Impact sound of timber floors in sustainable buildings

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ARTICLE INFO

Accepted 8 May 2017

Keywords:
Sustainable timber buildings
Acoustic
Impact sound insulation
Precast energy saving panels

ABSTRACT

Timber buildings represent a robust alternative to traditional heavyweight constructions. They allow CO_2 storage, high structure and performance reproducibility, fast assembly and final certification of every panel.

Nowadays, acoustic insulation is one of the most requested performances on the part of inhabitants, but not always fulfilled. Since these kind of edifices are relatively new in the market, there are very few studies on acoustic properties, regarding on impact sound performances. In this paper, an in-depth analysis of impact noise on bare timber floors is presented, focusing on how impact sound reduction cannot be as efficient as in heavyweight constructions. Two new equations are proposed, modelling the impact sound pressure level of common bare timber structures and the influence of traditional floating floor systems is analysed.

1. Introduction

Lightweight precast timber buildings are present worldwide and their market trend is growing, since the related thermal insulation performances provide very good final results. They allow CO_2 storage, since wood is widely used, as it is a renewable and environmentally friendly raw material and commonly a very good thermal insulation is provided thanks to traditional [1] and new materials [2] use. Generally, these constructions are built within industry plants where costs are minimised beforehand and where it is ensured that as little waste as possible is produced, according to Kyoto protocol purposes [3].

Furthermore, prefabrication often means high repeatability since specialised workmanship is used, including CAD-CAM technologies, permitting new and complex architectural shapes, concepts and tendencies. In addition, the final product needs CE certifications, so as to ensure quality.

Nevertheless, acoustic performances are not always at the top range. For example, impact noise in timber constructions is the most common cause of complaint on the part of inhabitants [4], because in this kind of lightweight buildings the usual impact reduction methods would not properly work.

In fact, in traditional heavyweight buildings high density solutions are often used in order to reduce the impact sound pressure level [5–8]; the standard ISO 12354-2 [9] includes the analytical model as reported in equation (1):

$$L_n = L_{n,0} - \Delta L \text{ (dB)} \tag{1}$$

where L_n is the resulting impact noise (dB), $L_{n,0}$ is the impact noise of the bare floor (dB), ΔL is the impact sound pressure level reduction (dB).

It is evident that the bare floor acts as starting point and so the type of partition is the primary source.

The floating floor is one possible solution for the reduction of the impact sound pressure level using the mass-spring-mass effect based on Cremer's theory [10]. This method is widely used and successfully applied from the design process to the realization of the building.

The floating floor is nowadays one of the best and safest solution to reduce impact noise in heavyweight constructions. It includes a heavy bare floor, a resilient layer and a heavy upper slab; the analytical method is reported in equations (2) and (3).

$$\Delta L = 30 \log(f/f_0) \text{ (dB)} \tag{2}$$

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where ΔL is the impact sound pressure level reduction (dB), f is the frequency [Hz] and f_0 is the resonance frequency [Hz] of the spring-mass system expressed by

$$f_0 = (1/2\pi)\sqrt{(s'/m')}\ [\text{Hz}] \quad (3)$$

where s' is the apparent dynamic stiffness per unit area [MN/m^3] and m' is the mass per unit area of the massive slab [kg/m^2].

As a matter of fact, the floating floor depends on the density of the upper slab and on the dynamic stiffness value of the resilient material [11–13] as explicated in equations (2) and (3). So what may change the final results is the bare floor impact noise trend. Furthermore, the reduction provided by the floating floor is not constant in the frequency domain [14–17].

In recent years many researchers have tried to deal with these new topics, stating that in particular the lightweight timber floors do not behave as the heavyweight ones [18–24]. Many project were developed; COST action FP90702 [25] reports that the wooden structures present a better insulation in middle and high frequency range than the heavy weight ones. As a consequence, the low frequency influence has to be further investigated.

Silent Timber Building project developed many tools and databases focusing on SEA calculation and prediction (as an example see Refs. [26–28]); this topic was also studied in independent researches (as an example see Refs. [29–31]) demonstrating the high interest on this type of constructions.

Many measurements were performed in years on different complete structures and an on line database was created [32]. Nevertheless, no bare structures is indexed in it.

All these studied reports similar initial or general results: timber structures are various and even if they are very repeatable, there are several differences between one producer to another.

Furthermore, applying the same prediction methods or analysis used for heavyweight constructions could yield rather approximate results. Recent studies [33,34] show how different bare floors (heavyweight concrete slab, beams and pots and lightweight timber concrete ones) present dissimilar impact sound pressure levels and consequently floating floor sound reduction could not ensure same results [35].

Nowadays the progress of modern constructions more and more includes lightweight buildings. At present 6 edifices out of 100 are erected using timber constructions in Europe [36]; in Japan the enforcement of the Act for Promotion of use of wood in Public Buildings pushed this technology to grow rapidly [37]. They provide many advantages like speed of assembly, industrial quality, reduction of workmanship errors, fast realization of difficult shapes, high integration of service equipment and windows [38].

The presence of timber buildings has grown in Europe since recent directive of the European Parliament [39] encourages the realization of new high performance buildings.

Different technologies are available but two types are most used: glulam beams with top boards (GLT) or cross-laminated timber panels (CLT). For both of them no standard or international literature provide a theoretical or empirical L_{n0} or frequency trend values in order to predict bare floors impact noise. This is the primary input data since the designing process is based on ISO 12354-2 [9] and Cremer's theory [10].

Especially at low frequency range (the more disturbing and annoying one [40–46]), this excitation is difficult to model because of two causes:

i. the typologies of glulam beams with top boards are various; this fact decelerates possible researches and makes them very difficult;
ii. the traditional models do not work with lightweight structures.

In this work, an in-depth study of the impact noise performance of bare timber floors is carried out, focusing on the results of in situ measurements. The aim of this paper is to provide empirical equations characterising the frequency behaviour trend, showing how different panels provide very similar performance and investigating the floating floor influence on impact noise reduction.

In appendix A, a list of abbreviation is provided.

2. Materials and methods

Timber floors are of various kinds, but could be divided into two categories: continuous and periodic. The first one is realized using different planks glued together until the final desired thickness is reached. The second possibility is to use glulam beams where, on top of them, boards (gypsum fibreboards, plasterboards, wooden chipboards, etc.) are secured using screws or nails.

These two kinds of structure were analysed using in situ impact noise measurements with an ISO tapping machine in multi-storey full-scale buildings. All rooms were closed using double plaster board panels or doors when available, in order to define single volumes; all tests were carried out according to ISO 16283-2 [47] using fixed microphones method with eight measures per room. All tests were repeated according to manual-scanning path technique (type 1, circle) [48] which always validated previous ones. In the first case, all measures were performed using a ISO tapping machine for 20 s each and were repeated twice. The resulting averages were used in this study.

No flanking transmission evaluation was performed since there is no need to measure or evaluate them concerning the goals of this study. These kind of buildings won't be finished at the bare structure step for fire resistance and thermal insulation issues. So always additional layers such as plaster or fibreboard with hollow spaces filled with porous materials are used in every wall. For these reasons final flanking transmissions values will change from the “bare” situation to the “final” one [49,50].

In all figures of similar type (from Figs. 5–9, for Fig. 13 and from Figs. 17–21) the y-axys represent the $L'_{n,T}$ measured or calculated levels.

2.1. Cross laminated structure

The tested building was a four–storey construction (Fig. 1) where 16 floors were measured (Fig. 2) on 16 different receiving rooms. General data of the bare buildings are reported in Table 1.

Fig. 1. Multi-storey Cross Laminated Timber building.

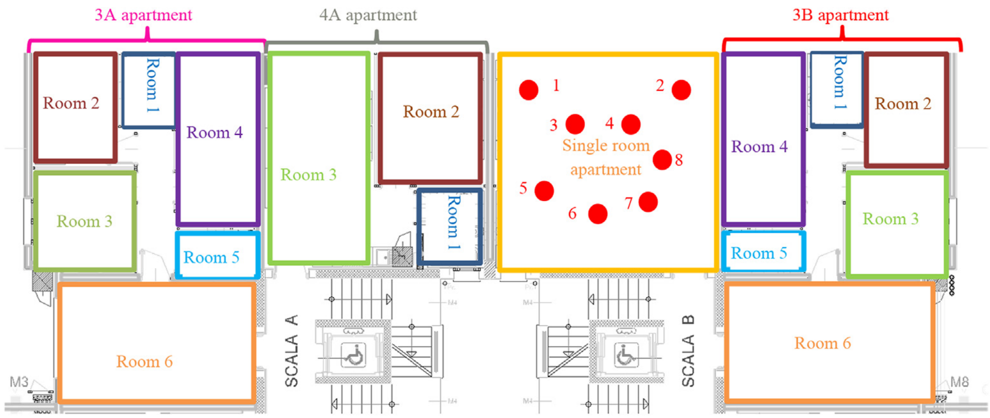

Fig. 2. Standard floor map. For 3A, 4A and 3B apartments room specification are highlighted. For single room apartment measurement positions are marked, as example.

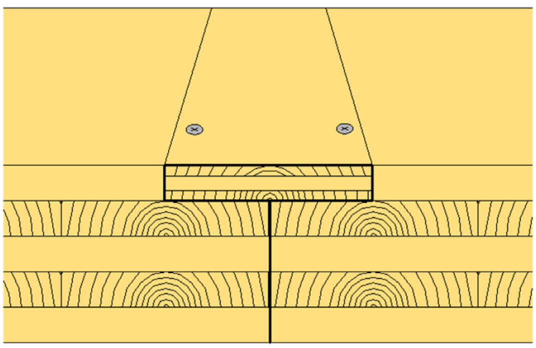

Fig. 3. Floor assembly detail.

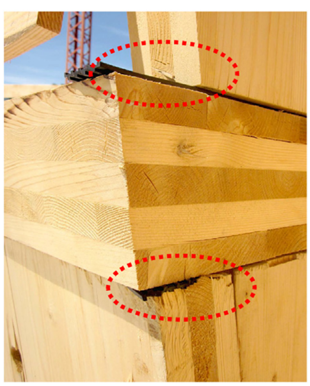

Fig. 4. Wall-floor junction detail with elastomeric layer.

The panels were consisted of 7 cross overlapping layers providing a final thickness of 25 cm. The floor assembly was secured using a board fixed with screws and glue between panels or external walls (see Fig. 3). A high density elastomeric material was included in wall-floor junctions (see Fig. 4). In dwelling 4B no internal partition was present, so it could be considered as a “single room” apartment (133.5 m^3).

2.1.1. *Cross laminated results*

Figs. 5 and 6 show the results of impact noise measurements for apartments 3 A and 3 B at the frequency ranges 1000 Hz–5000 Hz and 100 Hz–800 Hz respectively. For these frequency ranges, final values are not influenced by the receiving room dimensions or tapping machine positions, thus indicating a great evenness of precast panels.

In the low frequency range (50 Hz÷80 Hz) impact noise level results could vary a lot especially in small rooms, as expected (Fig. 7).

The same trends were found in the single room apartment (Figs. 8 and 9) where no appreciable difference was evidenced for middle and high ranges while for low frequencies no common behaviour is demonstrable.

For all the measured floors, the normalized impact sound pressure level provides a similar linear trend in the 1000 Hz÷5000 Hz range with a little variation around 2500 Hz (Fig. 10).

In the 500 Hz–800 Hz range the behaviour is quite similar but the level difference is quite higher. Under this threshold, a common trend with high level variations until 100 Hz is recognisable. In the lower range no common tendency is assessable.

The increase in frequency at about 2500 Hz could be ascribed to the resonance caused by the ISO tapping machine laid directly on the wooden floor [17].

In order to compare only single index results, the weighted sound reduction index $L'_{n,w}$ determined with ISO 717-2 method [51] as well as $C_{I,50\text{-}2500}$ factor were calculated (Table 2). It is possible to understand once more that the single number differences are caused by low frequency range.

2.2. *Glulam beams with top boards structure*

The tested building was a three – storey construction where floors were tested on different receiving rooms (Figs. 11 and 12). Panels were constituted of glulam beams (18 cm thickness) connected with wooden chipboard screwed on top of them (2.2 cm thickness), mineral wool between them (10 cm thickness, 55 kg/m^3 density) and laterally fastened with wooden closures (Fig. 13). These panels are laid in order to match the external border, so it was possible to find an air gap between them. This was filled using high sound insulation foam (Fig. 14).

2.2.1. *Glulam beams with top boards results*

As for Cross Laminated Timber structures, the same considerations could be applied here: different bare floors results are very similar due to industrial production, so here for brevity only average final values are worthy of being presented. In Fig. 15 the bare floor impact noise is reported both without and with insulating foam inserted inside the air gap between panels. It is evident how the insertion makes the panels work together, thus providing

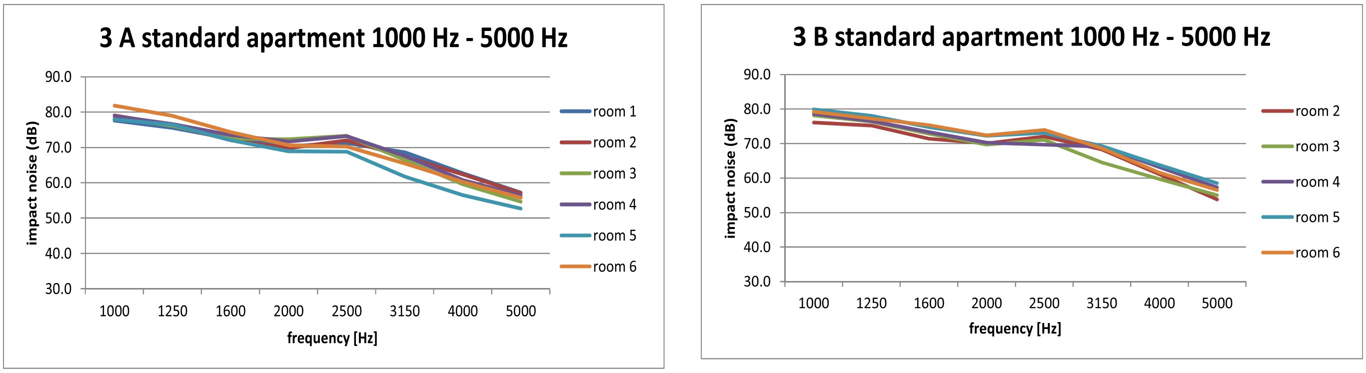

Fig. 5. High frequency trends for impact noise in apartments 3A and 3B.

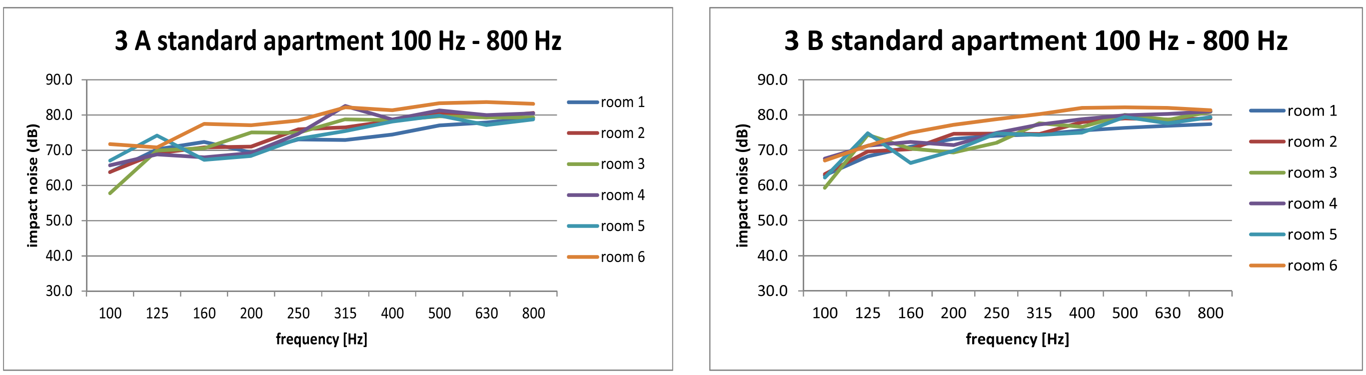

Fig. 6. Middle frequency trends for impact noise in apartments 3A and 3B.

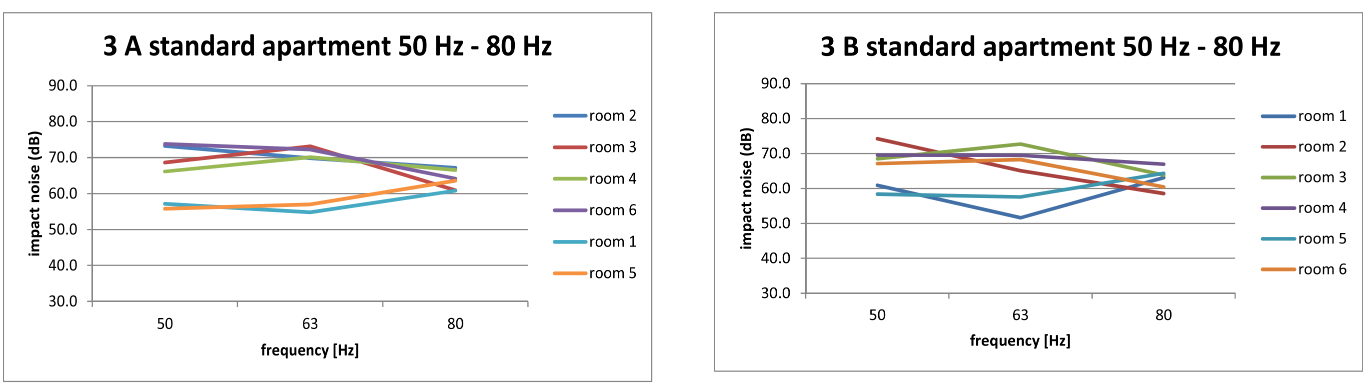

Fig. 7. Low frequency trends for impact noise in apartments 3A and 3B

more energy (more excited area) at low frequencies. Nevertheless, the airborne sound insulation performance improved. The single number value R'_w increased by 12 dB.

After these steps, a first floating floor was posed by the authors using the following layers (Fig. 16):

i. recycled cotton waste resilient layer (s' = 32 MN/m^3, d = 8 mm)
ii. marble powder in honeycomb paper panels (m' = 45 kg/m^2)

Then a second floating floor was laid upon the first one using the following coatings (Fig. 17):

iii. recycled cotton waste resilient layer (s' = 32 MN/m^3, d = 8 mm)
iv. two gypsum fibreboards (m' = 35 kg/m^2)

Impact noise tests using an ISO tapping machine were carried out (Fig. 18) and the influence of these sound reduction solutions is reported in Fig. 19.

Afterwards, a screwed ceiling was posed. This setup implies an additional plasterboard (1 cm thickness) underneath the timber floor. It was screwed on wooden beam (50 mm thickness) with a resulting air gap of 50 mm. In Fig. 20 the influence of the screwed

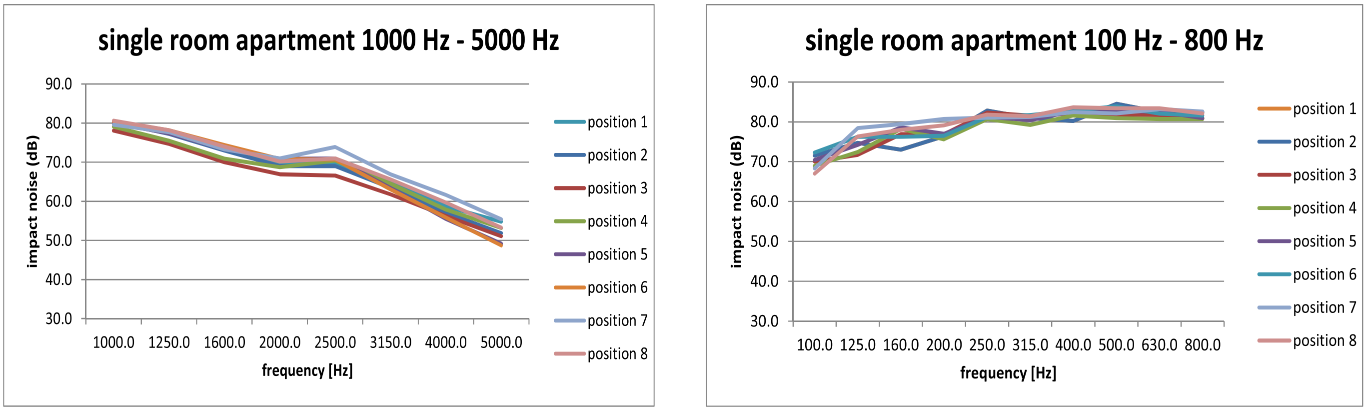

Fig. 8. Trends for impact noise in single room apartment: high frequency and middle frequency.

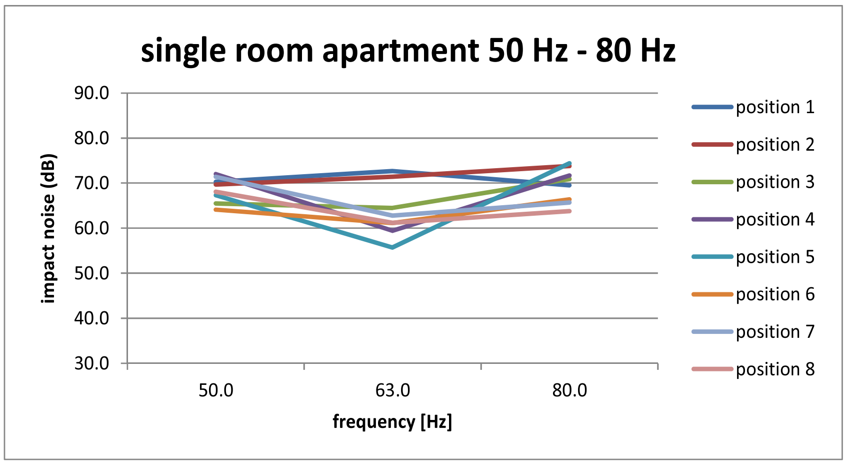

Fig. 9. Trends for impact noise in single room apartment: low frequency.

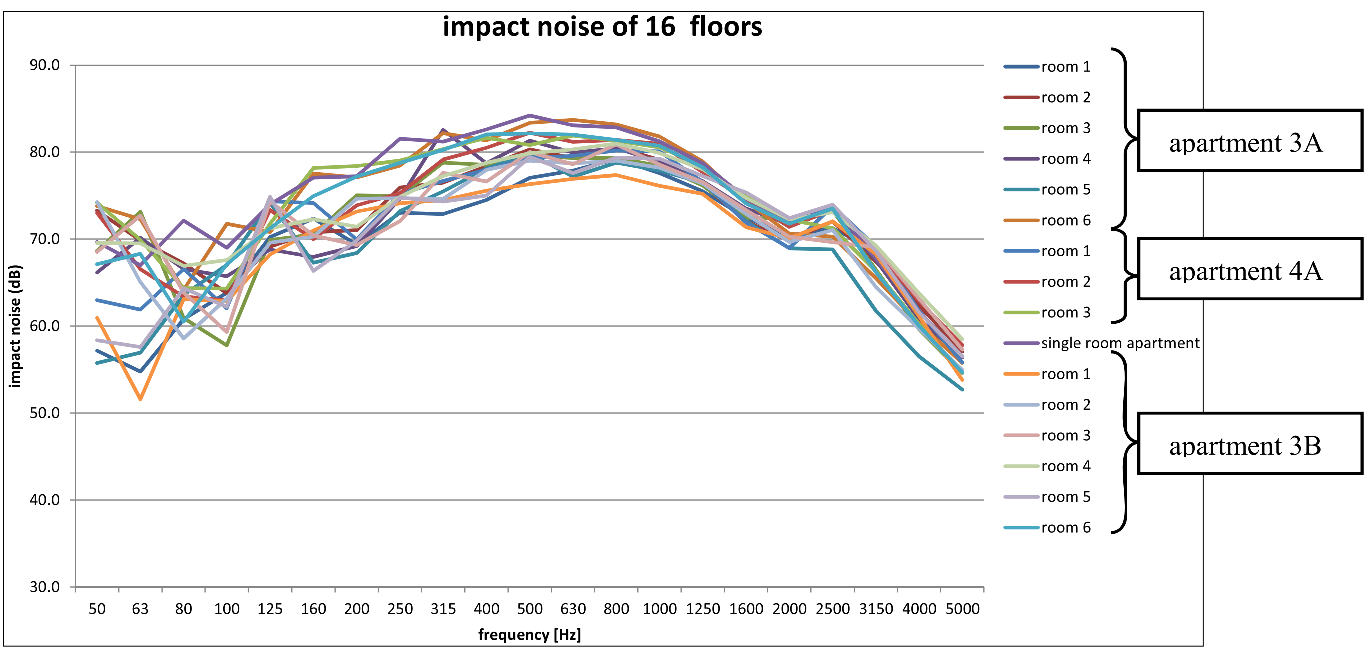

Fig. 10. Frequency trends for impact noise of 16 floors.

Fig. 11. Multi-storey glulam with top boards building.

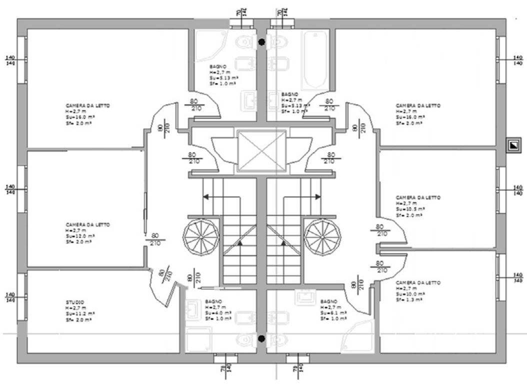

Fig. 12. Standard floor map.

ceiling is reported.

The worsening caused by the presence of this element is evident. At around 100 Hz its resonance frequency increases the impact noise, according to equation (4):

$$f_0 = 60/\sqrt{(m'/d)}\ [\mathrm{Hz}] \tag{4}$$

where *m'* is the mass per unit area [kg/m^2] of the plasterboard (6,5 kg/m^2) and *d* is the distance (0.05 m) from the floor structure [m].

In order to reduce this effect, the air gap was filled with mineral wool. This operation slightly lowed the middle frequencies but did not change the resonance influence on the impact noise.

2.3. Discussion of results

For the Cross Laminated Timber technology the average frequency trend was calculated using the 16 impact noise measurements reported in Fig. 10. At a latter time the linear regression was calculated in order to obtain a possible predicting equation of the impact noise of bare floor. The frequency trends are reported in Fig. 21.

The mean value of the frequency spectrum trend can be represented with the following equations:

$$L_{n,eq,avg} = -0.15\ (f) + 77.7\ (\mathrm{dB})\ \text{for}\ 50 < f < 80\ \mathrm{Hz} \tag{5}$$

$$L_{n,eq,avg} = 7.26\ \log\ (f) + 35.6\ (\mathrm{dB})\ \text{for}\ 100 < f < 630\ \mathrm{Hz} \tag{6}$$

$$L_{n,eq,avg} = -0.006\ (f) + 84.4\ (\mathrm{dB})\ \text{for}\ 800 < f < 5000\ \mathrm{Hz} \tag{7}$$

The calculated linear regression coefficient is $R^2 = 0.99$ for equation (5), $R^2 = 0.89$ for equation (6) and $R^2 = 0.97$ for equation (7)

A comparison can be carried out using the values provided by the literature for similar structures. In Fig. 22 the comparison between Cross Laminated Timber and timber concrete structures is reported. It is worth to note that the influence of the concrete slab starts from middle-high frequencies according to [14].

In Fig. 23 the comparison between different Cross Laminated Timber floors thickness is reported. It is evident that the influence of this parameter changes the frequency trend, altering the behaviour at almost every frequency. Nevertheless the comparison between laboratory results (Germany and Canada) shows how trends are almost the same and the difference is only depending on the thickness. This demonstrate once more the trustworthiness of measured data.

From the single index point of view, in Table 3, the normalized impact sound pressure index values, calculated according to ISO 12354-2 [9] are described. The first line reports the single index value calculated using ISO 717-2 methods [51]; for the 250 mm bare floor the frequency trend provided by equations (5)–(7) was used for calculation. No flanking transmissions were taken into account since the L_{nw} parameter was analysed (laboratory tests).

It is evident that the standard method does not provide reliable results. In fact it is suggested for homogeneous bare concrete floor

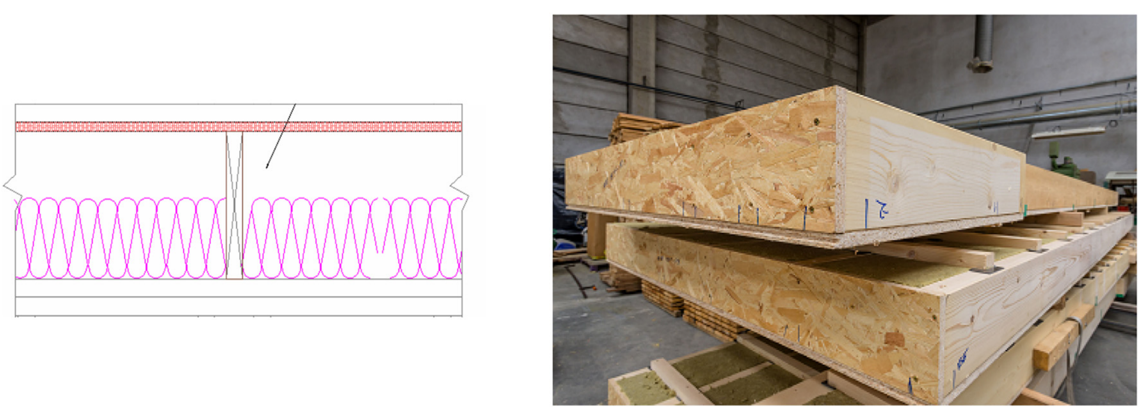

Fig. 13. Floor assembly scheme and closures detail. Materials and thickness from the top: 2.2 mm of wooden chipboard, 200 mm of wooden beams, 100 mm of rock wool density 55 kg/m^3.

Fig. 14. High sound insulation foam insertion.

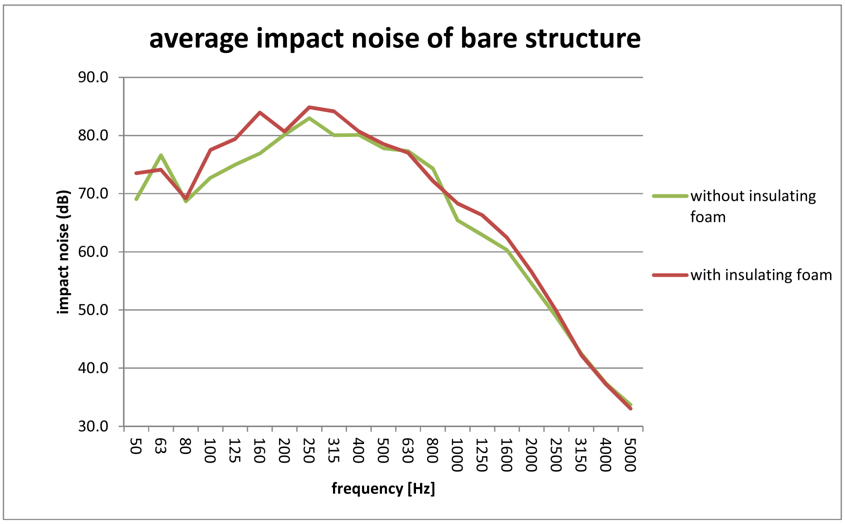

Fig. 15. Bare floor impact noise.

Fig. 16. First floating floor realization.

with a mass per unit area 100 kg/m^2<m'<600 kg/m^2. The provided results differ from the measured values up to 10.5 dB. Nevertheless, since this is the only available method, a correction is proposed according to equation (8):

$$L_{n,w,eq,corrected} = 134.5 - 25 \cdot \log(m') \text{ (dB)} \qquad (8)$$

where m' is the mass per unit area [kg/m^2] of the CLT floor. Using this method the measured and predicted results agree very well. These results are in a good agreement with literature one [50].

Fig. 17. Second floating floor realization.

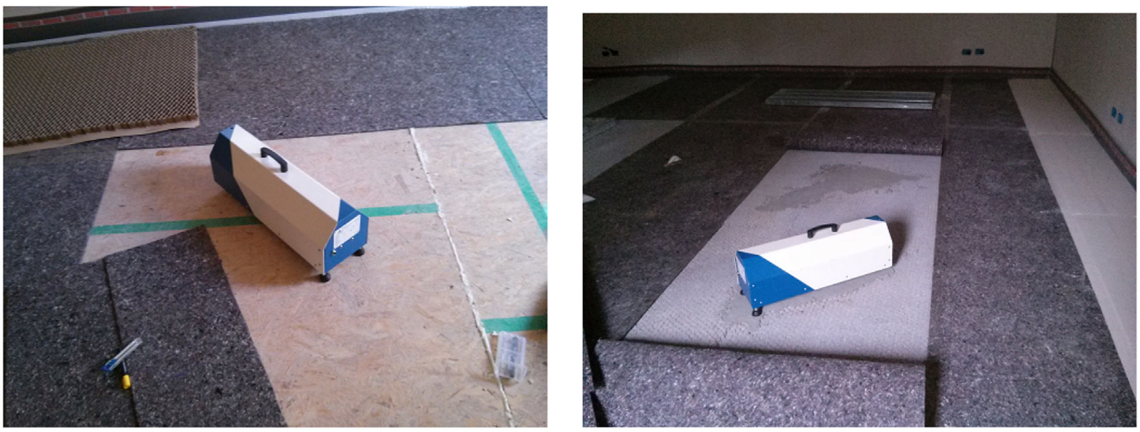

Fig. 18. Location of tapping machine during tests: bare floor (left) and first floating floor (right).

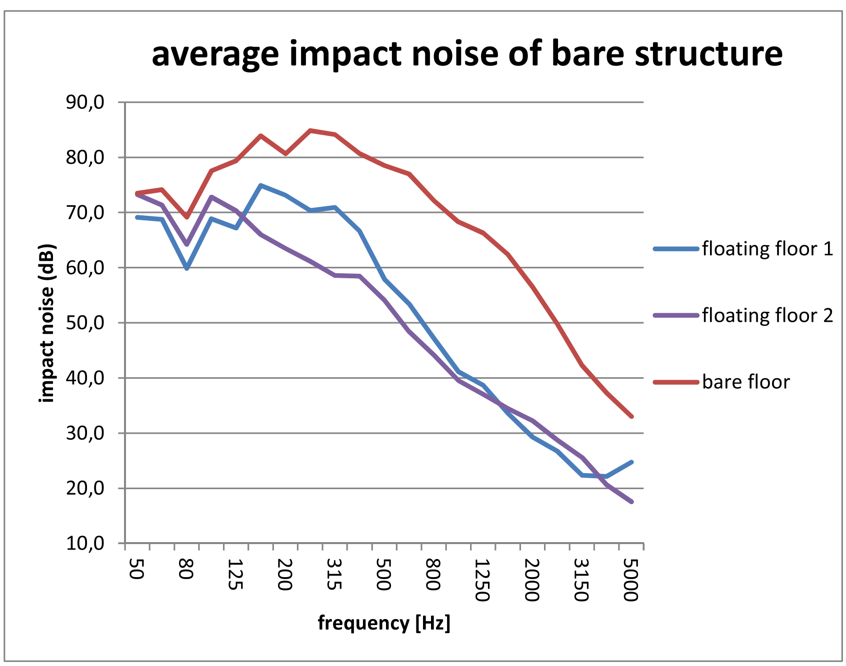

Fig. 19. Floating floors influence.

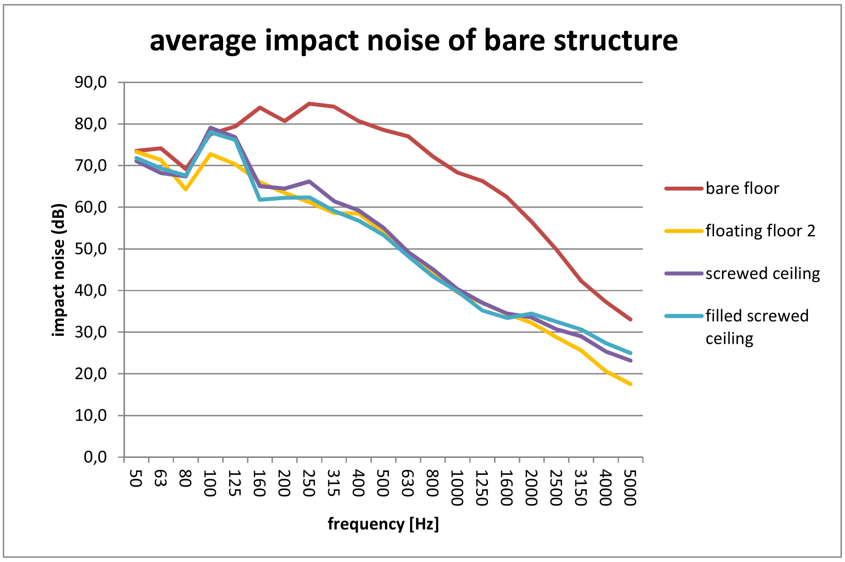

Fig. 20. Screwed ceiling effect.

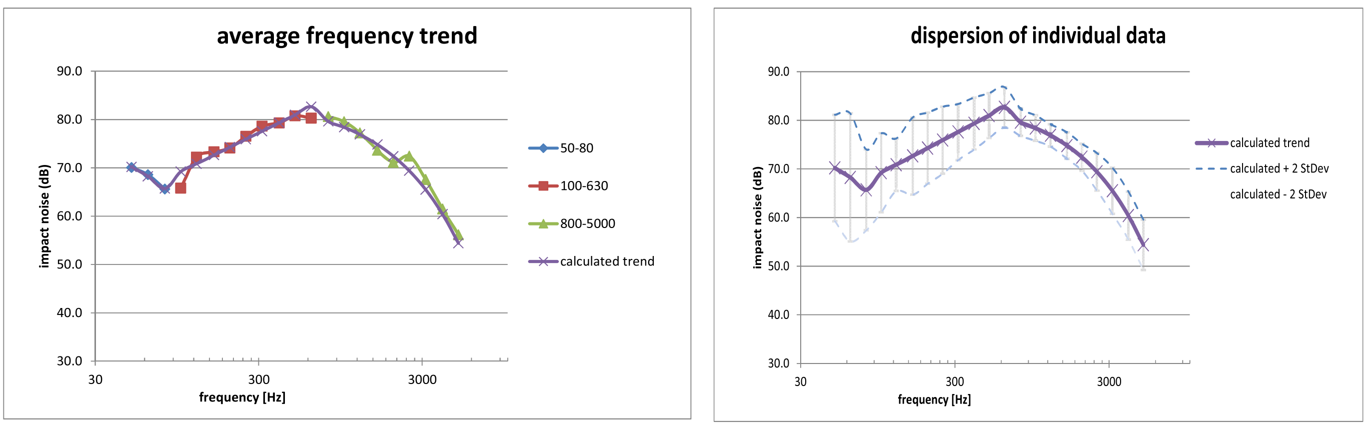

Fig. 21. Average frequency trends for impact noise and calculated linear regression and dispersion of individual data. 95% of the measured values are situated inside the yellow lined zone.

Table 1
General Cross Laminated Timber building data.

Conditions of the partitions	Bare Cross Laminated Timber on all surfaces
Room 1 3A/3B apartment	10 m^3
Room 2 3A/3B apartment	38.2 m^3
Room 3 3A/3B apartment	35.6 m^3
Room 4 3A/3B apartment	36 m^3
Room 5 3A/3B apartment	8.1 m^3
Room 6 3A/3B apartment	60 m^3
Apartment 4B	133.5 m^3

Table 2
Normalized impact sound pressure index values and $C_{I,50\text{-}2500}$ factor for Cross Laminated Timber bare floors of every tested room. Similar room are compared.

Apartment 3A	$L'_{n,w}$	$C_{I,50\text{-}2500}$	Apartment 3B	$L'_{n,w}$	$C_{I,50\text{-}2500}$
room 1	79	−7,6	room 1	78	−7
room 2	79	−5,6	room 2	79	−6,3
room 3	80	6,6	room 3	80	−6,9
room 4	80	5,7	room 4	81	−7
room 5	78	−5,8	room 5	80	−7,3
room 6	81	−4,3	room 6	81	5,3

For glulam beams with top boards, in Table 4 the comparison between ISO 12354-2 normalized impact sound pressure index models (see equation (9)) and measured values is shown. Presented results were calculated using the average of all tests.

$$\Delta L_{nw,\text{single number}} = 30\cdot\log(500/f_0) + 3\ (\text{dB}) \tag{9}$$

where f_0 is the resonance frequency of the floating floor.

It is clear that the relation is not applicable with timber structures since the bare floors are not of infinite mass in comparison with the floating layers. The difference in mass is reduced ($m'_{\text{barefloor}} = 130$ kg/m^2 whether $m'_{\text{overall floating floor}} = 80$ kg/m^2) in comparison with a concrete bare floor ($m'_{\text{concrete}} = 600$ kg/m^2) or beam and pot ($m'_{\text{beam and pot}} = 340$ kg/m^2). The focus is the impact of the traditional floating floor; since the flanking transmission value are constant from bare floor to covered floor the measured final values are influenced only by the additional floating layer.

In Table 5 a comparison of the sound reduction index of an ideal floating floor, used as example, on different structures is presented, using the frequency of Cremer's relation [10] reported in equation (9).

The floating floor is composed of a high density coating (90 kg/

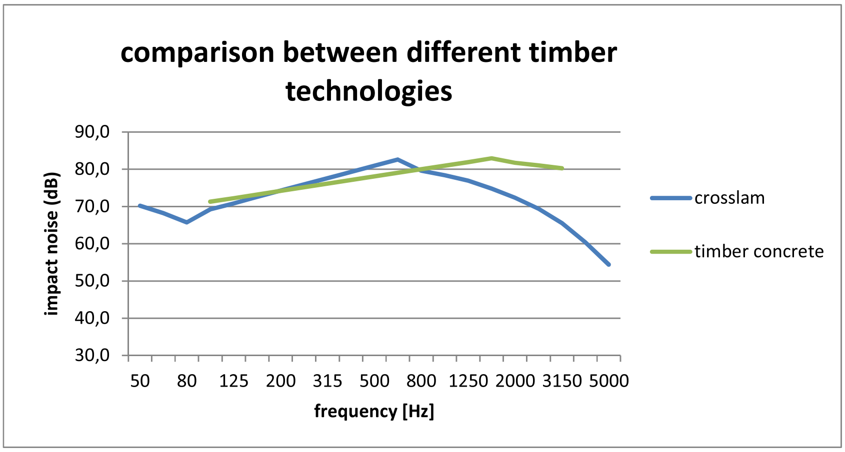

Fig. 22. Comparison between Cross Laminated Timber (equations (4)–(6)) and timber concrete [33] floors.

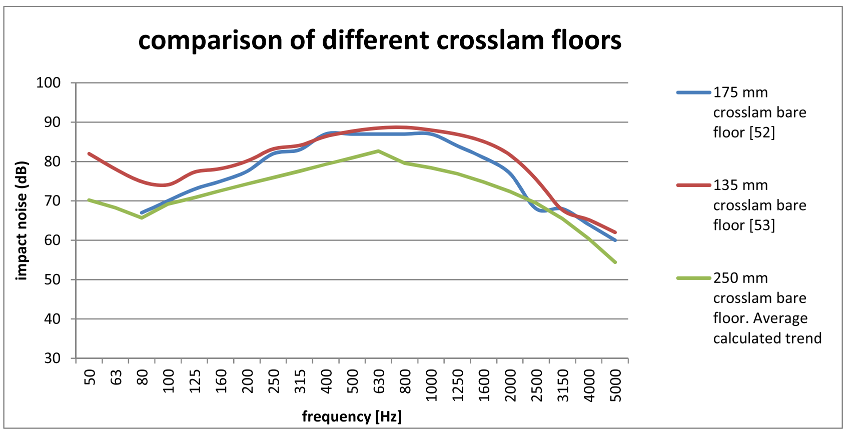

Fig. 23. Comparison between different thickness of Cross Laminated Timber floors: average calculated trend (equations (4)–(6)), and literature data [52,53].

Table 3
Normalized impact sound pressure index values for Cross Laminated Timber bare floors.

	135 mm bare floor [53]	175 mm bare floor [52]	250 mm bare floor eqs. (5)–(7)
Measured L_{nw}	88	85	80
$L_{n,w}$ according to ISO 12354-2 model	98.5	94.6	89.2
$L_{n,w}$ according to ISO 12354-2 modified model	87.7	84.9	81.0

Table 4
Floating floors normalized impact sound pressure index prediction for glulam bare floor. Single number identification.

TIMBER	Mass per unit area [kg/m^2]	Measured Normalized Impact sound pressure index $L'_{n,w}$ (dB)	Predicted Normalized Impact sound pressure index $L'_{n,w}$ (dB)	Difference (dB)
Bare floor	130	76	–	–
Floating floor 1	45	64	54	10
Floating floor 1 + 2	80	58	46	12

m^2, 50 mm thickness) and a resilient layer (s' = 16 MN/m^3).

Here, it is evident how the same impact sound reduction solution provides very diverse performance, depending on the type of bare horizontal partition. This result depends on the different distribution of the exciting energy coming from the ISO tapping machine [54–58] and on the specific limit of floating floor technology: low frequency reduction.

In Fig. 24 the impact noise of different bare floor technologies is presented. Traditional beam and pot and timber concrete floors tested previously by the authors [33] and laboratory test of concrete one [59] provide an interesting comparison. As a matter of fact, timber based structures provide more low frequency energy (up to 20 dB) than the concrete based ones, involving a lower floating floor influence on them.

Another feature concerns the high frequency trend. Timber concrete, concrete and beam and pot structures provides energy at

Table 5
Floating floor effect on same thickness different bare floor technologies using frequency Cremer's relation. Frequency trend calculation.

	Mass per unit area [kg/m^2]	Measured Normalized Impact sound pressure index of bare floor (dB)	Predicted Normalized Impact sound pressure index reduction of floating floor (dB)
Glulam	130	76	14
Concrete [59]	600	81	33
Beam and pot [33]	340	87	41

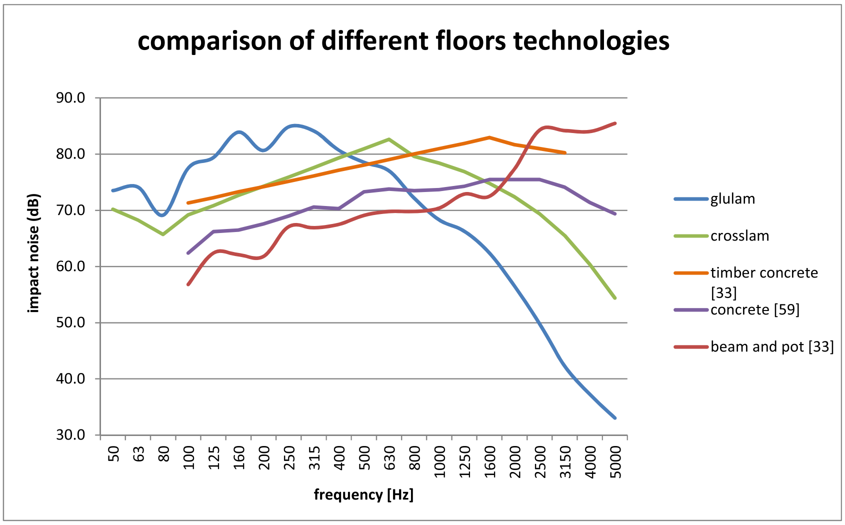

Fig. 24. Comparison of different bare floor technologies of impact noise: glulam, Cross Laminated Timber, timber concrete [33], concrete [59], beam and pot [33].

high frequency. This is highlighted also in hybrid cross laminated timber bare floors (CLT with an additional concrete layer) [60,61]. The high frequency sound pressure level is caused by the impact of the ISO tapping machine on concrete slab rising the trend and the final single index value.

The mineral wool effect on impact sound reduction is evident in glulam beams with top board partition, especially at high frequency according to [62]. Nevertheless, this range is the one in where the floating floor acts best. Once more its influence cannot be highlighted since this type of structures does not provide an ideal condition for the use of this sound reduction technology.

Finally, for the extension of the proposed formula to all type of floors, the flanking transmissions have to be considered and evaluated.

In the CLT case study, the transmission paths were identified both in CLT and GLT walls (lighter than the CLT tested floors), whether in the other one only timber frame structures were present.

Connection methods of cross laminated timber element affect the radiation efficiency of the bare construction. This is basically due to the fact that in laboratory all the mounting tolerances are very controlled. But the in situ situations will be surely different since there is no control in mounting tolerances and very different screws or angle brackets could be used as evidenced by Barbaresi et al. [49]. Nevertheless, the same authors conclude that if all the differences were due to the mounting tolerances, one could draw the conclusion that in situ realizations will provide a more uniform behaviour among the panels due to the greater number of constraints [ibid.]. In other words in situ realization are less affected by fastening systems, since they are more rigid tan laboratory ones.

This fact is now confirmed since from the mass ration point of view, flanking walls were various: CLT or GLT ones. Referring to Table 2, it did not seem to affect the final single number results. Hence a preliminary conclusion could be drawn: if the flanking walls are lighter than floors, then the influence of CLT and GLT flanking path difference could be very low.

As a matter of fact prISO12354-2 [63] does not include mixed structures evaluations since in section concerning the GLT technology the crosslam one is explicitly excluded. The topic of flanking transmissions in CLT-CLT constructions is implemented within pr ISO 12354-1 where a possible formulation is provided according to literature [64]. Here, no influence of the screwing or bracketing systems is descripted or requested, because it is almost impossible for designers to forecast how many fastening system will be used during construction and of which type, diameter or length.

Therefore, the validity of the proposed formula is limited by the assumption of similar connection conditions between the structures. To extend the results to other types of connections between nude structures also this aspect have to be considered and further investigation had to be performed.

3. Conclusions

In situ measurements on full-scale timber constructions were used to investigate the frequency behaviour of impact noise of bare floors and the influence of floating floor technology on timber horizontal partitions.

Two main typologies were analysed: Cross Laminated Timber and Glulam with screwed top boards. Results clearly indicate how the industrial production method of timber structures provides a very good repeatability and reproducibility of the measures on both technologies since all panels are manufactured, transported and assembled in the same way.

A new frequency model for impact noise of Cross Laminated

Timber bare floors is proposed and validated using literature, laboratory tests and in situ measurements, showing a bell trend with the peak centred on middle frequencies (315 Hz–1250 Hz).

Comparison between timber and traditional technologies is provided, showing how wooden structures irradiate up to 20 dB more energy in the low frequency range while concrete hybrid structures provide high frequency energy due to the influence of massive slab. A correction of the ISO 12354-2 model for single number prediction is proposed, related to Cross Laminated Timber structures.

Furthermore, the influence of floating floor is analysed on a GLT bear floors and a step-by-step measurement was performed after the realization of two different floating floors. The results highlight the minor impact of this technology on lightweight structures compared to the heavyweight traditional ones because of the big bare floors difference of mass per unit area.

Finally, the influence of mineral wool and screwed ceiling shows how the former acts on high frequencies and influences the effect of the floating floor, while the latter worsens the final impact noise level because of its resonance frequency. The suspended ceiling act as the best way to reduce impact noise while the fastened ceiling act as an additional radiant layer aggravating the noise level at its resonance frequency.

Author contributions

All authors contributed equally to the conception of this study.

Acknowledgments

This research was funded with a Ph.D scholarship by MIUR (Italian Ministry of University) which is gratefully acknowledged.

Appendix A

Abbreviation list

L_n	Resulting impact noise
$L_{n,0}$	Impact noise of the bare floor
ΔL	Impact sound pressure level reduction
f	frequency
f_0	resonance frequency
s'	apparent dynamic stiffness per unit area
m'	mass per unit area
$L'_{n,T}$	Impact noise in situ measured or calculated levels
$C_{I,50\text{-}2500}$	Correction coefficient for 50 Hz–2500 Hz frequency range
R'_w	Airborne sound insulation in situ measured value
d	distance
$L_{n,eq,avg}$	Impact noise level of regression calculation
R	calculated linear regression coefficient

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