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PREDICTION OF THE ACOUSTIC INSULATION OF A PREFABRICATED WOODEN-BASED SYSTEM FOR COLLECTIVE BUILDINGS

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ABSTRACT: Using wood, a renewable, carbon sink material with outstanding thermal properties associated with the prefabrication process and its benefits, a construction system for multi-storey multifamily buildings based on prefabricated wooden panels was developed to act as a tool for meeting the national carbon neutrality targets. It will contribute to the promotion of increasingly sustainable cities that optimise the use of materials and rely on highly energy-efficient buildings. This sustainable alternative to conventional construction materials was designed to comply with the Portuguese needs, regulations, and regulatory requirements regarding construction, structural, functional, and logistics demands. As the acoustic behaviour of wooden buildings is a sensitive subject due to the wood's lightweight and poor insulation performance for low-frequency sounds, this work aims to analyse the panels regarding their acoustic behaviour through INSUL software. The predictions showed favourable results for airborne insulation and partially favourable for impact sound insulation.

KEYWORDS: Wooden buildings, Acoustic, INSUL

1 INTRODUCTION

As a growth strategy for a competitive economy, efficient in the use of resources and, consequently, aligned with sustainable development, one of the European Union's priorities is to achieve carbon neutrality by 2050. As a result, Portugal has stipulated a reduction in greenhouse gas (GHG) emissions of between 85-90% [1].

In this context, reviewing the construction sector's conventional models becomes a priority given its impact: 40% of energy demand, 36% of GHG emissions, 40% of raw material consumption, and 33% of waste [2]. Materials processing holds the most significant share of energy consumption and GHG emissions [3], with cement and steel responsible for 4-7% [4] and 5% [5] of CO_2/year global emissions, respectively.

Wood re-emerges as a promising alternative due to its carbon storage capacity and lower embodied energy. Its processing/transport generally emits less carbon than that stored by wood, strengthening the carbon economy through local production. The buildings' operation phase, responsible for 45-80% of their carbon emission [6], benefits from the wood's high insulating capacity: 10 times higher than concrete and 400 than steel [2]. Also, at the end of its life, wood enables reuse to generate new products or energy [7].

Population and urban expansions (230bi m² of new constructions by 2060 [8]) dictate the need for increasingly denser forms and transform cities into opportunities for sustainable development, highlighting the wood sector's potential in offering carbon-neutral solutions for buildings. This modern application of wood was possible through the introduction of Engineered Wood Products, which optimised the timber structural capacity and overcame many of its limitations, reinventing the industry with competitive products to concrete and steel. Withal, the development of CAD/CAM technology, CNC equipment, and integrated design in BIM methodology has raised the degree of precision and quality of wood products that, produced in a factory, have the potential to reduce work times, site costs, noise, pollution, waste, accidents, and deterioration due to moisture exposure [9,10].

However, in the last decades, the diffusion of high-rise timber buildings, mainly in countries with cold climates, has promoted the development of knowledge and the proposal of solutions to this specific scenario, which does not apply to the Portuguese reality. Despite the rich history of using wood on floors and roofs, Portugal did not follow its transition to high performance, so the projects are few and conservative. It represents a missed opportunity for economic, social, and environmental gains, proving fundamental to developing specific knowledge of this typology application in the national context.

To make this typology compatible with the Portuguese context, a construction system for multi-storey buildings using prefabricated panels and 3D modules with a timber

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structure is proposed, designed to meet local needs and act as a tool to fulfil the national objectives of carbon neutrality.

Besides contributing to the reduction of carbon emissions in the production and operation phases of the buildings from the renewable nature and carbon storage potential of the wood itself, it makes use of the prefabrication process that, optimized to its maximum, contributes to the rationalization of the construction, reducing waste and, consequently, the ecological footprint of the system, besides providing healthy interior environments from the precise and controlled production process.

Based on features designed and validated for successful application in the Portuguese context, the aim was to propose a solution with high replication and sustainable impact potential in Portuguese cities, besides promoting scientific enrichment in the use of wood in multi-storey buildings. The construction system was, then, idealized based on the rules and good practices of design for timber structures identified in the literature, considering the supply and consumption patterns of the national market (species, products, and prefabrication technologies of the sector), the conditions and restrictions of production, transport and construction phases, as well as the applicable normative requirements.

Acoustics is an important performance aspect of wood construction and a prerequisite for the acceptance of wood buildings by the construction industry, owners, and consumers.

The acoustic behaviour of wooden buildings, whether for airborne or impact sounds, differs from that observed in heavy constructions, such as those in concrete. It is because the construction weight is a decisive parameter for its acoustic performance, especially for the lower frequency range (generally 20 – 200 Hz). Therefore, wooden constructions are often associated with poor acoustic insulation, suffering significant vibrations and disturbances, especially in this frequency range [11].

In this context, prediction models become indispensable tools in the wooden structures' design, despite the existing methods being more suitable for predicting the acoustic insulation of heavy and homogeneous structures. Moreover, low-frequency results are often associated with prediction difficulties, which makes them even more uncertain.

The alternative of using a test building is common practice, although it is an expensive process and therefore puts wood at a disadvantage compared to other materials. Furthermore, the results obtained through measurements are mostly exclusive to those specific conditions, so they may not be useful for application in non-similar projects. The variations in sound insulation measurements often imply over-qualifying the construction elements through a high safety margin in the design phase to secure the fulfilment of the appropriate requirements [12].

Aiming at developing a system that provides acoustic comfort to the occupants and that is adequate to the regulatory requirements for building performance in Portugal, in this work, the construction system panels, composed of timber-frame walls and CLT panels floors, are evaluated aiming for its acoustic performance validation regarding their airborne and impact sound insulation.

2 THE CONSTRUCTION SYSTEM

The construction system was developed from the identification of design constraints and strategies, which range from the definition of the concept and design assumptions determining the system's applicability to the detailing of the layers, materials, joints, and finishes. Based on the design objectives, the premises of the system were established:

- Use of timber as the sole structural material, except for the foundation and connections associated with the timber elements (that are metallic);
- Definition of the basic structural unit in 2D panels, whether for walls, floors or roofs;
- Suitability for multifamily building structures;
- Compliance with the structural, functional and logistic requirements and conditions imposed by national regulations, valuing safety, durability, comfort and applicability;
- Maximisation of the prefabrication process and off-site operations;
- Use of complementary materials in line with national consumption and technical-financial accessibility standards to facilitate replication and acceptance of the system;
- High potential for adaptation to various projects due to architectural versatility (dimensions, combinations, and modularity) and the possibility of combining different aesthetic solutions;
- Simple, fast, and precise production, transport, assembly, and installation processes.

The development and application of the construction system (besides the definition of the concept that stipulates its essence and purposes) are also subject to predefinitions that typify and specify the panels and confer the ideal design conditions for the fulfilment of the system's structural and functional objectives. Therefore, it is determined that:

- The wall panels resistant to vertical loads are made of light timber-frame structure, except for the core wall panels, which enclose stairwells and lift shafts and which, due to their function as a central core, can be materialised by CLT or mixed panels (CLT + timber-frame) (Figures 1 a-c);
- The floor panels, in order to produce resistant diaphragms in the structure, are made of CLT panels (Figures 1 d-e);
- The foundation must be made of reinforced concrete.

Besides the structural definitions, the functional layers of the system play a decisive role in guaranteeing its adequate performance and have the potential to ensure, for instance, the durability of the construction, one of the topics of greatest distrust regarding the use of wood in buildings.

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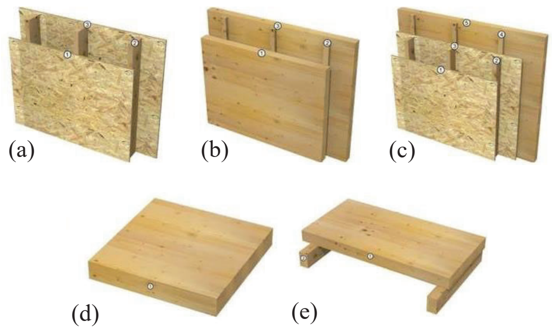

Figure 1: *Design strategies – Structural solutions. (a) Timber-frame; (b) CLT wall panels; (c) Mixed solutions with timber-frame and CLT; (d) CLT floor panels; (e) CLT floor panels with beams*

The critical functions to be performed and the functional layers that directly or indirectly contribute to this end were then identified (Figure 2). It was possible through an in-depth study of the literature, seeking to understand the behaviour of wooden structures and identify the traditional and innovative strategies/design practices specific to this construction typology and the existing solutions available on the market. In the scope of this work, the strategies pertinent to noise control stand out.

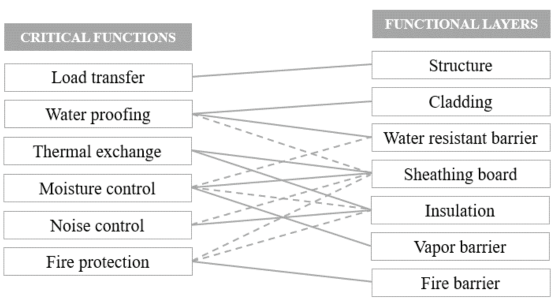

Figure 2: *Critical functions and the correspondent functional layers*

Thus, the noise control strategies adopted are (Figure 3):

- Use of rock wool as a thermal insulation layer and as an acoustic absorbing material to reduce the transmission of airborne sounds;
- Desolidarisation between rigid elements using resilient material layers or flexible connectors to reduce the transmission of impact-generated sounds;
- "Duplication" of elements, such as the construction of suspended ceilings, additional wall panels (such as a service layer, a layer originally conceived for MEP installations that can be filled with insulation to provide thermal and acoustic benefits) and floating floors, which are employed in association with resilient and absorbent materials;
- Double plasterboard internal lining and, for some panels, adoption of acoustic membranes. These solutions increase the system's mass and, consequently, the absorption of sound waves.

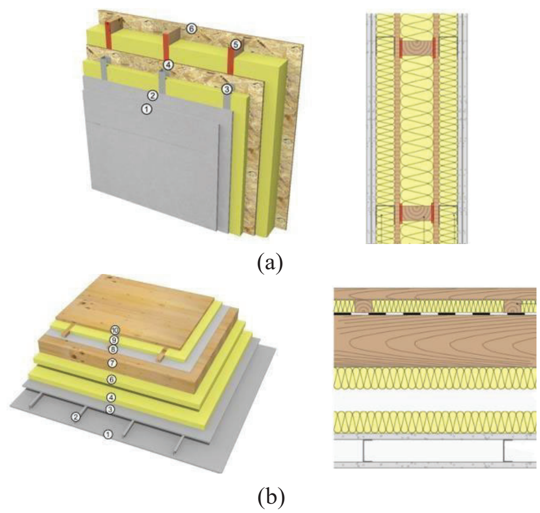

Figure 3: *Design strategies – Noise control. (a) Eg.: Internal walls (Par_Int_Nest_TF); (b) Eg.: Intermediate floors (Pav_Int_CLT)*

The panels developed for the various elements of the buildings, which make up the construction system, are shown in Figure 4. The construction details of each panel can be consulted at [13].

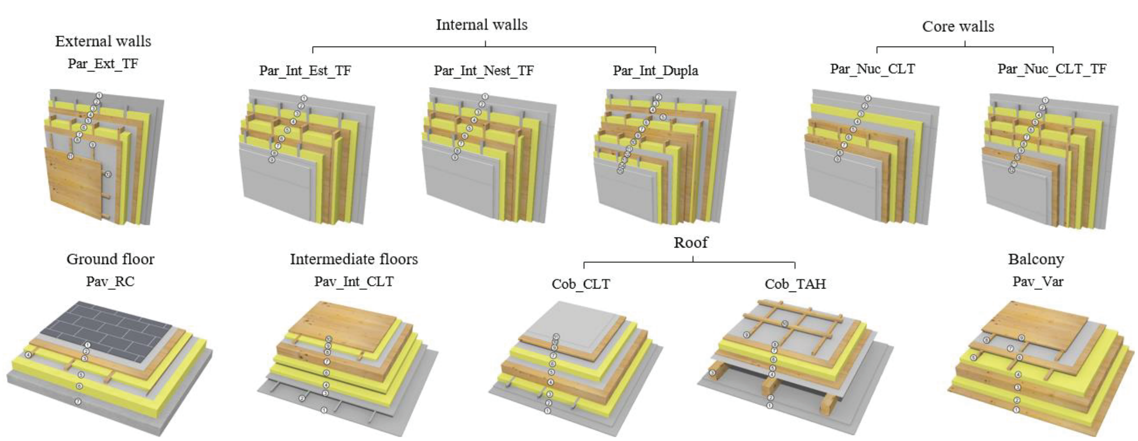

Figure 4: *Overview of the panels' configurations of the construction system*

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3 MATERIALS AND METHODS

The Portuguese Regulation on the Acoustic Requirements for Buildings (RRAE) (Decree-Law 129/2002, of 11 May 2002 [14]) regulates acoustic performance within the building regulations, contributing to improving the quality of the acoustic environment and the well-being and health of the population, in articulation with the Legal System on Environmental Noise. RRAE establishes minimum acoustic performance values for both new and existing buildings subject to reconstruction, extension, or alteration of the various building types, including multifamily buildings.

As the acoustic performance criteria are based on indexes dependent on the function of the element in the building (e.g. external wall, walls or floors between dwellings or dwellings and office spaces), the panels are assessed according to all their possible functions to consider the hypotheses that present the most rigorous criteria.

The determination of the sound reduction index for airborne and impact sounds to be compared with the maximum and minimum values established in the Portuguese Building Acoustic Regulation was obtained from the INSUL software [15], a tool for predicting the acoustic insulation in walls, floors, ceilings, and roofs. It models materials using well-known elastic plate theory, including allowances for thick panel effects, as stated by Ljunggren [16], Rindell [17] and others. More complex partitions are modelled using work by Sharp [18-20], Cremer [21,22] and others.

The software estimates transmission loss (TL) and sound insulation to impact sounds (L_n) in 1/3 octave bands. According to the concept of weighted value (single index) and from the comparison of the sound insulation curves with the reference curves contained in EN ISO 717-1 [23] and EN ISO 717-2 [24], it provides the sound reduction index (R_w) or sound insulation index to impact sounds ($L_{n,w}$).

The comparison between the curve described by the predicted values for TL and L_n, by frequency, with the conventional reference curve is performed by superimposing it so that the sum of the unfavourable deviations is as high as possible without exceeding 32 dB for 1/3 octave bands. Once this adjustment has been achieved, the value of R_w or $L_{n,w}$ corresponds to the value of the y-axis of the reference curve for the 500 Hz frequency.

As with any prediction tool, the INSUL software [15] is not a substitute for *in-situ* measurement. However, comparisons with test data indicate that it reliably predicts R_w values within 3 dB for most constructions [25].

As the objectives of the system design, which comprise the development only of the opaque panels and their suitability for various architectures, this study focuses on strategies detached from the architectural and location conditions. Therefore, for the acoustic analysis, aspects related to marginal transmission, interior acoustics, natural ventilation conditions in the façade or mechanical ventilation causing a break in acoustic insulation, and closure elements (such as doors, windows, and shutter boxes) will not be addressed.

4 RESULTS

The acoustic simulation produced in INSUL software [15] resulted in the sound insulation indexes to airborne and impact sounds (R_w and $L_{n,w}$) presented in Tables 1 and 2 for each of the construction elements developed. Tables 1 and 2 also present the minimum values for airborne sounds and the maximum values for impact sounds that each element must comply with, according to the RRAE. To specify these values, the supposed locations and functions that a given building element could assume in a building were considered, requiring the appropriate performance foreseen in the RRAE in terms of acoustic insulation.

It should be noted that the values obtained for the external walls through the simulation in the INSUL software correspond to panels without windows, while the values defined in the RRAE correspond to a wall with windows. For all simulations, a fixed spacing between laths and studs of 300 mm was considered, although the system accepts spacings of 300 mm up to 600 mm because this represents the worst case since it increases the points of support between the different panels of the construction elements. The construction elements comprising CLT panels were analysed for 72 mm thickness when applied to walls and 120 mm when applied to floors.

Although the software is a practical option for acoustic insulation prediction, limitations were found. The software's student version does not allow the parameterization of new materials, limiting the analysis to the pre-existing materials in its database. Thus, it was necessary to assume materials with similar properties to the original ones. Also, the methods employed by the software support, at most, triple elements, which implies a limitation to the number of cavities between the element's panels (maximum of two). For the proper analysis of the elements presenting more than two cavities, considerations and adaptations were necessary to allow all the layers to be considered in the prediction of their acoustic performance.

The prediction of the acoustic insulation of the external wall panels (Par_Ext_TF) presented a sound reduction index of 55 dB (Figure 5a). Additionally, simulations were made to identify the contribution of each component in ensuring the required and desired acoustic insulation.

If the resilient material used between the rigid elements (studs and OSB) was dismissed, the anticipated sound reduction index would decrease by around 6 dB. In the same way, when considering a stiffer metallic support for the plasterboard than the one originally considered, with a thickness of 0.55 mm, lower insulation levels are achieved: 53 dB with 0.75 mm studs and 49 dB with studs between 1 mm and 1.6 mm.

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Table 1: *Verification of the airborne sound reduction index according to RRAE*

Element	Sound emission space	RRAE $D_{2m,nT,w}$ or $D_{nT,w}$ (dB)	INSUL R_w (dB)
Par_Ext_TF	Exterior [1]	28 33	55
Par_Int_Est_TF	Common circulation area or a room [2]	48 50	63
Par_Int_Nest_TF	Common circulation area or a room [2]	48 50	63
Par_Int_Dupla_TF	Common circulation area or a room [2]	48 50	77
Par_Nuc_CLT	Vertical circulation [3]	40 48	63
Par_Nuc_CLT_TF	Vertical circulation [3]	40 48	65
Pav_Int_CLT	Garage or commercial or office areas [4]	50 58	61

[1] The standardised airborne sound insulation index measured two meters from the facade, $D_{2m,nT,w}$, between the outside of the building and bedrooms or living areas of dwellings shall be equal to or above 28 dB in sensitive areas (low noise neighbourhoods, mainly with residential buildings) and 33 dB in mixed areas (areas with residential and non-residential buildings).
[2] The standardised airborne sound insulation index, $D_{nT,w}$, between a room (emission) and bedrooms or living areas of another dwelling (reception) in a building shall be equal to or higher than 50 dB. When the emission comes from common circulation areas of the building, $D_{nT,w}$ should be equal to or higher than 48 dB in general conditions.
[3] The standardised airborne sound insulation index, $D_{nT,w}$, between a vertical circulation path (emission) of a building with lifts and bedrooms or living areas of dwellings (reception) shall be equal to or higher than 40 dB. When the building only has stairs, $D_{nT,w} \geq$ 48 dB applies, according to the previous item.
[4] The standardised airborne sound insulation index, $D_{nT,w}$, between a car parking garage (emission) and bedrooms or living areas of the dwellings (reception) should be equal to or higher than 50 dB. When considering the possibility of having a non-residential space on the ground floor of buildings, the acoustic insulation between commercial, industrial, offices or entertainment zones (emission), $D_{nT,w}$ $\geq$ 58 dB applies.

Table 2: *Verification of the impact sound insulation according to RRAE*

Element	Sound emission space	RRAE $L'_{nT,w}$ (dB)	INSUL $L_{nT,w}$ (dB)
Pav_Int_CLT	Dwelling rooms or building common circulation areas Office spaces [1]	60 50	51
Cob_CLT	Common circulation areas	60	64

[1] Inside the bedrooms or living areas of the dwellings (reception), the sound insulation index to impact sounds, $L'_{nT,w}$, from a standardised impact on floors of other dwellings or common circulation areas of the building (emission), should be equal to or less than 60 dB. When the emission occurs on the floors of the building with commerce, industry, offices or entertainment areas (emission), the sound insulation index to impact sounds, $L'_{nT,w}$, shall be equal to or less than 50 dB.

Instead of two layers of plasterboard, if only one layer is applied, a decrease of the sound reduction index to 52 dB and a worsening performance in low frequencies are observed. Still, when considering the exemption of the service layer keeping the two plasterboard finishing layers, an increase in the sound reduction index of 1 dB (56 dB) was observed. This fact can be justified by the lower stiffness of the gypsum plasterboard when supported on the rock wool compared to the case in which they are supported directly on the OSB, allowing greater oscillation of this layer and, consequently, the propagation of sound waves through its components. If the service layer is dismissed and the finishing is done with just one layer of plasterboard, the sound reduction index would be 52 dB.

Regardless of the variations imposed for simulation purposes, the opaque part of the external wall performs well. Its structural core (timber-frame with a cavity filled with rock wool and resilient material between the uprights and OSB) reaches a sound reduction of 46 dB itself. To meet the acoustic requirements, the external wall must have windows with high acoustic performance and adequate perimeter sealing.

Both interior walls, structural and non-structural timber-frame (Par_Int_Est_TF and Par_Int_Nest_TF), presented a sound reduction index of 63 dB, so the difference in thickness of the timber-frame and, consequently, of the acoustic absorbing material inside the cavities (140 mm and 90 mm, respectively) had no significant influence on the predicted performances. When the two service layers are removed, the sound insulation of both solutions decreases to 60 dB.

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The results obtained for the different simulations developed for the external walls and structural and non-structural internal walls show that the greatest contribution to sound insulation comes from the double plasterboard finish, its support conditions in the adjacent layer, and the dissociation between the rigid elements of the panels.

By analysing the double-walled configuration (Par_Int_Dupla_TF), which presented sound insulation of 77 dB, it was possible to quantify the contribution of the acoustic membrane layers. Once removed, the Par_Int_Dupla_TF achieved a sound reduction of 76 dB, a result very close to the original configuration which, because it is so robust and with acoustic insulation significantly higher than the minimum limits defined in the legislation, makes the use of acoustic membranes in the promotion of acoustic comfort unnecessary. A less robust configuration of this wall solution, exempting the service layers, presented a noise insulation prediction of 74 dB.

The same was observed for the core walls, Par_Nuc_CLT and Par_Nuc_CLT_TF, which presented a decrease of 1 dB and 0 dB compared to the original configuration by removing the acoustic membrane. The acoustic membrane use had a more relevant impact on the panels' behaviour for the low-frequency sounds (lower than 125 Hz).

Considering the core wall panels' behaviour, when the remotion of the plasterboard layers was simulated to consider situations where the exposure of the CLT is wanted for aesthetic purposes, the sound reduction index decreased from 63 dB to 57 dB in the Par_Nuc_CLT and from 65 dB to 62 dB in the Par_Nuc_CLT_TF.

Associating the removal of the plasterboard layers on the CLT face with the removal of the service layer, some changes are observed only in the Par_Nuc_CLT, which reduces its sound insulation to 54 dB and significantly worsens the insulation level for the low-frequency range (more evident due to the removal of the service layer). The Par_Nuc_CLT_TF, with an absorbing material inside the timber-frame cavity, didn't present any change with the removal of the service layer, keeping the sound insulation of 62 dB and, in all its configurations (original and alternatives), presented insulation indexes in the low-frequencies higher and more stable than the results presented by Par_Nuc_CLT.

In terms of the airborne sound insulation of Pav_Int_CLT, the element fulfils the acoustic requirement when the emitting space is an office or a commercial area. Knowing that the prediction of acoustic insulation is based on a delicate analysis that can often lead to misunderstandings when compared to the actual acoustic insulation of the element, additional studies are needed to rigorously determine the performance of this element to ensure the minimum required behaviour. However, variations in the original configuration that may increase its acoustic performance were evaluated: the increase of the floating floor cavity to 100 mm and the adherence of continuous acoustic membranes over the CLT, both motivated by the need to include service installations.

For the isolated or associated application of both strategies, the same increase in sound reduction to 62 dB was obtained. It should be noted that this analysis considered spacings between slats and hangers of the suspended ceiling of 300 mm, so for any higher spacing, the acoustic insulation will be favoured. Also, as observed for the walls when simulating the removal of the service layers and, essentially, of its interior acoustic absorbing material, for Pav_Int_CLT it was noted that the adoption of one or two layers of acoustic absorbing material inside the suspended ceiling did not result in variations in the acoustic insulation. However, it was noted an expressive contribution of the acoustic suspended ceiling in the insulation to low-frequency sounds, mainly when in association with the increase of the floating floor cavity to 100 mm. When used over garages, whose requirement is lower, one can consider replacing the suspended ceiling with a 60 mm rock wool layer under the CLT, resulting in an acoustic insulation of 55 dB. This configuration can also be increased by using an acoustic membrane and enlarging the cavity of the floating floor, resulting in an acoustic insulation of 56 dB, although this measure is not necessary.

In terms of impact sound insulation, Pav_Int_CLT has a reasonable performance when it comes from impacts produced in residential or common circulation areas of the building (Figure 5b).

Compliance with the requirements is maintained even when the acoustic suspended ceiling is replaced by the slenderest option for the element, in which a 60 mm layer of rock wool is placed under the CLT and with a double plasterboard layer, with sound insulation to impact sounds of 56 dB. The same was not observed when the emission is from places in the building intended for commerce, industry, offices, or entertainment. However, this work aims essentially to the analysis of the developed construction system when applied in multi-family buildings, so the most stringent requirement ($L'_{nT,w} \leq 50$ dB) does not apply. The evaluation of the construction system for other building programs will be the object of future studies. However, seeking to identify the potential of the solution also for these cases, the application of resilient ceiling suspenders and more efficient damping systems for the floating floor was simulated, with the potential to achieve about 45 dB for the sound insulation to impact sounds.

Furthermore, assuming that the slightly tilted visitable roof is a common circulation area for the building occupants, its impact sound performance was simulated. Although the original Cob_CLT configuration did not meet the requirements imposed on this case, when using resilient materials under the deck slats and acoustic suspenders for the 60 mm suspended ceiling, sufficient sound insulation was achieved, 57 dB.

All the results presented are a prediction based on considerations about the construction elements. Future studies based preferably on laboratory tests on prototypes and *in situ* measurements are required to determine the acoustic performance of the construction elements more reliably, including the effect of the connection between panels and the flanking transmissions.

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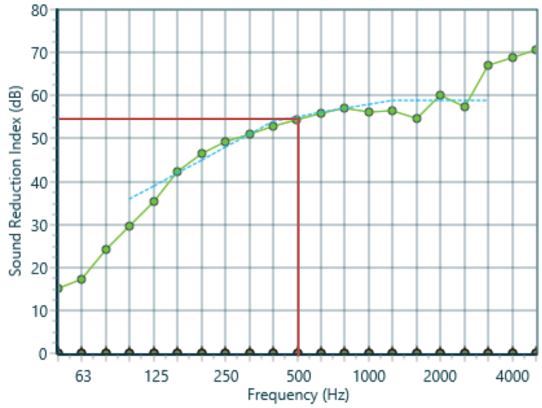
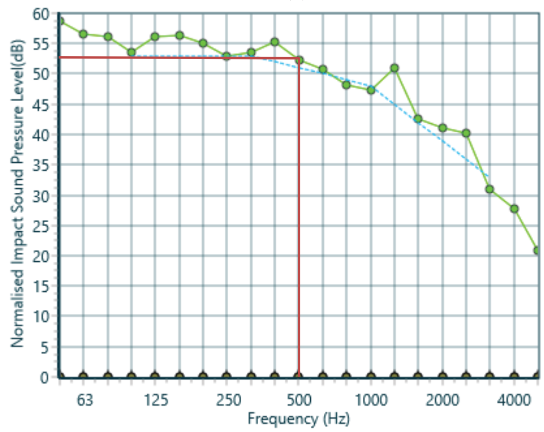


(a)



(b)

Figure 5: *Example of sound reduction index curve. (a) Example of predicted airborne sound insulation curve (in green) and reference curve (in blue) - Par_Ext_TF; (b) Example of predicted impact sound insulation curve (in green) and reference curve (in blue) - Pav_Int_CLT*

5 CONCLUSIONS

This paper describes numerical simulations carried out through INSUL software to predict the airborne and impact sound insulation of a construction system based on prefabricated wooden panels developed for the Portuguese market. The results of this investigation contribute to the validation of a construction system in terms of its acoustic performance.

The acoustic performance prediction showed favourable results for airborne sound insulation (Table 1) and partially for impact sound insulation (Table 2), depending on the type of emission space (another dwelling, office, circulation area). Note that all confirmed vulnerabilities have been mitigated.

The acoustic analysis was developed disconnected from a defined and invariable architecture, so it is essential to evaluate aspects such as flanking transmission, interior acoustics, natural ventilation conditions in the façade or mechanical ventilation causing a break in acoustic insulation, and closure elements such as doors, windows and shutter boxes for each project using this construction system.

Future studies based on laboratory tests on prototypes and *in situ* measurements will be carried out.

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