# Optimization of wood frame-based floors in order to improve impact noise

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# OPTIMIZATION OF WOOD FRAME-BASED FLOORS IN ORDER TO IMPROVE IMPACT NOISE

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## ABSTRACT

It has been introduced in 2018 by the French housing certification organism (QUALITEL) a new requirement concerning impact noise in order to improve occupants acoustic comfort. The impact noise requirement corresponds now to $L'_{nT,w}$ and $L'_{nT,w}+C_{I50\text{-}2500}$ equal to or below 55 dB. An investigation was undertaken in order to define a dry solution for wood frame-based floors fulfilling this requirement; by dry solution, it is intended to avoid standard screed requiring drying/curing time and introducing humidity during the construction of wood-based building. Therefore, the goal for the floor performance without any floor finishing was set to impact sound levels $L_{n,w}$ and $L_{n,w}+C_{I50\text{-}2500}$ equal to or below 50 dB. Adding a mass layer between the wood frame-based floor and a dry screed was selected as a potential solution. A prediction tool is used to evaluate impact sound level and an optimization tool based on evolutionary algorithm is implemented in order to define the density per unit area of the added weighting layer allowing to reach the chosen impact sound level. Based on these obtained results, laboratory measurements were carried out with different materials as mass layer; they demonstrate that the objective in terms of impact noise level is reached. Measured and predicted impact sound levels are compared and discussed. Laboratory measurements also included sound source and rubber ball as excitation, to determine sound transmission index and maximum impact noise level respectively, as well as different types of floor covering. These results are also presented.

## 1. INTRODUCTION

During the last decade, a lot of work has been carried out to predict acoustic performances associated to lightweight building and lightweight elements. Models have been developed to predict the acoustic performance for heavyweight (mostly concrete based) buildings and building elements, with respect to air-borne and structure-borne excitation. Lightweight buildings and elements are more complex, more diverse and more complicated to model: they are multi-cavity stiffened systems with different types of possible connections.

Different projects throughout Europe [1-3] have demonstrated that one of the major needs was the acoustic performance prediction model from lightweight elements (walls and floors); in order to predict the acoustic performance of the building, the performances of the building walls and floors are necessary and a rather large number of these elements is not tested in the laboratory. These projects also established that impact noise is a major annoyance for the occupants of lightweight wood-based buildings.

Thus, in order to improve occupants acoustic comfort, the French housing certification organism (QUALITEL) introduced a new requirement concerning impact noise; this new requirement corresponds to $L'_{nT,w}$ and $L'_{nT,w}+C_{I50\text{-}2500} \leq 55$ dB (while the French regulation for residences remains $L'_{nT,w} \leq 58$ dB). An investigation was undertaken in order to define solutions for wood frame-based floors fulfilling this requirement; by dry solution, it is intended to avoid standard screed requiring drying/curing time and introducing humidity during the construction of wood-based building. Therefore, the goal for the floor performance without any floor finishing was set to impact sound levels $L_{n,w}$ and $L_{n,w}+C_{I50\text{-}2500} \leq 50$ dB. Adding a mass layer between the wood frame-based floor and a dry screed was selected as a potential solution; obviously, the basic floor includes a suspended ceiling. A prediction tool combining wave-based transfer matrix and SEA approaches, is used to evaluate impact sound level and an optimization tool based on evolutionary algorithm is implemented in order to define the density per unit area of the weighting mass layer allowing to reach the chosen impact sound level. Based on these obtained results, laboratory measurements were carried out with different materials as mass layer; they demonstrate that the objective in terms of impact noise level is reached. Measured and predicted impact sound levels are compared and discussed. Laboratory measurements also included sound source and rubber ball as excitation, to determine sound transmission index and maximum impact noise level respectively, as well as different types of floor covering. These results are also presented

## 2. EXISTING SOLUTIONS

As a first step, available data were collected on wood frame-based floor composition allowing to reach the targeted impact sound level performance.

### 2.1 Acoubois Project

Based on laboratory results performed during the French Acoubois project [4], two wood frame-based floor type were identified in order to reach impact noise performance target.

The first one is implemented with

- a cement screed on a resilient layer (performance $\Delta L_w \geq 21$ dB),
- 18 mm thick OSB boards
- wood joists of dimensions 45 mm x 220 mm and spaced every 400 mm
- rigidly suspended ceiling with 2 layers of BA13 gypsum boards and 100 mm thick insulating mineral wool

The second one was based on a double independent frame for the floor and the ceiling. It still requires a floating screed (performance $\Delta L_w \geq 19$ dB).

Therefore, none of these two types corresponds to the desired design.

### 2.2 Lignum Database

The Lignum database [5] was also surveyed in order to identify laboratory evaluated wood frame-based floors reaching to targeted performance (most of the collected measured performances were from Ift Rosenheim laboratory).

A floor consistent with targeted performance is for example the floor referenced A2296 in the Lignum database. It corresponds to a total thickness of 430 mm and a total density per unit area of ~230 kg/m². The joist floor consists of a 22 mm OSB boards on 240 mm high (100 mm wide) joists. The ceiling incorporates a single layer of 13 mm thick plasterboard and 240 mm of fibrous insulation. Leveling granules are used to make the floor heavier (80 mm and 132 kg/m²). The floating system consists of a resilient underlay and a very specific 30 mm sheet of corrugated cardboard with heavy sand (density of ~1200 kg/m$^3$). The measured performance corresponds to $R_w+C = 76$ dB, $L_{n,w} = 37$ dB and $L_{n,w}+C_{I50\text{-}2500} = 50$ dB.

The collected results show the need to include a weighting layer, i.e. a layer making the floor heavier before installing a floating dry screed; this weighting layer should correspond to a density per unit area of about 100 kg/m² in order to reach the targeted performance.

## 3. OPTIMIZATION

With the aim of proposing solutions of joist floors in a dry structure, the CSTB tools [6-10] are used. The basic floor is composed of

- 18 mm thick OSB boards
- Wood joists of dimensions 45 mm x 220 mm and spaced every 400 mm
- Rigidly suspended ceiling with 2 layers of BA13 gypsum boards and 200 mm thick insulating mineral wool

On top of this floor is added a weighting layer, and then a dry floating screed. The optimization will be performed on the weighting layer characteristics only. Based on the results of this optimization, laboratory measurements on some optimized floor systems have been planned.

Components characteristics are taken from the AcouSYS software database [9].

### 3.1 Optimization Description

The optimization approach is based on a genetic algorithm (see [11] for an extensive literature survey of such a class of algorithms). This type of algorithm makes it possible to obtain an approximate solution to an optimization problem (cost function to be minimized); it does not require calculating the derivatives of the cost function with respect to the parameters to be optimized. A genetic algorithm is based on the notion of natural selection applied to a population of potential solutions to the given problem. Evolutionary algorithms are inspired from early Darwinian concepts such as survival and reproduction of the fittest on one hand and non-directed mutation of individuals on the other hand. From an initial population, only the best individuals will survive, reproduce and mutate from a generation to another. Thus, algorithms inspired by such concepts involve the following general structure with the usual terminology:

- Initialization of the individuals constituting the first generation
- Evaluation of the individuals with respect to a cost or fitness function
- Selection of the parents for the future generation
- Reproduction of the parents, through cross breeding, elitism or mutation

The optimized solution is thus approached by successive jumps.

In the present case, a population of 20 individuals and 10 generations of this population have been taken into account. The cost function to minimize is given by

$$F_{min} = (L_{n,w}+C_{I50\text{-}2500}) - L_{objective} \quad (1)$$

The $L_{objective}$ value corresponds to the targeted impact sound level performance including the low frequency adaptation term.

The verification on the indicator without adaptation term $L_{n,w}$ is carried out in a second stage.

### 3.2 Parameters Variation

The following characteristics for the weighting layer are considered during the optimization process:

- Thickness: between 10 and 60 mm
- Density: from 1000 to 2500 kg/m$^3$
- Elastic modulus: from 0.1 MPa to 5 GPa

Two rounds of optimization were carried out ; the first one considered an objective function value ($L_{objective}$) of 50 dB and a second one an objective function value of 48 dB in order to taken into account a 2 dB margin This margin should allow to take into account uncertainties on material properties as well as the model limitations. The results for the objective function of 48 dB are shown in this paper since similarities between the two rounds of optimization were observed.

## 4. OPTIMIZATION RESULTS

In this section, the optimization results are presented.

### 4.1 Optimization Results

The results for the objective function of 48 dB are presented in this section.

Figure 1 shows the cost function variation through the different generations. The convergence toward a minimum is relatively quick: after the fourth generation the tendency becomes very clear.

The individuals allowing to reach a cost function value of less than 0.5 dB (i.e. $F_{min} < 0.5$ dB), are selected. Figure 2 depicts for these individuals the thickness, the density and the elastic modulus as well as the density per unit area of the weighting layer. It appears that a weighting element with a density per unit area of about 70 kg/m² should allow reaching the targeted performance, i.e. an objective of $L_{n,w}+C_{I50\text{-}2500}$ = 48 dB (corresponding to 50 dB with a 2 dB margin). The elastic modulus seems to be of secondary importance: for the fifth generation (red square symbols), the large variation of the elastic modulus is not associated to an important change in performance.

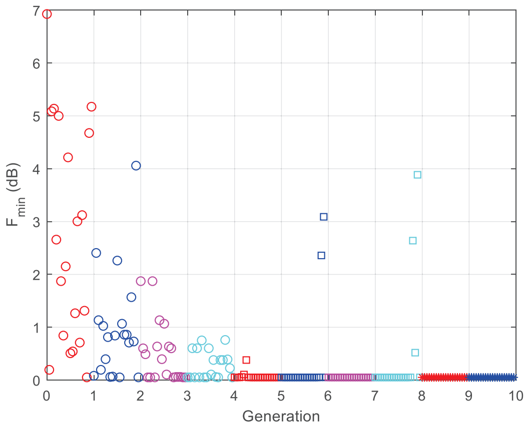
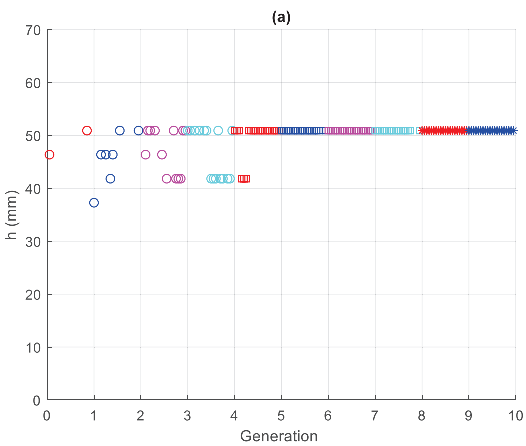



**Figure 1**. Cost function variation with respect to generation number – $L_{objective}$ = 48 dB.



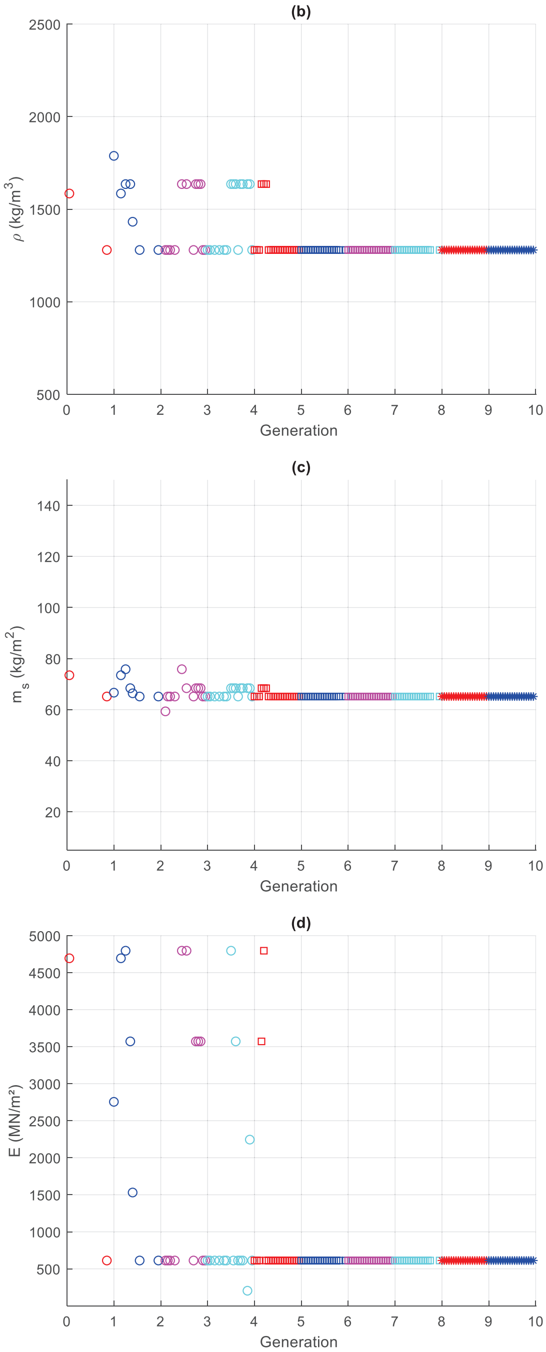




**Figure 2**. Individuals corresponding to $F_{min}$ < 0.5 dB – $L_{objective}$ = 48 dB; (a) Thickness, (b) Density, (c) Density per unit area and (d) Elastic modulus.

Figure 3 shows an example of impact sound level achieved at the fourth generation when $F_{min}$ < 0.5 dB. Difference between the different solutions are not observed in the low frequency range but rather in the mid to high frequency range (above the one-third octave band of 250 Hz). For the following generation, the impact sound level is very similar for the different solutions (individuals).

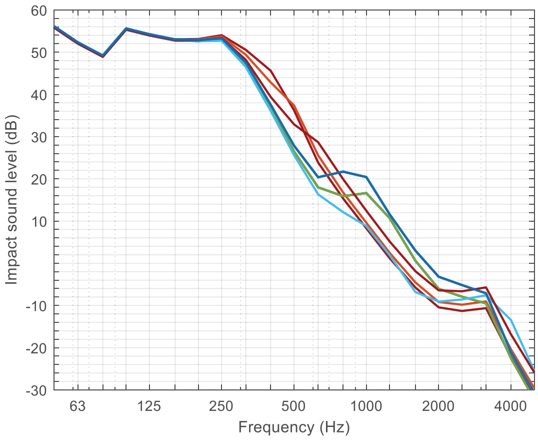



**Figure 3**. Impact sound level at 4th generation corresponding to $F_{min} < 0.5$ dB – $L_{objective} = 48$ dB.

### 4.2 Possible Solutions for Laboratory Testing

The presented optimization results show that a density per unit area of around 70 kg/m² for the weighting layer should make it possible to achieve the targeted impact sound level performance ($L_{n,w}$ and $L_{n,w} + C_{I50\text{-}2500} \leq$ 50 dB without the presence of a finishing floor covering), and with a margin of 2 dB compared to the predicted results.

In view of the collected existing data, indicating an added mass of around 100 kg/m², and the results of the optimization, indicating an added mass of around 70 kg/m², it appeared interesting to considered testing a weighting layer between 70 and 100 kg/m² in density per unit area, in order to assess the associated margin in relation to the modeling and also in relation to a finishing floor covering. The search for components to be used for weighting layer allowed to identify concrete outdoor tiles (used for outdoor pavement and available in general hardware store), solid bricks, and gravel. These three solutions were investigated in the laboratory floor tests.

## 5. PERFORMANCE RESULTS

Measurements were carried out at the FCBA laboratory. The basic floor is composed of

- 18 mm thick OSB boards
- Wood joists of dimensions 45 mm x 220 mm and spaced every 400 mm
- Rigidly suspended ceiling with 2 layers of BA13 gypsum boards and 200 mm thick insulating mineral wool

The implemented weighting layer corresponds to

- Configuration 1: concrete outdoor tiles of dimensions 400 mm x 400 mm and 35 mm in thickness, corresponding to a density per unit area of 82 kg/m²
- Configuration 2: solid terracotta bricks of dimensions 280 mm x 400 mm and 50 mm in thickness, corresponding to a density per unit area of 100 kg/m²
- Configuration 3: 0-14 gravel mix, 50 mm in thickness, corresponding to a density per unit area of 78 kg/m²

The difference between Configuration 1 and Configuration 3 lies in a difference of elastic behavior, the density per unit area being rather similar.

The dry screed corresponds to a composite system (FERMACELL 2 E 32 30 mm) integrating a 20 mm fiber reinforced board and 10 mm of rock wool as resilient layer. Three types of floor finishing were also investigated:

- Plastic PVC floor covering (2.3 mm in thickness)
- Carpet (7.3 mm in thickness)
- Laminated parquet (14 mm in thickness) mounted on top of a resilient layer (Assour Parquet) corresponding to $\Delta L_w$ of 20 dB.

Sound reduction index, impact noise level as well as heavy/soft ball maximum impact level were measured in the laboratory and are presented below. In this section, the measured performance of the three designed floors tested is first reported. Finally, measured and predicted impact noise performance are compared.


**Figure 4**. Illustration of the different weighting layers.

### 5.1 Performance Analysis

Table 1 gives the impact sound level performance for the different measurements conducted. All the configurations incorporating a weighting layer meet the targeted performance. As expected, Configuration 2 provides the best results since it is associated to the highest density per unit area of the weighting layer.

Table 2 presents the measured performances in terms of sound reduction and heavy/soft ball maximum impact index.

|  | $L_{n,w}$ | $L_{n,w}+C_{I50-2500}$ |
|---|---|---|
| Basic floor | 61 dB | 65 dB |
| Configuration 1 | 45 dB | 49 dB |
| Configuration 1 + PVC | 44 dB | 50 dB |
| Configuration 1 + Carpet | 42 dB | 49 dB |
| Configuration 1 + Parquet | 44 dB | 50 dB |
| Configuration 2 | 42 dB | 47 dB |
| Configuration 2 + PVC | 41 dB | 47 dB |
| Configuration 2 + Carpet | 38 dB | 48 dB |
| Configuration 2 + Parquet | 42 dB | 48 dB |
| Configuration 3 | 42 dB | 49 dB |
| Configuration 3 + PVC | 41 dB | 48 dB |
| Configuration 3 + Carpet | 40 dB | 50 dB |
| Configuration 3 + Parquet | 40 dB | 50 dB |

**Table 1.** Measured impact sound level performance for the different tested configurations.

|  | $R_w+C$ | $L'_{AFmax,V,T}$ |
|---|---|---|
| Basic floor | 53 dB | 67.6 dB |
| Configuration 1 | 66 dB | 53.6 dB |
| Configuration 2 | 68 dB | 51.4 dB |
| Configuration 3 | 67 dB | 51.9 dB |

**Table 2.** Measured impact sound level performance for the different tested configurations.

### 5.2 Measured Performance Analysis

Figure 5 presents the measured impact sound level spectrum for the different configurations considered. Configuration 2 corresponding the heaviest weighting layer (100 kg/m²) is associated to the best performance. Configurations 1 et 2 shows quite different behaviors between the one-third octave bands of 100 and 200 Hz. The use of gravel mix (Configuration 3) gives the lowest impact sound levels above the one-third octave band of 200 Hz; however; the impact sound level at the one-third octave band of 50 Hz is higher.

Figure 6 presents the maximum impact sound levels for a heavy/soft impact (rubber ball); the differences between the three configurations considered is noticeable above the one-third octave band of 80 Hz.

It should also be noted that the sound reduction index, depicted in Figure 7, for the Configuration 3 (gravel mix as weighting layer) is lower in the low frequency range, up to the one-third octave band 100 Hz, than that of Configuration 1 and Configuration 2.

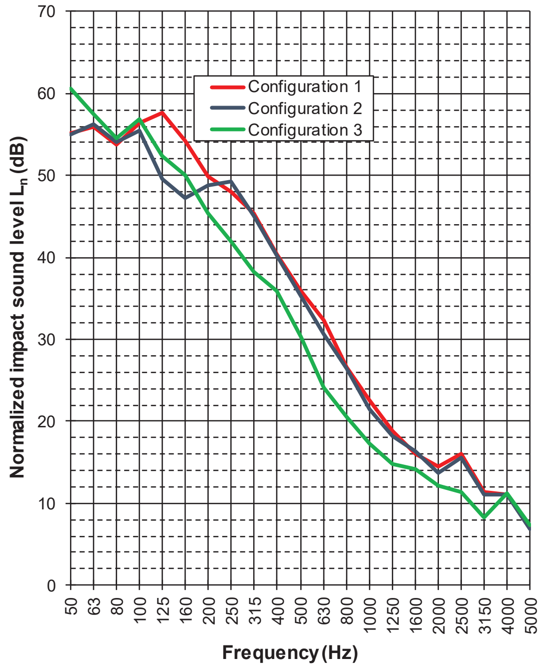



**Figure 5**. Measured normalized impact sound level – Weighting layer effect.

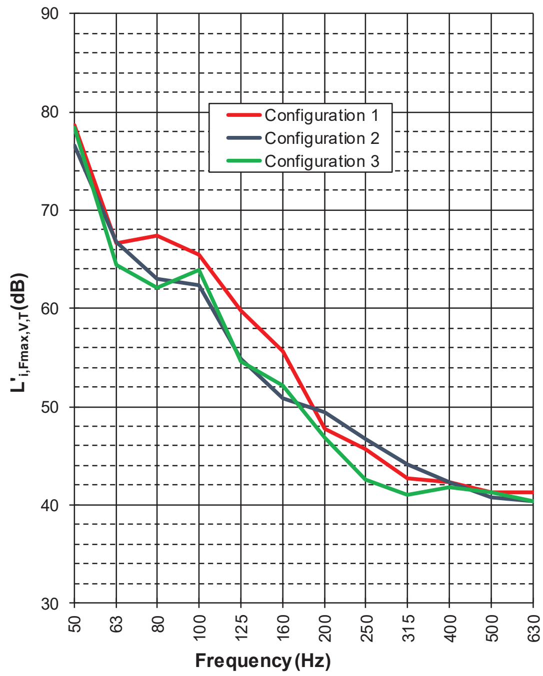



**Figure 6**. Measured maximum impact sound level – Weighting layer effect.

The effect of the floor finishing taken into account in the measurement investigation is studied next (see Figure 8). The impact sound improvement associated to the plastic floor covering is quite similar for Configuration 1 and 2 above the one-third octave band of 160 Hz; for Configuration 3, if the behavior is quite comparable the improvement level is slightly lower (especially above for the one-third octave bands from 800 to 3150 Hz). For the carpet as floor finishing, the frequency behavior of the impact sound improvement is similar for all 3 configurations; however, the best improvement is obtained for Configuration 2 especially in the one-third octave bands from 500 to 3150 Hz. It has to be stretched that the carpet has a negative effect on impact sound level in the low frequency range (one-third octave bands from 50 to 80 Hz). The impact sound improvement associated to the parquet is clearly lower that for the other floor finishing considered. For Configuration 3 (gravel mix as weighing layer); the impact sound improvement for the parquet is low and close to zero above the one-third octave band of 800 Hz.

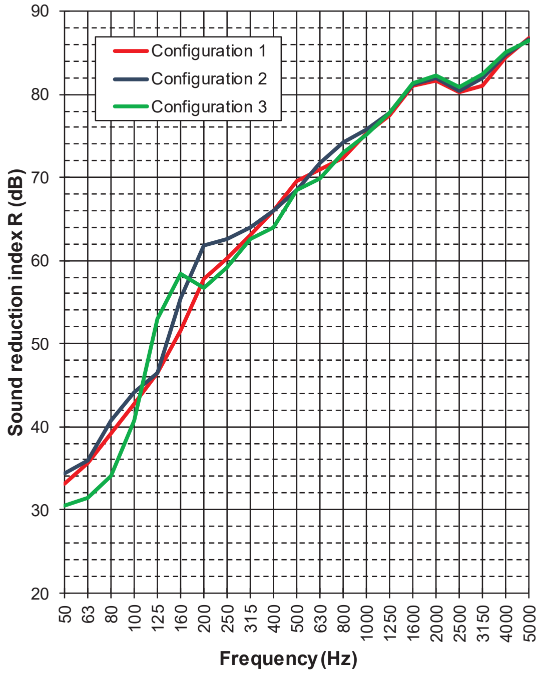



**Figure 7**. Measured sound reduction index – Weighting layer effect.

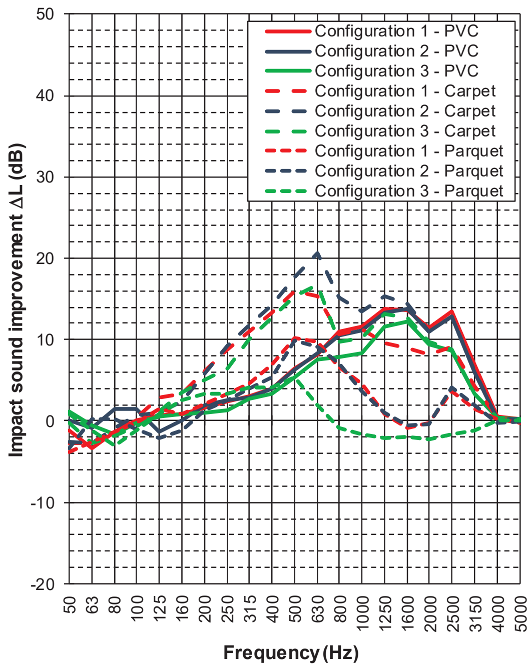



**Figure 8**. Effect of the floor finishing on impact sound level.

Unfortunately, the effect of the floor finishing was not evaluated using the heavy/soft impact source (rubber ball) except for the parquet. In this case, the improvement is close to 1 dB on average in the frequency range covering the one-third octave bands of 50 to 630 Hz for any floor configuration, the worst remaining Configuration 3.

### 5.3 Comparison between Measured and Predicted Impact Noise Performance

In this section, a comparison between the predicted and the measured impact sound levels is discussed. The floor finishings are not considered.

#### *5.3.1 Basic floor*

Figure 9 presents the impact sound level spectrum for the basic floor (i.e. before applying the weighting layer and dry floating screed). Table 3 gives the associated performance in terms of single number ratings.

The measured and predicted impact sound levels are relatively close except for the one-third octave band of 50 Hz for which the prediction over-evaluates le impact sound level. Therefore, the performance level integrating the low frequency range ($L_{n,w}+C_{I50\text{-}2500}$) is quite different between the measurement and the prediction (6 dB difference).

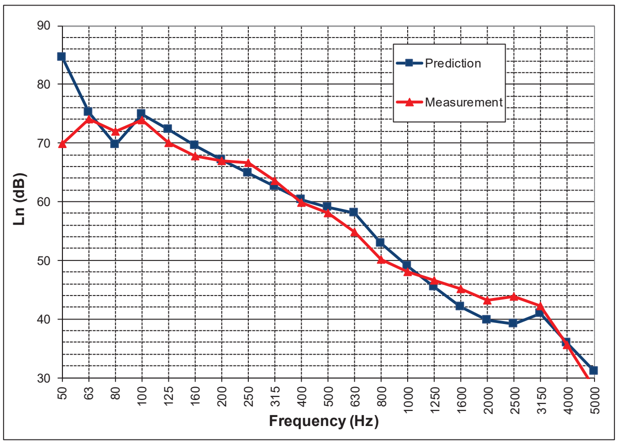



**Figure 9**. Comparison between predicted and measured impact sound level spectra – Basic floor.

| | $L_{n,w}$ | $L_{n,w}+C_I$ | $L_{n,w}+C_{I50\text{-}2500}$ |
|---|---|---|---|
| Measurement | 61 dB | 62 dB | 65 dB |
| Prediction | 62 dB | 63 dB | 71 dB |

**Table 3.** Comparison between predicted and measured impact sound performance – Basic floor.

#### *5.3.2 Configuration 1*

Figure 10 shows the measured and predicted impact sound level spectra for Configuration 1 (concrete based weighting layer). Table 4 gives the associated performance in terms of single number ratings. The measured and predicted impact sound levels reveal a similar behavior. The performance levels are also in line; however, a difference of 2 dB in performance level is observed when integrating the low frequency range ($L_{n,w}+C_{I50-2500}$).

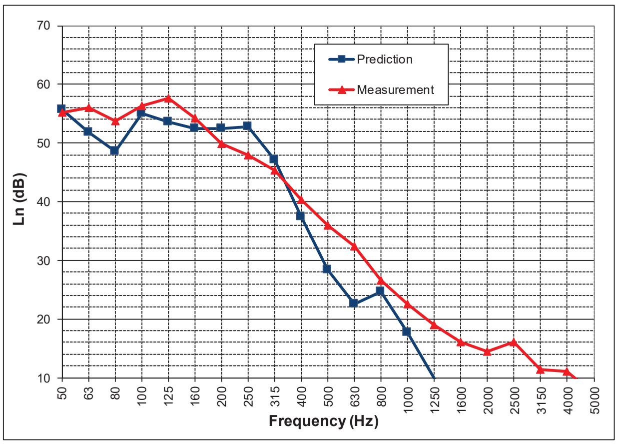



**Figure 10**. Comparison between predicted and measured impact sound level spectra – Configuration 1.

| | $L_{n,w}$ | $L_{n,w}+C_I$ | $L_{n,w}+C_{I50-2500}$ |
|---|---|---|---|
| Measurement | 45 dB | 47 dB | 49 dB |
| Prediction | 45 dB | 46 dB | 47 dB |

**Table 4.** Comparison between predicted and measured impact sound performance – Configuration 1.

*5.3.3 Configuration 2*

For Configuration 2, the comparison between the measured and predicted impact sound results are provided in Figure 11 and Table 5.

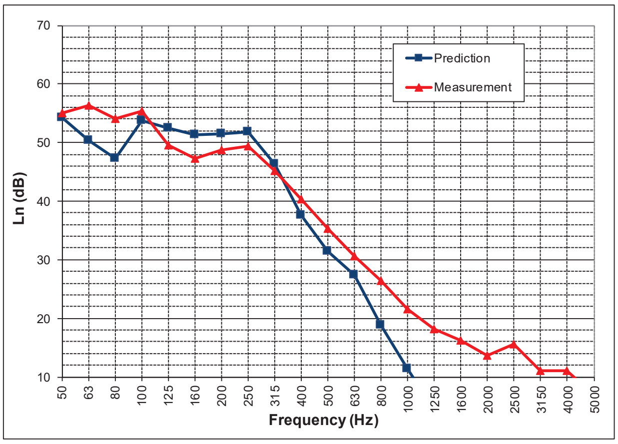



**Figure 11**. Comparison between predicted and measured impact sound level spectra – Configuration 2.

| | $L_{n,w}$ | $L_{n,w}+C_I$ | $L_{n,w}+C_{I50-2500}$ |
|---|---|---|---|
| Measurement | 42 dB | 43 dB | 47 dB |
| Prediction | 44 dB | 44 dB | 46 dB |

**Table 5.** Comparison between predicted and measured impact sound performance – Configuration 2.

The measured and predicted impact sound levels present a similar behavior. The performance levels are globally in line; however, a difference of 2 dB in performance level is observed on the commonly used single quantity number ($L_{n,w}$) and of 1 dB when integrating the low frequency range ($L_{n,w}+C_{I50-2500}$). The difference between Configuration 1 and Configuration 2 is also different between prediction and measurement. The effect of the weighting is more important on the measurement than on prediction. However, the prediction and measurement indicate clearly that Configuration 2 integrating the heaviest weighting layer is the best solution.

*5.3.4 . Configuration 3*

For Configuration 3, the comparison between the measured and predicted impact sound results are presented in Figure 12 and Table 6.

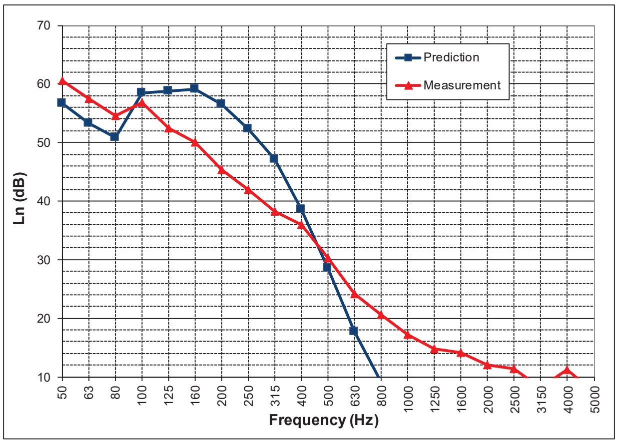



**Figure 12**. Comparison between predicted and measured impact sound level spectra – Configuration 3.

| | $L_{n,w}$ | $L_{n,w}+C_I$ | $L_{n,w}+C_{I50-2500}$ |
|---|---|---|---|
| Measurement | 42 dB | 44 dB | 49 dB |
| Prediction | 49 dB | 50 dB | 51 dB |

**Table 6.** Comparison between predicted and measured impact sound performance – Configuration 3.

In this case, difference can be observed between the predicted and measured impact sound level spectra. They are most probably related to the modeling of the gravel layer. Indeed, this layer is taken into account as a solid layer and not as a granular type layer without binding, since the prediction tool does not yet integrate models for such type of material. Differences are also recorded on performance indices, even if the performance rating integrating the low frequency range ($L_{n,w}+C_{I50-2500}$) shows a difference of 2 dB between prediction and measurement. The difference in performance between Configuration 1 and Configuration 3 is also dissimilar between prediction and measurement. The measured results demonstrate that the use of gravel mix is preferable than the use of concrete outdoor tiles; the prediction shows a opposite, probably due to the modeling approach of the granular material. It should be noted that the fitting of the measured and predicted impact sound level spectra should be possible by modifying the characteristics of the gravel mix layer; however, the characteristics that would be obtained for the gravel layer would not necessarily be appropriate for another gravel based situation. Therefore, this option was discarded.

## 6. CONCLUSIONS

An investigation was undertaken in order to define a dry solution for wood frame-based floors fulfilling impact noise requirement of $L'_{nT,w}$ and $L'_{nT,w}+C_{I50\text{-}2500} \leq 55$ dB; by dry solution, it is intended to avoid standard screed requiring drying/curing time and introducing humidity during the construction of wood-based building. Therefore, the goal for the floor performance without any floor finishing was set to impact sound levels $L_{n,w}$ and $L_{n,w}+C_{I50\text{-}2500} \leq 50$ dB. Adding a mass layer between the wood frame-based floor and a dry screed was selected as a potential solution. A prediction tool was used to evaluate impact sound level and an optimization tool based on evolutionary algorithm was implemented in order to define the density per unit area of the weighting mass layer allowing to reach the chosen impact sound level. A margin of 2 dB was introduced in the optimization process in order to cover uncertainties with respect the materials characteristics and modeling limitations. Based on these obtained results, laboratory measurements were carried out with different materials as mass layer; they demonstrate that the objective in terms of impact noise level is reached. Measured and predicted impact sound levels were compared and discussed. Laboratory measurements also included sound source and heavy/soft rubber ball as excitation, to determine sound transmission index and maximum impact noise level respectively, as well as different types of floor covering. These results were also presented.

Finally, this investigation has allowed to determine wood frame-based floor solutions with a dry floating system reaching the targeted performance in terms of impact sound performance $L_{n,w}$ and $L_{n,w}+C_{I50\text{-}2500} \leq$ 50 dB. These solutions require a weighting layer under the dry floating system, with a density per unit area of the order of 80 kg/m². The use of a denser material as weighting element allows to reduce the associated thickness of this necessary extra layer (between 30 and 50 mm). The total thickness of the weighting layer and the dry floating system is in the same order of magnitude as that of a standard cement based floating floor with a resilient layer. The identified possible solutions deduced from optimization were matched with existing and disponible building material as weighting layer in order to conduct laboratory measurements: concrete outdoor tiles, solid terracotta bricks and gravel mix. Other materials could have been implemented if the density per unit area criterium was matched. The developed solutions have been proposed to wood construction sector stakeholders and have recently been added to the examples of wood-frame based floor acoustic solutions by the French housing certification organism (CERQUAL QUALITEL Certification) in relation with the NF Habitat and NF Habitat HQE certifications.

## 7. ACKNOWLEDGEMENT

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