subjectivity in the definition of the surrounding noise class and the buildings located near airports, stadiums, highways, railways and other environments in which the standard recommends specific studies for the classification of surrounding noise, Proacústica—Brazilian Association for Acoustic Quality—has launched a Manual with the objective of bringing clearer information on the subject. Among other information, the Proacoustic Manual for noise class of housing buildings [17] establishes an objective criterion for defining the surrounding noise class, based on the equivalent sound pressure level, $L_{Aeq,T}$, incident on the façades, as presented in Table 2.

Table 2. Equivalent sound pressure levels $L_{Aeq,T}$, incidents on the façades of buildings for each noise class [17].

Noise Class	Equivalent Sound Pressure Levels $L_{Aeq,T}$	$D_{2m,nT,w}$ (dB)
I	<60 dB	≥20
II	61–65 dB	≥25
III	66–70 dB	≥30

It is important to note that the surrounding noise is dynamic, and may vary with the urban development of the city, either by the implementation of new roads, traffic changes or mainly by real estate expansion, as in the case of the implementation of housing estates in previously poorly inhabited areas. Regarding the insulation of internal walls, the Brazilian standard establishes criteria for twinning walls, which divide distinct housing units, blind walls that divide housing units and common areas, and set of walls and doors of distinct units separated by the hall, as presented in Table 3.

Table 3. Minimum values of the weighted standardized level difference, $D_{nT,w}$, between environments [15].

Element	$D_{nT,w}$ (dB)
Wall between autonomous housing units (twinning wall), in situations where there is no bedroom environment.	≥40
Wall between autonomous housing units (twinning wall), in case at least one of the environments is dormitory.	≥45
Blind wall of bedrooms between a housing unit and common areas of eventual transit, such as corridors and staircase on the floors.	≥40
Blind wall of rooms and kitchens between a housing unit and common areas of eventual transit, such as corridors and staircase on the floors.	≥30
Blind wall between a housing unit and common areas of permanence of people, leisure activities and sports activities, such as home theatre, gyms, ballroom, games room, bathrooms and locker rooms collective, kitchens and collective laundries.	≥45
Set of walls and doors of distinct units separated by the hall ($D_{nT,w}$ obtained between the units).	≥40

In relation to floor systems, according to the requirements presented above, in addition to air noise insulation, criteria are presented for noise insulation of impacts set out in Tables 4 and 5. It is important to highlight that the criterion of sound insulation refers to the wall system, and all the elements and components that compose it, such as, type of block in the case of masonry, windows, structural element, and layers of coatings, have influence on the final acoustic insulation. That is, it is important to know the contribution of each layer to size the wall system to meet the criteria prescribed in the standard NBR 15575-4 [15].

Table 4. Weighted standardized level difference, $D_{nT,w}$, for floor systems [15].

Element	$D_{nT,w}$ (dB)
Floor system between autonomous housing units, in case at least one of the environments is a bedroom.	≥45
Floor system separating autonomous units from common areas of eventual transit, such as corridors and staircase on the floors, as well as on different floors. Floor system between autonomous housing units, in situations where there is no bedroom.	≥40
Floor system separating autonomous housing units from common areas for collective use, for leisure and sports activities, such as home theatre, gyms, ballroom, games room, bathrooms and collective changing rooms, kitchens and collective laundries.	≥45

Table 5. Weighted standardized impact sound pressure level, $L'_{nT,w}$, for floor systems [15].

Element	$L'_{nT,w}$ (dB)
Floor system separating autonomous housing units positioned on different floors.	≤80
Floor system of public use areas (leisure and sports activities, such as home theatre, gyms, ballroom, games room, bathrooms and collective changing rooms, kitchens and collective laundries) on autonomous housing units.	≤55

Therefore, for systems analysis, it is important to understand the main characteristics of materials that interfere in the acoustic insulation of wall systems. The variation of sound pressure by which the building elements are submitted causes them to vibrate, and this vibration is controlled mainly by the surface mass. Eduardo et al. [11] highlight that the mass of the material influences the efficiency of the acoustic insulation of the elements; however, the importance of the mass depends on the sound frequency, since for low frequency sounds, the mass increase is less efficient than for high frequency sounds (mass law). However, it does not have satisfactory application for noise generated by impacts, which are transmitted mainly by the vibration of the elements of the wall system itself, as illustrated in Figure 1.

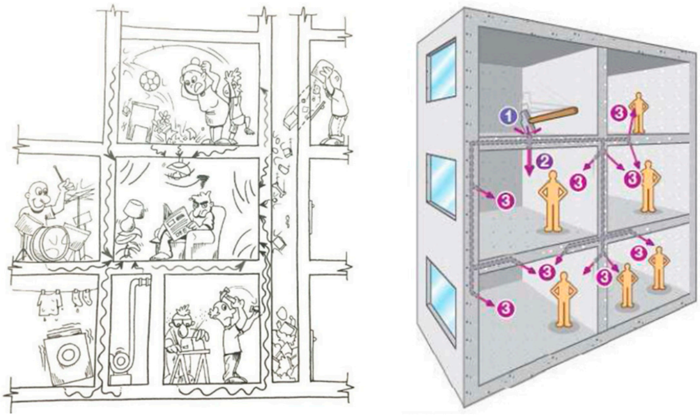

Figure 1. Illustrations of transmission of noise generated by impacts [18]. Legend: 1-Impact noise; 2-direct sound transmission and 3-indirect sound transmission.

2.2. *Thermal Performance of Housing Buildings*

NBR 15575-1 [13] establishes the thermal performance requirements, considering the Brazilian bioclimatic zone defined in NBR 15220-3 [19] and presented in Figure 2. NBR 15575-1 [13] recommends three procedures for thermal performance evaluation: measurement method, simplified method and numerical simulation method. The measurement method is based on the in-field temperature measurements in real-scale buildings. The difficulty of measurement on a day that is representative of a typical project day, winter or summer, brings a great uncertainty in the measurement, and this method is only informative, that is, it has no normative value, evidence nor proof of performance, and does not overlap with other methods: simplified nor numerical.

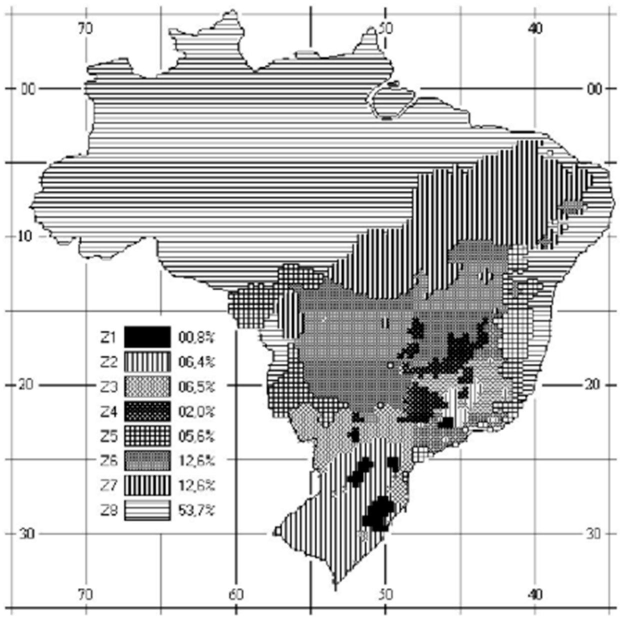

Figure 2. Brazilian climatic zones given by Reference [13].

The simplified method is based on calculating the thermal properties described in NBR 15220-2 [20], more specifically transmittance and thermal capacity, and aims at the analysis of the components and elements of the building (external walls and roofs), according to Table 6. Despite being a practical and relatively simple method of evaluating thermal performance, the simplified method in some situations presents results incompatible with reality, as in the case of external walls with large glazed areas. Simplified methods, while providing a quick tool for evaluating building performance, can compromise the process of analysis of the building. If the building does not meet the requirements established by the simplified method or when the person responsible for the analysis considers that this method is inadequate for analysis, it is evaluated by the numerical simulation method. In this method, it is verified the fulfilment of the requirements and criteria established in NBR 15575-1 [13]. This standard recommends the use of the EnergyPlus program [21,22]. Other simulation programs can be used, provided that they allow the determination of the thermal behavior of buildings under dynamic conditions of exposure to climate, are able to reproduce the effects of thermal inertia, and are validated by ASHRAE Standard 140 [23].

Table 6. Criteria for the simplified procedure.

External Wall Systems			**Roofing System**				
Thermal transmittance, *U* (W/m^2.K)							
Zones 1 and 2	**Zones 3–8**		**Zones 1 and 2**	**Zones 3–6**		**Zones 7 and 8**	
$U \leq 2.5$	$\alpha^{a} \leq 0.6$	$\alpha^{a} \geq 0.6$	$U \leq 2.3$	$\alpha^{a} \leq 0.6$	$\alpha^{a} \geq 0.6$	$\alpha^{a} \leq 0.6$	$\alpha^{a} \geq 0.6$
	$U \leq 3.7$	$U \geq 2.5$		$U \leq 2.3$	$U \leq 1.5$	$U \leq 2.3$FT	$U \leq 1.5$FT
Thermal capacity, *C* (kJ/m^2.K)							
Zones 1–7	**Zone 8**						
$C \geq 130$	No requirements						

[a] α is the Solar radiation absorptivity from the outer surface of the wall. The transmittance correction factor (FT) is established by Reference [13].

The numerical simulation method recommended in NBR 15575-1 [13] is based on the analysis of air temperatures inside the occupy living areas, and, for summer conditions, the maximum internal temperature cannot be higher than the maximum external temperature, as shown in Table 6, considering a typical summer day. For winter conditions, the minimum internal temperature cannot be lower than the minimum external temperature plus 3 °C, as shown in Table 7, considering a typical winter day.

Table 7. Minimum criterion simulation for summer and winter conditions [13].

Summer	**Winter**	
Zones 1–8	**Bioclimatic Zones 1–5**	**Bioclimatic Zones 6–8**
$T_{i,máx} \leq T_{e,máx}$	$T_{i,mín} \geq (T_{e,mín} + 3\ °C)$	No criterium

$\mathbf{T_{i,máx}}$ is the maximum daily air temperature value inside the building (°C); $\mathbf{T_{i,min}}$ is the minimum daily air temperature value inside the building (°C); $\mathbf{T_{e,máx}}$ is the maximum daily value of the air temperature outside the building (°C); and $\mathbf{T_{e,min}}$ is the minimum daily value of the air temperature outside the building (°C).

2.3. Luminous Performance of Housing Buildings

Built environments (internal and external) are illuminated to allow the development of visual tasks, as visual comfort is an important factor to be considered [24]. Among the many elements in the indoor environment, lighting seems to have the greatest impact on the human body. Several studies demonstrate that light has visual and non-visual influences on people. Among different lighting sources, it seems that sunlight is the most crucial and cannot be easily replaced by electric light because of its dynamic quality, as well as spectral characteristics. All these factors can be considered key aspects to optimize academic performance and professional performance [25]. A study conducted in two offices [26] concludes that different lighting conditions, particularly the availability of natural light, can be an indicator of satisfaction in the work environment.

NBR 15575-1 [13] not only establishes the two measurements criteria, numerical simulation method, and in-field measurement method but also recommends the requirements for natural and artificial lighting performance (see Table 8), establishing that:

- During the day, the housing building facilities of the rooms, dormitories, pantry/kitchens, and service areas must receive convenient natural lighting, coming from the outside or indirectly, through adjacent enclosures.
- For the night time, the artificial lighting system must provide satisfactory internal conditions for enclosure occupancy and circulation in environments with comfort and safety.

Table 8. Illuminance levels for natural lighting and daylight factor for different housing environments.

Building Division	Illuminance (lux) for Minimum Performance Level M	
	Illuminance Levels for Natural Lighting	Daylight Factor
Kitchen; Bedroom; Cup/kitchen; Service area	≥60	≥0.50%
Bathroom; Corridor or internal staircase; Common use corridor in flats; Common staircase in flats; Garages/parking lots (other environments)	Not required	

NBR 15575-1 [13] establishes that the numerical simulations should be performed in the morning (9:30) and afternoon (15:30), respectively, for 23 April and 23 October, and the evaluations should be carried out using the algorithm presented in NBR 15215-3 [14].

3. Methodology

3.1. Reference Model

The methodology adopted in this work initially consisted of the definition of a reference model for the numerical simulations of acoustic, thermal, and luminous performance.

In order to analyze the influence of the coating systems on the final performance and allowing a comparative evaluation, a reference model environment was adopted, with typical dimensions of a room with the following internal dimensions: width equal to 2.60 m; length equal to 3.20 m; and ceiling height equal to 2.60 m (see Figure 3). For the reference model used, with an area of 8.32 m^2, is a typical bedroom of residential buildings of economic standard. The reference model used in the study did not consider the existence of vegetation or buildings in the surroundings, although the influence of shading is known and relevant in the performance of the actual building. Corroborating this statement, Chan [27] indicates that the effect caused by adjacent apartments also reduces the gain of solar heat in cold season, resulting in an increased need for energy for heating. It was considered in the façade of the model the use of sliding windows with two movable sheets with dimensions 1.20 m × 1.20 m, typical of housing buildings of economic standard.

Building Components

Masonry of ceramic blocks of 8 holes horizontally (9 cm × 19 cm × 19 cm), internally coated with gypsum paste (thickness of 1 cm) and light color paint (acrylic pigment) and external coated with cementitious mortar (thickness of 3 cm) and light colored ceramic board were considered in the reference model. The windows present a typology of running with two movable sheets, with sound reduction index of 15 dB (R_w = 15 dB) and colorless float glass of 4 mm (see the first line of Table 9).

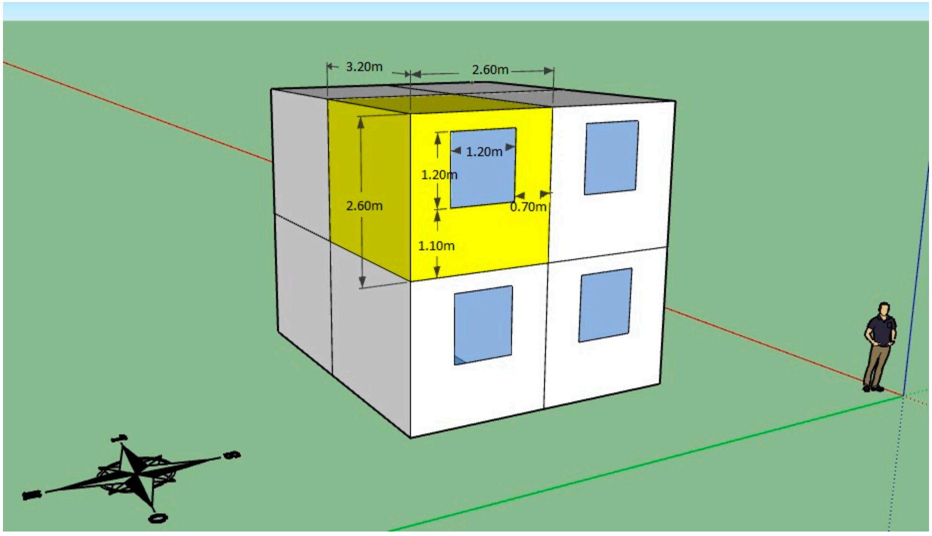

Figure 3. Reference model used in numerical simulations.

Table 9. External wall systems (EWS) considered in numerical simulations.

EWS	Internal Coating		Wall	External Coating		Window
1	PAINTα0.3	GP1	MCB9	MORT3	CERα0.3	WIND15Fg0.85
2	PAINTα0.5	GP1	MCB9	MORT3	CERα0.3	WIND15Fg0.85
3	PAINTα0.7	GP1	MCB9	MORT3	CERα0.3	WIND15Fg0.85
4	PAINTα0.3	GP3	MCB9	MORT3	CERα0.3	WIND15Fg0.85
5	PAINTα0.3	MORT2	MCB9	MORT3	CERα0.3	WIND15Fg0.85
6	PAINTα0.3	MORT4	MCB9	MORT3	CERα0.3	WIND15Fg0.85
7	PAINTα0.3	MORT6	MCB9	MORT3	CERα0.3	WIND15Fg0.85
8	PAINTα0.3	GP1	MCB14	MORT3	CERα0.3	WIND15Fg0.85
9	PAINTα0.3	GP1	BCO14	MORT3	CERα0.3	WIND15Fg0.85
10	PAINTα0.3	GP1	CW10	MORT3	CERα0.3	WIND15Fg0.85
11	PAINTα0.3	GP1	MCB9	MORT5	CERα0.3	WIND15Fg0.85
12	PAINTα0.3	GP1	MCB9	MORT7	CERα0.3	WIND15Fg0.85
13	PAINTα0.3	GP1	MCB9	MORT3	CERα0.5	WIND15Fg0.85
14	PAINTα0.3	GP1	MCB9	MORT3	CERα0.7	WIND15Fg0.85
15	PAINTα0.3	GP1	MCB9	MORT3	TEXα0.3	WIND15Fg0.85
16	PAINTα0.3	GP1	MCB9	MORT3	TEXα0.5	WIND15Fg0.85
17	PAINTα0.3	GP1	MCB9	MORT3	TEXα0.7	WIND15Fg0.85
18	PAINTα0.3	GP1	MCB9	MORT3	CERα0.3	WIND19Fg0.66
19	PAINTα0.3	GP1	MCB9	MORT3	CERα0.3	WIND23Fg0.52

PAINTα0.3|PAINTα0.5|PAINTα0.7: Painting with light color ($\alpha = 0.3$), medium ($\alpha = 0.5$) and dark ($\alpha = 0.7$). GP1|GP3: Gypsum plaster with thicknesses of 1 cm and 3 cm. MORT2|MORT3|MORT4 | MORT5|MORT6 | MORT7: Mortar with thicknesses from 2 cm to 7 cm. MCB9: Masonry of 8-hole ceramic blocks horizontally 9 cm × 19 cm × 19 cm; MCB14: Masonry of ceramic blocks with vertical hole 14 cm × 19 cm × 39 cm; BCO14: Concrete block masonry with vertical hole 14 cm × 19 cm × 39 cm; CW10: Concrete wall with 10 cm thick. CERα0.3|CERα0.5|CERα0.7: Ceramic boards with light, medium and dark color. TEXα0.3|TEXα0.5|TEXα0.7: Acrylic texture with light, medium, and dark color. WIND15Fg0.85: Window with R_w = 15 dB and colorless Float glass 4 mm (Solar Factor = 0.85). WIND19Fg0.66: Window with R_w = 19 dB and green Float glass 4 mm (Solar Factor = 0.66). WIND23Fg0.52: Window with R_w = 23 dB and grey laminated glass 6 mm (Solar Factor = 0.52).

In addition to the external wall system defined for the reference model (line 1), the following variations present in Table 9, and marked in yellow, were adopted for each numerical simulation. In each simulation, only one parameter was changed, related to the reference model, in order to analyze and quantify the influence of this parameter.

As shown in Table 9, the paint of the internal coating was changed with different colors (α = 0.5 and α = 0.7) and materials (gypsum plaster with thicknesses of 3 cm and mortar with thickness between 2 and 6). The structural material was changed from ceramic blocks of 8 holes horizontally (MCB9) to masonry of ceramic blocks with vertical hole 14 cm × 19 cm × 39 cm or concrete block masonry with vertical hole 14 cm × 19 cm × 39 cm or concrete wall 10 cm thick. The windows were upgraded with R_w =19 dB and green Float glass 4 mm (Solar Factor = 0.66) or R_w = 23 dB and grey laminated glass 6 mm (Solar Factor = 0.52).

For the internal vertical wall system of the reference model, masonry of 8-hole ceramic blocks was considered horizontal 9 cm × 19 cm × 19 cm coated with gypsum paste (thickness = 1 cm) and light color paint on both sides. In addition to the internal wall system defined for the reference model (line 1 of Table 10), the following variations present in Table 10, and marked in yellow, were adopted. As described in Table 10, the variations were made in the coatings and in the material used for the internal walls.

Table 10. Internal wall systems (IWS) considered in numerical simulations.

IWS	Coating 1		Wall	Coating 2	
1	PAINTα0.3	GP1	MCB9	GP1	PAINTα0.3
2	PAINTα0.5	GP1	MCB9	GP1	PAINTα0.5
3	PAINTα0.7	GP1	MCB9	GP1	PAINTα0.7
4	PAINTα0.3	GP3	MCB9	GP3	PAINTα0.3
5	PAINTα0.3	MORT2	MCB9	MORT2	PAINTα0.3
6	PAINTα0.3	MORT4	MCB9	MORT4	PAINTα0.3
7	PAINTα0.3	MORT6	MCB9	MORT6	PAINTα0.3
8	PAINTα0.3	GP1	MCB14	GP1	PAINTα0.3
9	PAINTα0.3	GP1	BCO14	GP1	PAINTα0.3
10	PAINTα0.3	GP1	CW10	GP1	PAINTα0.3

PAINTα0.3|PAINTα0.5|PAINTα0.7: Painting with light color (α = 0.3), medium (α = 0.5) and dark (α = 0.7). GP1|GP3: Gypsum plaster with thicknesses of 1 cm and 3 cm. MORT2|MORT4|MORT6: Mortar with thicknesses of 2 cm, 4 cm, and 6 cm. MCB9: Masonry of 8-hole ceramic blocks horizontally 9 cm × 19 cm × 19 cm. MCB14: Masonry of ceramic blocks with vertical hole 14 cm × 19 cm × 39 cm. BCO14: Concrete block masonry with vertical hole 14 cm × 19 cm × 39 cm. CW10: Concrete wall 10 cm thick.

Related to the floor system, of the reference model (line 1), it was considered concrete slab with 7 cm thickness, plasterboard lining with thickness 2 cm and a distance to the concrete slab of 20 cm, without mineral wool or acoustic blanket, cemented mortar floor with 3 cm thickness, and coating with light colored ceramic boards. Table 11 presents the different variations analyzed related to the floor system used in the reference model (marked in yellow). It was analyzed and quantify the influence of mineral wool, different thicknesses of the floor structure and sub-floor, the use of acoustic blanket with different ΔLw and coatings with different colors (α = 0.5 and α = 0.7).

Finally, for the roofing system, of the reference model, it was considered concrete slab with 7 cm thickness, plasterboard lining with thickness 2 cm, light color paint and distance to the concrete slab equal to 20 cm, without mineral wool or thermal blanket, a waterproofing with asphalt blanket with thickness 4 mm, mechanical protection with cementitious mortar of 5 cm thickness, and coating with light color paint. Table 12 presents the different variations analyzed related to the roof system used in the reference model (line 1 of Table 12). It was analyzed and quantified the influence of different colors on plasterboard lining, the use of mineral wool with different thicknesses, different thicknesses on the roof structure, thermal blankets, etc.

Table 11. Floor systems (FS) considered in numerical simulations.

FS	Lining		Structure	Sub-Floor		Coating
1	PL20	W/MW	CS7	W/AB	MORT3	CERα0.3
2	W/PL	W/MW	CS7	W/AB	MORT3	CERα0.3
3	PL20	MW5	CS7	W/AB	MORT3	CERα0.3
4	PL20	W/MW	CS10	W/AB	MORT3	CERα0.3
5	PL20	W/MW	CS13	W/AB	MORT3	CERα0.3
6	PL20	W/MW	CS16	W/AB	MORT3	CERα0.3
7	PL20	W/MW	CS7	ABΔ14	MORT3	CERα0.3
8	PL20	W/MW	CS7	ABΔ29	MORT3	CERα0.3
9	PL20	W/MW	CS7	W/AB	MORT5	CERα0.3
10	PL20	W/MW	CS7	W/AB	MORT7	CERα0.3
11	PL20	W/MW	CS7	W/AB	MORT3	CERα0.5
12	PL20	W/MW	CS7	W/AB	MORT3	CERα0.7

PL20: Plasterboard lining covering with distance of 20 cm for the slab concrete. W/PL: Without plasterboard lining. W/MW: No mineral wool; MW5: Mineral wool with a thicknesses of 5 cm on the lining. CS7|CS10|CS13|CS16: Concrete slab with thicknesses 7 cm, 10 cm, 13 cm, and 16 cm. W/AB: No acoustic blanket; ABΔ14: Acoustic blanket with ΔLw of 14 dB; ABΔ29: Acoustic blanket with ΔLw of 29 dB. MORT3|MORT5|MORT7: Cement mortar with thicknesses of 3 cm, 5 cm, and 7 cm. CERα0.3|CERα0.5|CERα0.7: Ceramic boards with light (α = 0.3), medium (α = 0.5), and dark color (α = 0.7).

Table 12. Roofing systems (RS) for numerical simulations.

RS	Lining		Structure	Sub-Roof		Coating
1	PL20α0.3	W/MW	CS7	W/TB	IMP0.4 + MORT5	PAINTα0.3
2	PL20α0.5	W/MW	CS7	W/TB	IMP0.4 + MORT5	PAINTα0.3
3	PL20α0.7	W/MW	CS7	W/TB	IMP0.4 + MORT5	PAINTα0.3
4	W/PL	W/MW	CS7	W/TB	IMP0.4 + MORT5	PAINTα0.3
5	PL20α0.3	MW5	CS7	W/TB	IMP0.4 + MORT5	PAINTα0.3
6	PL20α0.3	W/MW	CS10	W/TB	IMP0.4 + MORT5	PAINTα0.3
7	PL20α0.3	W/MW	CS13	W/TB	IMP0.4 + MORT5	PAINTα0.3
8	PL20α0.3	W/MW	CS16	W/TB	IMP0.4 + MORT5	PAINTα0.3
9	PL20α0.3	W/MW	CS7	XPS2	IMP0.4 + MORT5	PAINTα0.3
10	PL20α0.3	W/MW	CS7	EPS4	IMP0.4 + MORT5	PAINTα0.3
11	PL20α0.3	W/MW	CS7	W/TB	FCT	PAINTα0.3
12	PL20α0.3	W/MW	CS7	W/TB	IMP0.4 + MORT5	PAINTα0.5
13	PL20α0.3	W/MW	CS7	W/TB	IMP0.4 + MORT5	PAINTα0.7

PL20α0.3: Plasterboard lining with light color paint (α = 0.3) and distance of 20 cm to the concrete slab; PL20α0.5: Plasterboard with medium color (α = 0.5); PL20α0.7: Plasterboard with dark color paint (α = 0.7) W/PL: Without plasterboard lining; W/MW: No mineral wool; MW5: Mineral wool thickness 5 cm. CS7|CS10|CS13|CS16: Concrete slab with thicknesses 7 cm, 10 cm, 13 cm and 16 cm. W/TB: No thermal blanket; XPS2: Thermal blanket, XPS with 2 cm thick; EPS4: Thermal blanket, EPS 4 cm thick. IMP0.4 + MORT5: Asphalt blanket 0.4 cm thick and mechanical mortar protection 5 cm. FCT: Roof with fiber cement tiles and tube larger than 5 cm. PAINTα0.3|PAINTα0.5|PAINTα0.7: Painting with light color (α = 0.3), medium (α = 0.5), and dark (α = 0.7).

It should be noted that all the materials used as reference model are the most used in housing buildings of economic standard, of Recife.

3.2. Adopted Method for the Study of Acoustic Performance

For acoustic performance analysis through numerical simulation, two specific software's were used: *Insul* [28], used to predict the sound reduction index (Rw) of the opaque elements, simulating the characterization by the precision method, laboratory assay, as recommended by the precision method of NBR 15575-3 [14] and NBR 15575-4 [15]; and the SONarchitect ISO Professional, used to verify the acoustic insulation of the walls in the field, following the parameters of international standards ISO 12354-1 [29], ISO 12354-2 [30], ISO 12354-3 [31], simulating field trials by the engineering method, recommended in NBR 15575-3 [14], NBR 15575-4 [15], and NBR 15575-5 [8]. A study developed by Remígio et al. [32] showed a good agreement between the numerical simulations performed with SONarchitect and the in-field tests.

In the present study, to create the elements in *Insul*, laboratory tested systems were used as reference with results made available by the Guide to meet the performance standard. The walls and their sound reduction index (Rw) results used as initial reference are presented in Tables 13 and 14.

Table 13. Indicative values of weighted sound reduction index for some wall systems.

Type of Wall	Block/Brick Width	Coating	Approx. Mass	R_w (dB)
Concrete hollow blocks	9 cm	Mortar with 1.5 cm on each face	180 kg/m^2	41
	11.5 cm		210 kg/m^2	42
	14 cm		230 kg/m^2	45
Ceramic hollow blocks	9 cm	Mortar with 1.5 cm on each face	120 kg/m^2	38
	11.5 cm		150 kg/m^2	40
	14 cm		180 kg/m^2	42
Solid bricks of baked clay	11 cm	Mortar with 2.0 cm on each face	260 kg/m^2	45
	15 cm		320 kg/m^2	47
	11 cm + 11 cm *		450 kg/m^2	52
Walls of reinforced concrete	5 cm	No coating	120 kg/m^2	38
	10 cm		240 kg/m^2	45
	12 cm		290 kg/m^2	47
Drywall	2 boards + glass wool	No coating	22 kg/m^2	41
	4 boards		44 kg/m^2	45
	4 boards + glass wool		46 kg/m^2	49

* Double wall 11 cm + 11 cm, with 4 cm internal space filled with rock wool blanket of 70 kg/m^3.

Table 14. Indicative values of weighted standardized impact sound pressure index, $L'_{nT,w}$.

Type of Product Used in Floating Floor and Concrete Slab Results without Any Acoustic Treatment	Impact Sound Pressure Index (dB)
Concrete slab thickness with 10 cm, without resilient blanket and without sub-floor	82
Concrete slab thickness with 15 cm, without resilient blanket and without sub-floor	71
Blanket thickness 10 mm with synthetic rubber and 88% recycled material, without sub-floor	58
5 mm thick recycled rubber blanket (800 kg/m^3)—no flooring	58
Rubber blanket recycled thickness 3 mm (600 kg/m^3), plus 5 cm sub-floor	64
Synthetic wool blanket +sub-floor 5 cm	57
Polypropylene blanket with 10 mm + sub-floor 5 cm	52
Polypropylene blanket with 5 mm + sub-floor 5 cm	60

The material properties considered as input data in *Insul* are presented in Table 15. The sound reduction indexes obtained at *Insul* and used in numerical simulation are presented in Table 16 for internal walls and floor systems, respectively.

Table 15. Properties of materials used for modeling in *Insul* [28]/Engineering noise control—Theory and Practice [33].

Material	Density (kg/m^3)	Modulus of Elasticity (GPa)	Damping
Gypsum	1100	30	0.003
Mortar	1600	30	0.003
Concrete	2400	40	0.006
Ceramic block	616	10	0.011
Concrete block	896	40	0.001
Ceramic board	1600	4.68	4.68
Gypsum board	900	30	30
Glass wool	22	-	-

Table 16. Sound reduction indexes (R_w) and sound pressure level of weighted standard impact of floor systems and internal wall systems used.

IWS	R_w	FS	R_w	$L'_{nT,w}$
IWS1	36	FS1	59	70
IWS4	39	FS2	50	81
IWS5	39	FS3	61	67
IWS6	43	FS4	61	68
IWS7	47	FS5	62	67
IWS8	40	FS6	63	64
IWS9	44	FS7	59	58
IWS10	46	FS8	59	43
		FS9	60	69
		FS10	61	69

3.3. Adopted Method for the Study of Luminous Performance

For the analysis of luminous performance through numerical simulation, the DIAlux Evo 8.0 software was used. DIAlux Evo 8.0 is a free software that allows the import of the floor plan into DXF file, facilitating the modeling process.

In the numerical simulations, it was considered days with average cloudiness (cloud index 50%), artificial lighting deactivated and without the presence of opaque obstructions (windows and curtains open, internal doors open, without clothes extended on the clotheslines, etc.).

The illumination levels were obtained in the center of the environment at a height of 0.75 m above the floor level, for 23 April at 9:30 a.m. and 23 October at 3:30 p.m., following the recommendation of NBR 15575-1 [13]. For the reference model and each variation of the sealing systems, illumination levels were measured for the two dates and times presented.

It is noteworthy that in the computational simulation were not considered any shading generated by the surroundings. The numerical properties presented in Tables 17 and 18 were used for coatings and glass, respectively, considered in the computational simulations.

Table 17. Thermal property of translucent materials (glasses) used in the modeling and numerical simulation of thermal performance.

Glass	Tsol	Rsol1	Rsol2	Tvis	Rvis1	Rvis2	Emis1	Emis2
Colorless Float with 4 mm (SF = 0.85)	0.83	0.08	0.08	0.89	0.08	0.08	0.89	0.89
Green Float with 4 mm (SF = 0.66)	0.58	0.06	0.06	0.81	0.07	0.07	0.89	0.89
Grey laminate with 6 mm (SF = 0.52)	0.38	0.05	0.05	0.43	0.05	0.05	0.89	0.89

Tsol: Solar transmittance (normal incidence); Rsol: Solar reflectance (normal incidence) on face 1 and 2; Tvis: Visible transmittance (normal incidence); Rvis: Visible reflectance (normal incidence) on face 1 and 2; Emis: Long-wave emissivity on the face 1 and 2.

Table 18. Reflectance values used in numerical simulations.

Surfaces	Reflectance Bands NBR ISO/CIE 8995-1 (2013e)	Reflectance Used in Simulations		
		Dark Color	Medium Color	Light Color
Ceiling	0.6 to 0.9	0.6	0.75	0.9
Walls	0.3 to 0.8	0.3	0.55	0.8
Floor	0.1 to 0.5	0.1	0.3	0.5

In accordance with all defined situations modeled and the illuminance values recorded for each model, the methodology of this research consisted of the comparative analysis of the results in relation to the reference model, on which the results and discussions are presented in Section 4.2.

3.4. Adopted Method for the Study of Thermal Performance

The numerical simulations to analyze the influence of the different variables on thermal performance were performed with Sketchup 8 and EnergyPlusV8 software's. Climatic data from the city of Recife—PE were used, obtained from the website of the Laboratory of Energy Efficiency in Buildings of UFSC—Federal University of Santa Catarina [34].

EnergyPlusV8 used the information about model orientation, reference climatic data of Recife, for 1 year (TRY), ventilation (1 air change per hour), shading of the openings, thermal characteristics of all materials, etc. The thermal properties presented in Tables 18 and 19 were used for opaque and translucent materials, respectively, considered in the numerical simulations. Table 19 presents the materials typically most used in Brazil.

Table 19. Thermal properties of the materials used in thermal performance modeling.

Material	Thermal Conductivity (W/m.K)	Density (kg/m^3)	Specific Heat (J/kg.K)
Gypsum	0.5	1200	840
Mortar	1.15	1600	1000
Concrete	1.75	2400	1000
Ceramic block	0.7	1300	920
Ceramic board	0.9	1600	920
Gypsum board	0.35	900	840
Glass wool	0.45	22	700
XPS	0.035	40	1420
EPS	0.04	35	1420
Fiber cement tile	0.95	1900	840

The temperature data were exported from EnergyPlus8 to spreadsheet files, from which the maximum internal temperatures in the reference environment were specifically analyzed on the typical summer day for the city of Recife, 26 January. The external temperature on this day was 31.4 °C.

In summary, for each variation of the wall systems, a maximum temperature value was obtained for 26 January. These temperatures were analyzed compared to that obtained in the reference model, on which the results and discussions are presented in Section 4.3.

4. Results and Discussion

As defined in the Methodology section, variations in the external and internal wall systems, roofing systems, and floor systems were considered in the different building performance.

4.1. Acoustic Performance Results

The variations observed in the acoustic performance related to the reference model (ID1) are described in Table 20 and marked in green. In each simulation, performed with SONarchitect, the influence of different parameters related to external and internal wall systems and roofing systems on acoustic performance was analyzed.

Table 20. Sound insulation results obtained in numerical simulation considering different external wall systems (EWS), internal wall Systems (IWS), and floor systems (FS).

ID	EWS	$D_{nT,w}$ (ΔD) IWS (dB)	$D_{2m,nT,w}$ (ΔD) (dB)	$D_{nT,w}$ (ΔD) FS (dB)	$L'_{nT,w}$ (dB)
1	EWS1	35	22	49	76
2	EWS4	35 (0)	22 (0)	49 (0)	76 (0)
3	EWS5	35 (0)	22 (0)	49 (0)	76 (0)
4	EWS6	35 (0)	22 (0)	49 (0)	75 (−1)
5	EWS7	35 (0)	22 (0)	49 (0)	75 (−1)
6	EWS8	35 (0)	22 (0)	49 (0)	75 (−1)
7	EWS9	35 (0)	22 (0)	50 (+1)	75 (−1)
8	EWS10	35 (0)	22 (0)	50 (+1)	75 (−1)
9	EWS11	35 (0)	22 (0)	49 (0)	75 (−1)
10	EWS14	35 (0)	22 (0)	49 (0)	75 (−1)
11	EWS17	35 (0)	22 (0)	49 (0)	76 (0)
12	EWS18	35 (0)	26 (+4)	49 (0)	76 (0)
13	EWS19	35 (0)	30 (+8)	49 (0)	76 (0)
	IWS				
14	IWS4	37 (+2)	22 (0)	49 (0)	76 (0)
15	IWS5	37 (+2)	22 (0)	49 (0)	76 (0)
16	IWS6	41 (+6)	22 (0)	49 (0)	76 (0)
17	IWS7	44 (+9)	22 (0)	49 (0)	75 (−1)
18	IWS8	38 (+3)	22 (0)	49 (0)	76 (0)
19	IWS9	42 (+7)	22 (0)	49 (0)	75 (−1)
20	IWS10	43 (+8)	22 (0)	49 (0)	75 (−1)
	FS				
21	FS2	34 (−1)	22 (0)	44 (−5)	85 (+9)
22	FS3	35 (0)	22 (0)	49 (0)	75 (−1)
23	FS4	35 (0)	23 (+1)	50 (+1)	74 (−2)
24	FS5	35 (0)	23 (+1)	52 (+3)	72 (−4)
25	FS6	35 (0)	23 (+1)	54 (+5)	71 (−5)
26	FS7	35 (0)	22 (0)	49 (0)	64 (−12)
27	FS8	35 (0)	22 (0)	49 (0)	49 (−27)
28	FS9	35 (0)	23 (+1)	49 (0)	75 (−1)
29	FS10	35 (0)	23 (+1)	50 (+1)	74 (−2)

The numerical results presented in Table 20 for external walls show:

- The variation in the thickness of the internal and external coatings of the external wall (façade) does not increase the insulation of the external or internal walls (ID2-5, ID9, and ID10). They also do not show a significant increase in the insulation of the floor system or internal walls, with 1 dB being the largest recorded.
- The variations in the structural element of the external wall did not increase the acoustic insulation of the internal or external wall systems. They also do not show a significant increase in the insulation of the floor system or internal walls, with 1 dB being the highest recorded (ID6, ID7, and ID8). This not vulgar result is explained by the Rw of the window that governs the insulation of the external wall. In Brazil, the most used windows presented low values of Rw, and the increase in the sound reduction index (Rw) of the opaque element (wall) is not reflected in a correspondent increase in the insulation of the external wall, if this type of window is maintained (see simulation results ID12 and ID13).
- The variation of the external windows showed a significant increase, reaching an increase of 8 dB in relation to the reference model, in the acoustic insulation of the external walls (ID12 and ID13).

It can be concluded that the variations in the layers of finish, coating, and even of the structural elements of the external wall did not confer a significant increase in the acoustic insulation of the wall systems of the analyzed model.

In contrast, the variation in the sound insulation index of the external windows proved to be the main interference variable in the acoustic insulation of the model's external wall, governing the acoustic performance of the façade.

Making a comparison with the minimum performance criteria recommended in NBR 15575-4 [15], the reference model, with $D_{2m,nT,w}$ = 22 dB, would only meet the noise class I, while considering the variations in the sound reduction indices (R_w) of the windows to 19 dB and 23 dB, the external wall system presented $D_{2m,nT,w}$ = 26dB and $D_{2m,nT,w}$ = 30 dB, according to noise classes II and III, respectively.

In resume, considering the reference model, the main strategy for improving the acoustic insulation of the façade would be to improve the sound reduction index (R_w) of the window.

(a) For Internal wall systems, the results show:

  - The increase in the thickness of the coatings provides an important increase in the acoustic insulation of the internal walls. It is noticed that such increase has a direct correlation with the increase in the thickness of the coatings (ID14 to ID 17).
  - The alteration of the structural element of the internal walls provided a relevant increase in the acoustic insulation to aerial noise of the internal wall system (ID18 and ID20).
  - By comparing the use of MCB14 and BCO14, it can be seen that the increase in the density of the wall element has a direct correlation with the increase in sound insulation, thus, despite the same dimension, the concrete block has greater sound insulation.
  - The changes in the internal wall systems (IWS) have no significant increase in the insulation of the floor system or external or floor seals, with 1 dB being the largest recorded.

It can be concluded that the increase in coatings and the use of structural elements with greater density were presented as the main devices for increasing the acoustic insulation of the internal wall system of the reference model. This verification can be explained by the law of the masses.

Making a comparative analysis in relation to the criteria of the standard NBR 15575-1 [13], it appears that the reference model would not meet the minimum performance level, even if none of the environments is a dormitory ($D_{n,Tw}$ = 40 dB).

Only considering the alteration of the coating for mortar with a thickness of 4 cm on each side or the change of the structuring element for masonry of concrete blocks 14 cm × 19 cm × 39 cm, or solid concrete wall with a thickness of 10 cm, was it found results of insulation to aerial noise greater than 40 dB.

Still considering the minimum performance criteria of NBR 15575-1 [13], none of the results obtained for the reference model would be sufficient to meet the requirement if one of the environments was a bedroom.

In short, we can see that, for the variations considered in the reference model, the main vector for increasing the acoustic insulation of the internal wall system is the increase in the mass of its elements.

In addition, even considering the reference model, it is possible to verify that the vertical internal walls systems conventionally used for construction of residential buildings have low potential to meet the minimum performance level prescribed by the standard NBR 15575-1 [13], especially when one of the environments is a bedroom.

(b) The results presented for Floor Systems shows:

- The removal of the ceiling considered in the reference model caused a significant decrease in the acoustic insulation both to aerial noise and to the impact noise of the floor system and still had a less significant impact, reducing the acoustic insulation of the internal wall system (ID21).
- The use of mineral wool on the plaster lining provided an increase of only 1 dB in the insulation to noise from impacts of the floor system, and no increase in the acoustic insulation to aerial noise, showing itself as an ineffective solution (ID22).
- The increase in the thickness of the structural element of the reference model resulted in a positive increase in acoustic insulation for both aerial and impact noise, with a direct correlation between the increase in thickness and the increase in acoustic insulation (ID23 to ID25).
- The increase in the thickness of the structural element also generated a minor increase in the acoustic insulation of the external wall system (ID23 to ID25).
- The adoption of the acoustic blanket between the structural element and the subfloor in the reference model showed a very high increase in terms of acoustic insulation to noise from impacts of the floor system (ID26 and ID27). However, it did not confer any change in the insulation to aerial noise.
- The results presented in the simulation for the floor system without lining (ID21) and for the floor covering system with ΔLw equal to 29 dB (ID27) are compatible with the results obtained in tests presented in a scientific article by Zuchetto et al. [35].
- The increase in the thickness of the subfloor gave an insignificant increase in relation to the acoustic insulation to impact noise and aerial noise of the floor system (ID28 and ID29).
- The increase in the thickness of the subfloor also gave a minor increase in relation to the acoustic insulation of the external wall system of the reference model (ID28 and ID29).

It can be seen that the changes in the floor system of the reference model did not have a significant impact on the internal or external wall systems.

From the results presented, the use of ceiling and the increase of the thickness of the structural element can be considered as the main strategies for increasing the insulation to aerial noise of the floor system of the reference model.

Still regarding the isolation to aerial noise of the floor system, in all the evaluated variations, except the floor model of the reference model without the ceiling (FS2), they meet the minimum level of performance established in NBR 15575-3 [14], in the situation where one of the environments is a dormitory.

Compliance with the minimum level of performance related to the isolation of impact noise established in the standard NBR 15575-3 [14] is also met for most situations, except for the floor system of the reference model without the ceiling (FS2), considering the required criterion floor system between autonomous units.

However, if we consider the floor system of common area of prolonged use over housing unit, only the system with the use of an acoustic blanket with Weighted Reduction of the Impact Sound Pressure Level (ΔL_w) equal to 29 dB would meet the minimum level recommended in NBR 15575-3 [14].

That is, in the case of long-term common areas, the increase in the thickness of the structural element or the subfloor, or even the use of acoustic blankets with a low reduction in the impact sound pressure, will probably not be enough to guarantee the minimum acoustic performance established in the NBR 15575-3 [14].

In short, considering the study carried out in the reference model, the best interventions for increasing the isolation from aerial noise are the use of ceiling tiles and the increase in the thickness of the structural element. To increase the insulation to impact noise, the best strategy is to use an acoustic blanket followed by increasing the thickness of the structural element.

4.2. Luminous Performance Results

The preliminary simulations the results obtained showed that changes in the thicknesses of the structural elements, walls, and coating layers did not generate impact at the measured illuminance level. This verification can be explained by the fact that opaque systems do not allow the passage of light, and only their surfaces generate interference in luminous performance.

Thus, starting from the verification performed in preliminary analysis that only the finishing layers influence the luminosity of the environment and, consequently, in the luminous performance defined in the Brazilian standard, will be presented in this section only the results of illuminance of the reference model and proposed variations that contemplated changes in finishing materials and translucent materials (glasses). The variations related to the finishing layers of internal and external wall systems, floor systems, and roofing system and the results obtained in the computational simulations considering the reference model and such variations are presented in Table 21.

Table 21. Internal and external wall systems, floor systems, and roofing systems considered in numerical simulations and their results of luminous performance.

ID	EWS			IWS	FS	RS	23/04-09:30		23/10-15:30	
	Internal	External	Window				Illuminance (lux)		Illuminance (lux)	
30	PAINTα0.3	CERα0.3	WINDFg0.85	PAINTα0.3	CERα0.3	PLα0.3	738	Inc.	10938	Inc.
31	PAINTα0.5	CER@0.3	WINDFg0.85	PAINT@0.3	CERα0.3	PLα0.3	703	−5%	10796	−1%
32	PAINTα0.7	CER@0.3	WINDFg0.85	PAINT@0.3	CERα0.3	PLα0.3	629	−15%	10465	−4%
33	PAINTα0.3	CERα0.5	WINDFg0.85	PAINT@0.3	CERα0.3	PLα0.3	730	−1%	10926	0%
34	PAINTα0.3	CERα0.7	WINDFg0.85	PAINT@0.3	CERα0.3	PLα0.3	726	−2%	10919	0%
35	PAINTα0.3	TEXα0.3	WINDFg0.85	PAINT@0.3	CERα0.3	PLα0.3	734	−1%	10932	0%
36	PAINTα0.3	TEXα0.5	WINDFg0.85	PAINT@0.3	CERα0.3	PLα0.3	734	−1%	10932	0%
37	PAINTα0.3	TEXα0.7	WINDFg0.85	PAINT@0.3	CERα0.3	PLα0.3	726	−2%	10919	0%
38	PAINTα0.3	CER@0.3	WINDFg0.66	PAINT@0.3	CERα0.3	PLα0.3	651	−12%	9856	−10%
39	PAINTα0.3	CER@0.3	WINDFg0.52	PAINT@0.3	CERα0.3	PLα0.3	348	−53%	5249	−52%
40	PAINTα0.3	CER@0.3	WINDFg0.85	PAINTα0.5	CERα0.3	PLα0.3	621	−16%	10482	−4%
41	PAINTα0.3	CER@0.3	WINDFg0.85	PAINTα0.7	CERα0.3	PLα0.3	395	−46%	9484	−13%
42	PAINTα0.3	CER@0.3	WINDFg0.85	PAINT@0.3	CERα0.5	PLα0.3	624	−15%	10375	−5%
43	PAINTα0.3	CER@0.3	WINDFg0.85	PAINT@0.3	CERα0.7	PLα0.3	568	−23%	10091	−8%
44	PAINTα0.3	CER@0.3	WINDFg0.85	PAINT@0.3	CERα0.3	PLα0.5	557	−25%	10087	−8%
45	PAINTα0.3	CER@0.3	WINDFg0.85	PAINT@0.3	CERα0.3	PLα0.7	475	−36%	9730	−11%

The numerical results presented in Table 21 shows:

- The color of the internal coating of the external wall system has a significant influence on the luminous performance of the model (ID32 and ID32).

– The color of the façade lining did not present a relevant influence on the luminous performance of the model (ID32 to ID37).
– The types of glasses considered had a very significant influence on the luminous performance of the model (ID38 and ID39).
– The color of the lining of the internal walls showed a very significant influence on the luminous performance of the model (ID401 and ID41).
– The colors of floor and ceiling coatings showed significant influence on the acoustic performance of the model (ID42 to ID45).

4.3. Thermal Performance Results

In order to check the software used, the preliminary simulations results obtained showed, as expected, none or very insignificant variations in temperature, in relation to the reference model, for the different changes suggested in floor system and internal wall systems. These results demonstrate that the external wall systems (façade) and roofing systems govern the thermal performance of the buildings and justify the specific analysis of these systems in the simplified evaluation method recommended by NBR 15575-1 [13].

Table 22 shows the results obtained in the numerical simulations, with SketchUp 8 and EnergyPlusV8, considering the reference model and the different external wall systems (EWS) and roofing systems (RS) analyzed (see Section 3.4). The numerical results presented for External Wall Systems shows:

– The increase in the thickness of the coating layers, both internal and external, showed a direct correlation with the decrease in temperature in the evaluated environment, contributing significantly to the improvement of the thermal performance of the model (ID49–ID52, ID56, and ID57). The changes in the structuring elements of the external walls also resulted in significant changes in temperature inside the environment, and the solid concrete wall presented the best result among the evaluated systems (ID53 to ID55).
– Changes in the color of the external lining of the façades resulted and very significant variations in the temperature values measured in the environments and the darker the temperature were, consequently, worse thermal performance (ID58 to ID62). It can also be observed that models with coating on ceramic boards present temperatures slightly lower than textures with the same color.
– It can also be observed that the lower the Solar Factor of the windows of the external windows of the model, the lower the temperature measured in the environment (ID63 and ID64).

From the results presented, it can be verified that all variations of the external wall system considered in the reference model, except for the color of the internal finish, have significant interference in the final thermal performance.

The study presented by Mendonça et al. [36] allowed visualizing the significance of the elements of external wall in the energy consumption of buildings. This corroborates the results presented in this work, demonstrating a correlation between the thermal and energetic performance of the building. Considering the results obtained in the reference model, it was verified that the main influencers of thermal performance were: the color/absorbance of the finish of the external face of the façade; the thickness of the internal and external coatings of the façade; the typology of the structuring element of the walls; and the solar factor of the glasses.

(a) The results for Roofing Systems shows:

  – The change in the color of the lining, that is, the color of the ceiling, does not significantly interfere with the temperature of the environment (ID65 and ID66).
  – The removal of the plaster lining of the model represented a significant increase in the temperature measured in the environment, representing a loss of thermal performance in the building (ID67).

- The increase in the thickness of the structural element, solid concrete slab, presented a direct correlation with the improvement of thermal performance, resulting in a relatively relevant decrease in ambient temperature (ID69–ID71).
- The use of thermal blanket, either with XPS or EPS, in the roof, even with relatively small thicknesses, proved to be an intervention with significant effect on thermal performance and reduction of ambient temperatures (ID72 and ID73).
- The roof with fiber cement tiles showed a significantly lower thermal performance than the reference model, even considering the air layer between the roof and the structural element (ID74).
- The change in color/absorbedness of the external finishing layer of the roofing system had a very significant impact on the thermal performance of the model, having a direct relationship between the increase in absorbedness and internal temperature (ID75 and ID76).

Considering the results obtained in the reference model, it was verified that the main influencers of thermal performance were: the color/coating of the external face of the roof; the use of a thermal blanket; the use of lining under the structural element; increasing the thickness of the structural element; and the use of mineral wool on the lining.

Table 22. External walls and roofing systems considered in numerical simulations and respective thermal performance results (green shading—negative values of ΔT and orange shading for positive values of ΔT).

ID	EWS	T (ΔT) (°C)	ID	RS	T (ΔT) (°C)
46	EWS1	33.48	46	RS1	33.48
47	EWS2	33.48 (0)	65	RS2	33.50 (+0.02)
48	EWS3	33.48 (0)	66	RS3	33.49 (+0.01)
49	EWS4	33.32 (−0.16)	67	RS4	34.00 (+0.52)
50	EWS5	33.19 (−0.29)	68	RS5	33.21 (−0.26)
51	EWS6	32.92 (−0.56)	69	RS6	33.26 (−0.22)
52	EWS7	32.73 (−0.74)	70	RS7	33.10 (−0.37)
53	EWS8	33.12 (−0.36)	71	RS8	32.99 (−0.48)
54	EWS9	33.26 (−0.22)	72	RS9	32.86 (−0.62)
55	EWS10	32.74 (−0.73)	73	RS10	32.84 (−0.64)
56	EWS11	33.24 (−0.24)	74	RS11	33.98 (+0.50)
57	EWS12	33.06 (−0.41)	75	RS12	34.70 (+1.15)
58	EWS13	34.80 (+1.33)	76	RS13	35.72 (+2.25)
59	EWS14	36.15 (+2.67)			
60	EWS15	33.61 (+0.13)			
61	EWS16	35.00 (+1.52)			
62	EWS17	36.38 (+2.90)			
63	EWS18	33.18 (−0.30)			
64	EWS19	32.96 (−0.52)			

4.4. Resume

Taking as a reference the qualitative rating scale in the level of influence (Increment (i) ≤ ±2 dB—Low, filled white; ±2 dB < i ≤ ±5 dB—Medium, filled yellow and i > ±5 dB—High, filled red) and the results obtained in the acoustic performance simulations presented in Table 20, it is possible to make the classification as shown in Table 23.

For luminous performance and taking as reference the qualitative scale of classification in the level of influence (Increment (i) ≤ ±5%—Low, filled white; ±5% < i ≤ ±20%—Medium, filled yellow and i > ±20%—High, filled red) and the numerical results presented in Table 21, it is possible to present the following classification, as describes in Table 24.

Table 23. Level of influence of the variations adopted in the acoustic performance in relation to the reference model.

System	System Variation	$D_{2m,nT,w}$ (EWS)	$D_{nT,w}$ (IWS)	$L'_{nT,w}$ (Floor)	$D_{nT,w}$ (Floor)
EWS	Internal coating thickness	Low	Low	Low	Low
	Wall structuring element	Low	Low	Low	Low
	External coating thickness	Low	Low	Low	Low
	Thickness of external coating layer	Low	Low	Low	Low
	Type of external coating	Low	Low	Low	Low
	External windows	High	Low	Low	Low
IWS	Coating thickness	Low	High	Low	Low
	Wall structuring element	Low	High	Low	Low
FS	Use of lining	Low	Low	High	High
	Use of mineral wool on the lining	Low	Low	Low	Low
	Structural element thickness (Slab)	Low	Low	Medium	Medium
	Use of acoustic blanket	Low	Low	Low	High
	Sub-floor thickness	Low	Low	Low	Low

Table 24. Influence level of the variations adopted in the luminous performance in relation to the reference model.

System	System Variation	Level of Influence
EWS	Color of inner coating	Medium
	Type and color of external coating	Low
	External windows	High
IWS	Color of inner coating	High
FS	Color of the floor coating	Medium
RS	Ceiling flooring color	High
	External color of the roofing system	Low

Corroborating the result presented in Table 24, the research developed by Husin and Harith [37] concludes that type of glass and window results in a major influence on the performance of natural light in the environment.

Finally, for thermal performance, considering a qualitative scale of classification in the level of influence (Increment (i) ≤ ±0.5 °C—Low, filled white; ±0.5 °C < i ≤ ±1.0 °C—Medium, filled yellow and i > ±1.0 °C—High, filled red) and the numerical results presented in Table 22, it is possible to present the following classification, as described in Table 25.

Table 25. Influence level of the variations adopted in thermal performance in relation to the reference model.

System	System Variation	Level of Influence
EWS	Color of inner coating	Low
	Thickness of the inner coating	Medium
	Wall structuring element	Medium
	Thickness of external coating	Medium
	Type and color of external coating	High
	External windows	Medium
RS	Use of lining	Medium
	Ceiling flooring color	Low
	Use of mineral wool on the lining	Medium
	Structural element thickness (Slab)	Medium
	Use of thermal blanket	High
	Typology of the roofing system	High
	External color of the roofing system	High

5. Conclusions

The Brazilian standard NBR 15575 "Housing Buildings—Performance" is under review in order to be published at the end of 2020, as a new version. In accordance with this, the present work intends to help the Brazilian decision-makers and give an applied and helpful guide for designers.

Considering the responsibility of the designers to correctly specify materials to be used in the new constructions in order to meet the performance levels established in the Brazilian Standard—NBR 15575-1 [13], the study presented a summary of the influence on acoustic, thermal and luminous performance for each variation tested in the reference model, as shown in Tables 23–25.

In summary, considering the reference model, the methodology adopted and the main analyses, the following conclusions were obtained:

(a) Acoustic performance

1. Façades
   - The coating systems have low influence on the acoustic performance of the façade, and external windows are the main element of influence in this requirement.
2. Internal walls
   - Coating systems have a high influence on the acoustic performance of internal walls, being of the same order of magnitude as the influence of the façades. However, the largest increments were obtained with high thicknesses, from 4 cm on each side, which may not be feasible from an executive point of view.
3. Floor systems
   - The use of liners in the floor system has provided an important increase in insulation for both air and impact noise. On the other hand, the use of mineral wool has not been shown to be an efficient solution for sound insulation.
   - The increase in the thickness of the structural layer of the floor system provided an increase in acoustic insulation for both air and impact noise. However, increasing the thickness of the floor proved to be an ineffective solution.

   - The use of resilient acoustic blankets in a floating floor system has proved to be the most efficient solution for increasing insulation to impact noise, although the solution does not present a relevant increase in air noise insulation.

(b) Thermal performance

- Thermal performance is influenced by virtually all elements and components of external wall systems (façades) and roofing system, with the colors of the façade and roofing system, use of thermal blanket, and typology of the roofing system being the main factors of influence.
- Thermal performance is not significantly influenced by the floor system or internal wall system.

(c) Luminous performance

- The main variations that influenced the luminous performance were the external windows and the color of the coatings of the internal walls and ceiling. As more translucent is the glass and lighter the color of the internal walls and ceiling, higher is the level of illuminance in the environment.
- The colors of the external coating and the floor also have an influence on the luminous performance, although with less importance.

In resume, the most important ideas to the scientific community, decision-makers, engineers, and academics can be expressed in "guidelines" to improve the acoustic insulation, to improve thermal performance, and to improve the luminous performance:

- To improve the acoustic insulation of external vertical seals (facades), considering the construction systems studied here, the best strategy is to improve the insulation of the frames, being the optimization obtained mainly by using better components and glasses with larger thicknesses. To increase internal vertical seals or walls between buildings acoustic insulation, it is necessary to use heavier building systems (masses law) or that use the mass-spring-mass law, such as drywall systems or double walls. To increase noise isolation from the floor system impacts, percussion, the most efficient way identified was the use of resilient blankets under the floor. There are several materials available on the market for this purpose, from bituminous products, such as rubbers, polymers, such as expanded polypropylene, to natural material blankets or cork, for example. The most important thing is to evaluate the impact sound loss transmission appropriate to the project.
- To improve thermal performance, several strategies can be used, from the use of external coatings of external walls and coverage with lower absorbedness, in the case of hot climates, to the use of materials of low thermal conductivity in sealing systems, such as EPS, drywall counter-wall with blanket, or coatings with low thermal conductivity. The use of glasses with smaller Solar Factors, more specifically with lower transmittance to solar radiation are also an interesting possibility.
- To improve the luminous performance, the use of internal coatings, especially floors and walls, with greater reflectance to visible radiation and glasses with greater transmittance to visible radiation are the best strategies for optimizing natural lighting.

Author Contributions: All the authors contributed to the development, analysis, writing, and revision of the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by: Base Funding—UIDB/04708/2020 and Programmatic Funding—UIDP/04708/2020 of the CONSTRUCT—Instituto de I&D em Estruturas e Construções—funded by national funds through the FCT/MCTES (PIDDAC) and CNPq, CAPES and FINEP (Brazilian Research Agencies).

Conflicts of Interest: The authors declare no conflict of interest.

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