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Acoustic and thermal properties of timber constructions: theoretical and experimental investigation

Settore Scientifico Disciplinare ING-IND/11

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Preface

Lightweight buildings are present worldwide and their construction trend is growing, pushed by the Kyoto protocol. They allow CO_2 storage, since wood is widely used as it is renewable and environmental friendly raw material. Generally, these constructions are built within industry plants where very few waste and little energy consumption are possible and allowed. Furthermore, prefabrication often mean high quality since educated workmanship is used, as well as CE certifications are required. The production methods generally include CAD-CAM technologies, permitting new and complex architectural shape, concept, tendencies (fashion trends).

The speed of assembly is an interesting point since it is possible even to obtain multi-storey buildings within prefabricated volumes. As a matter of fact, within two week, a multi-storey building could be constructed thanks to the previous high in-depth design and industrial production precision.

In years many researchers try to handle with these new topics but what they found is very difficult to understand at a first view: timber structures are various. Every producer, every industrial plant, every designer presents different solutions using the same raw constructing materials and features: wood, wool, boards. Besides, multiple joints, screws, fastenings and locking are possible and every precast wall, floor or roof presents different types of junction

The aim of this study is to investigate the acoustic and thermal behaviour of timber construction and to provide new predicting models able to fit precast lightweight edifices request.

The work starts with an in-depth literature overview on acoustic properties these structures concluding that there is the need to investigate many aspects related to the inner comfort:

1) bare floors acoustic behaviour
2) influence of floating floors on timber horizontal partitions
3) resilient layer influence and their time-dependent performances
4) natural/recycled layer impact noise attenuation
5) windows energy performances and possible correlation
6) service equipment acoustical design using ISO 12354-5 models
7) influence of the subjective evaluation of lay people on precast building
8) low frequency noise objective evaluation inside apartment

Though, for every issue, a dedicated section is present herein containing a brief introduction on the theme, a description of materials and methods used, a dissertation of the obtained results and a final discussion. All section end with dedicated conclusions and references.

1 Acoustic of lightweight timber buildings: a review

1.1 Introduction

Lightweight buildings are present worldwide and their construction trend is growing, pushed by the Kyoto protocol [1]. They allow CO_2 storage, since wood is widely used as it is renewable and environmental friendly raw material. Generally, these constructions are built within industry plants where very few waste and little energy consumption are possible and allowed. Furthermore, prefabrication often mean high quality since educated workmanship is used, as well as CE certifications are required. The production methods generally include CAD-CAM technologies, permitting new and complex architectural shape, concept and tendencies.
The speed of assembly is an interesting point since it is possible even to obtain multi-storey buildings within prefabricated volumes. As a matter of fact, within two week, a multi-storey building could be constructed thanks to the previous high in-depth design and industrial production precision. In Figure 1 an example of wall assembly is shown: from a) to c) the precast panel fits perfectly in to the spaces of the flanking walls. Using crane, its trip starts from the truck, ends upon the final position falling in its pre designed location. Then it is fixed using long screws.

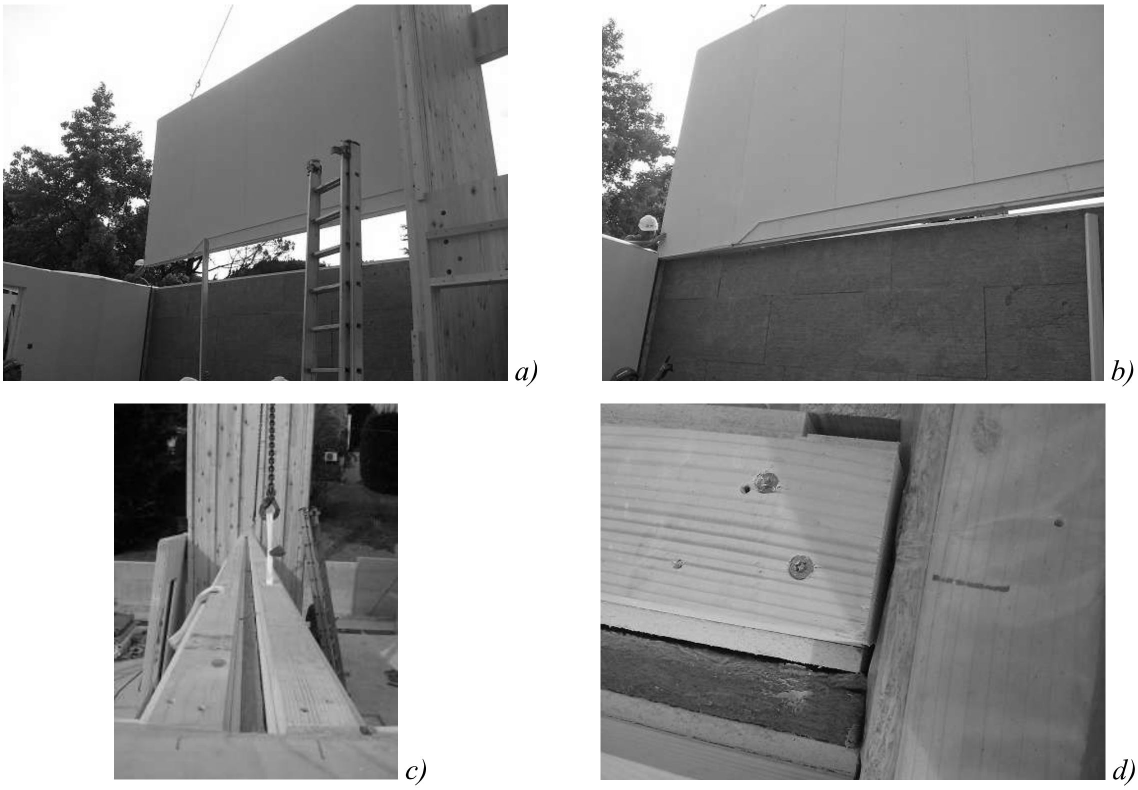


Figure 1 – Example of wall assembling in a multi-storey light weight timber building. From a) to c) the panel is let down using crane. In d) the high requested precision and accuracy is highlighted

Finally, normally customers request the use of recycled - natural insulating materials and then their behaviour have to be investigated [2].Nevertheless it is very few years since multi-storey timber construction are possible e.g. in Europe [3], Japan [4], New Zeeland [5] and so many issue are grown in last years. One of these is sound insulation.

In years many researchers try to handle with these new topics but what they found is very difficult to understand at a first view: timber structures are various. Every producer, every industrial plant, every designer presents different solutions using the same raw constructing materials and features: wood, wool, boards. Besides, multiple joints, screws, fastenings and locking are possible and every precast wall, floor or roof presents different types of junction (Figure 2).

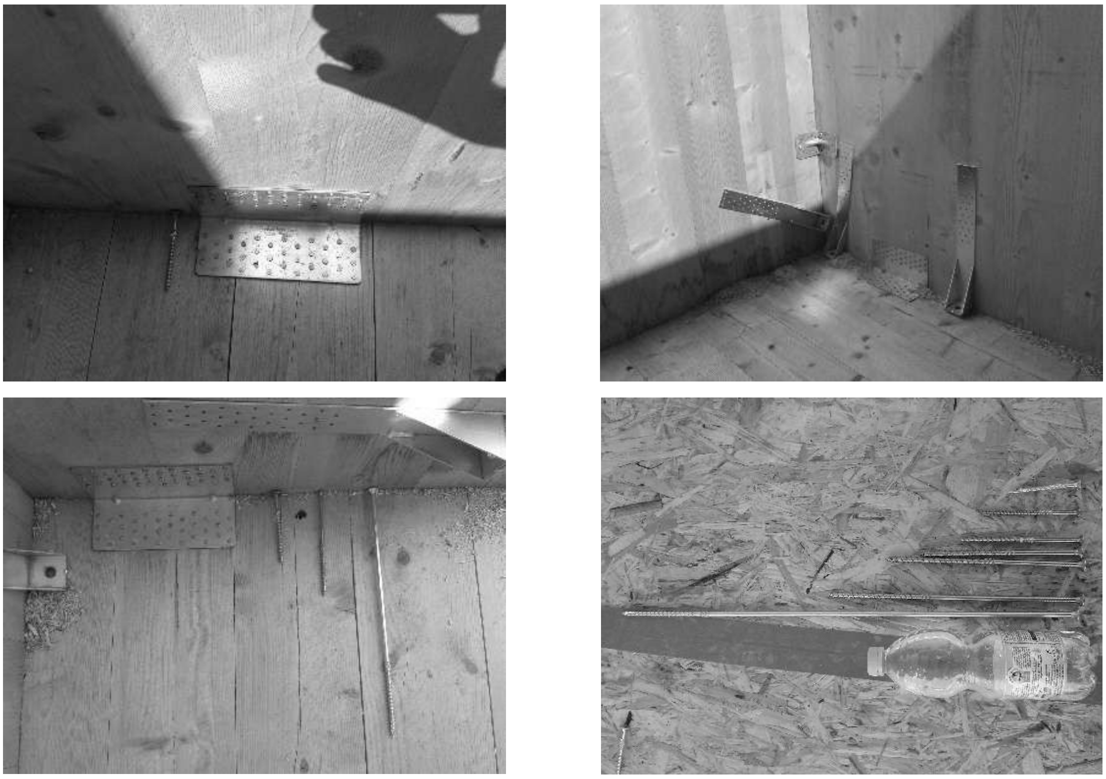


Figure 2 – different types of screws, joints and junctions used with precast timber panels. Picture from different building constructions

Furthermore, it turns up to be rather approximated to use the same prediction methods or analysis used for heavy weight constructions. Bettarello et al. [6] show how different bare floors (heavy weight, beam and pots and lightweight) present dissimilar impact sound pressure level and the consequent floating floor sound reduction [7] could not assures same results.

It is possible to find the same conclusion for vertical partitions too [8]-[10]. On this topics the authors demonstrate how sound insulation is affected by low frequency and underline the difficulty to predict composite walls insulation in this range [11]. In the same paper, many prediction methods applicable for sound insulation in timber structure are described. The study divides them into two different categories: i) energy combined with empirical knowledge and data approach and

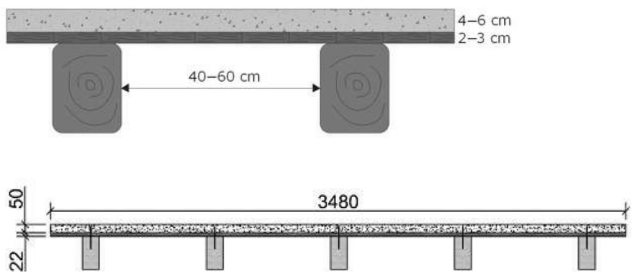
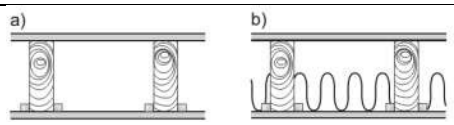
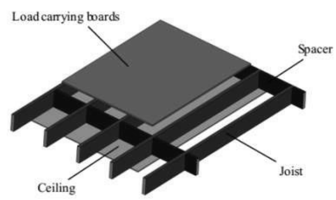
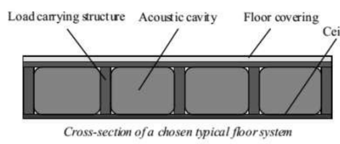
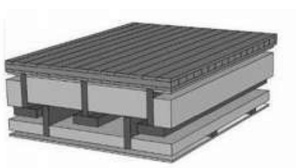
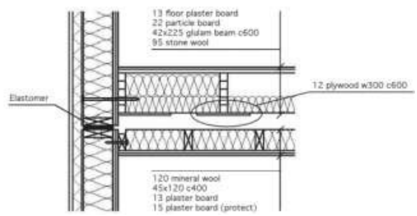
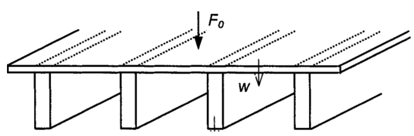
ii) deterministic, numerical and analytical approach. The overview concludes that there are good models handling point forces, radiation and periodicity and the authors intend to use this latter as suitable for timber structures.

From subjective point of view, many investigations are possible, since it is not clear if people living inside lightweight buildings feel better wellbeing compared to heavy weight structures [12].

The aim of this literature overview is to understand the state-of-art of the acoustics research results on lightweight timber buildings and to understand different structure performance. A graphical summary of how many possible structures are present is reassumed in Table 1.

According to Table 1, paper is sorted in to different sub section analysing separately different technologies. In the first section dedicated papers on impact sound pressure level both of bare and treated floors are presented. Afterwards, airborne sound pressure level, new prediction methods and subjective response are investigated. The overview ends with final evaluations and conclusions.

Table 1 – Types of lightweight bare partitions included in literature

Code	Description	Graphic representation (from papers)
A	Timber-concrete floor. It consists of timber structure of glulam beams with wood/plaster board(s) screwed on it. An additional layer of concrete is added on top [6],[49].	
B	Particle or gypsum board on top of wooden glulam beams with screw attaching the boards to the beams. The use of wool between beams and/or ceiling/suspended ceiling (made of plaster or chipboards or cross laminated timber) is often present. See as example [15]-[22]. These structures could be both walls and floors.	     

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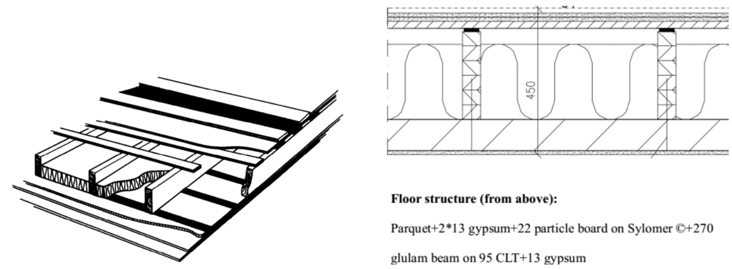
<tr><td></td><td></td><td>
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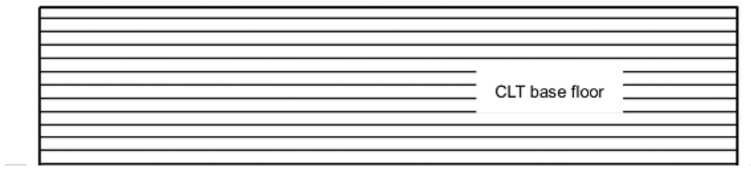
<tr><td>C</td><td>Cross laminated timber [23]-[24]. These structures could be both walls and floors.</td><td>
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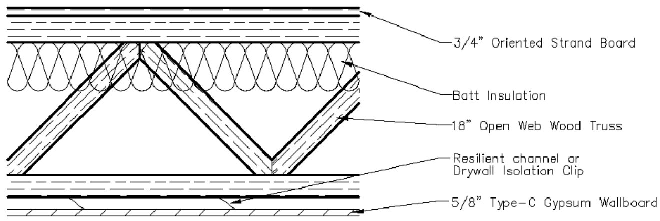
<tr><td>D</td><td>Wood Frame open-truss [25].</td><td>
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1.2 Impact sound of horizontal partitions

Many studies are present in literature concerning the determination of bare partition performance as well as floating floor-suspended ceilings effects and subjective response to vibrational excitation.
The determination of frequency trend of bare floor is of paramount importance [6]. The method presented in EN 12354-2 standard [13] provides the possible impact sound reduction according to equation (1):

(1) $$L_{n,W}=L_{n,W,eq} - \Delta L_W \quad \text{(dB)}$$

where $L_{n,w}$ is the resulting impact noise (dB), $L_{n,w,eq}$ is the impact noise of the bare floor (dB), ΔL_w is the impact sound pressure level reduction (dB).
It is clear that the bare floor acts as a starting point and so the type of partitions is the primary source. In timber structures there are many and very different technologies.
The common issues are focused on low frequency range: impact sound pressure level is higher in lightweight wooden buildings than in heavyweight ones. Though, the noise caused by walking neighbours is object of most protests in apartments [26].

Type A

The A technology is more studied and probably more used in Mediterranean country. Bettarello et Al. [6] performed in situ ISO tapping machine measurements in order to investigate the impact sound pressure level of three kinds of bare floor, including the type A. The results provide an empirical equation useful to be used as input data for EN 12354-2 model. This equation takes in to account the frequency trend as follows:

(1)
$$L_{n,eq,avg} = 10.4\log(f) + 50 \quad \text{(dB)} \qquad \text{for f} < 1600 \text{ Hz}$$
$$L_{n,eq,avg} = -6.1\log(f) + 129 \quad \text{(dB)} \qquad \text{for f} > 1600 \text{ Hz}$$

On the other hand Martins et al. [14] investigate the same structure using laboratory ISO tapping machine tests adding on the top of the bare structure a floating floor, then studying the influence of suspended ceiling. Then all results are compared with European requirements [27] stating that the bare structure does not fulfil any limits while the addition of ceiling does.

Hiramatsu [28] tested a three-story full scale school within type A floor, using three different sources: car tire, rubber ball and tapping machine. The results show a similar ISO tapping machine frequency trend compared to the previous studies tests, but the other two sources, as expected [29]-[32], provide very different behaviours and the author concludes that the best source for A type is the car tire while on the other hand Bettarello doesn't [6].

Type B

The B technology is the most studied and presents much more variants. The ones shown in Table 1 are just few available studied cases and typologies. In order to point out which of the numerous parameters of type B floor are important, Brunskog and Hammer [15],[16] investigated the structure using analytical models considering the excitation force and the interaction of ISO tapping machine on lightweight floors [29]. Their conclusions report the following considerations:

- mineral wool (of different flow resistivity) in cavity reduce the impact noise starting from 250 Hz
- different mass plates gives better performance instead of just a heavy one
- the periodic distance of the beams influences the low frequency range
- the construction depth decreases the impact noise and when the wool is present the reduction could rises up to 15 dB.

What is more interesting is that the low frequency range is caused by the structure itself and does not significantly vary if big changes (high density added layer, very thick suspended ceilings, etc.) aren't applied on it. Coguenanff et al. [17] state that strongly dominant modal behaviour is present below 200 Hz. According to the COST action FP90702 report [34], the wooden structures present a better insulation in middle and high frequency range than the heavy weight ones. Though, the low frequency influence has to be further investigated. Johansson [22] carried out tests in a series of timber floors arrangements in order to understand the influence of different layers and beams and concluded that in most cases when an improvement is seen at low frequency range, the structures show high frequencies worsening.

Sjöström et al. [35] focused on top layer consisting of one or two attached chipboards. Using vibration measurements method in low frequency range (10-600 Hz) they conclude that the low frequency energy propagation is lowered by the second not overlapping layer. Nevertheless as previously found [22] at higher range this benefit disappears.

Chung et al. [36] measure several examples of lightweight timber based floor/ceiling systems, having higher sound insulation performances than the concrete slab based ones. Via laboratory vibration measurements they obtained the resonance frequencies and the modal shape. Then three upper layers were put on the top of the basic structures. The conclusions (using ISO tapping machine) show how the inclusion of sand-sawdust mixture layer provides effective vibration dampening of the whole composite structure over a wide frequency range.

Späh et al. [37], [38] realized measurements with different sources both in laboratory and in situ. Both ISO tapping machine, rubber ball and "real" sources (walking people) were used. Then a subjective survey was realized to compare which source is most appropriate to represent real walking noise. The results show how both rubber ball and ISO tapping machine are good to represent the real walking noise.

On the other hand Hiramatsu et al. [39] investigated floor impact sound insulation on a full scale timber construction, using rubber ball, car tire and tapping machine. Results present a difficulty in the case of rubber ball source: many changes were found due to different source positions. Therefore, from measurement method viewpoint, the excitation position needs to be taken in to account.

Lentzen et al. [40] handle with the flanking transmission issue. The authors state that the ISO 12354 [13] methods could cope only with heavy monolithic buildings. Though, the adaptations and points of interest for lightweight buildings are analysed. FEA-SEA simulation models are used and results are compared. The paper concludes that good indications could be provided using these methodologies.

Ingelaere [41] and Wuyts [42] point out that the investigation of the perceived (dis)comfort has to be performed below 50 Hz even down 20 Hz implying a new single rating indicator. Blazer [43] noted that the footfall noise rise its peak below 100 Hz as well. Nevertheless this topic is very difficult to realize since new in situ measurements standards ISO 16283 [44] do include the low frequency procedures but they are not compulsory yet. Furthermore the methods provide a 50 Hz – 5000 Hz range and so no investigation outside this scale is even possible so far. As a matter of fact, the new standards include rubber ball impact source outlining that it is suitable for assess the bare feet walking and children jump; though the standards connect these results to human disturbance and state an international method to realize what Ingelaere and Wuyts suggested.

Back to their publication, in [42] a very interesting survey on basic design and stereotype errors is reported. The authors clearly state why the sound reduction on a floating floor on to light weight floor provides minor performance: the mass-spring-mass effect is much lighter than heavy weight construction. This fact has to be investigated and clarified and though a brief deepening is descripted below.

The sound reduction on a floating floor ΔL_w (see equation 2) depends on Cremer theory:

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

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:

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

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

Floating floor technology is based on the mass-spring-mass effect as shown in Figure 3: m_1, called "infinite mass" is the structural and static mass; the spring effect is ensured by the resilient layer (where k is the elastic constant) acting with m_2 as a "resonant system". The whole system decreases the impact sound pressure transmission emitted by footsteps, object fall, etc.

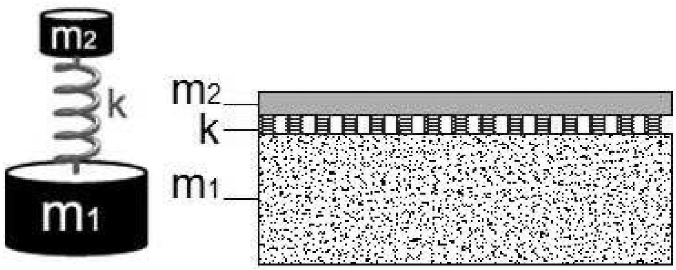

Figure 3: Floating floor representative scheme [45].

In light weight construction various issues are involved:

I. the m_1 contribution is quite smaller than the solid floors due to much lighter masses involved

II. the m_2 influence is very resized compared to heavy weight construction tradition

III. the dynamic stiffness of the resilient layers is not always effective.

In the first case the masses difference is easily calculated. In ISO 12354 [13] and ISO 10140 [46] standards the solid reference heavy weight floor has a mass per unit area at about 300-350 kg/m^2. On the other hand the reference lightweight floors masses are 120-200 kg/m^2; so the difference is at about 50 %.

In the second case, the usual m_2 value is 100 kg/m^2 according to ISO 10140 [46] and EN 29052-1 [47] and in situ realization normally respects this rule. On the other hand, traditions, stereotypes, habits, practices etc. imply the use of different technologies from heavy weight buildings and though the m_2 mass is limited and often not efficient.

Because of the same reasons, resilient layers are frequently characterized by higher values of dynamic stiffness, causing a less efficient sound reduction. It is worthy to highlight that not because a recycled or natural resilient layer is chosen, then the dynamic stiffness will be higher [48]-[53].

Moreover, in [42] the authors stress the point that the ISO tapping machine excites the heavy and light weight floor in two diverse ways: in the first one it generates more high frequencies whether in the second one more sound power is radiated in low frequency range. Finally, the ceiling fixed on wooden battens contributes to radiate low frequency noise and then a suspended solution is suggested.

The aim of Sjöström et al. [54], using real and simulated floor, is to model the human walking. A previous work by Bard et al. [55] investigated the direction and deflection of human walking on timber floors. The aim of these two papers is not an easy task yet because deciding which correct force profile to use requires further investigation. The literature contains multiple force profiles for different walking speed, shoe type and gait and so the authors concluded that a final robust results is far to come.

De Geertere and Ingelaere [56] compared the heavyweight performance to the lightweight ones. The former is considered as reference. A $L_{n'T,w}$+ $C_{I,50\text{-}2500}$ of 48 dB is requested as desired parameter for both floor technologies. The authors report that in order to achieve this aim it is possible to use suspended ceilings [34] or adding a concrete or sand slab [57] or a sand-sawdust layer [36]. In the authors' opinion, timber industry will not apply these systems because of cost and/or market issues. So, they try to handle this topic realizing a mock-up and studying the influence of reduced sand layer and line-wise resilient connections between the joists; the solution was investigated and optimized.

On the same topic, Chung and Emms [58] studied the influence of 8.5 cm sand-sawdust upper layer determining that it acts as a damping vibrator insulator.

Type C

The cross-laminated timber (CLT) panels are constituted of thin beams or planks laid on top of each other and, using high pressure, glued together in order to form a solid uniform board. Though, the horizontal (as well as vertical) partitions seem to behave like homogenous slab. Very few studies are present in literature for this kind of structure. Nevertheless this technology is commonly used in Europe, North America, Australia, New Zeeland, etc.

In his work [23] Byrick present laboratory tests showing the frequency trend of a 175 mm bare floor (Figure 4) and then compare different improvements for noise reduction.

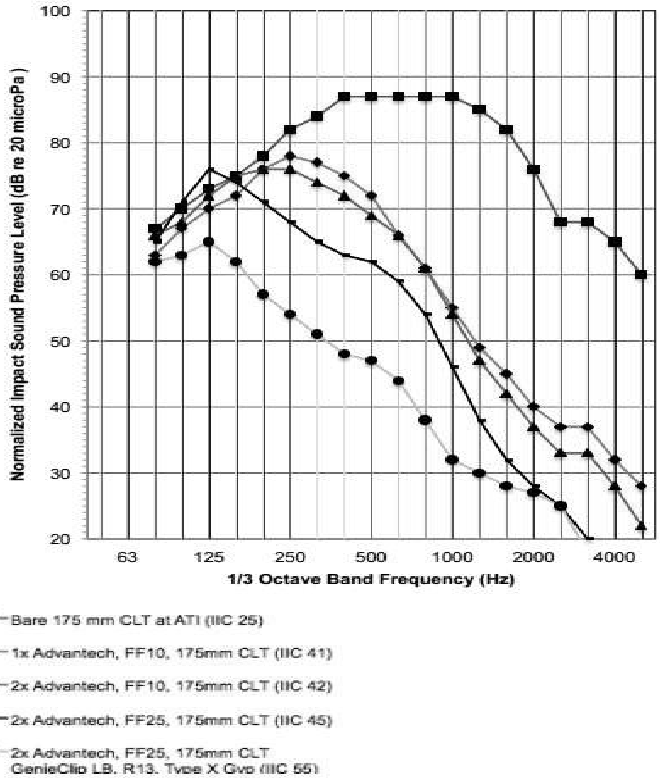

Figure 4 – Laboratory measurements of CLT floor [23].

If the homogeneous mass hypothesis is applicable to C typology, then the $L_{n,w,eq}$ value is obtainable using ISO 12354-2 [13] method:

(5) $$L_{n,W,eq}=164-35log(m') \quad \text{(dB)}$$

The results are reported in Table 3. It is evident that no homogeneous mass hypothesis could ever be proved on CLT impact noise of bare floors. The main difference lies at high frequencies where the ISO tapping machine excites the timber floor differently to concrete ones [42].

Table 2 – $L_{n,w,eq}$ values obtained using ISO 12354-2 method and laboratory measurement

description	ISO 12354 $L_{n,w,eq}$ (dB)	Measured $L_{n,w,eq}$ (dB)
CLT floor. 175 mm thickness [23]	94	85
CLT floor. 135 mm thickness [59]	98.5	88
Concrete floor. 140 mm thickness [60]	79	81

In their work, Völt et al. [24] aimed to understand the vibrational response and the sound transmission using vibrational tests and FEM models; the influence of the floating floor and suspend ceiling were investigated too. Results show how there is no clear correlation between suspended ceiling eigenmodes and the radiated sound power.

Type D

For type D technology only one conference paper appears so far, describing its noise impact and the influence of different added layer or ceilings. Though, the interest on this singular technology is very low at the moment.

1.3 Airborne sound insulation

Type A

The only works concerning this technology and reporting an airborne sound insulation investigation is that of Martins. et al. [14]. Here, laboratory tests were performed on the bare structure (TF) and adding ceilings (TC1 and TC2). The trends are reported in Figure 5 were the influence of the suspended layers is highlighted.

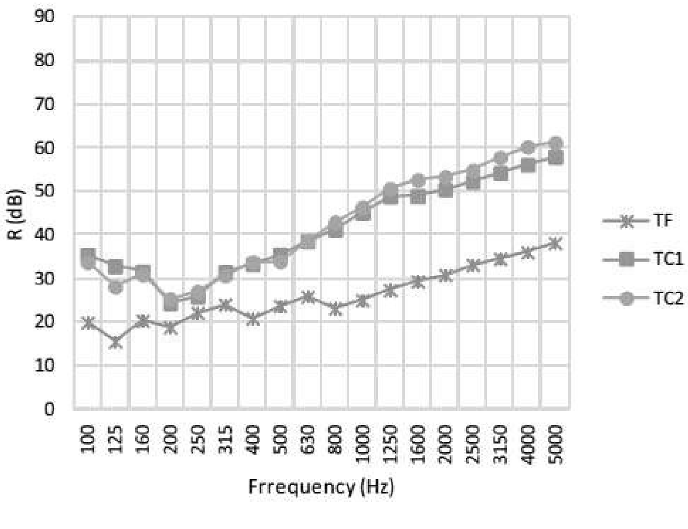

Figure 5 – Laboratory measurements [14].

Type B

The airborne sound insulation is generally less investigated than the impact sound pressure level reduction. Many prediction models are presented and proposed in literature; Mak and Wang [59]analysed over 20 recent papers on this topic and their conclusions are that major contribution for general air borne sound come from analytical studies. This is true, but from the point of view of the number of published works. As a matter of fact, real or simulated test – based paper contains many cases whether theoretical workstudy only a well-defined limited topic. But, for lightweight timber partitions the analytical proposed methods often treat, within the same paper, only one or two simplified cases.

As an example Davy [63] proposed a very interesting analytical model to predict air borne sound insulation of single leaf walls, extending the Cremer's theory [64] down to the critical frequency. In following works, Davy prolonged his previous theory to double leaf cavity walls caused by structure born sound transmission through air gap via line [65] or point connections [66]. The effect of the bending stiffness on laminated panels was studied [67] stating that the theory and the experiment haven't a good agreement because many of the prediction frequencies lie in the critical dip. This is due to the Young's modulus and the effective damping loss factor changing in frequency. In the paper three cases were analysed and the results show that two of them have not a good agreement with the prediction method over-estimating the air borne sound insulation at low frequencies.

Many other theoretical examples are included in literature coping with this issue [68] - [71]. On the other hand, measurement-based or computer-aid researches include many cases and stratigraphy. More recent works try to solve the problem using SEA [8], [40], [72], [73], FEM analysis [74], or FEA analysis [8], [75] models trying to cover other possibilities.

Kouyoumji and Guigou [73] report the activities of AcouBois project where a big database of different typologies (Figure 6 – Different typologies tested on AcuBois project [73].) and a new methodology based on partially measured and partially calculated walls, using direct SEA technique is presented. The method decomposed the precast panels into components, setting modal density and damping loss factor. The obtained results show a good agreement between calculated and measured values.

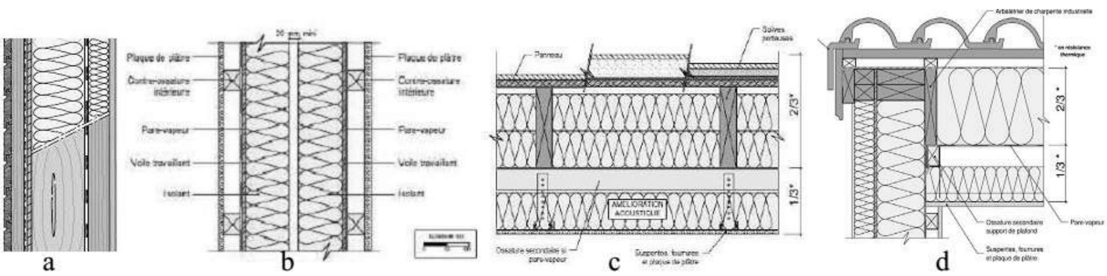

Figure 6 – Different typologies tested on AcuBois project [73].

Using numerical FEA analysis, Henning et al. [75] analysed the variations in sound insulation in low frequency range of nominally identical prefabricated lightweight timber panels. The objects of the investigation were the rigid connection between partitions and the influence of the workmanship on the junctions. The final outcomes highlighted that the stiffness of the connections do influence the sound propagation. The more rigid the connection, the higher velocity levels were found.

Other works studied the influence of the flanking transmissions. The available ISO 12354 models are intended to operate within homogeneous and heavy partition range.

These methods are currently under review since they are not applicable to many partitions coupling. New parameters were introduced such as the normalized direction-average velocity level difference, the vibration reduction of the junction, the element attenuation and sound reduction index for resonant transmission. It is evident that new input data are necessary in order to calculate flanking transmission of lightweight junctions.

Crispin and Ingelaere [76] tested, using laboratory measurement, these innovative parameters. The authors suggest how to obtain various factors and compare diverse methods to assess them.

De Geetere [77] measured the newly introduced normalized direction-averaged vibration level difference $D_{,v,ij,n,R}$ in timber frame mock-up in order to provide input data for pr EN 12354-1. Results demonstrate the difficulties of test flanking transmission down to 50 Hz caused by shielding issues, negative intensities, bidirectional measurements of vibration level very difficult to realize, etc. Nevertheless the expression contained in the revision of the standard are in quite agreement with measurement and though no correction is necessary.

A very complete work was conducted by Quirt et al. [78] where an in-depth laboratory measurement campaign was performed. The authors report many measurements and quality rating (see Figure 7) of the possible layer improvements. Starting from the bare partition, they upgraded it step by step and reported the single index results for sound insulation (see Figure 8). Furthermore they comment the flanking transmissions, providing many suggestions for in situ realization (see Figure 9).

Change in Construction	**Typical Effect due to *one* flanking wall**	**Resulting Apparent-STC**
Changing Floor Materials OSB subfloor ⇒ plywood, or dimensional wood floor joists ⇒ wood-I joists	not significant	53-55
Changing Framing of floors, or of walls, or of floor/wall junction	may be significant (see next case)	53-55
Changing Walls Below On walls below, 1 layer ⇒ 2 layers of gypsum board	less flanking	54-55
On walls below, mount gypsum board on resilient metal channels	negligible flanking	55

Figure 7: Typical brief summary of a different layers effect [78].

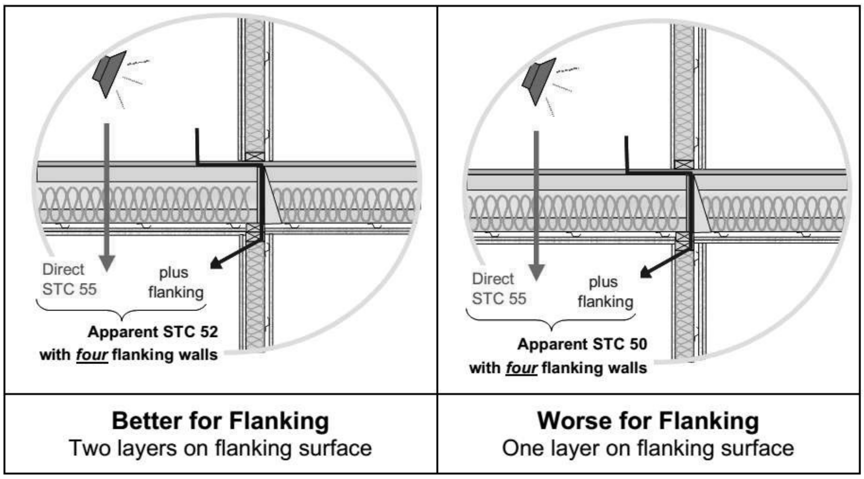

Figure 8: Typical brief summary of a single tested structure [78].

	Worse Floor 1 layer of gypsum board on resilient metal channels spaced @400 mm (Direct STC 51 with no topping)	**Basic Floor** 2 layers of gypsum board on resilient metal channels spaced @400 mm (Direct STC 55 with no topping)	**Better Floor** 2 layers of gypsum board on resilient metal channels spaced @600 mm (Direct STC 59 with no topping)
Worst Case Walls: Single layer applied to all walls, one is shear wall	48	49	50
Walls with 1 layer of gypsum board applied directly to the studs	49	51	52
Walls with 2 layers of gypsum board applied directly to the studs	49	52	54
All Walls with resilient channels supporting gypsum board in room below **(Best case: no flanking)**	51	55	59

Figure 9: Typical brief summary of flanking transmission effects [78].

The only little flaw is that no frequency analysis is included throughout the publication. This is a real pity because considering the big amount of single parameter and layer measurements, the frequency trend alteration would provide many interesting information.

Zeitler et al. [79] assessed whether a shear added layer could improve the acoustical performance of walls.

After laboratory measurements, they demonstrated that it is beneficial for direct sound insulation and for vertical flanking sound insulation. On the other hand horizontal flanking insulation shows a worsening in 1/3 octave bands above 125 Hz.

Öqvist et al. [19] investigate the same topic, but focusing on the weight-difference influence. In their field study, 30 nominally identical apartments were tested. Results demonstrate how the elastomer used in floor junction was affected by thickness reduction due to bearing load. The upper floor shown better sound insulation than the lower one; this indicates a difference in resilient performance and consequently in sound reduction.

Lentzen et al. [40] used SEA-models suitable for impact noise and for airborne one; their method consists of symmetrically as well as unsymmetrically varying the dimensions of the panels and therefore also the coupling length of junction and concluded that it is a good method to provide indication for sound insulation prediction.

De Geertere and Ingelaere [56] also studied the airborne sound insulation of vertical panels. They reported that moving different layers from centre party wall to external surface avoids leaf resonance, thus enhancing human noise protection.

Type C

The bare CLT airborne sound insulation performances are not investigated in any of the paper correlated to this topic. The reasons could be explained referring to

Table 3, where a comparison between ISO 12354-1 model and laboratory measured values is reported. The model and the measurement provide high agreement. Though no further investigation are needed

Table 3 – $R_{,w}$ values obtained using ISO 12354-1 method and laboratory measurement

description	ISO 12354-1 (dB)	Measured R_w (dB)
CLT floor. 175 mm thickness [23]	40.1	39
CLT floor. 135 mm thickness [59]	38.2	39

1.4 Subjective evaluation

The literature review on this topic does not divide effects connected to different structures. The main topics, as previously reported, are the low frequency range effects.

Medved et al. [80] used a mock-up model to investigate how mass effect interact with low frequency impact noise showing how the use of pre-mixed concrete gravel acts better than extra boards as impact sound reduction.

Ljunggren and Ågren [81] studied the influence of elasticity in the construction. In order to rise low frequency insulation performance, it can be introduced the use of elastic connections. So, multi-storey lightweight constructions tests were performed in order to understand if sound reduction and impact sound pressure levels may be improved in this frequency range. The final tests show how vibration junction could be reduced up to 13 dB in frequency range 50 Hz – 5000 Hz.

In a similar topic, Bolmsvik and Brandt [82] investigated damping elastomers and their structural behaviour in the joints. The use of a mock-up in two different configurations with and without damping elastomer material in the joints allows measurements and comparison with FEM calculation. It was observed that damping varies with frequency. The elastomeric configuration has shown to significantly change the dynamic behaviour of the system, especially at low frequency range.

Ryu et al. [83] highlight that the ISO 717-2 curve [84] is flat at low frequencies of 100-315 Hz. Related to this matter, in years there were several general paper, i.e. not strictly related to lightweight building. As an example in 80's Bodlund [85] proposed a subjective survey in order to establish the rating curve values. For rating lightweight and heavyweight impact sound insulation in Japan, [87] and Korea [88],[89]. In their work, the authors used laboratory measures to investigate the connection between annoyance and single-number quantities. The results shown how the arithmetic average $L_{iFavg,Fmax}$ measured with fast constant and Zwicker's percentile loudness (N_5) [90] indicates a good annoyance rate.

Brunskog et al. [91] expressed the hypothesis that the subjective judgment of impact noise is more annoying if the source position can be localized; lightweight structures have a more localized radiation than heavy structures ones then this could be the reason why a lightweight structure is often subjectively judged more annoying than a heavy homogeneous structure. As a matter of fact, for the heavy structures, the reverberant vibration field is dominant, and then it has a distributed radiation not allowing localization of source. Using laboratory test, listening playback were used both permanent and moving sources, presenting different *stimuli*. The test results were opposite to the aim of their paper. They concluded that localized factor did not play a major role in the annoyance assessment, even if it was well recognized by all tested subjects.

Likewise, Sato et al. [92] prosecute their previous work [93] playing the floor impact sound from a ceiling loud speaker in anechoic chamber. The tests were evaluated using Maximum Zwicker loudness. This study intends to investigate the relationship between subjective evaluation on floor impact sounds and measures. The conclusions demonstrated that both Maximum Zwicker Loudness and $L_{A,F,max}$ can predict annoyance response to floor impact sound of wood-frame construction. The annoyance can vary by situations and repeating times.

Ljunggren et al. [94] used on site measurements of airborne and impact sound insulation. Besides they use questionnaire to investigate inhabitants' perceptions, developed within European Network COST TU 0901 project [96] and reported in Figure 10. The results have demonstrated once again that the source that produces the greatest individual annoyance is the impact sound In their opinion, since the single rating numbers calculated using ISO 717-2 and ISO 717-1 [97] standards could not connect annoyance and measurements results, they suggest a new spectrum adaptation term which takes into account the relation between the objective and subjective methods.

Liebl et al. [98] used both subjective survey in timber constructions in Germany and Switzerland and noise listening. They report that the annoyance overall isn't high but general noise is judged higher than individual noise sources. Thus noise annoyance seems to be an aggregation of annoyance caused by individual sources. Furthermore the listening tests provide a very interesting

outcome: the short-term subjective impression obtained during laboratory assessments corresponds to long-term acoustic impression deduced from inhabitants questionnaires.
On the contrary, in a succeeding paper Liebl et al. [99] concluded that the short-term evaluation laboratory tests couldn't substitute long-term results. In this paper two out of three case demonstrate what previously stated [98] but the third one didn't.
Negreira et al. [100] described an investigation on human walking: acceleration measurements were carried out while a person either was walking on a particular floor or was seated in a chair placed there while someone was walking on the upper floor. The participants filled out a questionnaire regarding their perception and experiencing of the vibrations. A total of 60 people were involved in the subjective tests. Five different floors technologies were tested. The answers provided by participants could be useful to calculate new parameters do determine the best design indicators of vibration acceptability and annoyance.

1.5 Discussion and conclusions

It is evident that the acoustic studies on wooden lightweight buildings start from real needing and applications. The most investigated issues are the impact noise and the low frequency insulation and their effects on human perception. This latter topic requires further deepening since there is not a full agreement between scientists about usable methods and interpretations of results.
An interesting point is shown in Figure 11 and Figure 12. In the first one, the number of papers is related to author(s)' origin continent. It is manifest that Europe is the major supplier, followed by Asia and Oceania and then North America.
From the single country point of view, Sweden is the main leader followed by Belgium and New Zeeland. It can be concluded that in these nations the acoustic of lightweight buildings research has more financial support and as a consequence more lightweight wooden buildings are presents.
Finally, no focused researches are currently available both on duct-borne sound (both from air and from water waste) due to service equipment and to façade sound insulation and the influence of windows (glazing and materials frame). Besides, even if the impact noise and vibration reduction is the most studied topic very few works analyse the bare floor behaviour as well as the influence of the floating floor and the effect of time and load on resilient layers both from synthetic and natural or recycled origin.

Instructions: v1.0 2011-05

Choose an answer on the 0-to-10 scale for how much noise bothers, disturbs or annoys you when you are in your house.

if you hear a small amount of noise AND you are not at all disturbed by it, ***choose 0***	*if you are extremely bothered, disturbed or annoyed by it,* ***choose 10***	*if you are somewhere in between,* ***choose a number from 1 to 9***	*if you do not hear anything at all, the source does not exist or if you cannot answer,* ***choose "Don't know"***

Thinking about the last 12 months in your house, how much are you bothered, disturbed or annoyed by	0 Not at all	1	2	3	4	6	6	7	8	9	10 Extremely	Don't know
1. Noise **in general** e.g. from neighbours, technical installations	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Thinking about the last 12 months in your house, how much are you bothered, disturbed or annoyed by ***these sources of noise?***	0 Not at all	1	2	3	4	6	6	7	8	9	10 Extremely	Don't know
2. Neighbours; daily living, e.g. people talking, audio, TV through the **walls** (what is heard:______)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
3. Neighbours; daily living, e.g. people talking, audio, TV through the **floors / ceilings** (______)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
4. Neighbours; Music with bass and drums	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
5. Neighbours; footstep noise, i.e. you hear when they walk on the floor	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
6. Neighbours; rattling or tinkling noise from your **own** furniture when the neighbours move on the floor above you	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
7. Staircases, access balconies etc; people talking, doors being closed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
8. Staircases, access balconies etc; footsteps or other impact sounds	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9. Water installations; plumbing, using or flushing WC, shower	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
10. Climate installations; heaters, air condition, air terminal devices (______)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
11. Service installations; elevators, laundry machinery, ventilation machinery (______)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
12. Premises; garages, shops, offices, pubs, restaurants, laundry rooms or other, heard **indoors** with windows closed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
13. Traffic (cars, buses, trucks, trains or aircraft); heard **indoors** with **windows closed**	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
14. Own family; heard **within your dwelling** with doors **closed**	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Before *moving to the apartment, how important was the sound insulation to you, with respect to*	0 Not at all important	1	2	3	4	6	6	7	8	9	10 Extremely important
15. Noise in general e.g. from neighbours, technical installations	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Are you tolerant or sensitive with respect to	0 Tolerant, not at all sensitive	1	2	3	4	6	6	7	8	9	10 Extremely sensitive
16. Noise in general e.g. from neighbours, technical installations	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Comments (describe important sources of noise, type of premises, neighbour activities etcetera):

Figure 10: Subjective questionnaire [96].

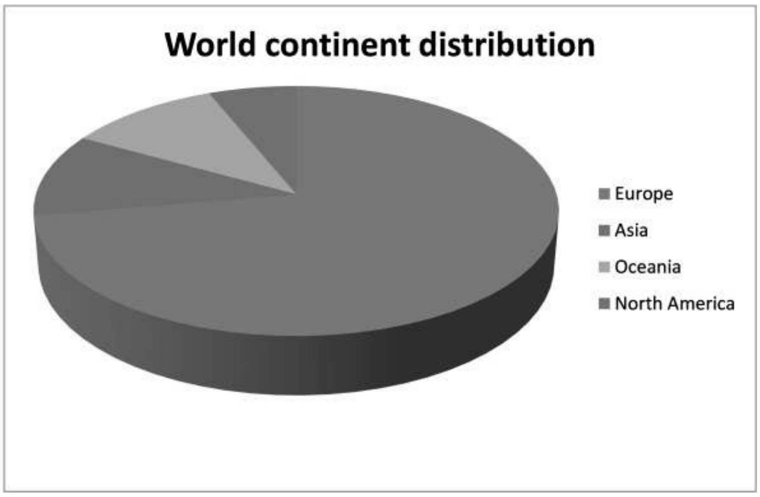

Figure 11: Papers geographical distribution – continent influence.

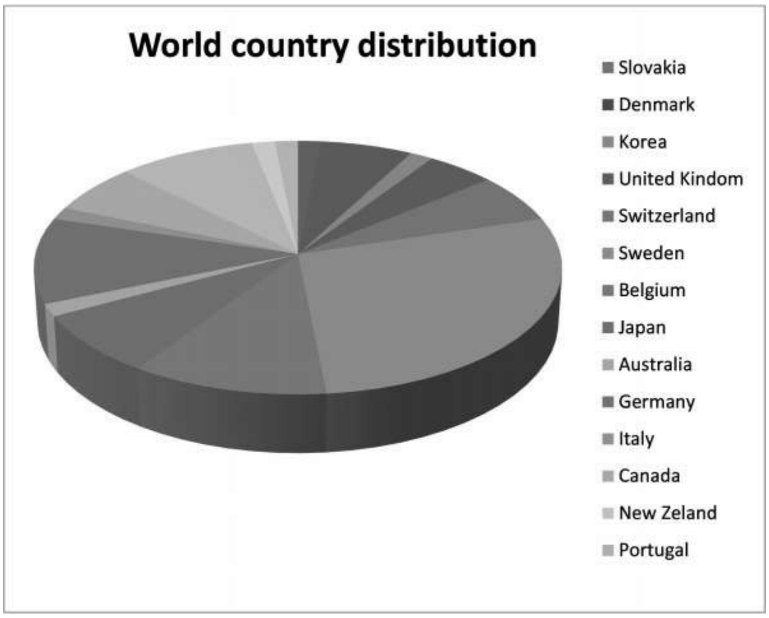

Figure 12: Papers geographical distribution – single country influence.

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2 Acoustic of timber floors

2.1 Introduction

Lightweight buildings are becoming a present technology in the construction actuality. At present 6 edifices out of 100 are erected using timber constructions. They provide many advantages like speed of assembly, industrial quality, reduction of workmanship errors, fast difficult shapes realization, high service equipment and windows integration.

Timber building presence is rising in Europe since the recent directive of the European Parliament [2] pushes new high performance building realization.

Different technologies are available but two types are the most used ones: glulam beams with top boards or cross laminated timber panel. For both of them no standard or international literature provide a theoretical or empirical frequency trend for bare structure impact noise. This is primary input data since the designing process is based on ISO 12354-2 [1] and Cremer's theory [3].

Impact noise in timber buildings is the most inhabitants' complained issue [4]. Especially at low frequency range, this excitation is difficult to model because of two causes:

i. the typologies of glulam beams with top boards are wider
ii. the traditional models do not work with lightweight structures [5].

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

2.2 Materials and methods

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

So this two kind of structure where analysed using in situ impact noise measurements with 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 border single volumes; all tests were carried out according to ISO 16283-2 [6].

2.3 Cross laminated structure

The building was a four–storey construction where 16 floors were tested on 16 different receiving rooms (Figure 1 and Figure 2).

Panels were constituted of 7 cross overlapping layers providing a final thickness of 25 cm. The floor assembly is secured using a board stared with screws and glue between panels or external walls (see Figure 3) within wall-floor junction a high density elastomeric materials is included (see Figure 4). In the 4B dwelling no internal partition was present, so it could be considered as a “single room” apartment (133.5 m^3).

Figure 1 - multi-storey crosslam building

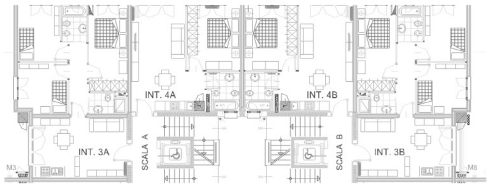

Figure 2 – standard floor map

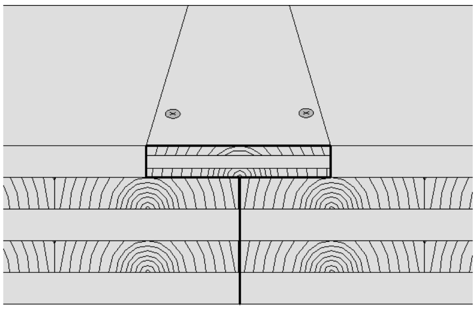

Figure 3 – floor assembly detail

Figure 4 – wall-floor junction detail with elastomeric layer.

2.4 Crosslam results

Figure 5 and Figure 6 show the results of impact noise measurements for standard apartments 3 A and 3 B at the frequency rage 1000 Hz – 5000 Hz and 100 Hz – 800 Hz one 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.

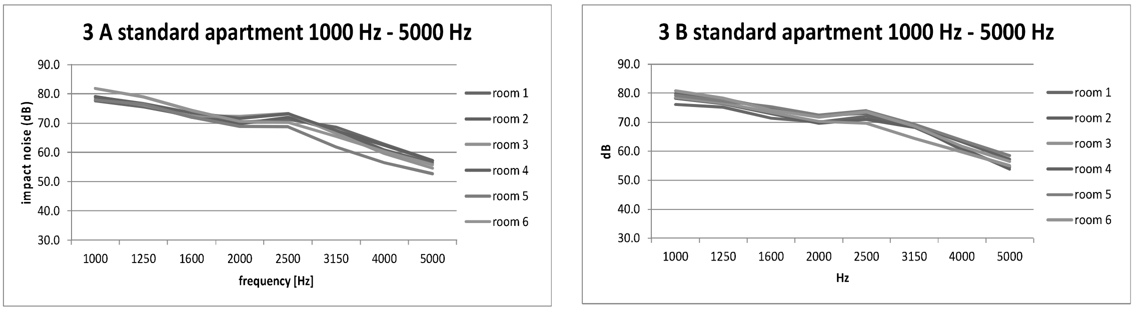

Figure 5 –high frequency trends for impact noise in standard apartments.

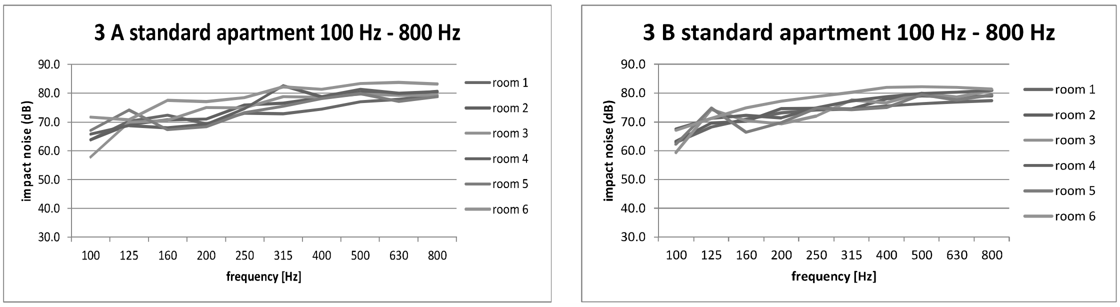

Figure 6 – middle frequency trends for impact noise in standard apartments.

In the low frequency range (50 Hz÷80 Hz) results could be very variable especially in little rooms (Figure 7).

The same trends could be found in single room apartment (Figure .1, 8.2 and 8.3) where no appreciable different is verifiable for middle and high ranges whether for low frequencies no common behaviour is demonstrable.

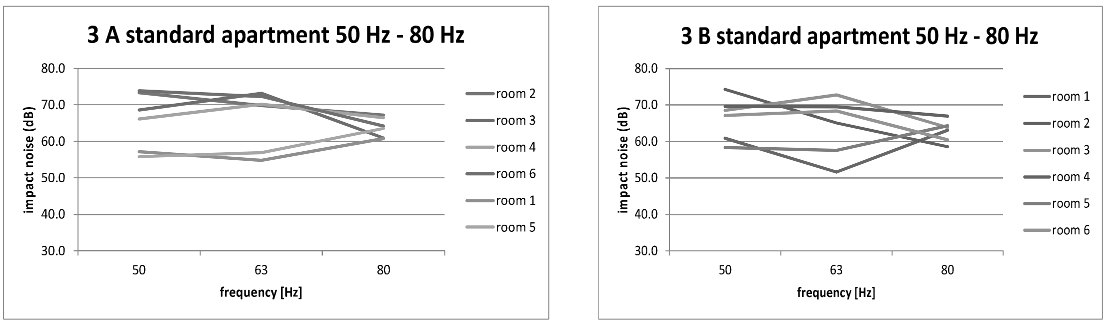

Figure 7 – low frequency trends for impact noise in standard apartment

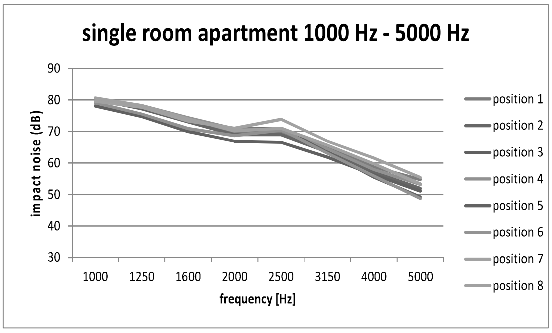

Figure 8.1 –trends for impact noise in single room apartment: high frequency

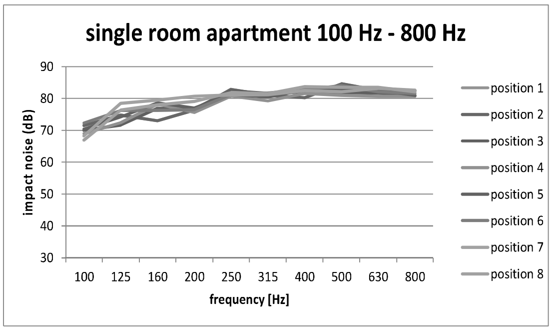

Figure 8.2 –trends for impact noise in single room apartment: middle frequency

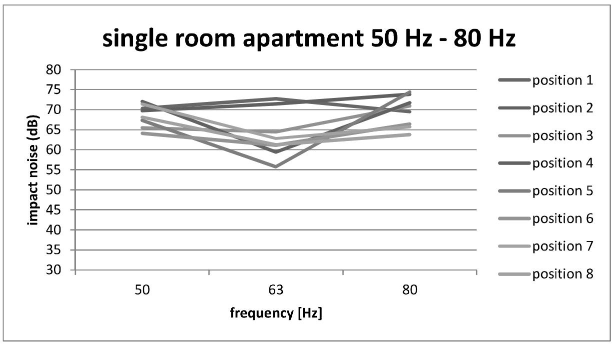

Figure 8.3 –trends for impact noise in single room apartment: low frequency

For the whole 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 (Figure 8).

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

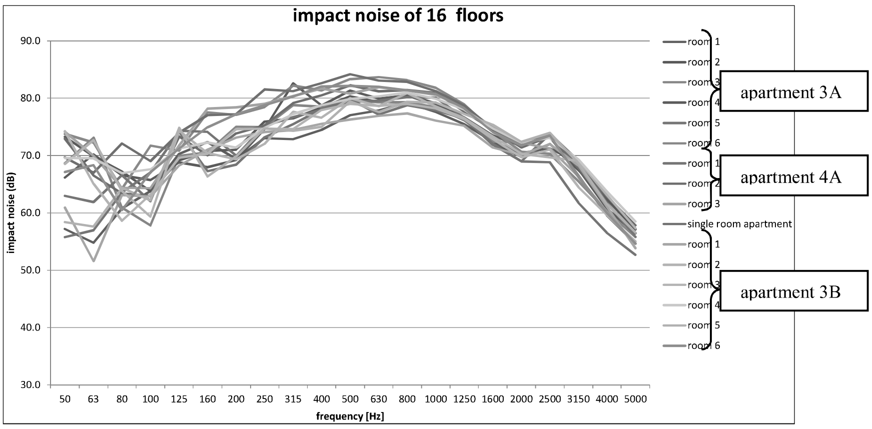

Figure 8 –frequency trends for impact noise of 16 floors

2.5 Glulam beams with top boards structure

The building was a three – storey construction where floors were tested on different receiving rooms (Figure 9 and Figure 10). Panels were constituted of glulam beams connected with wooden chipboard screwed on top of them and within mineral wool and laterally fastened with wooden closures (Figure 11). These panels are laid in order to match the external border. So between them it could be possible to find an air gap. This was filled using high sound insulation foam (Figure 12).

Figure 9 – multi-storey glulam with top boards building

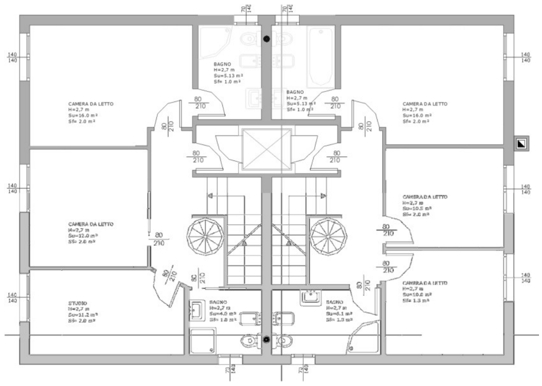

Figure 10 – standard floor map

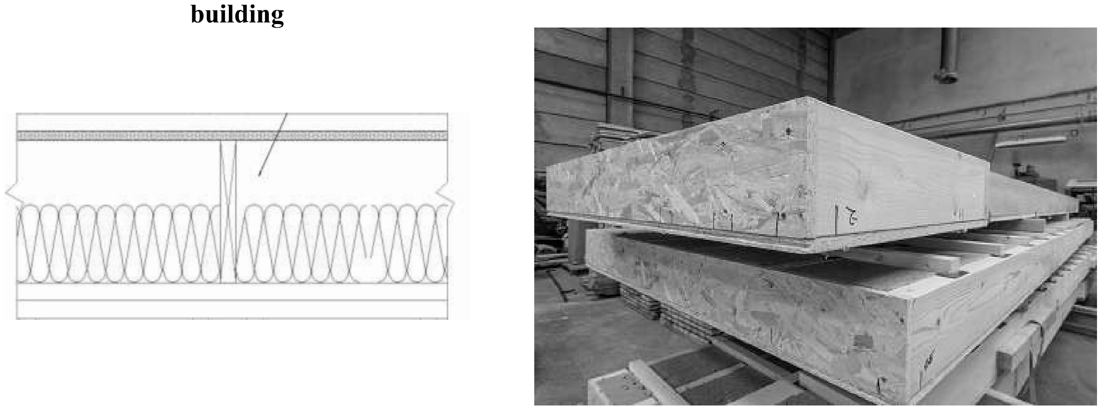

Figure 11 – floor assembly scheme and closures detail

Figure 12 – high sound insulation foam insertion

2.6 Glulam beams with top boards results

As for crosslam structure, the same considerations could be applied here: the different bare results are very similar due to industrial production, so only the average final values are worthy to be presented. In Figure 13 the bare floor impact noise are 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 and thus providing more energy (more excited area) at low frequencies. Nevertheless the airborne sound insulation gained 12 dB.

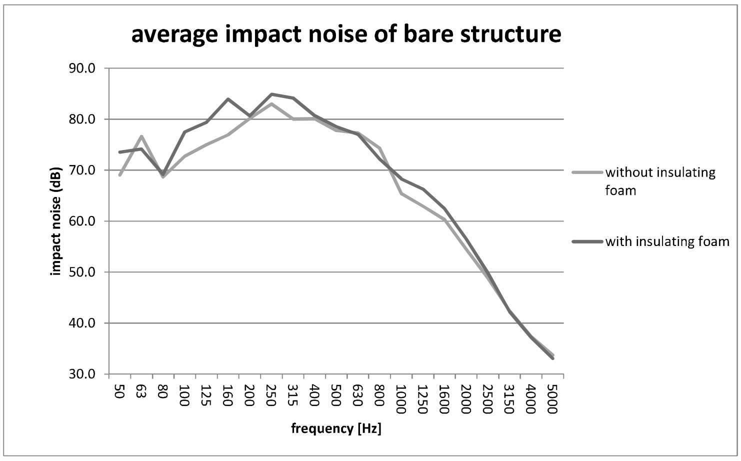

Figure 13 – bare floor impact noise

After these steps, a first floating floor was posed using the following layers (Figure 14):

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

Then a second floating floor was laid using the following coatings (Figure 15):

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

Impact noise test using ISO tapping machine were carried out (Figure 16) and the influence of these sound reduction solutions is reported in Figure 17.

Figure 14 – first floating floor

Figure 15 – second floating floor

Figure 16 – example location of tapping machine during tests: bare floor (left) and first floating floor (right)

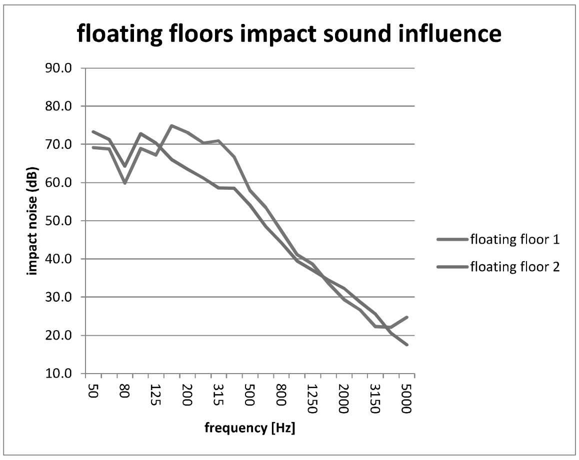

Figure 17 – floating floors influence

In Figure 18 the influence of the screwed ceiling is reported. It is evident the worsening provided by the presence of tis element. At around 100 Hz its resonance frequency rise up the impact noise; in order to reduce this effect, the air gap was filled with mineral wool. This operation slightly lowed down the middle frequencies but it did not change the resonance influence on the impact noise.

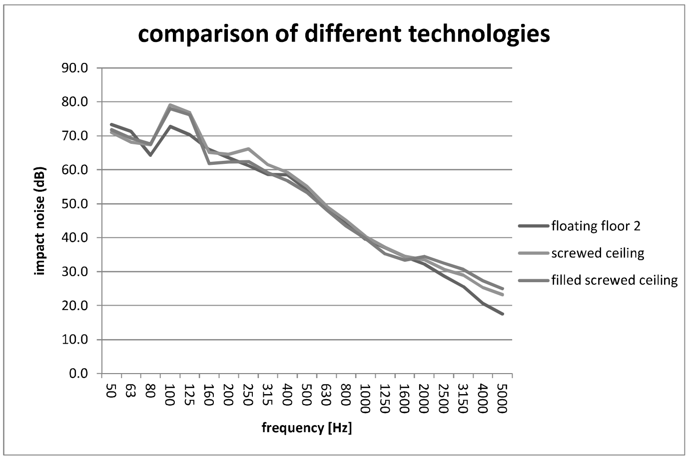

Figure 18 – screwed ceiling effect

2.7 Discussion of results

For crosslam technology an average frequency trend is reported in Figure 19 where all the 16 behaviour as well as the calculated linear regression are reported

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

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

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

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

The calculated linear regression coefficient is R^2=0.99 for equation (1), R^2=0.89 for equation (2) and R^2=0.97 for equation (3)

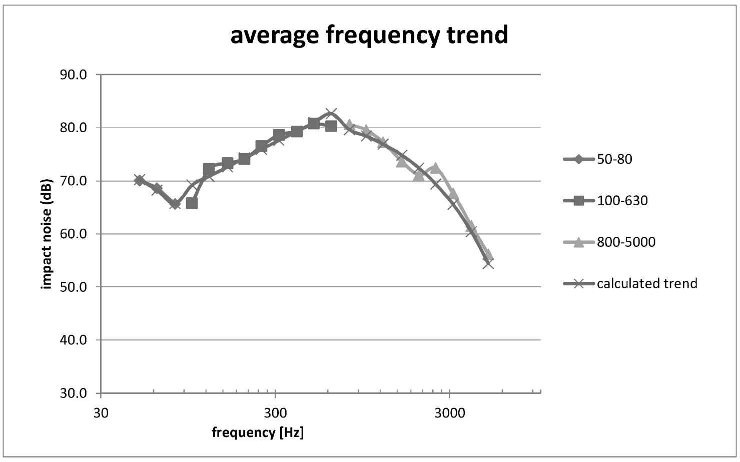

Figure 19 –Average frequency trends for impact noise

A comparison could be carried out using literature provided values for similar structures. In Figure 20 the comparison between crosslam and timber concrete structures is reported. It is worthy to note that the influence of the concrete slab starts from middle-high frequencies according to [5].
In Figure 21 the comparison between different floors is reported. It is evident that the influence of the thickness changes the frequency trend, altering the behaviour at almost every frequency.

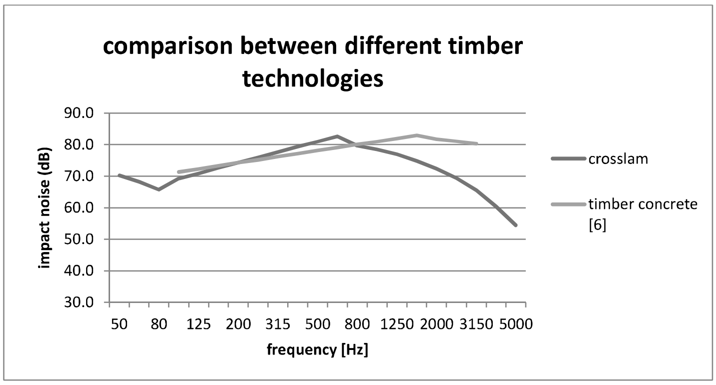

Figure 20 –comparison between crosslam and timber concrete floors

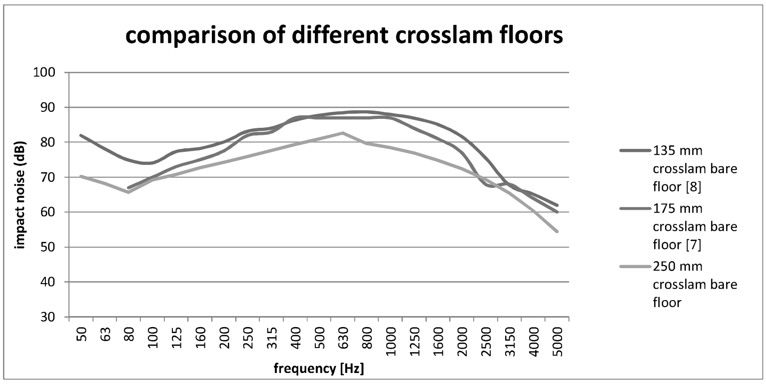

Figure 21 –comparison between different thickness crosslam floors

In Table 1, the normalized impact sound pressure index values, calculated according to ISO 12354-2 [2] are reported. It is evident that the proposed method does not provide reliable results. In fact it is suggested for homogeneous bare concrete floor with a mass per unit area 100 kg/m^2<m'<600 kg/m^2. Since this is the only available method a correction is proposed according to equation (4):

$$L_{n,w,eq,corrected} = 134.5\text{-}25\cdot\log(m')\ \text{(dB)} \quad (4)$$

where m' is the mass per unit area [kg/m^2].

Table 1 – normalized impact sound pressure index values

	135 mm bare floor	175 mm bare floor	250 mm bare floor
Measured L_{nw}	88	85	80
ISO 12354-2	98.5	94.6	89.2
modified ISO 12354-2	87.7	84.9	81.0

For glulam beams with top boards, in Table 2 the comparison between ISO 12354-2 normalized impact sound pressure index models (see equation (5)) and measured values is shown.

$$\Delta L_{nw,single\ number} = 30\cdot log(500/f_0) + 3\ \text{(dB)} \quad (5)$$

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 of masses is reduced ($m'_{barefloor}$=130 kg/m^2 whether $m'_{overall\ floating\ floor}$=80 kg/m^2) in comparison with a concrete bare floor ($m'_{concrete}$=600 kg/m^2) or beam and pot ($m'_{beam\ and\ pot}$=340 kg/m^2).

Table 2 – floating floors normalized impact sound pressure index prediction

TIMBER	Mass per unit area [kg/m²]	Measured Normalized Impact sound pressure index (dB)	Predicted Normalized Impact sound pressure index (dB)	Difference (dB)
Bare floor	130	74	--	--
Floating floor 1	45	64	54	10
Floating floor 1+2	80	58	46	12

In Table 3 a comparison of the sound reduction index of the same floating floor on different structures is presented, using frequency Cremer's relation. 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 exciting energy distribution coming from the ISO tapping machine and on the proper floating floor technology limit: the low frequency reduction.

Table 3 – floating floor effect on same thickness different bare floor technologies using frequency Cremer's relation

	Mass per unit area [kg/m²]	Measured Normalized Impact sound pressure index of bare floor (dB)	Predicted Normalized Impact sound pressure index reduction of floating floor (dB)
timber floor	130	74	11
Concrete [1]	600	81	33
Beam and pot [7]	340	87	41

In Figure 22 the impact noise distribution is presented. As a matter of fact, timber based structures provide much more low frequency energy (up to 20 dB) than the concrete ones, involving a lower floating floor influence on them.

The mineral wool effect is evident in glulam beam with top board partition, especially at high frequency according to [11]. Nevertheless, this range is the one where the floating floor acts best. Once more its influence cannot be highlighted since this type of structures does not provide ideal condition for the use of this sound reduction technology.

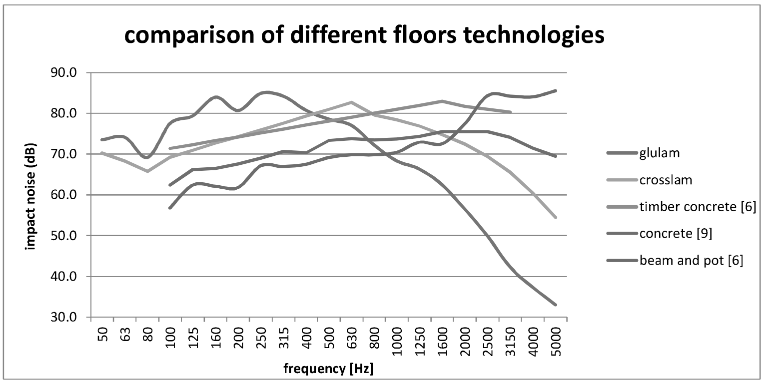

Figure 22 – comparison of different bare floor technologies of impact noise

2.8 Conclusions

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

Two main typologies were analysed: crosslam 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 since all panels are manufactured, transported and assembled on the same way. Fastening methods were described and their influence was highlighted.

Comparison between these two technologies and with traditional ones is provide showing how timber structures irradiate up to 20 dB more energy in the low frequency range. A correction of the ISO 12354-2 model for single number prediction is proposed, related to crosslam structure.

Finally, the influence of mineral wool and screwed ceiling shows how the former acts on high frequencies and influence the effect of floating floor, whether the latter aggravates the final impact noise level because of its resonance frequency.

2.9 References

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3 Time-depending performance of resilient layers under floating floors

3.1 Introduction

At these days, buildings are complex constructions within several engineered materials, layers and structures. For the indoor comfort, several parameters have to be taken into account: thermal distribution, air quality, radiated energy and sound insulation. The latter issue include both airborne and impact sound pressure level.

In multi-story lightweight buildings, the resident activities could produce impact sound pressure inside the apartment of the floor below. Many building technologies can be employed to reduce this problem such as resilient covering (i.e. fitted carpet), supported ceilings and floating floors.

Floating floors is one of the most effective solutions to cut the impact sound pressure level by decoupling the upper level (slab) from the structural construction. This mass-spring-mass system is able to moderate effectively sound transmission through walls [1-3].

Adopting floor structures such as concrete, beam and pot, timber frame etc. direct and flanking transmissions could affect the acoustic comfort of different dwelling in the same building. To avoid this problem a reduction system, such as the abovementioned floating floor, should be designed and laid [4,5].

Recently, many resilient materials (such as natural or synthetic wools, felts, foams and various recycled products) have been produced and tested for the reduction of the impact sound pressure level in buildings [6, 7], even if the number of resilient layer's studies is still limited.

For these material types, due to their peculiar roles, the "spring" behaviour, time resistance under constant stress and the response when subjected to unexpected loads are important and must be evaluated. As a consequence, the main parameters characterizing their mechanical properties are three: (i) dynamic stiffness, (ii) compressive creep and (iii) compressibility.

As mentioned above (cap. 1), floating floor technology is based on the mass-spring-mass effect with m_1, called "infinite mass" (the structural and static mass), the spring effect is ensured by the resilient layer (where k is the elastic constant) acting with m_2 (the floating mass) as a "resonant system". The whole system decreases the impact sound pressure transmission emitted by footsteps, object fall, etc.

Dynamic stiffness determination is essential to choose the mass and thickness of all floating floor components: in particular this parameter defines the ability of a system to damp vibration transmission. The impact sound pressure level reduction can be evaluated applying Cremer's equation [8]:

(1) $$\Delta L = 30 log \frac{f}{f_0} \quad \text{(dB)}$$

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:

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

where s' is the apparent dynamic stiffness per unit area [MN/m^3] and m' is the mass of m_2 per unit area [kg/m^2].

This property is correlated to the stiffness of a single layer and it depends on density, shape, thickness and static load [7]. It supplies the needed design value to estimate how much the floating floor can reduce the impact sound pressure level.

The compressibility is referred to the dynamic load that a layer can tolerate maintaining its elasticity, without non-reversible strain occurs.

The compressive creep is related to resistance under static load in the time domain.

The identification of the proper resilient layer is possible only if all these three parameters are measured.

Dynamic stiffness and compressive creep tests are strictly related to real-use conditions. The spring-mass effect and the static load are achieved placing a 200 kg/m^2 mass upon the resilient layer, that simulates a real slab (bed mortar). The former test provides the parameter to calculate impact sound pressure level reduction (ΔL) while the latter evaluates if the layer could withstand static load and guarantee the spring-mass effect over time.

The compressive creep analysis is a direct examination. For relevant thickness reduction, the resilient layer is not able to preserve its original configuration in time domain, inducing significant difference between predicted and measured ΔL. If the thickness reduction is not so evident, the material could have some internal rearrangements with a consequent dynamic stiffness increase.

On the other hand, the compressibility test is not related to any particular *in situ* case. Even if this value is not used in any predictive or design calculation, it supplies very important information, such as the resilient layer capability to maintain its peculiar acoustic and mechanical properties under unexpected dynamic loads. A complete thickness and shape recovery indicates good elastic properties, otherwise an incomplete restoration, caused for example by poor inner aggregation (i.e. ceramic fibre layers [9]), limits the spring effect (poor compressibility level).

Calculated and measured ΔL values can be sometimes very different [10-12], due to: (i) the same material of prediction study has not been used for in situ realization; (ii) human errors have been occurred during installation, or (iii) resilient layer mechanical properties have changed due to loading-time or loads. While conditions (i) and (ii) can be easily overcome choosing the proper material and increasing the quality control during installation, the third situation needs a comprehensive study of material properties. Compressibility and compressive creep are of paramount importance and must be measured in laboratory to evaluate if the selected resilient layer is suitable for building's expected lifetime. In many countries (e.g. Italy and France) this service life is at least 10 years.

Compressibility is a short-time test (about 1 hour), on the contrary, the compressive creep takes at least three months in order to estimate resilient layer behaviour for 7.5 years and up to five months for a 10 years forecast, as expressed by Findley equation [13,14]. Since compressive creep is a long-lasting measurement, it is not usually studied, tested or certified at all.

Considering the aforementioned point, in the last few years, the main purpose of researchers [15-18] and suppliers is focused on the survey of a relationship between compressive creep and other parameters, in order avoid the creep test implementation.

Schiavi et al. [15] have tested 6 types of material with different densities, that could be classified as: i) rubber or recycled tyres, ii) wood or cork, iii) textiles, iv) polyurethane, v) glass or rock wool, vi) synthetic fibres. A method has been proposed to evaluate the long-term behaviour under continuous compressive load and the acoustical performance of resilient layers. For the before-mentioned materials compressibility and 10 years extrapolated compressive creep show quite comparable values. Dikavicius et al. [16] have examined stone and glass wool (open cell material) and elastic polystyrene (closed cell material) showing a decrease in the dynamic stiffness values after compressibility test. Gnip et al. [17] have studied long-term (about 5 years) compressive creep effect on expanded polystyrene proposing a predicting law for the behaviour up to 50 years. Cho [18] has identified a method to determine dynamic stiffness variation induced by creep, by means of quasi-static mechanical analysis, with the assumption that the modification of the resilient material structure caused by creep does not depend on time and stress. The investigated materials have been expanded polypropylene, expanded polystyrene and polyester felt single layer.

The scope of the present study is to verify i) if there exist a correlation between compressibility and compressive creep for different resilient layer types, ii) if their mechanical and acoustical properties are affected by service time and iii) if density, shape and surface coating may influence their performance.

In this paper, instead of "material", the term "resilient layer" will be used, because layers are not always composed of a single bulk material.

3.2 Materials and methods

Twenty resilient layers (Table 1) were tested in order to evaluate dynamic stiffness, compressibility and compressive creep as specified in the following paragraphs. In compliance with standards, all tests were performed in a chamber under controlled temperature (20±3°C) and relative humidity (50±10%).

3.2.1 Dynamic stiffness

Dynamic stiffness for unit area was determined in compliance with UNI EN 29052-1 [19], three specimens for each layer. The apparent dynamic stiffness per unit area s'_t [MN/m3] is related to the extrapolated resonant frequency f_r of the fundamental vertical vibration of the resilient layer, as given by the equation (3):

$$s'_t = 4\pi^2 m'_t (f_r)^2 \qquad [MN/m^3] \qquad (3)$$

where m'_t [kg/m^2] is the total mass per unit area used during the test (a steel load plate size 200x200 mm and weight of 8±0.5 kg).

For porous materials, if the lateral airflow resistivity, measured in accordance to ISO 9053 [20], is in the range 100 kPa·s/m^2÷10 kPa·s/m^2, the contribution of the enclosed air s'_a has to be considered (4):

$$s' = s'_t + s'_a \qquad [MN/m^3] \qquad (4)$$

Resonance frequency was assessed by pulse signal technique as described in ISO 7626-5 [21]. The measurement set-up Figure 1 consists of: impact hammer PCB Piezoeletronics® Mod. 086C03, N. 26753; accelerometer Dytran® Mod. 3023M2 Triaxial (ref.sens. 10.1mV/g); acquisition system National Instruments® mod. NI 9234; software LabVIEW® Sound and Vibration Toolkit for signal acquisition (24bit, 48000Hz sampling).

Figure 1: Measurement set-up for apparent dynamic stiffness test.

Dynamic stiffness measurements were performed before (t_0) and after compressive creep test at 90 and 150 days.

3.2.2 Compressibility

The compressibility c_p was determined as thickness variation during a load cycle. UNI EN 12431 [22] specifies equipment and procedures for the determination of thermal insulating products thickness.

The thickness was measured for ten specimens as distance between two rigid plates under specified pressure levels: d_L, thickness at 250 Pa; d_F, thickness at 2 kPa; d_B, thickness at 2 kPa after additional load (48 kPa) applied for two minutes. Results are expressed as thickness mean value, rounded to the nearest 0.1 mm.

Resilient layer compressibility c_p [mm] is given by:

(5) $$c_p = d_L - d_B \quad \text{[mm]}$$

The measurement set-up for thickness determination (Figure 2) is composed of a reference steel plate (200x200 mm), a 1 kg steel load plate (200x200 mm), a 8(±0.5) kg steel load plate (200x200 mm), a hydraulic press Paul Weber Types PW 40 (load range 0 ÷ 11 tons) and an analogue dial gauges (precision of 0.1 mm)

Figure 2: Set-up for thickness measurement under different static loads.

In addition, the *modified* c_p (mc_p) [mm] was also calculated as:

(6) $$mc_p = d_F - d_B \quad \text{[mm]}$$

The difference between c_p and mc_p is $(d_L - d_F)$, and it represents the pre-load influence on resilient layers.

3.2.3 Compressive creep

Compressive creep test is regulated by UNI EN 1606 [23], which specifies the equipment and procedures to be implemented. The compressive creep X_{ct} is expressed as thickness decrease X_t under constant compressive stress at given conditions (temperature, humidity and time). In order to compare creep results with those obtained by dynamic stiffness and compressibility tests, a 8(±0.5) kg steel plate (200x200 mm) has been used as compressive weight.

The relative deformation ε is the ratio between thickness variation X_t and initial thickness d_S measured in load direction. Thickness variation X_t [mm] has to be measured after load application with logarithmic timeline, for a minimum of 90 days. Using Findley equation (7) [13,14], extrapolation is permitted for a maximum of thirty times test duration:

(7) $$X_t = X_0 + m \cdot t^b \quad \text{[mm]}$$

where X_0 is the thickness [mm] after 60 seconds under 2 kPa static load, m and b are constants (see Table A2).

The results were reported as the mean value on a minimum of three test specimens.

The measurement set-up (Figure 3), is composed of a steel base plate, a 8(±0.5) kg steel load plate (size 200x200 mm) and a digital micron gauge (precision of 0.1mm in the range between 0 and 12.7 mm). For all specimens, each thickness was evaluated as the average value in two different positions on the load plate.

Figure 3: Measurement set-up for compressive creep test.

3.3 Results and discussions

Dynamic stiffness s', compressibility c_p, 7 years extrapolated compressive creep X_{7y} and relative deformation ε_{7y} results are summarized in Table 1. A new parameter Δcx is introduced and calculated as:

(8) $$\Delta cx = 100 \cdot (c_p - X_t)/c_p \quad \text{[mm]}$$

All parameters for the compressibility values calculation (according to UNI EN 12431 [22]) and for compressive creep determination (in compliance with UNI EN 1606 [23]) are reported in annex A, Table A1and A2 respectively. For dynamic stiffness, the value at t_0 is reported.

Table 1: Resilient layers description, dynamic stiffness *s'*, compressibility c_p, 7 years extrapolated compressive creep X_{7y}, relative deformation ε_{7y} and Δcx results.

code	Resilient layer	*s'* at t_0 [MN/m^3]	c_p [mm]	X_{7y} [mm]	ε_{7y} %	Δcx %	*d* *[mm]*
A	Expanded PE + high density polymeric sheet 4.4 kg/m^2	34.0	0.3	2.27	21	-683	8.5
B	Cotton waste + high density polymeric sheet 5.3 kg/m^2	31.1	1.6	0.47	5	71	9.5
C	Cotton waste + PE foil 1.2 kg/m^2	15.4	1.9	0.80	12	57	7
D	PE fibre 0.8 kg/m^2	20.0	3.9	4.55	53	-16	10
E	PE fibre 1 kg/m^2	20.0	3.8	4.47	45	-18	10
F	Expanded rubber line shaped 3.6 kg/m^2	38.0	2.7	0.66	7	76	9.6
G	Expanded rubber spot shaped 3.2 kg/m^2	27.0	1.4	0.35	5	74	6.6
H	PE hemisphere shaped 0.4 kg/m^2	11.5	1.6	1.80	26	-14	8
I	Expanded PE 0.8 kg/m^2	27.5	0.9	2.4	24	-166	10
L	Expanded rubber line shaped 1 kg/m^2	34.0	4.5	0.67	8	85	7
M	Expanded rubber spot shaped 3.9 kg/m^2	23.0	1.3	0.89	9	31	10
N	Expanded rubber wave shaped 2 kg/m^2	32.0	2.9	1.89	27	36	7
O	Expanded rubber line shaped 3 kg/m^2	24.0	2.8	1.83	20	36	9
P	Expanded rubber spot shaped 2.5 kg/m^2	21.8	1.5	1.60	21	-10	7
Q	Expanded cured PE + bituminous layer 4.1 kg/m^2	34.0	0.4	2.06	26	-379	7.7
R	Non-woven PE fabric + bituminous layer 3.5 kg/m^2	24.0	1.9	1.34	17	29	7.5
S	Expanded cured PE + bituminous layer 8.2 kg/m^2 – Double layer	18	0.6	2.95	21	-376	15.4
T	Non-woven PE fabric + bituminous layer 7 kg/m^2 – Double layer	11	2.0	1.62	14	19	15
U	Expanded rubber 2.7 kg/m^2	44.6	2.1	0.67	11	67	6
V	Not compacted tyres shave 2.6 kg/m^2	15.8	1.4	1.94	28	-43	7

3.3.1 Comparison between compressibility and compressive creep

Compressibility and 7 years estimated compressive creep values, reported in Table 1, are quite comparable only for few resilient layers, as already found in previous study [15]. In the present work this could be suitable for D (PE fibre 0.8 kg/m^2), E (PE fibre 1 kg/m^2), H (PE hemisphere shaped 0.4 kg/m^2), P (Expanded rubber spot shaped 2.5 kg/m^2) and T (Non-woven PE fabric + bituminous layer 7 kg/m^2 – Double layer), where Δcx is within ±20%. On the contrary, for D, E, H and P Δcx is negative and it implies that X_{7y} is higher than c_p and employing c_p instead of X_{7y} leads to an underestimation of X_{ct}.

It is important to highlight that for the other samples the abovementioned difference is more than 30%; in particular for A (Expanded PE + high density polymeric sheet 4.4 kg/m^2), Q (Expanded cured PE + bituminous layer 4.1 kg/m^2) and S (Expanded cured PE + bituminous layer 8.2 kg/m^2 – Double layer) it is more than -300%. For these layers the X_{ct} underestimation becomes very important.

In Figure 4 data are reorganized at increasing c_p values, to verify if there is any relationship between c_p and X_{7y}. It is evident that a general correlation does not exist. Moreover, considering the possible influence of sample's initial thickness, in Figure 5 the increasing c_p and ε_{7y} are reported. Also in this case no relationship can be deduced.

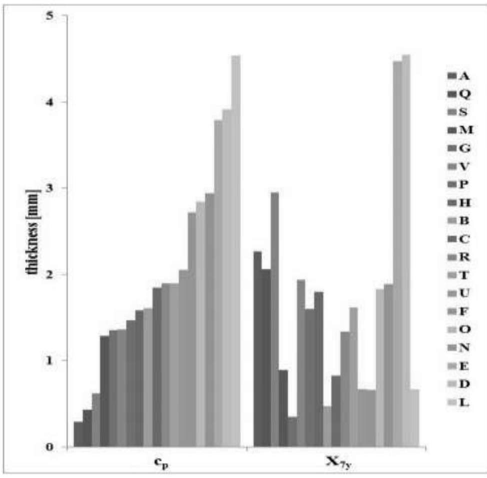

Figure 4: Comparison between increasing compressibility (c_p) and compressive creep values (X_{7y}). No correlation could be found between compressibility and compressive creep.

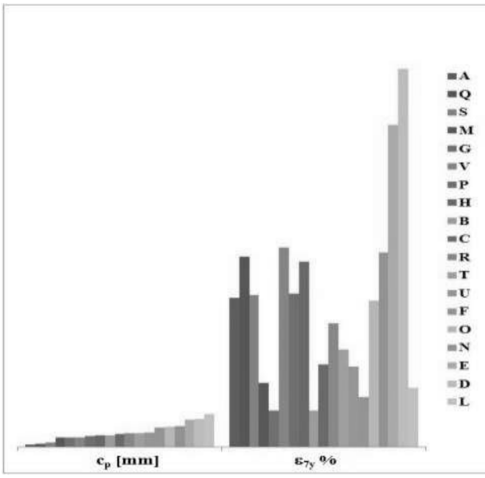

Figure 5: Comparison between increasing compressibility (c_p) and percentage compressive creep values (ε_{7y}). A general correlation between compressibility and percentage compressive creep could not be found.

Taking into account the *modified c_p mc_p* (Table A1) instead of c_p, to exclude the pre-load influence, the comparison between mc_p and X_{7y} are reported in figure 7. Even considering the modified c_p a generic law cannot be found.

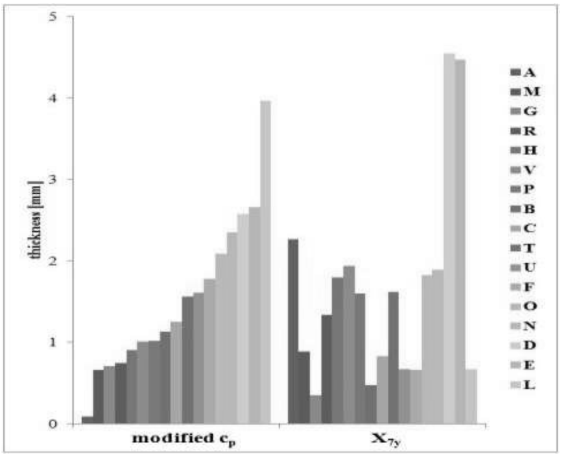

Figure 6: Comparison between modified c_p and X_{7y}. There is no relationship between modified c_p and X_{7y}.

3.3.2 The compressive creep analysis

For numerical results see table A1 in annex A. If the attention is focused on time evolution of the thickness change, some interesting considerations could be pointed out. In figure 7 percentage thickness reduction vs. time is reported, grouping resilient layers with similar compressibility value; for each curve, the coefficient of determination r^2 is also shown.

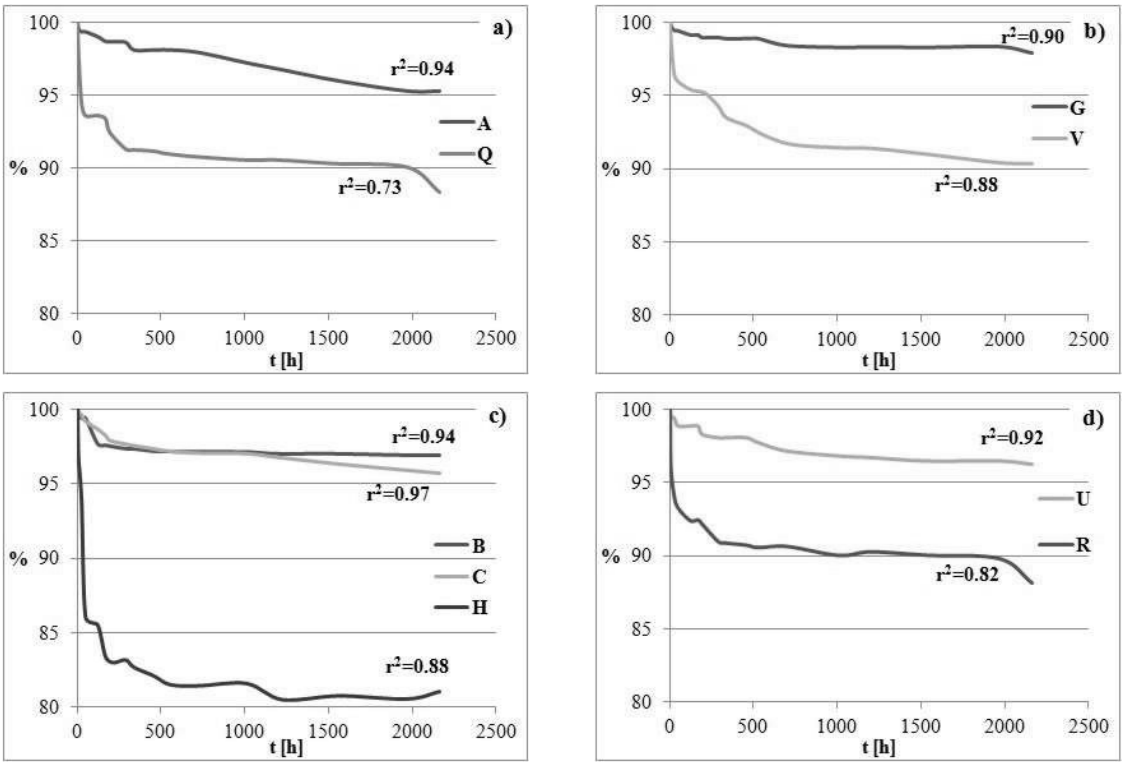

Figure 7: Percent thickness reduction vs. time for resilient layer with similar compressibility value: a) $c_p < 1$, b) $c_p = 1.35$, c) $1.5 < c_p < 1.9$, d) $c_p = 2$. The determination coefficient r^2, reported in the figures, is related to values calculated with Findley equation, as reported in table A2.

It is noteworthy that some resilient layers, such as H (PE hemisphere shaped 0.4 kg/m^2); for Q (Expanded cured PE + bituminous layer 4.1 kg/m^2) and R (Non-woven PE fabric + bituminous layer 3.5 kg/m^2) show an important change in the slope during creep; in particular a significant decrement at the end of test is evident. For the other resilient layers the behaviour is quite stable. This fact can be relate to the determination coefficient r^2: if it is greater than 0.9 a linear trend for X_t can be considered, otherwise adopting X_{ct} as the final value could be misleading.

3.3.3 The influence of density, coating and contact shape to the slab floor

Referring to Table 1, some considerations are possible. If the layer has low density or poor cohesion, it is characterized by higher compressibility and compressive creep values because the material is not able to stand loads (both static and dynamic). The only density parameter cannot explain any performance improvement or deterioration.

For composite resilient layers (more than one material), the final s' result is the sum of the single layer value [7]. The effect of an additional layer is evident (Table 1), as an example, for Cotton waste (B and C) or Expanded PE (A, I and Q): coupling a more compact coating, the s' value increases and the final performance (ΔL_n) of the whole layer decreases. On the other hand, the compressibility and the compressive creep results show a better consistency: the more the coating is rigid, compact and compatible with the lower layer, the more these two parameters improve.

So the Cotton waste + high density polymeric sheet 5.3 kg/m^2 layer (B) has lower c_p and X_{7y} than the Cotton waste + PE foil 1.2 kg/m^2 (C), that is B has better performance than C. The PE fibre shows very poor values but with the bituminous coating it gains higher performance.

From preliminary data, it seems that dynamic stiffness rises depending on contact shape (point, line, wave, etc.). This may be due to the reduction of vibration transmission area which acts as a "damper" for sound wave transmission. Further investigations will be carried out in order to better understand the phenomenon.

So density, coating and contact shape contribute to the final results of all three parameters s', c_p and X_{7y}. The modification of a characteristic could lead to a decrease of one mechanical parameters but an increase of the others.

3.3.4 The influence of compressibility and compressive creep tests on dynamic stiffness

In order to evaluate if the compressibility and compressive creep tests may influence the dynamic stiffness, experiments on some layers were carried out.

In table 2 the percentage variation of s' before and after compressibility tests are reported.

Table 2: Comparison between dynamic stiffness before and after compressibility test.

Code	**Resilient layer**	***s'* before c_p test [MN/m^3]**	***s'* after c_p test [MN/m^3]**	**(s'$_{before}$-s'$_{after}$)/s'$_{before}$ %**
C	Cotton waste + PE foil 1.2 kg/m^2	15.4	16.4	-6
H	PE hemisphere shaped 0.4 kg/m^2	11.5	11.9	-3
I	Expanded PE 0.8 kg/m^2	27.5	25.9	6
L	Expanded rubber line shaped 1 kg/m^2	29.1	17.8	39
P	Expanded rubber spot shaped 2.5 kg/m^2	19.8	18.0	9
U	Expanded rubber 2.7 kg/m^2	44.6	44.5	0

These results demonstrate that compressibility test has a very little influence on *s'*, except for layers subjected to irreversible compaction, as an example due to the contact shape (L).

Unlike the conclusions suggested by other authors [16], the influence of compressibility test does not provide always positive effects on *s'*.

In Table 3 the dynamic stiffness at different time step (0 days, 90 days and 150 days) during compressive creep test, the relative ΔL_{500Hz} and the ε_{7y} parameter are reported.

ΔL_{500Hz} has been determined in compliance with relations (1) and (2), using *m'* of 100 kg/m^2 according to ISO 10140 [24].

Table 3: Dynamic stiffness and ΔL_{500Hz} before and after compressive creep test.

Code	**Resilient layer**	***s'* at t_0 [MN/m^3]**	***s'* after creep 90 days [MN/m^3]**	***s'* after creep 150 days [MN/m^3]**	**ΔL_{500Hz} at t_0 (dB)**	**ΔL_{500Hz} 90 days (dB)**	**ΔL_{500Hz} 150 days (dB)**	**ε_{7y} %**
C	Cotton waste + PE foil 1.2 kg/m^2	15.4	22.3	20.9	27.1	24.7	25.1	12
P	Expanded rubber spot shape 2.5 kg/m^2	21.8	36.3	36.2	25.3	21.5	21.5	21
U	Expanded rubber 2.7 kg/m^2	44.6	54	59.7	20.2	18.9	18.3	11
V	Not compacted tyres shave 2.6 kg/m^2	15.8	29.8	34.1	26.8	22.8	21.9	28

After 90 days, the value of dynamic stiffness rises for all layers as expected, showing an increase from 21% (U) to 67% (P). After 150 days layers behaviour changed, for P and C *s'* slightly decreases, for V and U increases of another 10%.

It is valuable to note that three of the four tested layers are composed of non-continuous materials: shaped (P) and recycled (C and V). These materials have demonstrated not to withstand applied load for prolonged service time. Even if Expanded rubber 2.7 kg/m^2 (U) shows the highest s' before compressive creep, the increase after 90 days is limited if compared with Expanded rubber spot shaped 2.5 kg/m^2 (P), that reveals a better initial performance but a significant drop after 90 days.
It can be stated that for a compressive creep higher than 20%, the difference in term of ΔL is more than 3 dB; if the value is near or lower than 12% the final difference is lower than 3 dB.

3.4 Conclusions

An in-depth analysis on twenty resilient layers was performed, with the determination of the three mechanical parameters, c_p, X_t and s', in order to verify if a correlation between the short time test and the long term performance may exist. Results indicate that a general rule cannot be defined and, as a consequence, the creep test must be performed for a correct floating floor design.
The presence of a coating on layer surface, as well as different density and/or contact shape, can influence the final performance; the variation of these characteristics could lead to a decrease of only one of the mechanical parameters but an increase of the others.
It was found a possible correlation between compressive creep and impact sound pressure level reduction: if ε_{7y} is lower than 20%, s' could be considered quite constant and the ΔL variation is below 3dB; if ε_{7y} is higher than 20%, s' increases and the ΔL variation is over 3dB.
Taking into account only the forecast X_{ct} value, instead of the complete characterization, the long term performance could be affected by significant inaccuracy.
Taking into account these considerations, standards and laws should make these tests compulsory; thus, designers and layers producers would have scientific and robust data to handle and manage. A choice based on possible relations between the three parameters could in many cases lead to different real results.
Furthermore, laws should include a mandatory sets of tests repeated over years in order to guarantee the declared performances to final costumers.
Finally, an in-depth analysis on recycled materials is necessary in order to understand if their behavior is constant in time and if their performances are comparable to traditional layers.

3.5 Annex A

Table A1: Parameters for the compressibility values calculation.

code	Resilient Layer	d_L	d_F	d_B	d_L-d_F	d_L-d_B (c_p)	d_F-d_B (modified c_p)
A	Expanded PE + high density polymeric sheet 4.4 kg/m^2	8.58	8.38	8.29	0.20	0.29	0.09
B	Cotton waste + high density polymeric sheet 5.3 kg/m^2	9.46	8.98	7.85	0.48	1.61	1.13
C	Cotton waste + PE foil 1.2 kg/m^2	7.65	7.05	5.80	0.60	1.85	1.25
D	PE fibre 0.8 kg/m^2	11.00	9.67	7.09	1.33	3.91	2.58
E	PE fibre 1 kg/m^2	10.77	9.64	6.98	1.13	3.79	2.66
F	Expanded rubber line shaped 3.6 kg/m^2	9.86	8.92	7.14	0.94	2.72	1.78
G	Expanded rubber spot shaped 3.2 kg/m^2	7.27	6.63	5.92	0.64	1.35	0.71
H	PE hemisphere shaped 0.4 kg/m^2	7.08	6.41	5.50	0.67	1.58	0.91
I	Expanded PE 0.8 kg/m^2	12.28	11.89	11.38	0.39	0.90	0.51
L	Expanded rubber line shaped 1 kg/m^2	8.17	7.60	3.63	0.57	4.54	3.97
M	Expanded rubber spot shaped 3.9 kg/m^2	9.46	8.83	8.17	0.63	1.29	0.66
N	Expanded rubber wave shaped 2 kg/m^2	6.90	6.31	3.96	0.59	2.94	2.35
O	Expanded rubber line shaped 3 kg/m^2	8.90	8.15	6.06	0.75	2.84	2.09
P	Expanded rubber spot shaped 2.5 kg/m^2	7.76	7.32	6.30	0.44	1.46	1.02
R	Non-woven PE fabric + bituminous layer 3.5 kg/m^2	6.77	5.62	4.87	1.15	1.90	0.75
T	Non-woven PE fabric + bituminous layer 7 kg/m^2 – Double layer	--	--	--	0.44	2.00	1.56
U	Expanded rubber 2.7 kg/m^2	5.50	5.06	3.45	0.44	2.05	1.61
V	Not compacted tyres shave 2.6 kg/m^2	8.52	8.17	7.16	0.35	1.36	1.01

Table A2: Parameters for compressive creep determination.

Code	Resilient Layer	*a*	*b*	r^2	*m*	X_{7years}
A	Expanded PE + high density polymeric sheet 4.4 kg/m^2	-1.82	0.45	0.94	0.02	2.27
B	Cotton waste + high density polymeric sheet 5.3 kg/m^2	-0.82	0.08	0.94	0.15	0.47
C	Cotton waste + PE foil 1.2 kg/m^2	-1.13	0.21	0.97	0.07	0.80
D	PE fibre 0.8 kg/m^2	-1.86	0.52	0.95	0.01	4.55
E	PE fibre 1 kg/m^2	-1.62	0.47	0.90	0.02	4.47
F	Expanded rubber line shaped 3.6 kg/m^2	1.29	0.23	0.91	0.05	0.65
G	Expanded rubber spot shaped 3.2 kg/m^2	-1.49	0.21	0.90	0.03	0.35
H	PE hemisphere shaped 0.4 kg/m^2	0.00	0.05	0.88	0.99	1.80
L	Expanded rubber line shaped 1 kg/m^2	-0.84	0.13	0.82	0.15	0.67
M	Expanded rubber spot shaped 3.9 kg/m^2	-0.44	0.08	0.82	0.36	0.89
N	Expanded rubber wave shaped 2 kg/m^2	-1.70	0.40	0.82	0.02	1.89
O	Expanded rubber line shaped 3 kg/m^2	-1.38	0.34	0.97	0.04	1.83
P	Expanded rubber spot shaped 2.5 kg/m^2	-1.82	0.42	0.90	0.02	1.60
Q	Expanded cured PE + bituminous layer 4.1 kg/m^2	-1.08	0.29	0.73	0.08	2.06
R	Non-woven PE fabric + bituminous layer 3.5 kg/m^2	-0.22	0.07	0.82	0.61	1.34
S	Expanded cured PE + bituminous layer 8.2 kg/m^2 – Double layer	-0.48	0.20	0.98	0.33	2.95
T	Non-woven PE fabric + bituminous layer 7 kg/m^2 – Double layer	-0.88	0.22	0.98	0.13	1.62
U	Expanded rubber 2.7 kg/m^2	-1.93	0.36	0.92	0.01	0.67
V	Not compacted tyres shave 2.6 kg/m^2	-0.49	0.16	0.88	0.33	1.94

3.6 References

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4. Recycled materials for noise reduction in floating floors

4.1 Introduction

In the last years, sustainability sensitivity has grown up. In particular, re-use and recycle education leads to a wide public awareness.

In buildings, environmental and energy saving protocols such as Leed, Itaca, GreenStar, Casaclima etc. motivate the availability of these types of materials [1]. In this regard, many manufacturers placed more and more often, alongside the traditional materials the recycled ones. The same trend is found within scientific literature [2-7].

In acoustic field, materials could be placed inside a double wall, within the hollow space, or under a floating floor system. In the first case, they offer an impedance alteration between two denser layers. Suitable materials could be open cell or fibre ones, in order to absorb the reverberated noise within the interspace [8].

In floating floors systems, several types of layers could be found: (i) open cells (ii) closed cells and (iii) fibrous. The formers are e.g. foams such as polyurethane, the second ones are for example tyre or gasket shaves; the latter one are cotton, wool, textile or wood waste.

The development of a recycled layer poses new problems, since novel production technologies are also needed.

Final product is usually obtained by junk grinding to reduce their size. Afterwards the particulate is handled with heat and/or pressure plus some adhesives in order to gather the constituent parts. The original properties of the starting material are therefore rather modified.

In this paper, some recycled materials are analysed, in order to understand if they could be similar to traditional ones used as resilient layers and if their performances are stable over time.

4.2 Materials and methods

The types of analyzed resilient layers are described in table 1. Dynamic stiffness tests according to ISO 9052-1 [9], ISO 9053 [10] e ISO 7626-5 [11] standards were carried out and the results were compared with thermogravimetric analysis.

Dynamic stiffness determination is essential to design and choose the correct mass and thickness of all floating floor components. In particular, this parameter defines how much a system can decrease the vibration transmission. The impact sound pressure level reduction can be evaluated applying the Cremer's relation [12]:

(1) $$\Delta L = 30 log \frac{f}{f_0} \quad \text{(dB)}$$

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 obtained with equation (2):

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

where s' is the apparent dynamic stiffness per unit area [MN/m^3] of the resilient layer measured after few seconds the application of the standardized load t_0 and m' is the mass per unit area [kg/m^2] of slab.

Table 1. tested layers.

code	Resilient layer	s' at t_0 [MN/m^3]
A	Not compacted tyres shave	15.8
B	Mixed textile fibre waste – producer A	15.4
C	Mixed textile fibre waste – producer B	29.7
D	Cotton – wool waste	18.4
E	Expanded rubber – control layer	44.6

These layers were tested at t_0 time and after 210 days (t_{210}) under static load of 200 kg/m^2; during this period the dynamic stiffness value was measured.
For the characterisation of the materials, simultaneous thermal analysis (STA), that is thermogravimetric and differential thermal analysis with instrument STA 409 Netzsch has been carry out, using about 30 mg for each layer. For all the specimens the test conditions were: heating rate of 10K/min, atmosphere air, crucible in alumina, final temperature 1050°C.
STA is a technique in which a physical property of a substance is measured as a function of temperature whilst the substance is subjected to a controlled temperature programme [13].

4.3 Results

4.3.1 Dynamic stiffness analysis

For dynamic stiffness test it was voluntarily chosen a non-automatic system both for excitation and for post processing: impact hammer PCB Piezoeletronics® Mod. 086C03, N. 26753; accelerometer Dytran® Mod. 3023M2 Triaxial; hardware National Instruments® mod. NI 9234; software LabVIEW® Sound and Vibration Toolkit for signal acquisition.
With this method, it is possible to move both source and receiver along the whole specimen surface, changing mutual positions. This choice, pointless with homogenous traditional layers, may show the phase differences within a single sample. Afterwards it is possible to study the FFT fre-

quency trends, in order to understand whether these curves were just like or different from traditional ones.

Obtained results, both at t_0 and after 210 days under static load (compressive creep test [14]), show a frequency shift of the resonance amplitude peak at higher values. This fact implies a reduction of the floating floor performances according to relation (1) and is caused by compressive creep phenomenon both for traditional and recycled layers. Nevertheless, for recycled materials the appearance of a second peak at higher frequencies is visible.

As an example, in figure 1 and 2 graphical trends of resonance frequencies for A and B are reported. No influence of excitation amplitude is to be taken in to account. In order to compare the behaviour of recycled layers with traditional ones, in figure 3 a typical trend (expanded rubber- E) is shown as a "control specimen".

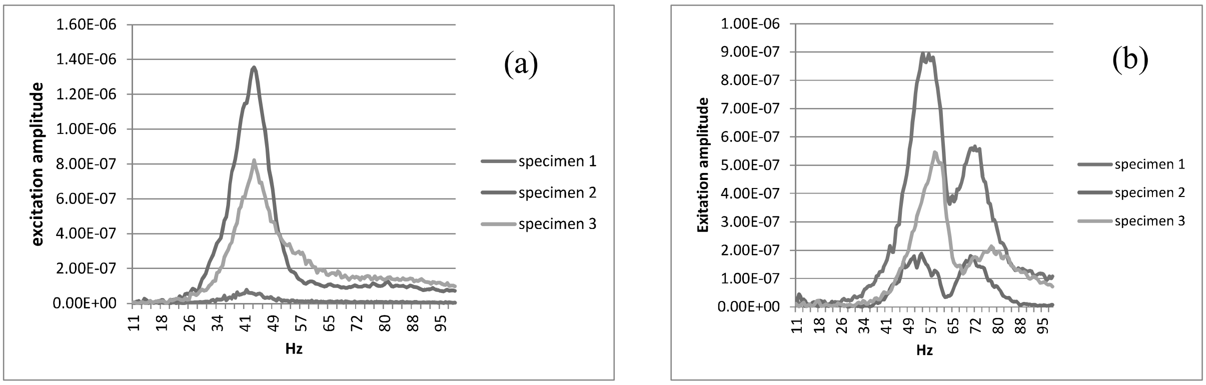

Figure 1. Resonance Frequency for not compacted tyres shave (A) at t0 (a) and t = 210 days (b).

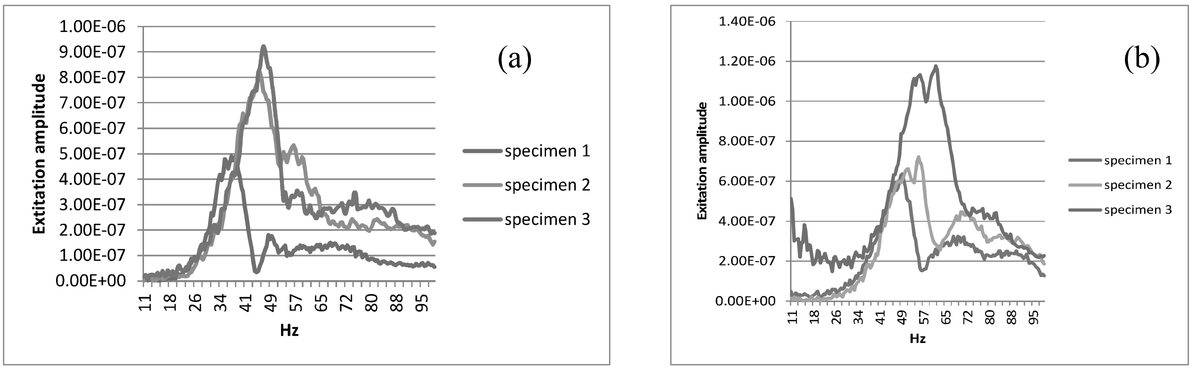

Figure 2 Resonance Frequency for mixed textile fibre waste (B) at t0 (a) and t = 210 days (b).

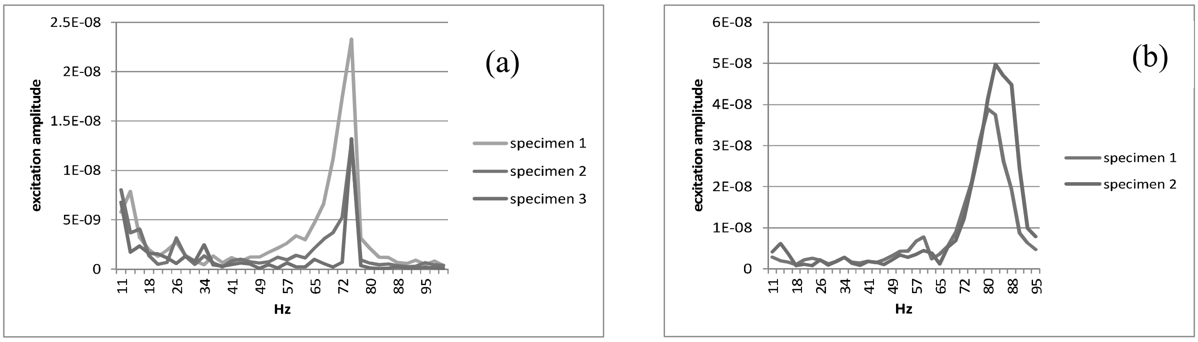

Figure 3. Resonance Frequency for expanded rubber (E) at t_0 (a) and t = 210 days (b).

4.3.2 Simultaneous thermal analysis.

In order to explain the changes in mechanical behavior observed along the time (fig. 1 and 2) and to be sure that the second peak correspond to a second phase, thermogravimetric analysis was used.

4.3.2.1 Not compacted tyres shave (A)

These materials appear visually non homogeneous, it is possible to distinguish at least two types of pieces: compact grains and fibrous pieces. These two parts are used for the thermogravimetric analysis. In Fig.4 the resultant curves are reported.

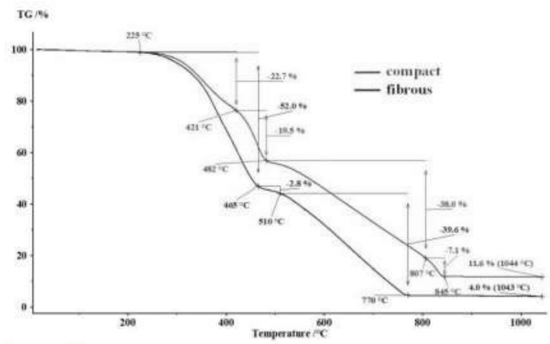

Figure 4. Thermogravimetric curves for the two pieces (compact and fibrous) of the not compacted tyres shave material (A)

The thermal behaviour of these two pieces is clearly different, showing differences in both final decomposition temperature of about 70°C and in the inorganic residual filler quantities of almost 12% for the compact grain and 4% for the fibrous part.

The differences can be due, other than the filler content, in different rubber blend.

4.3.2.2 Cotton waste (B, C, D)

The three types of cotton waste resilient layer B, C and D have been analysed.

The cotton waste materials are intrinsically non homogeneous being composed of different types of fibres materials (basically not only cotton) and colour (that is different pigments).

The thermal behaviour of the three samples is reasonably similar, except for the presence of different types and amount of adhesive used during compaction.

From fig. 5, it is possible to see that the thermogravimetric curves (TG) are coincident, some different weight loss step are due to the different sample sizes into the crucible; the D sample has the first decomposition step a little bit slower. The differential thermal analysis (DTA) curves are also similar in the decomposition part (from 200°C to 670°C), but not at lower temperature (from 25°C to 200°C), as shown in fig. 6. The endothermic peaks refer to the melting of thermoplastics LDPE (T_m= 125°C) and PP (T_m = 161°C) [15] that presumably are use as glue. In the B and D materials both PE and PP are present, only PP in C.

The STA results indicate that effectively, as supposed from the frequency resonance graphs, the materials are not homogeneous. In particular, the “tyres shave” is composed of two different rubber blends, whereas in the “cotton waste” also polymers are present (used as glue) in different amount and composition.

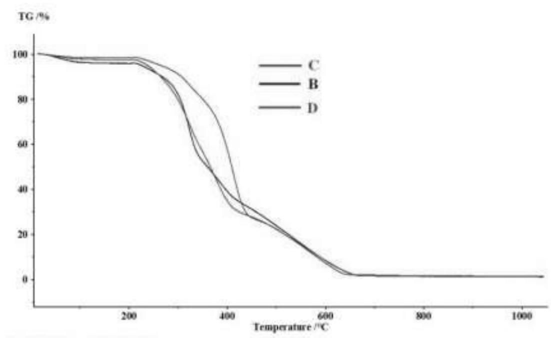

Figure 5. Thermogravimetric (TG) curves for the three samples (B, C and D) of the cotton waste material.

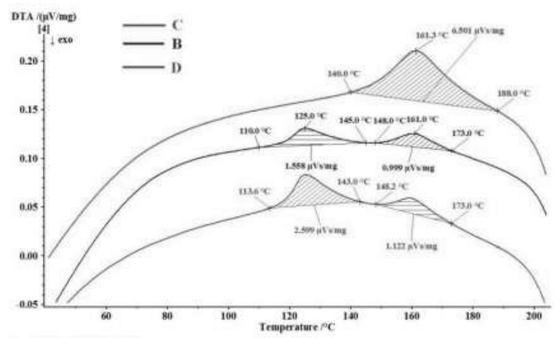

Figure 6. DTA curves for the three cotton waste samples (B, C and D) in the lower temperature range (before the decomposition).

4.4 Discussion

Layer A shows a very different resonance frequency trend from t_0 to t_{210}. This is a conglomerated layer. At the last time step, the layer split in two different and independent materials with two diverse resonance frequencies. Even if the higher peak is at lower value in two of the three specimens, the presence of another peak implies a reduction of acoustic insulation calculated by relation (1).

The thermogravimetric analysis shows clearly this difference (fig. 4). Even if at the t_0 step the production method could make the two phases get together, the static load forces split up them again.

Layer B shows a double peak from t_0 to t_{210}. This is a compacted layer that contains glue in order to supply the needed consistency. The constant double peak indicates a two-phase layer.

STA shows the presence of these two phases, and it is possible to determine which type of adhesive is used (fig. 6). The difference in term of dynamic stiffness value is due to the different glue type and content. So the resilient characteristic is deeply linked with glue rather than the waste.
In figure 3 the control specimen is shown. This is a traditional compact layer with a clean peak at t_0 and at t_{210}. So no different phases could be found in this resilient layer, as expected. Nevertheless, even this kind of material is susceptible to static load effects.

4.5 Conclusions

Recycled resilient layers were tested in order to understand if their behaviour is similar to the traditional ones. Dynamic stiffness trends were analysed both at t_0 and after 210 days with static loads. Two or more dissimilar phases were found, with different resonant frequencies, at different time steps. STA have pointed out how these phases are present within the different part composing the layers.
Recycled resilient layer could supply good acoustic performances, but their resonance frequency behaviour has to be controlled during compressive creep test in order to understand if the production method may guarantee inner stability.

4.6 References

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5. Energy performances of windows

5.1 Introduction

Worldwide, air, water and soil pollution derives more and more from human beings behaviour. Transports, industries, commerce, entertainments, influence and condition our lives. Human indoor noise disturbance is caused by humans themselves. High thermal and air infiltration insulation is needed in order to ensure good life conditions.

Buildings are constructed in order to protect people from these effects, opposing their external envelope to outside environment. This peripheral skill defends from rain, wind, cold and hot seasons, dust, noise, etc. Though, it is of paramount importance for our way of living, working and sleeping. Many studies have been carried out during last years, because the performances of this building parts are the base of energy saving [1]-[5], inner comfort [6] - [8] and possible shape and realization solutions [9].

Nevertheless, on this topic many other in-depth studies are necessary because these vertical or horizontal partitions are not homogenous and composed by many other big or small components like opaque wall, glazing, air inlet systems, traditional or peculiar shapes and projections.

Opaque vertical and horizontal parts are of simple analysis. In last years external walls and floors become thicker. The addition of thermal insulation or resilient layers [10], air and water insulations sheaths, aerogel-based finishing [11],[12] or paintings [13] are used to improve or restore building technologies.

In this field, walls, floors and roofs thermal insulation reached its bests performances since even if the thermal insulation layer become very thick, no appreciable effect will be ever felt inside buildings [14]. It is evident that over 28-30 cm of a good insulating materials (typically with a thermal conductivity $\lambda < 0.035$ W/mK) no energy saving will be performed so far.

Projections and traditional or peculiar shapes are simple to manage. First one are very useful to shadow form hot sunny weather. They are very necessary for the reduction of hot sun radiation and help to limit the air conditioning use [15],[16],[17].

On the other hand, glazed windows present different issues to solve. They are an openable component (for natural ventilation) and though the air insulation could not be perfect. This implies a lack in term of thermal and acoustic protection. Moreover, the presence of see-through component is compulsory for natural daylight lightning [18]. It is evident that the study of this latter element is very important, due to its peculiar performances of “barrier” and “hole” at the same time.

The European Directives, as well as Kyoto protocol, invite designers to drive buildings performances to higher or the highest levels, in order to improve inner comfort and energy savings

[1]. Such buildings needs important designing efforts in terms of material sorting, shape and orientation choice, global close environment analysis and possible needs knowledge of future occupants.

For all these reasons and for the aim of this work, precise and robust technical information about all products are essential for the final result.

The windows "product" is growing [8] both in industrial and technological field. In 90's it was almost impossible to test or find windows with more than two glazing, laminated glass, different gasses inlet(s), etc. On the other hand in last years it is possible to find different application for separated technologies like thermal [19]-[26] or acoustic [27]-[28] insulation.

Windows producers always advertise their products as the best ones for acoustics, thermal, lighting, and environmental performances. Concerning this latter factor, a very interesting paper was published [29] where the three principal types of materials or coupling were analysed. The study concludes that wooden windows are the best and the PVC ones are the worst in term of global environmental pollution, taking into account production methods, life cycles and recyclability. Nevertheless, the study does not take into account possible performances obtainable with these different materials.

As an example, if a PVC windows may insulate 200% more than the wooden ones this could lead to the fact that the PVC would be better than wood. This simple aspect, fundamental for the present research, shows how the possible constituting material choice must have robust scientific bases in term of global energy insulation

Glazing is common to every windows. This aspect was already studied both as itself [30] and as laminated with or without PVB [31] and as primary sample [32]. Furthermore, it is the necessary component of the lighting system and it cannot be changed.

The two parameter globally considered as representative of windows energy insulation performances are sound reduction level R and thermal transmittance U_w.

The first one can both be measured and calculated (see paragraph 2.1). It represents the global windows impedance opposed to sound propagation.

The measurers are carried out in laboratories designed according to series ISO 10140 standards [33]. As shown in Figure 1, these test centres are constituted of two acoustically independent rooms. The sample is included in a wall placed in the middle of the laboratory.

Figure 1 – a typical test specimen

The measurement technique avoids flanking transmission and try to limit workmanship effects; though it could be used both to compare and to choose products for final destination in buildings. Sound insulation level R is requested for the overall sound reduction level of façade D_{2m} prediction (see paragraph 2.1 for details).
Prediction methods are available in international standards [34],[35], [36]. Nevertheless, they only can predict up to low R levels (typically 36 dB – 37 dB) or they request the laboratory measured value of primary glass samples.
In the first case, the obtained values are too low to be used in nowadays buildings; this method could be suitable in the past when the windows were very simple (e.g. 4/12/4). Nowadays, this element improves a lot its thermal and acoustical performances adding PVB (PoliVinylButhile) layers, laminated glasses, one or more inlets and so on. In the second case a laboratory test is needed and consequently few advantages could be gained, since a laboratory test has to be performed in any case.
On the other hand, thermal transmittance can be both measured with laboratory tests or easily calculated using international standards methods (see paragraph 2.2). It represents the global resistance windows would be able to oppose to thermal energy diffusion in cold weather condition. It is very useful both to compare products and to evaluate energy saving in buildings.
On the other hand, it does not take into account workmanship effect and hot weather condition since it considers only conductivity (λ [W/mK]) and area parameters (S_i [m^2]) of single component such as glass, frame, type of material and length of the glass seal.
Consequently, sound reduction level has to be measured, but single result won't show why this peculiar window has this particular performance, since no mathematical and parametrical model is available.
On the other hand transmittance is easy to manage and to calculate.

Moreover, acoustical and thermal energy windows performances are in some way obtained with same procedures: air infiltration insulation and multiple component and layer coupling. Therefore a possible correlation between the two parameters could be investigated and would be really appreciated both in research and in designing field.

The aim of the present work is to deeply analyse the dedicated literature and then study windows constituted of different acoustical and thermal insulation characteristics in order to understand if a connection between them may exist, which is the best technology (if any) and finally if there is a possible formulation for the prediction of the sound insulation, in order to avoid laboratory tests in the former step.

Starting from acoustic laboratory results, R and U_w results were analysed and compared in order to understand if there is any connection between their variation and window dimensions, number and type of glazing, inlet(s) number and thickness, etc.

5.2 Materials and methods

Over than 45 different kind of windows have been studied and analysed (Table 2), characterized by diverse construction technologies, in order to investigate performances issues and understand their acoustic and thermal behaviours.

Frames are realized mostly with three different raw materials:

- Wood
- Aluminium
- PVC.

5.2.1 Sound reduction level

The windows are usually the weakest part of the sound reduction of the façade. This fact is due to their inner nature of mobile, openable and mountable component, causing a leakage in the external structure and a possible performances loss.

Sound reduction of façade is a major topic of several studies [40]-[42]. The final predicted value (D_{2m}) is calculated with the methods described in international standard [35] according to (1):

(1)
$$D_{2m} = R' + 10\log\left(\frac{V}{6 \cdot T_0 \cdot S}\right) + \Delta L_{fs}$$

where:

R' is the composite sound reduction (dB)

T_0 is the reference reverberation time equal to 0.5 s

S is the area of the façade [m^2]

ΔL_{fs} is the correction for the shape of the façade (dB)

The composite sound reduction is calculated according to equation (2)

$$R' = -10\log\left(\sum_{i=1}^{n}\frac{S_i}{S}10^{\frac{-Ri}{10}} + \frac{A_0}{S}\sum_{i=1}^{n}10^{\frac{-Dn,e,i}{10}}\right) - K \tag{2}$$

where:

S_i is the area of the single component of the façade [m^2]

R_i is the sound reduction of the single component of the façade (dB)

A_0 is the reference area equal to 10 m^2

S is the area of the façade [m^2]

$D_{n,e,i}$ is the sound reduction of the single little element in the façade (dB)

K is the flanking transmissions (dB)

Thus, this method requires the knowledge of sound reduction values R_i of all the single components, i.e. opaque and transparent. For the first ones, many calculation techniques are available [43]-[47].

On the other hand, no empirical models, tabular data, provisional formula or mathematical models are offered for windows so far, extended to contemporary usable values (R_w > 38 dB). The standards [36] provides only models up to $R_i \approx 38$ dB, as mentioned before; these values are nowadays too low to be used in standard buildings constructions. Databases on primary glass sample laboratory measurements are rare, approximated and with very few references [48].

So it is very difficult to estimate with a good and robust process the sound reduction of façades.

In order to study if some components may influence final values some comparisons were analysed (see paragraph 3). Refer to Table 1 for the symbols used in Figure 7 to Figure 12

Table 1 – legend of symbol for Figure 7 -Figure 12

Symbol	Reference
*	PVB layer
**	Double PVB layer
‘	Double gas inlet

In order to analyse robust results, this investigation is based in first step on sound reduction values obtained from 5 different laboratories in Europe with all the same features and accredited for ISO 10140 [33] tests (Sound Reduction R).

Then the sound reduction index R_w parameter, calculated using standard ISO 717 [49] proposed method, is used in order to evaluate and compare different solution.

5.2.2 Transmittance value

Windows turn up to be a weak component from thermal insulation point of view. For this reasons, the energy passing through this element both in cold and in hot climate must be restricted and limited. In last years many efficient components were then added such as thermal insulating spacers, low emitting glasses, thicker and multiple inlets, gasses insertion like Argon, Xenon, etc. (Figure 2). This process implied a very good thermal performances achievement, but on the other hand, these technologies reached its top limits. A U_w maximum value of about 0.6 W/m^{2}K is now possible with a usual mean value (in temperate climates) of about 1 W/m^{2}K.

In this work, the thermal transmittances (U_w) are calculated according to (3) [37],[38]:

$$(3) \qquad Uw = \frac{\sum A_g U_g + \sum A_f U_f + \sum l_g \psi_g}{\sum A_g + \sum A_f}$$

where:

U_g is the heat transfer coefficient related to the glazing

U_f is the heat transfer coefficient related to the frame

ψ_g is the linear heat transfer coefficient related to the insulated glazing edge seal

A_g is the area of the glass

A_f is the area of the frame

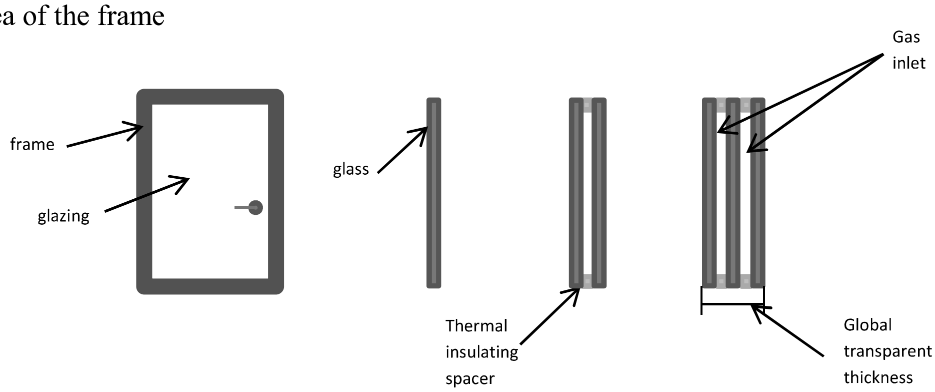

Figure 2 – Schematic representation of window.
Single, double and triple glazing front view and section

For some of the windows a comparison between calculated values and producers declarations was performed. In the 89 % of the cases, the two values overlap; in other cases the worst values were considered.

5.2.3 Samples investigated

In order to achieve the aims previously presented the acoustic performances of over 45 types of windows were tested and calculated according to ISO 10140. As it was pointless to calculate the U_w of every samples, some interesting examples were estimated according to ISO 10077-1, as reported in Table 2.

Table 2 – description of the studied windows

WOOD							
Code	Glazing I [mm]	Inlet [mm]	Glazing II [mm]	Inlet [mm]	Glazing III [mm]	R_w (dB)	U_w [W/m^{2}k]
1	3/PVB/3	16	4	--	--	37	1.3
2	4/PVB/4	12	4	12	3/PVB/3	38	1.1
3	4/PVB/4	14	4	14	4/PVB/4	38	--
4	6	12	4	--	--	38	--
5	3/PVB/3	16	4	16	3/PVB/3	39	0.76
6	3/PVB/3	18	4	18	3/PVB/3	39	--
7	4/PVB/4	15	3/PVB/3	--	--	39	--
8	4/PVB/4	15	3/PVB/3	--	--	39	1.3
9	5/PVB/5	15	3/PVB/3	--	--	39	1.3
10	8/PVB/9	16	6/PVB/6	--	--	39	--
11	3/PVB/3	12	4	--	--	39	--
12	4/PVB/4	16	3/PVB/3	--	--	40	1.3
13	3/PVB/3	15	5	--	--	40	--
14	3/PVB/3	15	4	--	--	40	--
15	4/PVB/4	15	3/PVB/3	--	--	40	--
16	4/PVB/4	15	5/PVB/5	--	--	40	1.3
17	4/PVB/4	9	6	--	--	40	--
18	3/PVB/3	9	3/PVB/3	--	--	41	--
19	4/PVB/4	16	4	16	4/PVB/4	41	0.9
20	4/PVB/4	16	6/PVB/6	--	--	41	1.3
21	4/PVB/4	16	6/PVB/6	--	--	42	1.3
22	4/PVB/4	14	4	14	4/PVB/4	43	0.9
23	4/PVB/4	14	4	14	3/PVB/3	43	--
24	3/PVB/3	14	6	14	3/PVB/3	44	--
25	4/PVB/4	14	4	14	4/PVB/4	44	0.8
26	6/PVB/6	12	6	12	6/PVB/6	44	0.9
27	6/PVB/6	12	6	12	4/PVB/4	44	0.9
28	4/PVB/4	15	4	15	5/PVB/5	44	--
29	4/PVB/4	14	4	14	4/PVB/4	45	0.77
30	6/PVB/6	16	4/PVB/4	--	--	47	1.3
Aluminium							
31	4/PVB/4	20	4/PVB/4	--	--	42	0.9
32	6/PVB/6	20	4/PVB/4	--	--	43	0.9
33	5/PVB/5	16	4/PVB/4	--	--	43	1.6
34	6/PVB/4	12	4/PVB/4	--	--	44	1.1

35	6/PVB/6	20	4/PVB/4	--	--	45	1.6
36	8/PVB/9	15	6/PVB/4	--	--	46	1.1
37	6/PVB/6	24	4/PVB/4	--	--	46	0.9
PVC							
38	4	22	4			35	1.3
39	6	22	4			38	1.0
40	6	20	4	20	4	40	0.7
41	4/PVB/4	20	3/PVB/3			41	1.3
42	4/PVB/4	18	4	18	3/PVB/3	43	0.7
43	4/PVB/4	18	4	15	4/PVB/4	43	0.7
44	4/PVB/4	20	3/PVB/3			44	1.3
45	6/PVB/6	18	4/PVB/4			44	1.3
46	4/PVB/4	18	4	15	4/PVB/4	45	0.7

5.3 Results and discussion

Using the U_w values, the single windows component influence was analysed in order to understand if one part may only impact the final value.

In Figure 3 glass thickness compared to the U_w value is presented. Glazing itself is the most transmitting part (see Table 3) as it is the most extensive part in windows. Nevertheless, it is evident that this parameter does not clearly influence final thermal insulation for any typology. It is interesting to point out that, for all materials frame, overall glass thickness could be double, but with the same U_w results.

Glazing thermal insulation is then guaranteed by the low emitting treatments on glasses, as shown in Figure 4. Nevertheless, the low emitting treatment alone would not guarantee optimum thermal insulation.

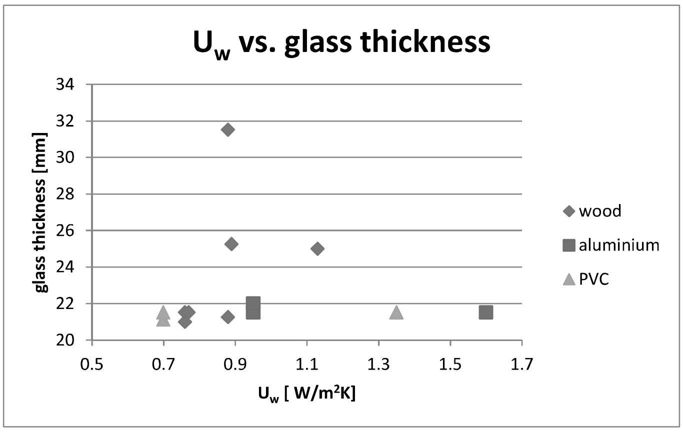

Figure 3 – comparison between U_w value and glass thickness

Table 3 – typical conductivity values for windows components [37]

component	λ [W/mK] [38]	U [W/m²K] [37]
Single glass	1	5.8
Insulated aluminium frame	--	2,2-3.8
Wood frame	0.12	2.0
PVC frame	0.16	2.0

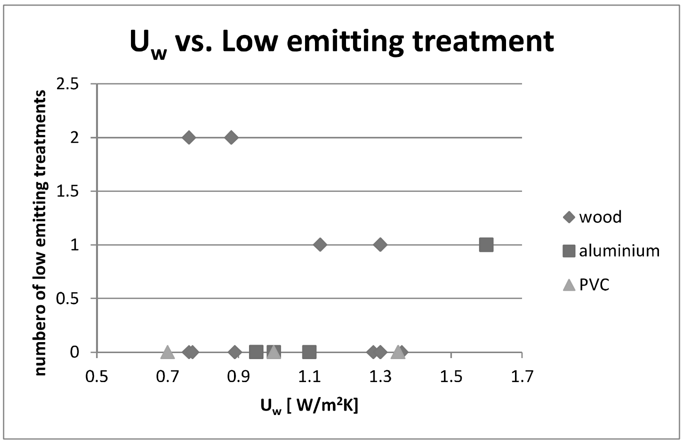

Figure 4 – comparison between U_w value and low emitting treating presence

In Figure 5 frame thickness compared to the U_w value is presented. As for the former case, no evident correlation is possible. Especially for wood frame, thickness influence is homogeneously distributed in all U_w performances.

In Figure 6 overall transparent thickness compared to the U_w value is presented. It is evident that no possible correlation could be found, since for constant transmittance values the transparent component thickness is even 80% higher.

As a consequence for all these analyses it can be concluded that no single part influences the final result but the all parts jointly contribute to ultimate thermal insulation performance.

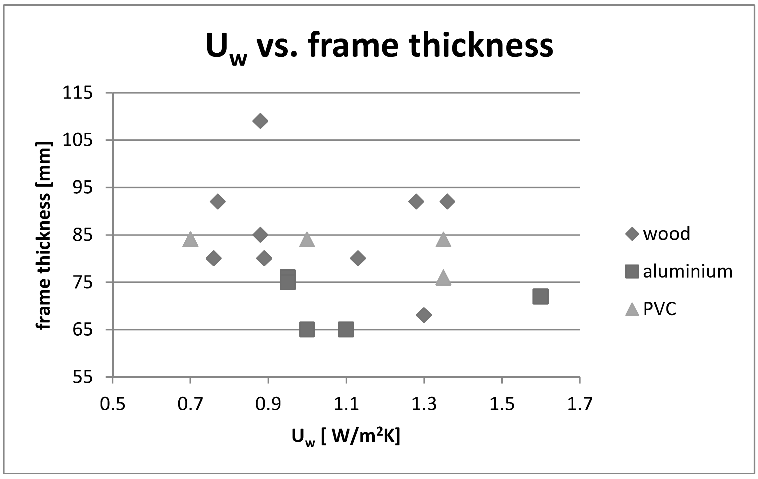

Figure 5 - comparison between U_w value and frame thickness

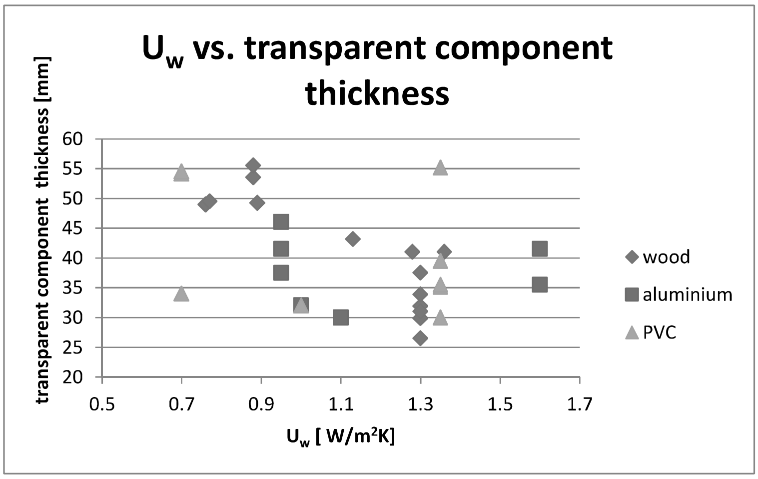

Figure 6 – comparison between overall transparent thickness and U_w value

5.3.1 Sound Reduction R

Sound insulation is of paramount importance for hearing protection. All the analysed parameters influence the R values in frequency domain. As a matter of fact different external sources have different and peculiar frequency emissions [50]-[55]. Though, windows sort for buildings applications in noisy soundscapes have to consider possible frequency sources emissions ranges in order to actually reduce human exposure to annoyance and sleeping disturbance. This consideration could not be performed if a simple index calculation is made using the methods proposed in international standards.

As a consequence, frequency sound reduction level R has to be studied for different material frames.

Despite U_w performances, R shows different behaviour for diverse windows technologies. Using the R values, the influence of single windows component was analysed in order to understand if one part may only impact the final value.

On the other hand, the use of R_w is necessary to quickly compare many different solution. In conclusion, both R (for designing purpose) and R_w (for comparison purpose) are essential parameters.

5.3.2 Wooden frame

In Figure 7 gas inlet as first parameter was identified to influence R_w < 40 dB performances in middle frequencies. As evidenced in many other studies [27], [31], [32], [48], PVB presence influences coincidence limitation in high frequency range (see for example sample 4 for PVB absence and samples and 11 for only one PVB layer, Figure 7).

In Figure 8 overall glass thickness as second parameter was identified to influence 40 dB ≤ R_w ≤ 41 dB performances in middle frequencies.

In Figure 9 overall PVB thickness as third parameter was identified to influence 42 dB ≤ R_w ≤ 48 dB performances in middle and high frequencies.

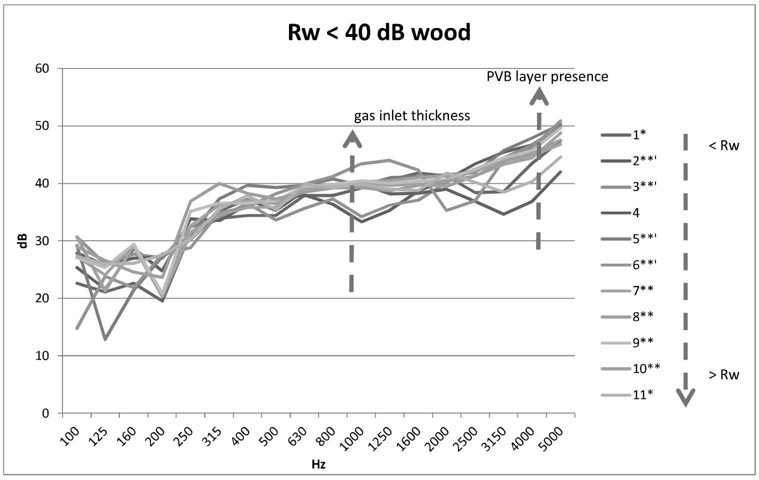

Figure 7 – influence of gas inlet thickness and PVB presence

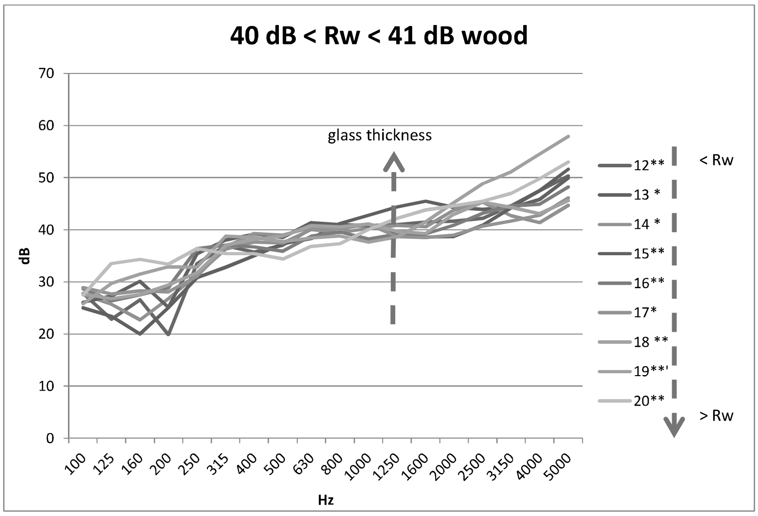

Figure 8 - influence of overall glass thickness

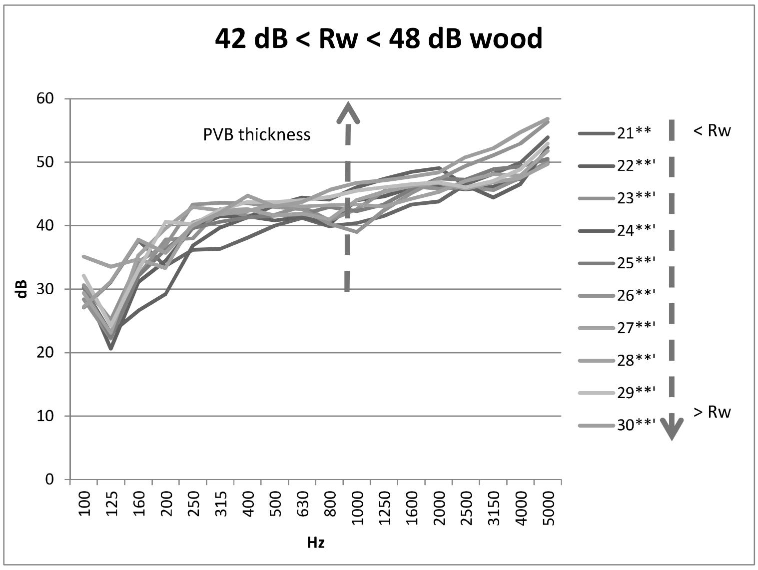

Figure 9 - influence of overall PVB thickness

5.3.3 Aluminium frame

In Figure 10 jointly glass and gas inlet thickness influence is evidenced in aluminium frame. From middle – low frequency range the behaviour is quite linear and constant and it rises according to the increase of transparent overall thickness.

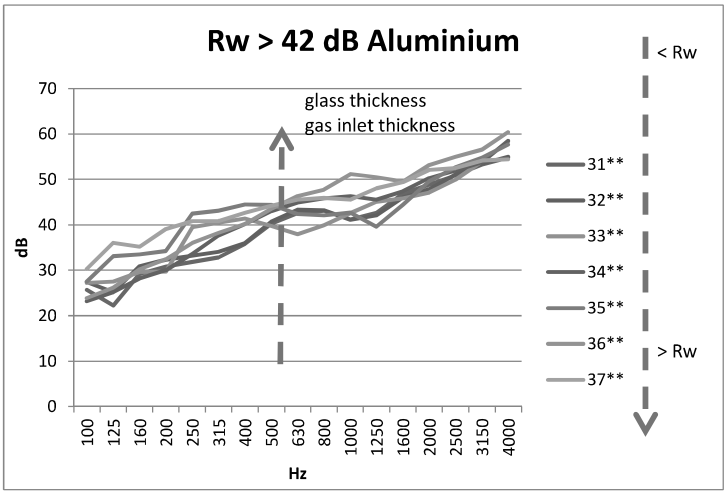

Figure 10 - influence of overall glass and gas inlet thickness

5.3.4 PVC frame

In Figure 11 jointly glass thickness and PVB presence influence is evidenced in PVC frame. From middle – low frequency range the performances are clearly influenced from the first issue; on the other hand the PVB presence (as for the other materials) modifies high coincidence frequencies.

In Figure 12 the only sensible variable is the glass thickness, influencing low and middle-high frequencies. In 46 samples it is worthy to note that the overall structure is able to nullify both resonance and coincidence phenomena.

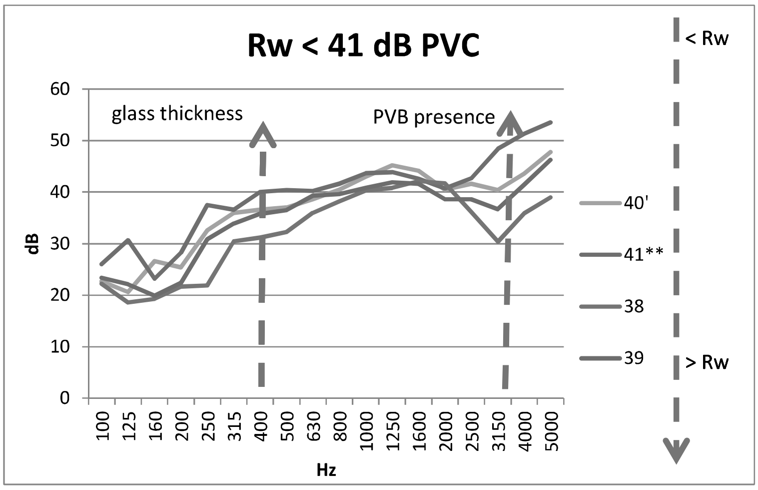

Figure 11 - influence of overall glass thickness and PVB presence

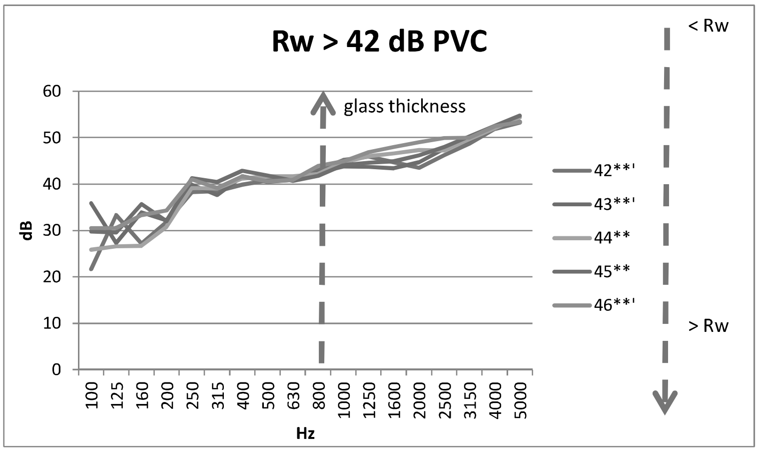

Figure 12 - influence of overall glass thickness

5.4 Thermal vs. Acoustical insulation

From previous paragraphs, it is evident that if a correlation between R and U_w would be possible it could be a great help for researchers, designers, producers and users, because of the easiness in determining the latter parameters [56] - [58].

For this reason, a comparison between the two final values was carried out. In order to compare only index results, the weighted sound reduction index R_w determined with ISO 717-1 method [49] was used.

In Figure 13 the comparison between R_w and U_w values is reported. As an overall overview no direct correlation could be found. High sound insulation index values do not always correspond to low transmittance and vice versa.

So in Figure 14 the wooden frame transmittance is kept constant whether the sound reduction index is compared with overall glass thickness. Here the influence of the overall glass thickness is explicit, and once more, this parameter alone does not imply an increase in transmittance.

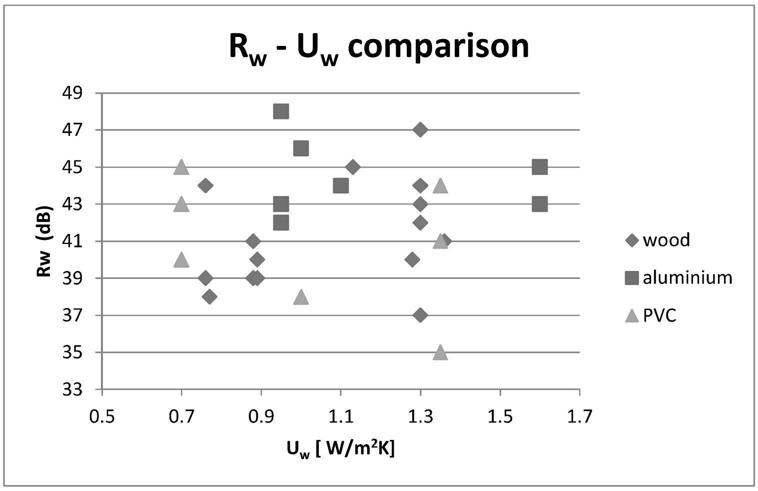

Figure 13 – R_w – U_w comparison for all windows typologies

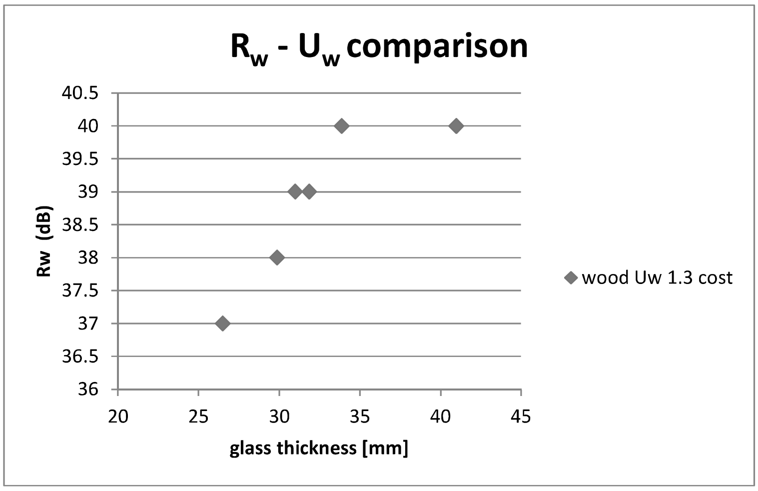

Figure 14 – R_w – U_w comparison for wooden frame at U_w = 1.3 W/m^{2}K

In Figure 15, for wooden frame technology, the best U_w values are kept constant, whether the R_w parameter shows an increase if the PVB thickness rises. So this component acts only as sound insulation improvement , since overall glass thickness is irrelevant from a limit of $U_w \approx 0.9$ W/m^{2}K and $R_w \approx 41$ dB.

In Figure 16 the aluminium frame is analysed. Even if there are very few samples for this analysis, as before for medium U_w values, the overall glass thickness improve the sound insulation performances.

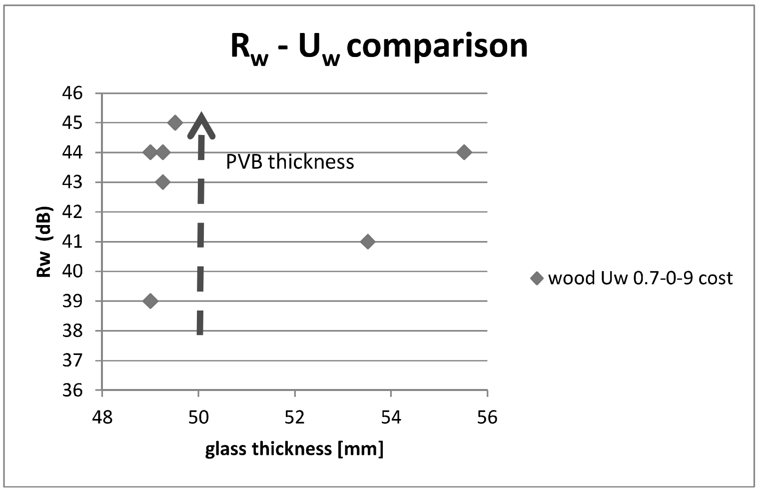

Figure 15 – Influence of PVB thickness on sound insulation improvement with U_w constant

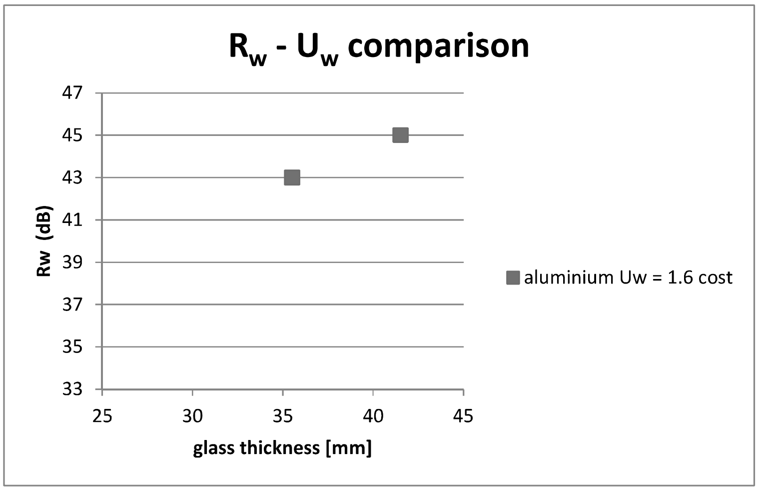

Figure 16 - R_w – U_w comparison for aluminium frame at U_w = 1.6 W/m^{2}K

In Figure 17 for aluminium frame technology, the best U_w values are kept constant, whether the R_w parameter shows an increase if the PVB and overall glass thickness rise. So these components act only as sound insulation improvement.

In Figure 18 the PVC frame transmittance is kept constant whether the sound reduction index is compared with overall glass thickness. Here once more the influence of the overall glass thickness is explicit, and once more, this parameter alone does not imply an increase in transmittance.

In Figure 19 for PVC frame technology, the best U_w values are kept constant, whether the R_w parameter shows an increase if the PVB thickness (within laminated glasses) rises. So this component acts only as sound insulation improvement, since overall glass thickness is irrelevant from a limit of $U_w \approx 0.8$ W/m^{2}K and $R_w \approx 40$ dB.

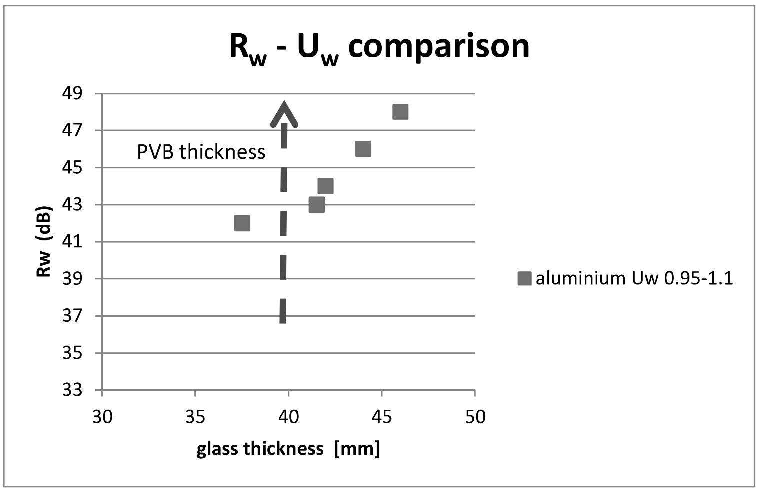

Figure 17 - Influence of PVB and overall glass thickness on sound insulation improvement keeping U_w constant

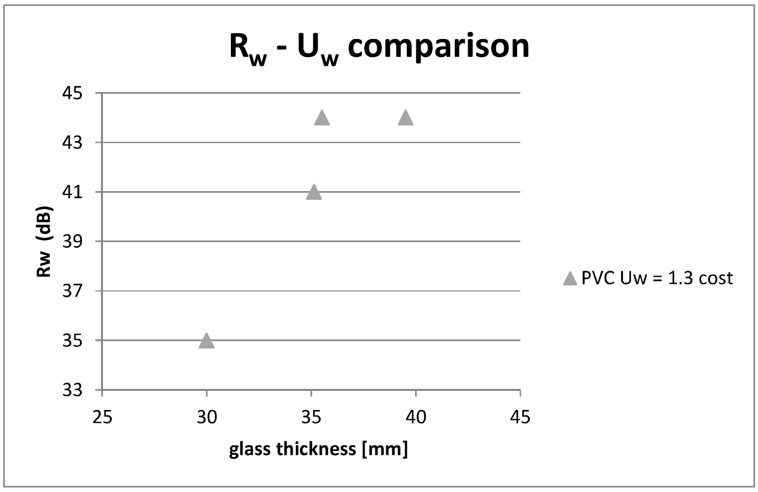

Figure 18 - R_w – U_w comparison for aluminium frame at U_w = 1.3 W/m^{2}K

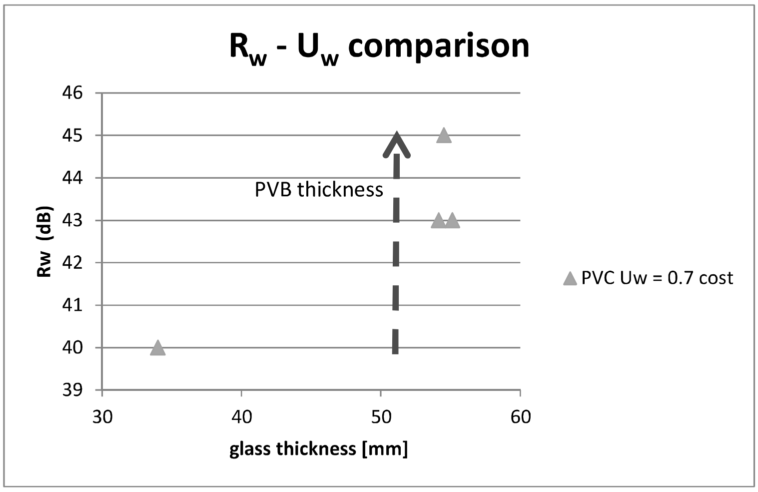

Figure 19 - Influence of PVB thickness on sound insulation improvement with U_w constant

5.5 Sound reduction prediction

After all this considerations, it is evident how glasses, gas inlet(s), PVB presence within laminated glasses and thickness influence final R_w result. Nevertheless, no prediction method included in literature or in international standards considering this issues exists so far.
Though, using the available laboratory tests, a prediction method could be stated.

(4) $$R_w = 20 \log m' + A \log d_1 + 1.9 \log d_2 - B \log e + 5 \log (P) + C \quad \text{(dB)}$$

where:
m' is the mass of present glass per unit area [kg/m^2];
A = 10 for two gas inlets; 14.5 for single gas inlet; (dB);
B = 10 for wooden and PVC frame; B= 9 for Aluminium single gas inlet frame; (dB);
C is a corrective term. For PVC frames C= - 10dB when no PVB is present for one gas inlet; for PVC frames C = -6 dB when no PVB is present for two gas inlets; in other cases C= 0; (dB);
d_1 is the first gas inlet dimension [mm];
d_2 is the second gas inlet dimension [mm]. If only one gas inlet is present then d_2 =1;
e is the thicker laminated glass dimension [mm]. e=1 with only 1 laminated glass [mm];
P is ten times the PVB overall thickness sum. It is used only when two gas inlets and two laminated glasses layers are present. In other cases, P=1;

A,B and C corrective terms are obtained from regression procedure.
This method shows a very good agreement with laboratory values for all frame typologies as it is shown from Figure 20 to Figure 22. For aluminium the prediction works up to $R_{w,max}$ = 44 dB.

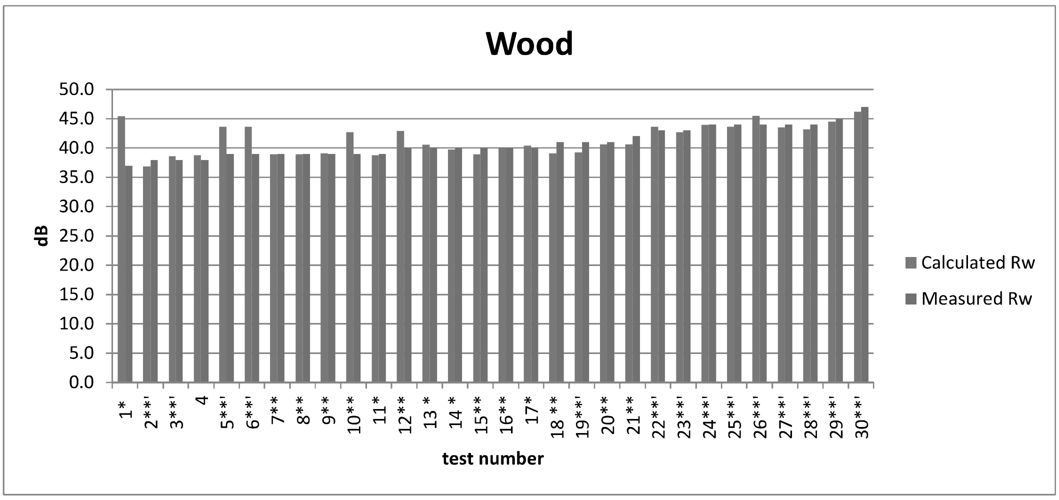

Figure 20 – $R_{w,lab}$ vs. $R_{w,pred}$: results comparison between the two methods for wooden frames
For 1*, 5', 7**, 10** and 12** samples, there were workmanship effects during laboratory tests. Though, calculated values seems to be more correct than tested values.**

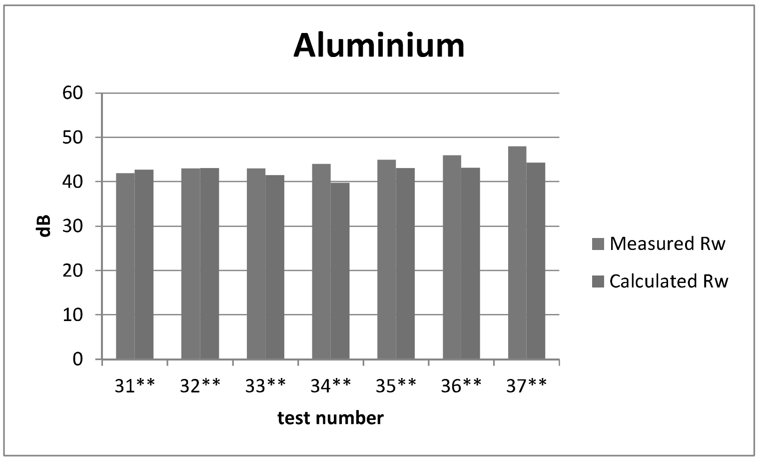

Figure 21 - $R_{w,lab}$ vs. $R_{w,pred}$: results comparison between the two methods for aluminium frames

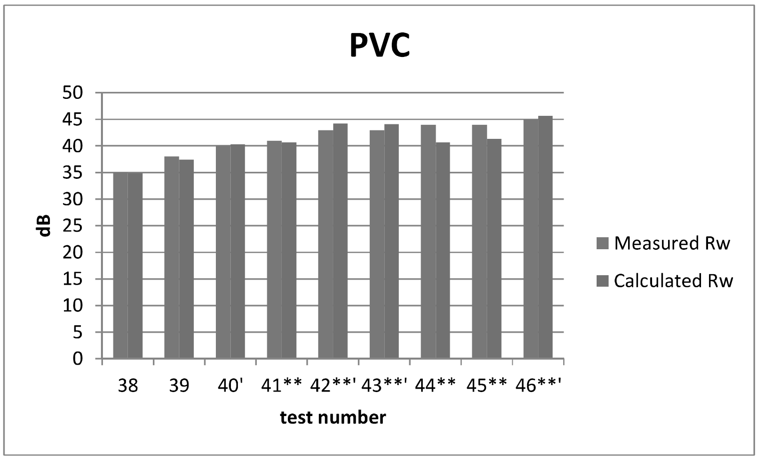

Figure 22 - $R_{w,lab}$ vs. $R_{w,pred}$: results comparison between the two methods for PVC frames

5.6 Conclusions

An in-depth analysis of more than 45 different frame windows was performed comparing thermal and acoustical insulation. The examination of transmittance U_w and sound reduction frequency values R and sound reduction index R_w shows that no possible correlation between these parameters is possible.

From the thermal insulation point of view results demonstrated that no single windows component could influence final performances, but all constituents have to jointly participate to final insulation effect. On the other hand acoustic insulation has shown dependence from single parameters such as PVB for coincidence reduction, overall glass and gas inlet(s) thickness for improve middle and in some case low frequencies insulation.

Both thermal and acoustic best performances are obtainable with all of available material frames. So when choosing the best one, wooden is the less environmental impactful, with higher insulation values.

Finally, a new prediction method was proposed for the R_w estimation; calculated values show a very good agreement with tested ones. This new method could be used to improve international standards in order to help designers and producers to predict final sound reduction index values when planning new products. This would not replace the fundamental laboratory test, which has to be used as final confirmation.

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6 Noise levels due to service equipment: the use of ISO 12354-5 models on waste water installations

6.1 Introduction

Service equipment is the most usual noise source in buildings. As a matter of facts, moving air and water provide sound waves spreading through the whole buildings. Waste water as well as air conditioning noise prediction methods refers to ISO 12354-5 models [1].

Air equipment such as HVAC are widely studied and well described in literature. Sharland [2] described methods for noise reduction and control of pipes, silencers, etc. Beranek and Ver [3] proposed empiric formulations to predict airborne sound source and its possible attenuation.

On the other hand, concerning waste water flushing system prediction models, only a single international study is available so far. Even in their recent review, Mak and Wang [4] did not report the waste water noise topic, but only the air one. Then, the only available work is the Villot's one [5]. Here, he described the application of the ISO 12354-5 standard to some cases.

Other studies on the same standard deal with other issues, such as laboratory [5]-[9] or field [10] structure borne sound measurements.

This lack of studies on ISO 12354-5 waste water noise prediction methods is related to several issues:

I. complexity of the proposed models
II. trouble to find starting input data
III. Source directivity is almost unknown data for pipes
IV. lack of precise indication on how input data are to be applied
V. not univocal interpretation of included parameters
VI. Source is often close to reflecting partitions; though, the diffuse field approach could not be used.

The aim of this study is to deeply analyse the ISO 12354-5 method for waste water pipe source and then apply it to possible case studies.

The first section presents the complex calculation method described in the standard with all the external references contained therein.

The second section deals with all the bullets point described before and it tries to give an interpretation of possible solutions.

In the last section the calculation is applied to many case studies and compared with field measurements.

6.2 Materials and method

The formulation contained in the standard is elaborated and requests an in-depth overview in order to unroll all steps.

6.2.1 Analytical process

The waste water source is related with two different noise natures:

I. airborne
II. vibration

Both of them come from waste water pipe, but for model purpose they are split up, because the propagation paths, as well as the modalities, are different.

The former is generated inside the pipe. A part of it continues the path inside the conduit and it will exit where the travel ends. The other portion will get out of the pipe and starts spreading within the building (see Figure 1).

The latter is caused by impact of the flushed water with the pipe. The induced vibration finds a solid propagation path within both the conduit sides and, where it could find a solid junction, the building partitions (see Figure 2).

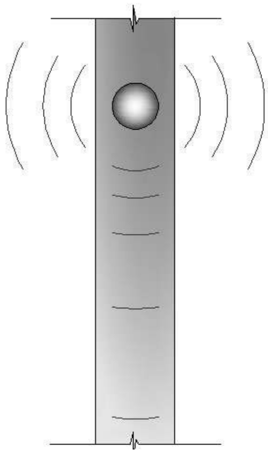


Figure 1 – Airborne propagation paths

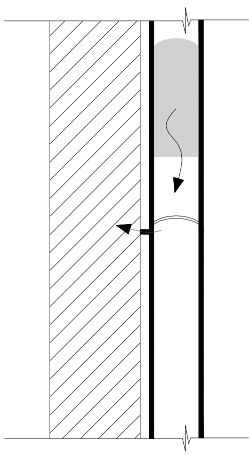


Figure 2 – Vibrations propagation paths

The general expression of the sound pressure level at receiver follows from the sum of the described parameters

(1)
$$L_n = 10 \cdot \log\left(\sum 10^{\frac{L_{n,d}}{10}} + \sum 10^{\frac{L_{n,a}}{10}} + \sum 10^{\frac{L_{n,s}}{10}}\right) \qquad dB$$

where:

L_n is the total normalized sound pressure level due to the source(s), in decibel

$L_{n,d}$ is the sound pressure level due to the sound transmission through the pipe, in decibel

$L_{n,a}$ is the sound pressure level due to airborne sound transmission through the building structure, in decibel

$L_{n,s}$ is the sound pressure level due to structure-borne sound transmission through the building structure, in decibel

If more than one pipe is included in the room, then the total normalized sound pressure level and its included parameters will be the result of the sum of multiple contributions.

In the standard, equation (1) is valid both for air conduits and for waste water pipe. Though, it has to be fitted to individual case.

The sound pressure level due to the sound transmission through the pipe $L_{n,d}$ is connected to the airborne sound following the waste water falling. So, it can be considered of no importance since the waste water does not flow into building room.

The sound pressure level due to airborne sound transmission through the building structure $L_{n,a\ it}$ is constituted of different components such as sound power level of the source L_w, flanking transmission R_{ij}, sound transmission to element in the source room D_s and two constant adaptation terms.

The first one is derived from the laboratory test according to EN 14366 standard, the second from ISO 12354-1 standard [12] and the third is expressed as follows (equation (2)).

$$D_s = 10log\left(\frac{Q'}{4\pi r^2} + \frac{e^{-\frac{A_s}{S_t}}}{A_s}\right) \cdot S_i \qquad dB \tag{2}$$

where Q' is the source directivity, r is the average distance from source to element [m], A_s is the equivalent absorption area in the source room, S_t is the total area of boundaries of the source room [m^2].

The sound pressure level $L_{n,s}$ due to structure-borne sound transmission through the building structure is formed of different components such as the characteristic structure-borne sound power level of the source $L_{ws,c}$, the coupling term for the source of the supporting building element D_c, the adjustment term from structure-borne to airborne excitation for supporting building element D_{sa}, the flanking transmission R_{ij}, and two constant adaptation terms.

The first one is derived from the laboratory test according to EN 14366 standard, the second takes in to account the mobility of the supporting element, the third refers to sound radiation and critical frequency and could be expressed using ISO 12354-1.

6.2.2 Discussion and analysis of the theoretical expression

The complexity of presented model lies in the dual nature of the noise. The first phase is to obtain EN 14366 laboratory results from pipe producers. Then, these certificates have to be deeply and well analysed because very often they include the structure-borne sound insulating support. This fact deeply change the former input data as seen in Figure 3. Configuration A refers to a waste water pipe fastened with rigid support , whether configuration B refers to a conduit secured with sound insulating support.

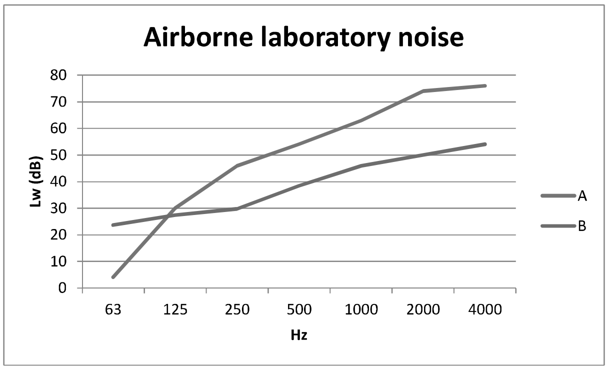


Figure 3 – Airborne laboratory result for different configurations; A with rigid support and B with sound insulating support.

It is evident how the two configurations provide very different final values. So the equations have to offer adaptation terms in order to well calculate the final values. At this time no such terms are provided.

Furthermore, within the D_s, directivity of the source as well as the average distance from source to element are required. As Villot previously highlighted [5], it is almost impossible to determine the directivity of a waste water pipe without assuming approximations. The distance from the element is often very short. In the case of a waste water pipe inserted in to a wall, the distance is almost 0 and the D_s ratio tends to infinite. Even using small distance (i.e. one or two centimetres) the final values do not result effective.

The R_{ij} evaluation could be easily performed using ISO 12354-1 models. On the other hand, this standard was intended to operate on heavy weight homogeneous partitions [13] - [15], while, the use in lightweight or double leaf structures is compromised. As it could be understood from equation (3), the K_{ij} terms are based on the mass ratio between the walls composing the junctions. As seen before, in timber buildings many technologies are possible; the most used and studied is the one composed by particle or gypsum board on top on wooden glulam beams, with screw attaching the boards to the beams. Concerning this type, no mass ratio could effectively be computed.

(3) $$K_{13} = 5,7 + 14.1 \cdot M + 5.7 \cdot M^2$$

$$K_{12} = 5{,}7 + 5.7 \cdot M^2$$

$$M = \frac{m'_{i\neg}}{m'_i}$$

where:

$m'_{i\neg}$ is the mass per unit area of the element in the transmission path ij [kg/m^2]

m'_i is the mass per unit area of the other perpendicular element composing the junction [kg/m^2]

In the second phase the EN 14366 laboratory results for structure-borne sound are analysed. As before, these certificates have to be deeply and well analysed because very often they include the structure-borne sound insulating support. This fact deeply change the former input data as seen in Figure 4. Configuration A refers to a waste water pipe fastened with rigid support, whether configuration B refers to a conduit secured with sound insulating support.

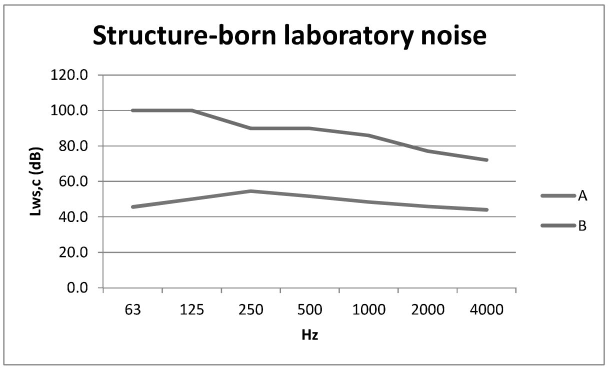


Figure 4 – Structure-born laboratory result for different configurations; A with rigid support and B with sound insulating support.

Here, the effect of the vibration insulating support is evident but the A type values could not be used as input data for equation (1) because they do not represent the real structure born sound power level.

Another issue regards the B type. When the elastic support is not present the D_c influence depends on the mobility of the system. This effect is related to the elasticity of the support. The ISO 12354-5 standard proposes the following equation (4) in order to analytically solve the composed system:

(4) $$D_c = -10 \log \mathrm{Re}\,\{Y_i\} - 30 \quad \text{dB}$$

(5) $$Y_i \approx \frac{f_c}{150000 \cdot t} \quad [\mathrm{m/Ns}]$$

where Y_i is the mobility of the system [m/Ns] and f_c is the critical frequency [Hz]. This could be calculated using ISO 12354-5 as reported in equation (6)

(6) $$f_c = \frac{c_0}{1.8 \cdot c_L \cdot t} \qquad [Hz]$$

where t is the element thickness [m], c_0 is the sound speed in air [m/s], c_L the longitudinal velocity inside the propagating material [m/s]. The longitudinal velocity is expressed using following equation (7):

(7) $$c_L = \sqrt{\frac{E}{\rho}} \qquad [m/s]$$

where E is Young's modulus [Pa] and ρ is the density of the element [kg/m^3].
The typical resilient materials used as vibration insulators are e.g. expanded rubber, expanded PE, etc. (see Figure 5)

Figure 5 – Typical vibrant insulator for water pipes a) expanded PE, b) resilient ring

The Young's modulus values of these materials are very difficult to find. Moreover, often the resilient rings have not regular shapes since they present "wave" or "point" features (see Figure 6). The final performance of the linear materials is not equal to the shaped one.

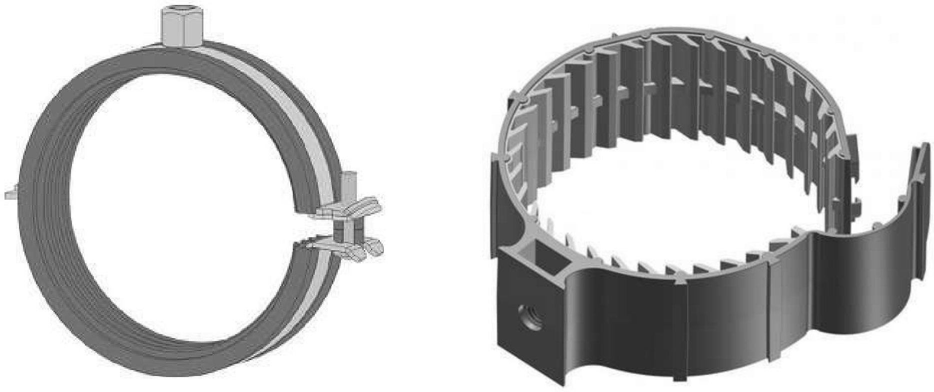


Figure 6 – Vibration insulator shaped support [16],[17]

This could be overcome using EN 29052-1 [18] where the equation (8) is reported.

$$E = s' \cdot d \quad (8)$$

where s’ is the dynamic stiffness of the resilient layer [Mn/m^3] and d is its thickness [m].

6.2.3 Analysis of the indication contained in the standard

Since the available methods were studied both for air and for water service equipment, the terminology is unfortunately ambiguous. As an example, the term “element” is used in almost every description. Nevertheless this is a very general subject, not identifying a precise object or case. Even if in the “air” case the “elements” are easy to identify, in the “water” instance some specifications could be very useful. As an example, the D_s term (equation (2)) is described as “the sound transmission to element in the source room”. In the case of a pipe included in a wall or in a shaft both in heavy weight or light weight construction, source and receiver room coincide. So the “element” is not of clear identification. In the same way, the average distance r from source to element is difficult to interpret, because the “element” is not clearly identified.
The calculation of the sound power levels L_w and L_{wsc} derives from EN 14366 results according to equations (9) and (10).

$$L_w = L_a + 10 \cdot \log\frac{A_{ref}}{4} = L_a + 4 \quad dB \quad (9)$$

$$L_{wsc} = L_{sc} + 8 \cdot \log f + 23.5 \quad dB \quad (10)$$

As it is evident, L_w has no frequency term so it is not possible to perform frequency domain calculations as for L_{wsc}.

6.3 Application to real cases

In this section the models discussed before are applied to possible in situ cases both in heavyweight and lightweight timber constructions. Then, for the latter ones, a comparison with field measurements is provided.

6.3.1 Case 1 – Heavyweight - Pipe within a wall

This analysis takes into account a waste water installation embedded in a wall separating to different apartments.

The conduit has a 5 mm expanded PE layer all around it and lays within a 25 cm hollow bricks walls. The flanking walls are realized with 8 cm hollow bricks (see Figure 7). The noise source is in apartment A when a 2 l/s water flow is released (flushing cistern) on the upper floor. The prediction is performed in apartment A

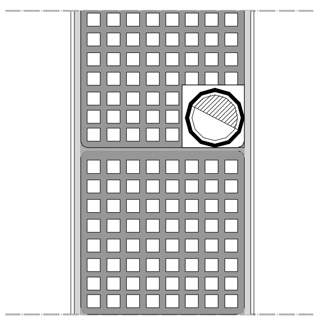


Figure 7 – Case one scheme

In order to acquire the input data, a certificate according to EN 14366 standard is required [19]. Considering the topic discussed above, some approximation have to be done. In Table 1 and Table 2 a summary of 500 Hz 1/3 octave band are reported.

Table 1 – Calculations and considerations concerning airborne sound pressure level

- Sound power level L_w:	Using EN 14366 results and equation (9), the sound power level results $L_{w\ 500\ Hz}$= 38,4 dB(A)
- Direct transmission D_s:	No distance from source to element is present. then D_s=0
- Flanking transmissions $R_{ij,ref}$:	- dividing wall (d): m'= 287 kg/m^2 $R_{w500\ Hz}$ =52 dB; S =8,1 m^2 - mortar covering layer (D): m'= 110 kg/m^2 $R_{w500\ Hz}$ =24,3 dB - flanking walls (1, 2): m'= 136 kg/m^2

	$R_{w500\ Hz}$ =44 dB; S =8,1 m^2 - upper floor (3): m'= 458 kg/m^2 $R_{w500\ Hz}$ =54,3 d; S =9 m^2 - lower floor (4): m'= 458 kg/m^2 $R_{w500\ Hz}$ =54,3 dB; S =9 m^2 Though, final values results: ➢ $R_{Dd\ 500\ Hz}$ = 26,5 dB ➢ $R_{1d\ 500\ Hz}$ = 59,2 dB ➢ $R_{2d\ 500\ Hz}$ = 59,2 dB ➢ $R_{3d\ 500\ Hz}$ = 63,8 dB ➢ $R_{4d\ 500\ Hz}$ = 63,8 dB
- Airborne sound pressure level $L_{n,a,A,500Hz}$:	8,8 dB(A)

Table 2 - Calculations and considerations concerning structure born sound pressure level

- structure born sound power level L_{wsc}:	Using EN 14366 results and equation (9), the sound power level results $L_{wsc,\ 500\ Hz}$= 51,7 dB(A)
- coupling term D_c:	In the laboratory certificate the test is described. It is reported that the pipe was fastened using a vibration insulating support. Though, it is not possible to compute the mobility using equations (4)-(8) since the final values are already affected by its decoupling influence. Here it could be assumed that the insulating results are equal both using expanded PE and insulating support(s).
- Flanking transmissions $R_{ij,ref}$:	- dividing wall (Dd): m'= 285 kg/m^2 $R_{w500\ Hz}$ =52 dB, S =8,1 m^2 - flanking walls (1,2): m'= 136 kg/m^2 $R_{w500\ Hz}$ =44 dB, S =8,1 m^2 - upper floor (3): m'= 458 kg/m^2 $R_{w500\ Hz}$ =54,3 dB, S =9 m^2 - lower floor (4): m'= 458 kg/m^2 $R_{w500\ Hz}$ =54,3 dB, S =9 m^2 Though, final values results: ➢ $R_{Dd\ 500\ Hz}$ = 52 dB ➢ $R_{1d\ 500\ Hz}$ = 40 dB ➢ $R_{2d\ 500\ Hz}$ = 40 dB ➢ $R_{3d\ 500\ Hz}$ = 61,5 dB ➢ $R_{4d\ 500\ Hz}$ = 61,5 dB
- adjustment term D_{sa}:	The pipe excites the dividing wall ($c_{L,D}$=3500 m/s,

	t=25 cm) and this transmits to the flanking vertical partitions ($c_{L1,2}$=2600 m/s, t=12 cm) and horizontal ones ($c_{L\,3,\,4}$=3500 m/s, t=24 cm) ➢ $D_{sa\,D}$ = -32,6 dB (A) ➢ $D_{sa\,1,2}$ = -26,2 dB (A) ➢ $D_{sa\,3,4}$ = -35,7 dB (A)
- Structure born sound pressure level $L_{n,s,A,500Hz}$:	38,4 dB(A)

Summing the two terms the final sound pressure level results $L_{n,A,500Hz}$= 38,4 dB(A). The final frequency level is reported in Table 3.

Table 3 – final results for case 1

Hz	*125*	*250*	*500*	*1000*	*2000*	*4000*	$L_{n,A}$ dB(A)
$L_{na,A}$	8,6	5,6	8,8	10,9	9,6	8,2	16,7
$L_{ns,A}$	33,0	39,4	38,4	38,4	35,6	39,1	45,6
$L_{n,A}$	33,1	39,4	38,4	38,4	35,6	39,1	45,6

6.3.2 Case 2– Heavyweight - Pipe within a shaft

This analysis takes into account a waste water installation inserted in a shaft and fastened on a wall separating to different apartments using vibration insulator support (Figure 8). The noise source is inside apartment and the prediction is provided in the same dwelling when a 2 l/s water flow is released (flushing cistern).

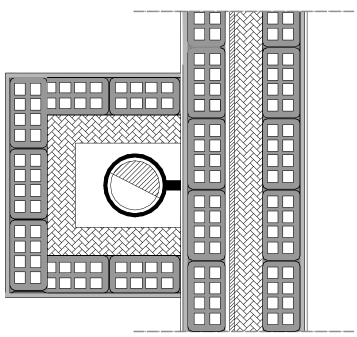


Figure 8 – Case two scheme

In order to acquire the input data, a certificate according to EN 14366 standard is required [19]. Considering the topic discussed above, some approximation have to be done. In Table 4 and Table 5 a summary of 500 Hz 1/3 octave band is reported.

Table 4 – Calculations and considerations concerning airborne sound pressure level

- Sound power level L_w:	Using EN 14366 results and equation (9), the sound power level results: $L_{w\ 500\ Hz}$= 38,4 dB(A)
- Direct transmission D_s :	- Assuming that the pipe is a cylindrical source the directivity results: Q'=1 - average distance: r=15 cm - Shaft total area: S_t = 2,43 m^2 - Equivalent absorption area: A_s =2,19 m^2 ➢ D_s = 13,9 dB
- air propagation paths $R_{ij,ref}$:	- shaft walls (Dd): m'= 136 kg/m^2 , $R_{w500\ Hz}$ = 44 dB, S =2,43 m^2 - dividing wall (1, 2): m'= 285 kg/m^2 $R_{w500\ Hz}$ =52 dB, S =8,1 m^2 - upper floor (3, 4, 5): m'= 458 kg/m^2 $R_{w500\ Hz}$ =54,3 dB, S =9 m^2 - lower floor (6, 7, 8): m'= 458 kg/m^2 , $R_{w500\ Hz}$ =54,3 dB, S =9 m^2 Though, final values results: ➢ $R_{Dd\ 500\ Hz}$ = 44 dB ➢ $R_{1d\ 500\ Hz}$ = 49,1 dB ➢ $R_{2d\ 500\ Hz}$ = 49,1 dB ➢ $R_{3d\ 500\ Hz}$ = 60,7 dB ➢ $R_{4d\ 500\ Hz}$ = 60,7 dB ➢ $R_{5d\ 500\ Hz}$ = 60,7 dB ➢ $R_{6d\ 500\ Hz}$ = 60,7 dB ➢ $R_{7d\ 500\ Hz}$ = 60,7 dB ➢ $R_{8d\ 500\ Hz}$ = 60,7 dB
- Airborne sound pressure level $L_{n,a,A,500Hz}$:	11,3 dB(A)

Table 5 - Calculations and considerations concerning structure born sound pressure level

- structure born sound power level L_{wsc}:	Using EN 14366 results and equation (9), the sound power level results: $L_{wsc\ 500\ Hz}$= 51,7 dB(A)
- coupling term D_c:	In the laboratory certificate the test is described. It is reported that the pipe was fastened using a vibration insulating support. Though, it is not possible to compute the mobility using equations (4)-(8) since the final values are already affected by its decoupling influence. Here it could be assumed that the insulating results are equal both using expanded PE and insulating support(s).

- adjustment term D_{sa}:	As for D_c term, it is not possible to compute the parameter, since the pipe is never in solid contact with partitions
- Flanking transmissions $R_{ij,ref}$	- dividing wall (Dd): m'= 285 kg/m^2 $R_{w500\ Hz}$ =52 dB, S =8,1 m^2 - Shaft walls (1,2): m'= 136 kg/m^2 $R_{w500\ Hz}$ =44 dB, S =2,43 m^2 - upper floor (3): m'= 458 kg/m^2 $R_{w500\ Hz}$ =54,3 dB, S =9 m^2 - lower floor (4): m'= 458 kg/m^2 , $R_{w500\ Hz}$ =54,3 dB, S =9 m^2 Though, final values results:: ➢ $R_{Dd\ 500\ Hz}$ = 52 dB ➢ $R_{1d\ 500\ Hz}$ = 49,1 dB ➢ $R_{2d\ 500\ Hz}$ = 49,1 dB ➢ $R_{3d\ 500\ Hz}$ = 65,2 dB ➢ $R_{4d\ 500\ Hz}$ = 65,2 dB
- Structure born sound pressure level $L_{n,s,A,500Hz}$:	13,3 dB(A)

Summing the two terms the final sound pressure level results: $L_{n,A,500\ Hz}$ = 15,4 dB(A). The final frequency level is reported in Table 6.

Table 6 – final results for case 2

	125 Hz	*250 Hz*	*500 Hz*	*1000 Hz*	*2000 Hz*	*4000 Hz*	$L_{n,A}$ dB(A)
$L_{na,A}$	8.0	7.3	11.3	14.6	13.4	16.6	20.8
$L_{ns,A}$	18.7	20.2	13.3	7.8	-0.9	-1.6	23.2
$L_{n,A}$	19.0	20.4	15.4	15.4	13.6	16.7	25.1

6.3.3 Case 3– lightweight - Pipe within a wall

This analysis takes into account a waste water installation inserted in a precast lightweight wooden panel and fastened on a wall separating to different apartments using vibration insulator support (Figure 9). The noise source is in apartment A whereas the prediction is provided for the other one (B) when a 2 l/s water flow is released (flushing cistern).

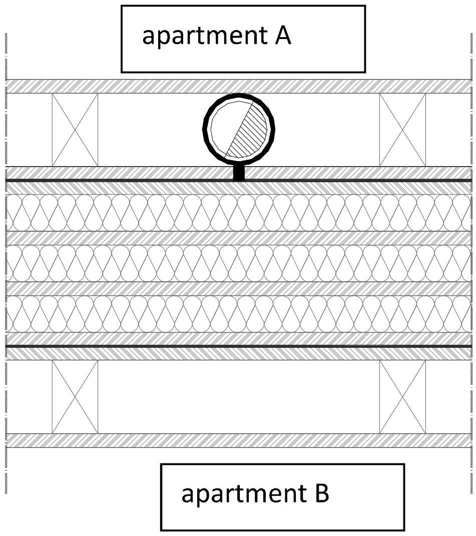


Figure 9 – Case three scheme

In order to acquire the input data, a certificate according to EN 14366 standard is required [19]. Considering the topic discussed above, some approximation have to be done. In Table 7 and Table 8 a summary of 500 Hz 1/3 octave band is reported.

Table 7 – Calculations and considerations concerning airborne sound pressure level

- Sound power level L_w:	Using EN 14366 results and equation (9), the sound power level results: $L_{w\ 500\ Hz}$= 38,4 dB(A)
- Direct transmission D_s:	No distance from source to element is present. then D_s= 0
- Flanking transmissions $R_{ij,ref}$:	- dividing wall (d): m'= 160 kg/m^2 $R_{w500\ Hz}$ =54.8 dB, S =8,1 m^2 - flanking wall (1): m'= 140 kg/m^2 $R_{w500\ Hz}$ =56.3 dB, S =8,1 m^2 - flanking wall (2): m'= 101 kg/m^2 $R_{w500\ Hz}$ =28 dB, S =8,1 m^2 - upper floor (3): m'= 180 kg/m^2 , $R_{w500\ Hz}$ =56,3 dB, S =9 m^2 - lower floor (4): m'= 180 kg/m^2 , $R_{w500\ Hz}$ =56,3 dB, S =9 m^2 Though, final values results: ➢ $R_{Dd\ 500\ Hz}$ = 54,8 dB ➢ $R_{1d\ 500\ Hz}$ = 65,72 dB ➢ $R_{2d\ 500\ Hz}$ = 51,8 dB ➢ $R_{3d\ 500\ Hz}$ = 63,7 dB ➢ $R_{4d\ 500\ Hz}$ = 63,7 dB

- Airborne sound pressure level $L_{n,a,A,500Hz}$:	not influent for final prediction, since the final value results negative

Table 8 - Calculations and considerations concerning structure born sound pressure level

- structure born sound power level L_{wsc}:	Using EN 14366 results and equation (9), the sound power level results $L_{wsc,\ 500\ Hz}$= 51,7 dB(A)
- coupling term D_c:	In the laboratory certificate the test is described. It is reported that the pipe was fastened using a vibration insulating support. Though, it is not possible to compute the mobility using equations (4)-(8) since the final values are already affected by its decoupling influence.
- Flanking transmissions $R_{ij,ref}$:	see Table 7
- adjustment term D_{sa}:	The pipe excites the dividing wall. Nevertheless this is constituted of many different impedance layers. The hollow space damping effect do not permit a solid transmission and as a matter of fact it is the most vibration insulator. Though, $c_{L,D}$=100 m/s, t=60 cm ➢ $D_{sa\ D}$ = -18,6 dB (A)
- Structure born sound pressure level $L_{n,s,A,500Hz}$:	17,8 dB(A)

Summing the two terms the final sound pressure level results $L_{n,A,500\ Hz}$ = 17,8 dB(A). The final frequency level is reported in Table 9.

Table 9 - final results for case 3

Hz	125	250	500	1000	2000	4000	$L_{n,A}$ dB(A)
$L_{na,A}$	--	--	--	--	--	--	--
$L_{ns,A}$	16,8	18,3	17,8	19,2	13,5	17,5	25,3
$L_{n,A}$	16,8	18,3	17,8	19,2	13,5	17,5	25,3

6.3.4 Case 4– lightweight - Pipe within a shaft

This analysis takes into account a waste water installation inserted in a shaft (0,30x0,30x2,7 m) lying in the corner of the room (see Figure 10).

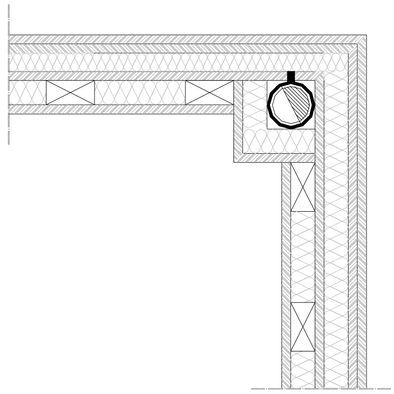


Figure 10 – Case four: scheme

The noise source is in apartment as well as the prediction when a 2 l/s water flow is released (flushing cistern).

In order to acquire the input data, a certificate according to EN 14366 standard is required [19]. Considering the topic discussed above, some approximation have to be done. In Table 10 and Table 11 a summary of 500 Hz 1/3 octave band is reported.

Table 10 – Calculations and considerations concerning airborne sound pressure level

- Sound power level L_w:	Using EN 14366 results and equation (9), the sound power level results: $L_{w\ 500\ Hz}$= 38,4 dB(A)
- Direct transmission D_s:	- Assuming that the pipe is a cylindrical source the directivity results: Q'=1 - average distance: r=15 cm - Shaft total area: S_t = 1,62 m^2 - Equivalent absorption area: A_s =1,46 m^2 D_s = 9,4 dB
- Flanking transmissions $R_{ij,ref}$:	- shaft walls (Dd): m'= 35 kg/m^2 $R_{w500\ Hz}$ =29 dB, S =1,62 m^2 - supporting wall (1): m'= 140 kg/m^2 $R_{w500\ Hz}$ =54.8 dB, S =8,1 m^2 - corner wall (2): m'= 160 kg/m^2 $R_{w500\ Hz}$ =56.3 dB, S =8,1 m^2 - upper floor (3): m'= 180 kg/m^2 $R_{w500\ Hz}$ =54.8 dB, S =9 m^2 - lower floor (4): m'= 180 kg/m^2 $R_{w500\ Hz}$ =54.8, S =9 m^2 Though, final values results: ➢ $R_{Dd\ 500\ Hz}$ = 29 dB

	➢ $R_{1d\ 500\ Hz}$ = 44,9 dB ➢ $R_{2d\ 500\ Hz}$ = 45.2 dB ➢ $R_{3d\ 500\ Hz}$ = 65.5dB ➢ $R_{4d\ 500\ Hz}$ = 63,7 dB
- Airborne sound pressure level results $L_{na,A,500\ Hz}$:	23 dB(A)

Table 11 - Calculations and considerations concerning structure born sound pressure level

- structure born sound power level L_{wsc}:	Using EN 14366 results and equation (9), the sound power level results $L_{wsc,\ 500\ Hz}$= 51,7 dB(A)
- coupling term D_c:	In the laboratory certificate the test is described. It is reported that the pipe was fastened using a vibration insulating support. Though, it is not possible to compute the mobility using equations (4)-(8) since the final values are already affected by its decoupling influence.
- Flanking transmissions $R_{ij,ref}$:	see Table 10 – **Calculations and considerations concerning airborne sound pressure level**
- adjustment term D_{sa}:	As for D_c term, it is not possible to compute the parameter, since the pipe is never in solid contact with partitions
- structure born sound pressure level results $L_{n,s,500Hz}$:	16,9 dB(A)

Summing the two terms the final sound pressure level results $L_{n,A,500\ Hz}$ = 23,9 dB(A). The final frequency level is reported in Table 12.

Table 12 - final results for case 3

Hz	125	250	500	1000	2000	4000	L_A dB(A)
$L_{n,A}$	32.7	28.5	23.9	19.4	23.8	28.4	35.8

6.4 Comparison with in situ measurements

In situ measurements were carried out in order to understand if some of the approximation described in previous paragraphs may be acceptable or are just theoretical assumption with no real implications.

For the lightweight cases (similar to case study 3 and 4, see Figure 11, during construction) on field tests methods were performed using ISO 16032 [20], when the building was concluded. Results are reported in Table 13 and Table 14, providing a final value of L_a = 25.2 dB(A) and L_a = 35.3 dB(A).

Figure 11 – Realization of waste water pipe inside a lightweight construction

Table 13 – In situ results for case 3

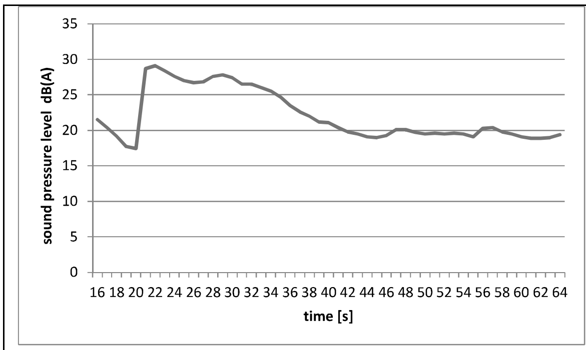
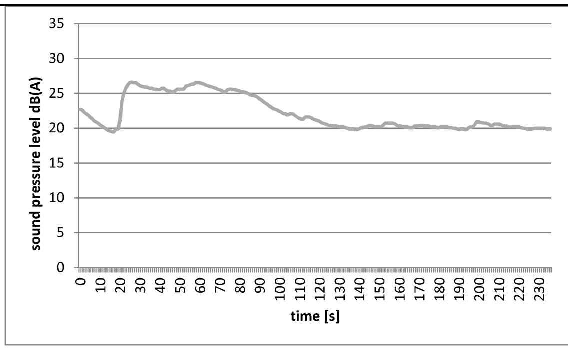
<table>
<tr><td>
</td><td>
</td></tr>
<tr><td>Corner measured average value:
L_{ASmax}= 29,1 dB(A)</td><td>Centre measured average value:
L_{ASmax}= 26,2 dB(A)</td></tr>
<tr><td colspan="2">Adjustment term: k=2.15</td></tr>
</table>

Table 14 – In situ results for case 4

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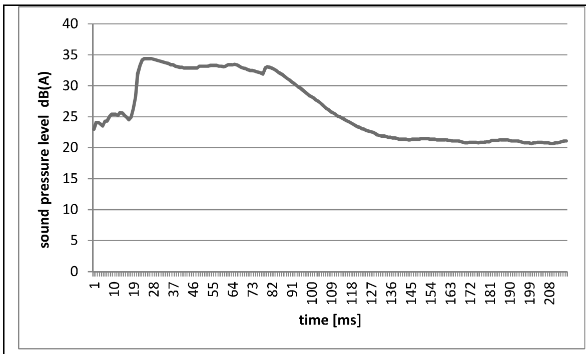
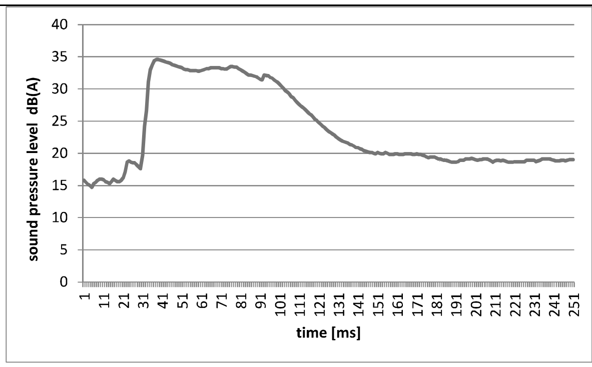
<tr><td>
</td><td>
</td></tr>
<tr><td>Corner measured average value:
L_{ASmax}= 36,8 dB(A)</td><td>Centre measured average value:
L_{ASmax}= 36,8 dB(A)</td></tr>
<tr><td colspan="2">Adjustment term: k=1.56</td></tr>
</table>

6.5 Conclusions

The standard model was used in order to predict the final sound pressure level due to water waste source. Many issues were managed and some solutions were proposed. The first point is how to consider the coupling term D_c when the laboratory measurement are performed using an insulating support. The choice was to not consider this term at all since its effect is already computed in the EN 14366 tests. This is an approximation, because the support won't perfectly stop all vibrations. Another strong choice was to consider insignificant the D_s effect when the pipe was enclosed in wall, since the average distance to the element r forces this term to infinite.

In situ measurements show a good agreement with the prediction model made with the approximation described above.

It is evident how every adjustment term has to be deeply investigated every time the method is applied and there is no general rule to be followed. This study aims not to solve every issue, but to start a discussion on them and to stimulate new studies on these topics in order to improve the complex methods presented by the ISO 12354-5.

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7 Subjective comparison of timber and traditional buildings: an international survey

7.1 Introduction

People always want to live well. In history, architects, engineers and, in general, designers try to understand how physics phenomena behave in order to improve their constructions [1]. First constructions were realized using the only available plastic material: wood. Then, in years, the use of concrete became bigger and slowly the lightweight buildings were forgotten, mainly because of fire resistance issues.

Nevertheless, recently their construction has begun quickly to rise induced by Kyoto protocol [2]. The use of renewable raw materials is firmly encouraged all over the world [3]-[5], since they could help CO_2 storage and control.

Technologies progresses transformed building from "construction" to "production", moving from yard to industry. This paramount transition changed the house from a slowly hand-made artefact to a serial industrial precast fast product. This formed pros and cons.

Secure advantages are higher quality, repeated and repeatable controls during process, possible complex shapes, very few waste production, optimization of transports, high final performances.

Disadvantages are correlated to lack of mass and then poor sound insulation, especially at low frequency range [6], limits in height or length of the inner volumes; another big difficulty is a non-standardization of the building technologies (crosslam, gluelam, timber-concrete, wood-frame open-truss, etc.).

Nowadays, lightweight constructions are present sensibly more in cold northern countries for two reasons:

I. availability of raw material
II. high thermal insulation performances provided.

Nevertheless in the same regions, traditional buildings are present at the same time and often provide the same performance [7]. People are used to heavyweight constructions because in recent years (usually after Second World War) new edifices of this type quickly rose up and are yet used nowadays.

Both construction technologies could use the same insulating layers [8]-[9], but gaining different final results [10].

However, in lay people's mind seems to coexist two different stereotypes:

1. lightweight buildings are very comfortable, every single parameter or results is good for living and nothing could be wrong

2. heavyweight buildings are humid, cold (or hot) in dedicated season, mildew is a constant presences and there is poor sound insulation.

The aim of the present work is to investigate the subjective evaluation of lay people to a questionnaire describing some features of house and comparing them to wooden or traditional technology

7.2 Materials and methods

A web-based questionnaire was sent to lay people in many countries (such as Italy, Austria, Spain, Slovenia, Belgium, United Kingdom, Japan, Australia, Kenya) asking to complete it without thinking that there might be a correct answer, but just marking their own personal opinion on the presented topic.

The survey is described in Figure 1, where only the "timber" questions are reported, as the same were proposed for traditional building too. Only one answer per question was requested and allowed.

The questions were divided in to four different blocks, referring to dedicated topics:

1. general issues
2. influence of the structural material
3. influence of the conditioning systems
4. influence of design

The principal aim was to analyse what people think about a single aspect. The comparison with traditional construction is aimed compare heavyweight and lightweight lay people feelings. In fact the wooden structures are seen like new, odd and ecofrendly houses, whether traditional are evaluated as old fashioned and pollutant buildings.

Another result of the comparison is to avoid focusing the people attention on just lightweight houses, though letting them free to express their opinion on both of them.

Some questions (like insulation from rain, healthy inner environment, fire resistance) were inserted only with the aim to divert people's concentration on the main investigation (thermal and acoustic insulation, service equipment influence) and though to obtain non affected answers. Figure 1 shows some of the topic included in the questionnaire

The same survey was given to people attending a lightweight wooden building open-day. Here it was asked to complete the same questionnaire before and after the visit, where the persons were divided in group of three-four people; one group per time was introduced in the construction with an accompanying guide explaining every single aspect related to energy saving, thermal, air, fire and acoustic insulation, ecocompatibility, structural stability and durability.

*** 1. Please rate the importance of the following aspects when living in a TIMBER building:**

	very important	important	irrilevant	not so important	not at all important
Acoustic insulation	○	○	○	○	○
Thermal insulation	○	○	○	○	○
Structural stability	○	○	○	○	○
Durability	○	○	○	○	○
Insulation from rain	○	○	○	○	○
Resistance to mold	○	○	○	○	○
Healthy inner environment	○	○	○	○	○
Sustainability	○	○	○	○	○

*** 3. To what extent do you agree with the following statements concerning TIMBER buildings?**

	Completely agree	Agree	Irrelevant	Only partly agree	Completely disagree
Wood creates a confortable home environment	○	○	○	○	○
Wood ensures thermal insulation	○	○	○	○	○
Wood ensures acoustic insulation	○	○	○	○	○
Wood ensures structural stability	○	○	○	○	○

*** 5. To what extent do you agree with the following statements concerning TIMBER buildings?**

	Completely agree	Agree	Irrelevant	Only partly agree	Completely disagree
The heating system comes with a number of radiators	○	○	○	○	○
Radiant heating is used (e.g. floor heating)	○	○	○	○	○
Warm air is used to heat the building	○	○	○	○	○
No heating is needed	○	○	○	○	○
Windows need not be opened	○	○	○	○	○

*** 7. How important are to you the following aspects when in a TIMBER building**

	Very important	Important	Irrelevant	Not so important	not at all important
Properly designed thermal insulation	○	○	○	○	○
Properly designed acoustic insulation	○	○	○	○	○
Properly designed fire-proof structures	○	○	○	○	○
Structural design	○	○	○	○	○
Turnkey project delivery	○	○	○	○	○

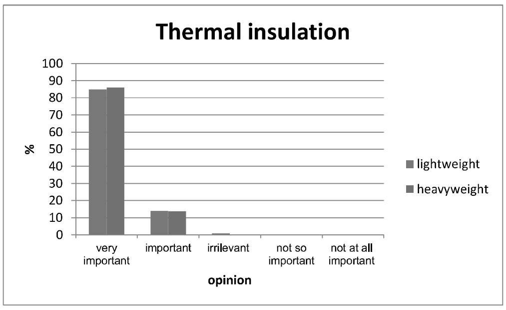
Figure 1 – Web-based questionnaire

7.3 Results and discussion

For every answer, a percentage comparison is reported. In order to compare difference from Italian answers to international ones a first section is dedicated to the former whether another to the latter ones.

7.3.1 Italian results

The Italian answers to the survey are reported below. Starting from Figure 2 the general requirements are described. For thermal and acoustic insulation it is evident how people have two different approaches: For the first one, almost everyone thinks that is very important for both technologies whether for acoustic insulation only half of them behave that it is real significant aspect. However in both cases, the comparison gives almost the same percentage results.



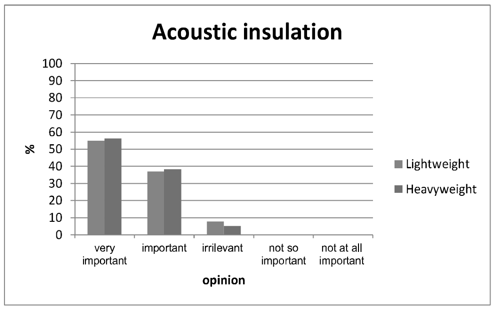
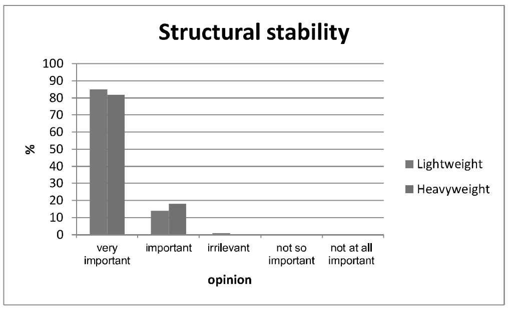


Figure 2 – Italian results - Thermal and acoustic insulation topic

In Figure 3 the opinion on structural stability and time influence (durability) are shown. These topics are very important for lay people as they expect the same performances from both technologies. This is very important related to "time influence", since one of the typical stereotype related to wooden structures is that they can not last in years as their "traditional" competitors.



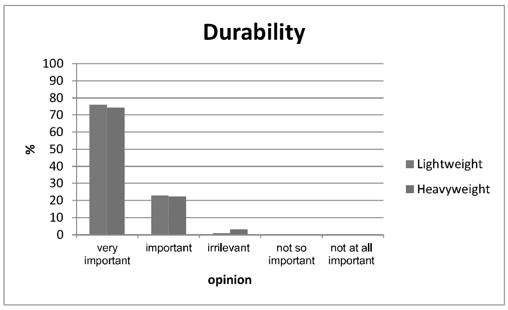


Figure 3 – Italian results - Structural stability and durability topic

In Figure 4 the water (rain and mold) resistance is highlighted. Here a big difference is evident referring to rain insulation: the heavyweight shown minor interests than the lightweight ones. This could be explained because another stereotype related to wooden structures is that they could not resist to water. This is clearly not true since wood could stands water for years without losing its performance.

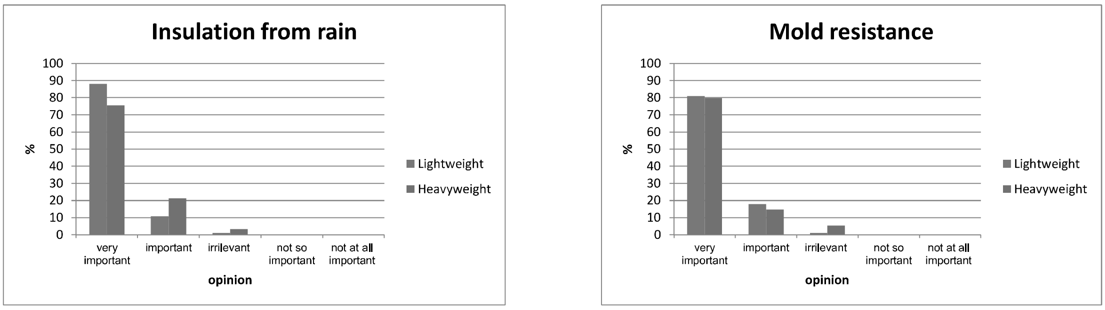


Figure 4 – Italian results - water (rain and mold) resistance topic

In Figure 5 the inner health and ecocompatibility topic were analysed. As a matter of fact, people expects the same performance from both technologies and would not chose the wooden one for Environmental friendly purpose, this topic seems to provide less interest than the other ones

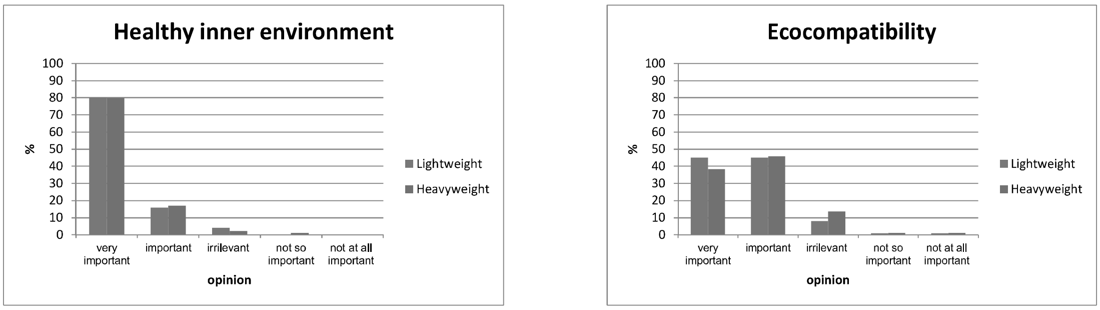


Figure 5 – Italian results - Health and Ecocompatibility topic

It can be concluded that people expect the same general feature from both lightweight and heavyweight buildings.

Figure 6 describes the opinions on the influence of the materials constituting the structures. Here, it is evident how there is no common trend at all. The wood is believed to provide some kind comfortable influence to home environment and the wooden structure is quite imagined to guarantee thermal insulation. What is peculiar is the result of the opinion related to the structural stability.

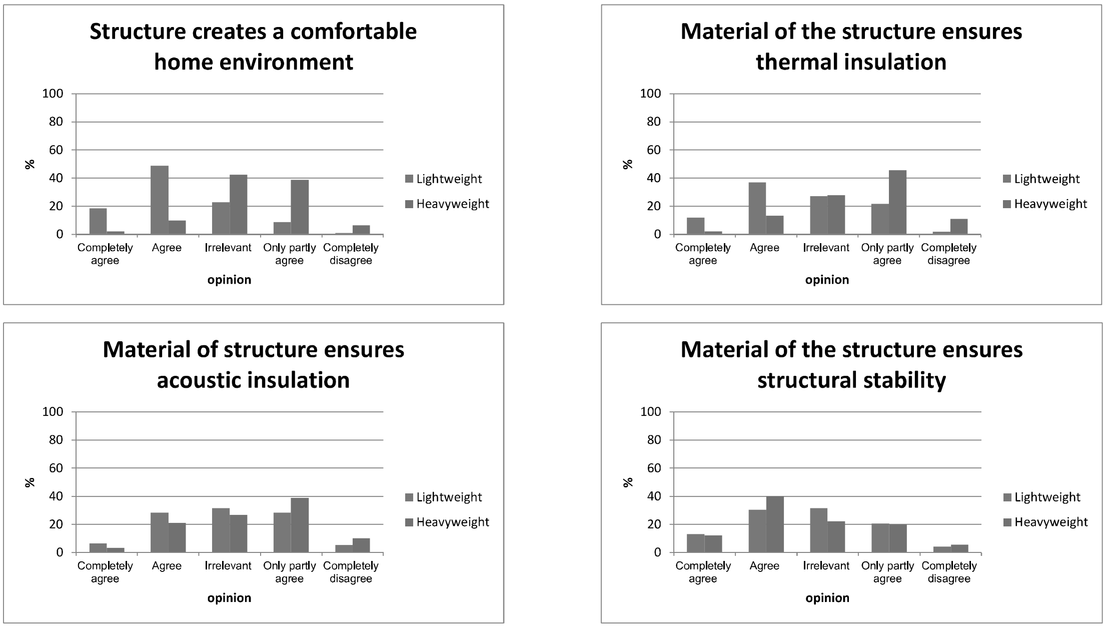


Figure 6 – Italian results - Influence of the materials

Figure 7 describes the opinions on the conditioning technologies. Here, it is evident how there is no common trend. Radiators are very associated with traditional heavyweight buildings. Nevertheless, when asked on radiant or air system, people connect them to both types of constructions. This demonstrates how nowadays service equipment are changing in our houses. However, the topic "no heating" is reputed as impossible in any case. This is not true since passive buildings currently do not need external thermal aids.

In Figure 8 the opinions on the importance of the design step are reported. Once more, thermal insulation is the most valued parameter in spite of acoustic protection.

The comparison provides same trend except for fire resistance. Here, it is believed that a proper design is need for wood structures. Nevertheless, precast panel are always covered with gypsum or fibre board in order to protect the structure from fire incidents, so there is no need of a proper and dedicated design.

In Figure 9 the opinion on the issue "There is no need to open windows" is reported. It is clear how people is not ready yet to manage with high energy saving buildings and has to be deeply educated to this paramount topic. In fact in this kind of building a high thermal insulation performance is expected (see Figure 2), but no such result could be obtained if a good mechanical ventilation with heat exchange isn't present. Though, the windows have not to be open in order not to waste energy.

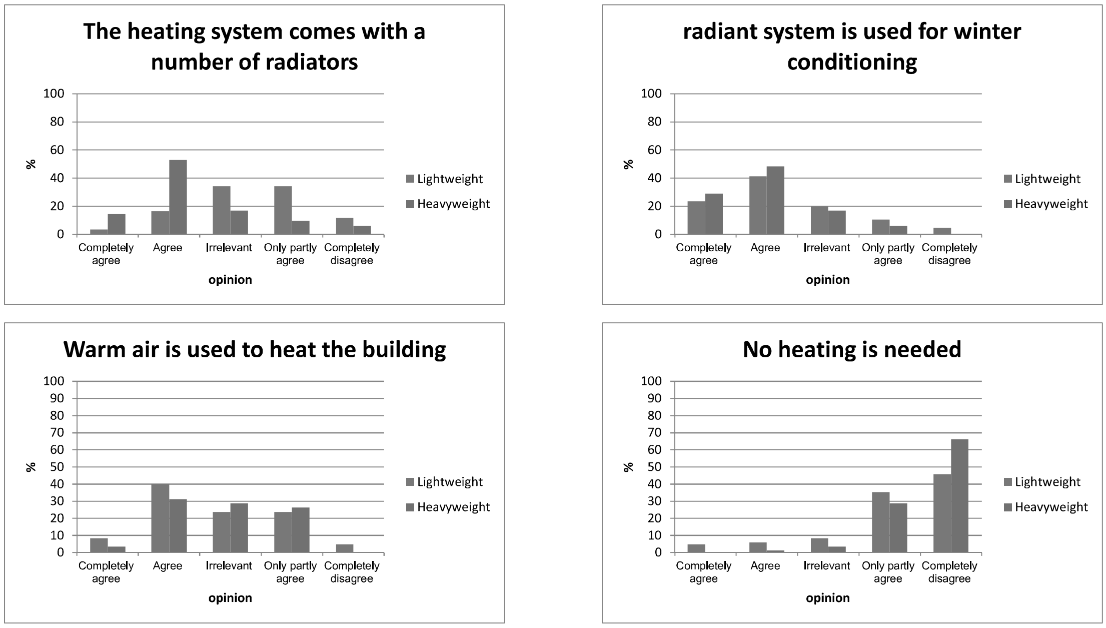


Figure 7 – Italian results - Influence of the conditioning technologies

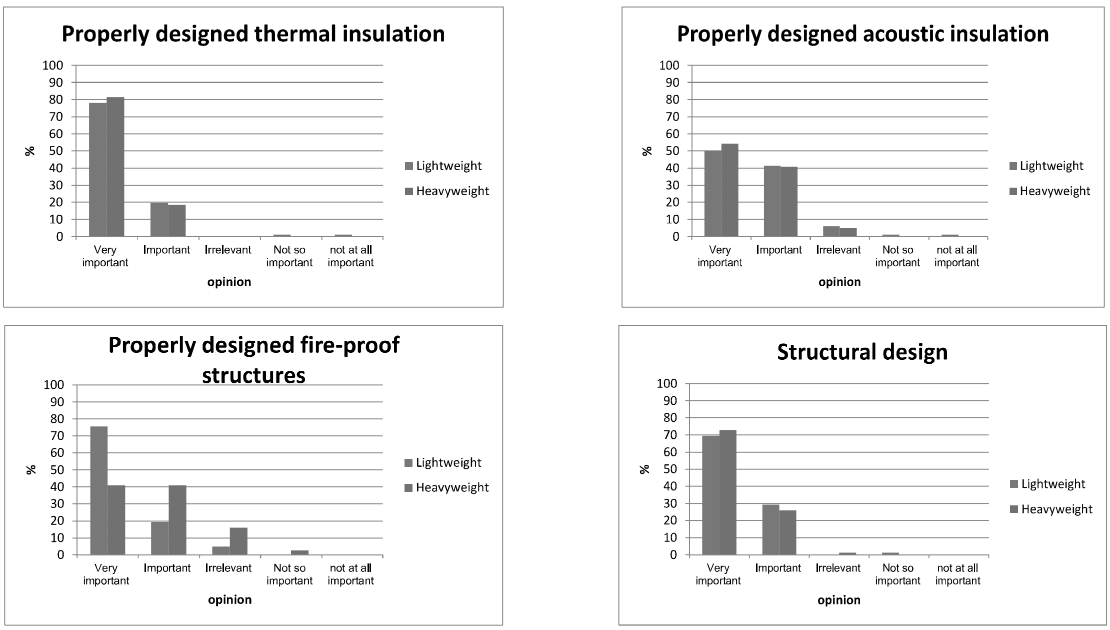


Figure 8 – Italian results - opinion on design importance

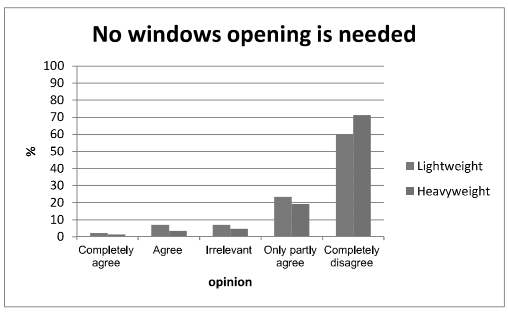


Figure 9 – Italian results - Opinion on window opening needing

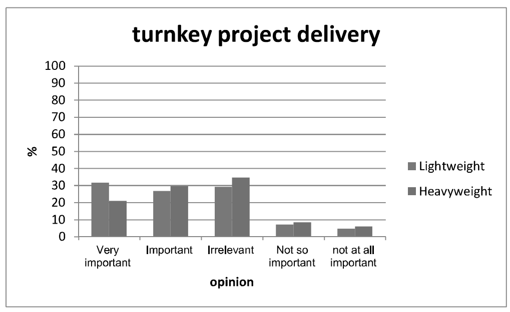


Figure 10 – Italian results - opinion on turnkey project delivery

In Figure 10, the opinion on a turnkey delivery service is reported. It is clear that it is more requested for lightweight construction than for the other ones, but this point it is not of major interest. Though, people like and want to follow their houses step by step.
As a general conclusion, it could be understood that people expect very good thermal insulation and inner comfort performance from lightweight building and that they take them for granted. On the other hand, very important educational project have to be carried out, since no energy saving results could be achieved if the same people are not aware on how this kind of house have to be used and how they provide insulation from cold, hot, rain, wind, etc.
As a control, a small group of selected persons was chosen in order to verify if only lay people may have these opinions. Though, 110 architecture students were asked to compile the web-based questionnaire. They were chosen because they will be the future designers, teachers, construction managers, etc. The students were attending the third of five years and at this point they did not have focused exams on these topics except for material science.
It is evident how students and lay people have the same opinion on general topics (see Figure 11). Nevertheless, the influence their previous studies is clear in Figure 12, where the difference from lay people's opinions is greater and wider.
In Figure 13 and Figure 14 the bigger differences are included in the radiators influence and in the fire-resistance design. All other fields are almost similar.
These comparisons show the effect of education and its influence on students, being the future inhabitants, designers, constructor and/or producers of these houses.

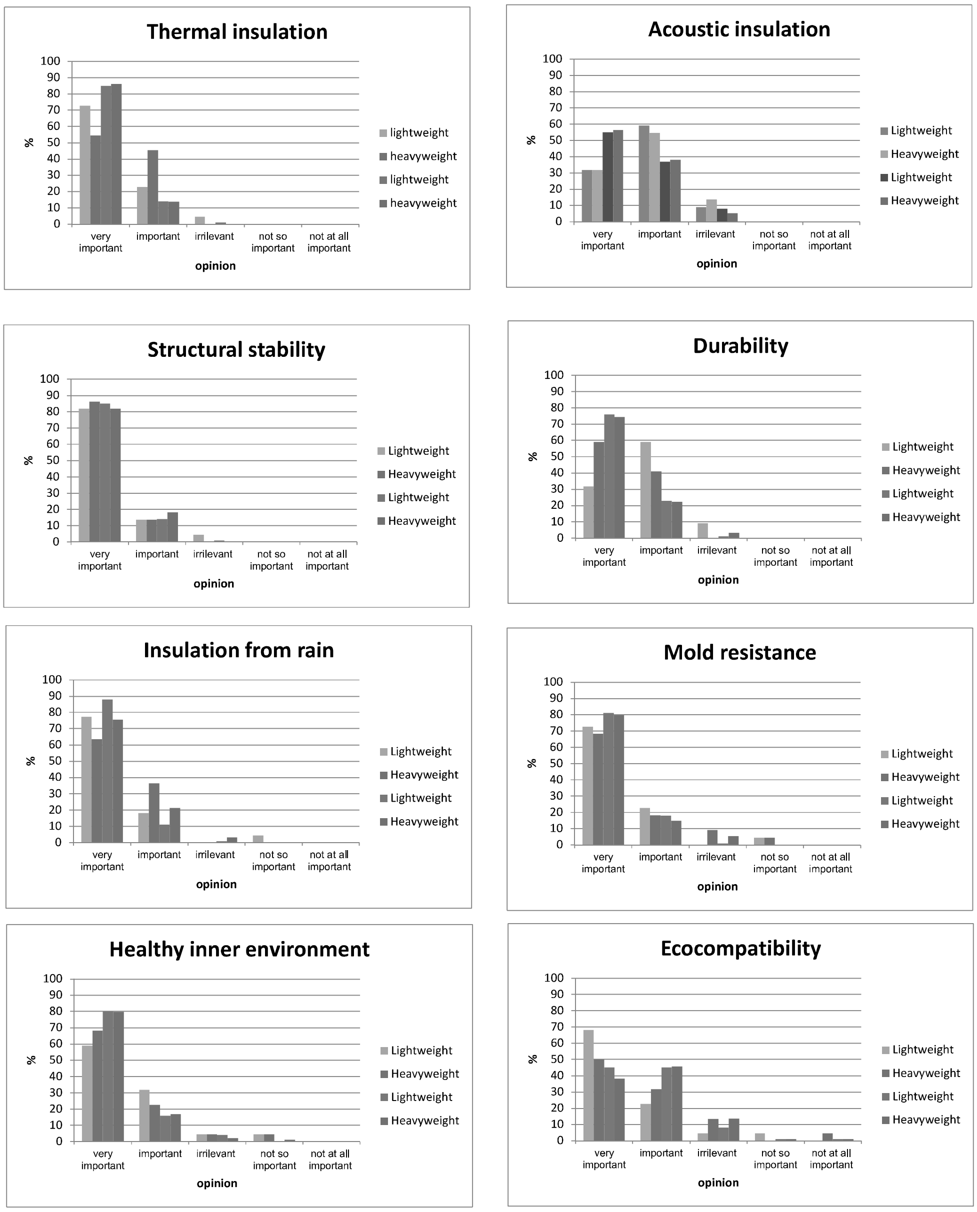


Figure 11 –Comparison between lay people and students' opinion. The Green and Purple series are the one associated to the students' opinions – General topic

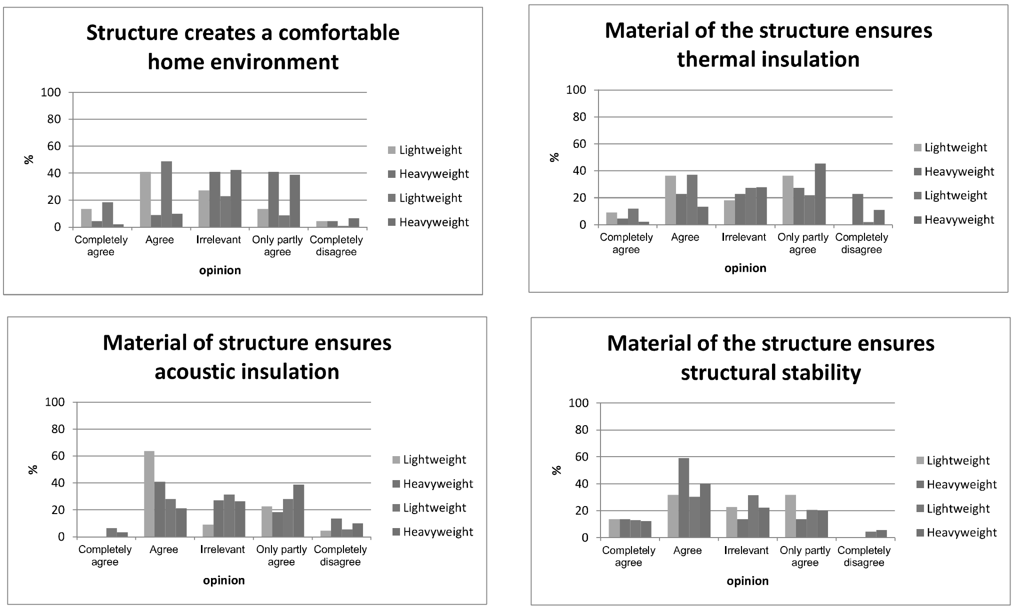


Figure 12 –Comparison between lay people and students' opinion.

The Green and Purple series are the one associated to the students' opinions.

Influence of the materials

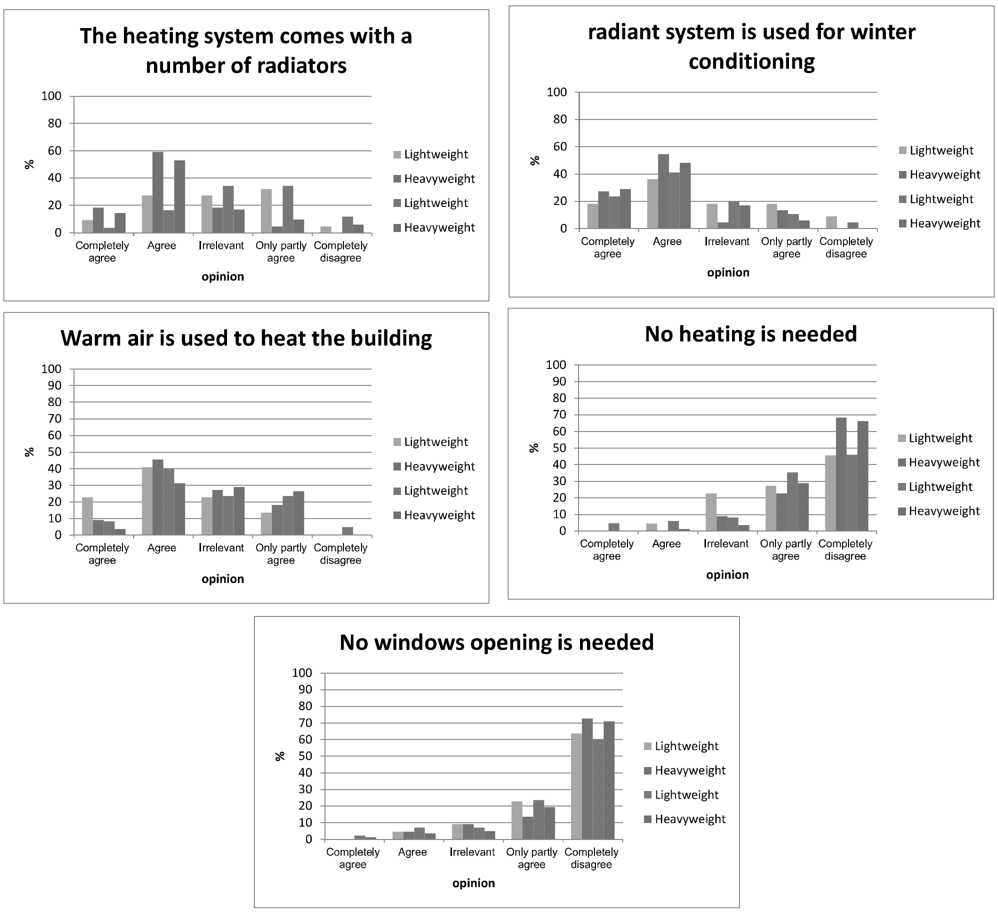


Figure 13 –Comparison between lay people and students' opinion.

The Green and Purple series are the one associated to the students' opinions.

Influence of conditioning system

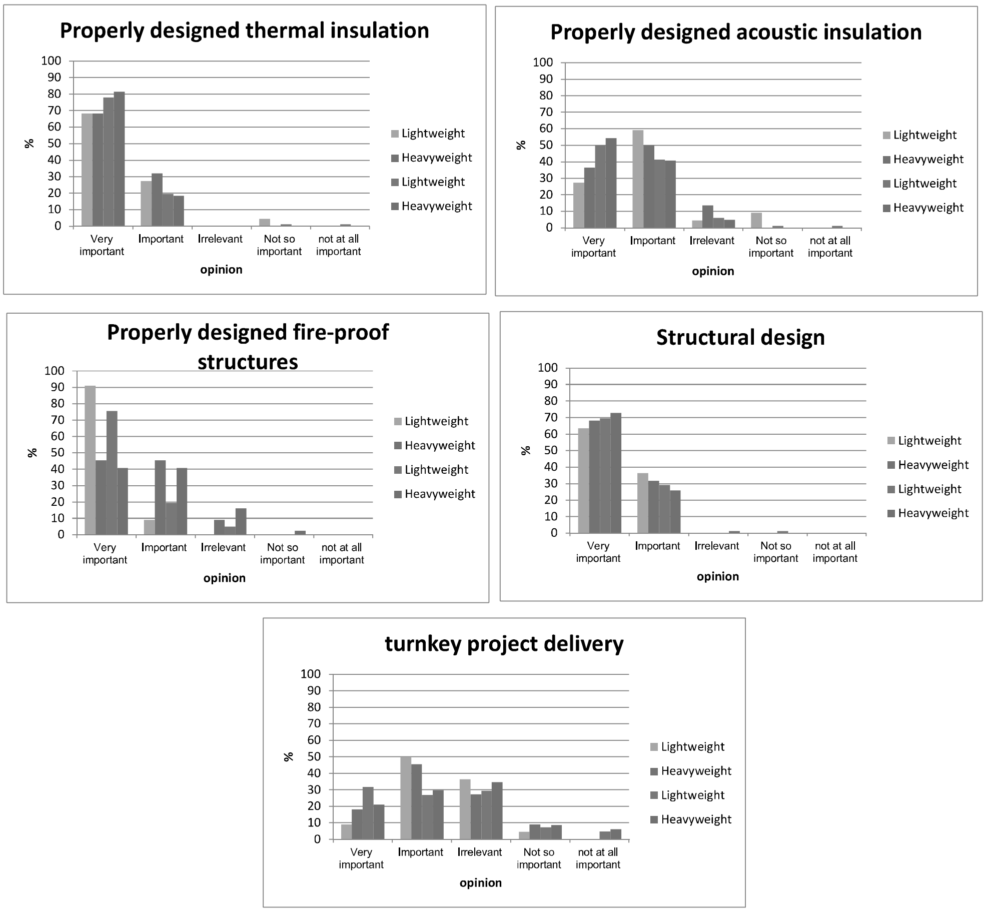


Figure 14 –Comparison between lay people and students' opinion.

The Green and Purple series are the one associated to the students' opinions.

Influence of conditioning system

7.4 International results

The international answers to the survey are reported below. Starting from Figure 15 the general requirements are described. For thermal and acoustic insulation it is evident how people have two different approaches: for the first one, almost everyone thinks that is very important for both technologies whether for acoustic insulation only half of them behave that it is real significant aspect. However in both cases, the comparison gives almost the same percentage results.

Similar trends and values are found for Italian opinions (see Figure 2 - Figure 3).

In Figure 16, the opinions on the influence of the materials are reported. Here, there is no similar trend to the Italian ones as the materials of the heavyweight constructions are believed to create comfortable home environment and to influence the thermal insulation.

In Figure 17 the results concerning the influence of conditioning systems is reported. Here, similar trends could be found to Italian ones, except the one related to radiators (lightweight) and war air (both). The needing of windows opening is almost the same.

In Figure 18 the influence of proper design is reported. As for the Italian opinions, similar trends could be verified. A major importance is related to the thermal and acoustic insulation of heavyweight constructions indicating that for this kind of construction people doesn't feel confident on final results whether for lightweight does. On the other hand, the opposite is found for proper fire-resistance design.

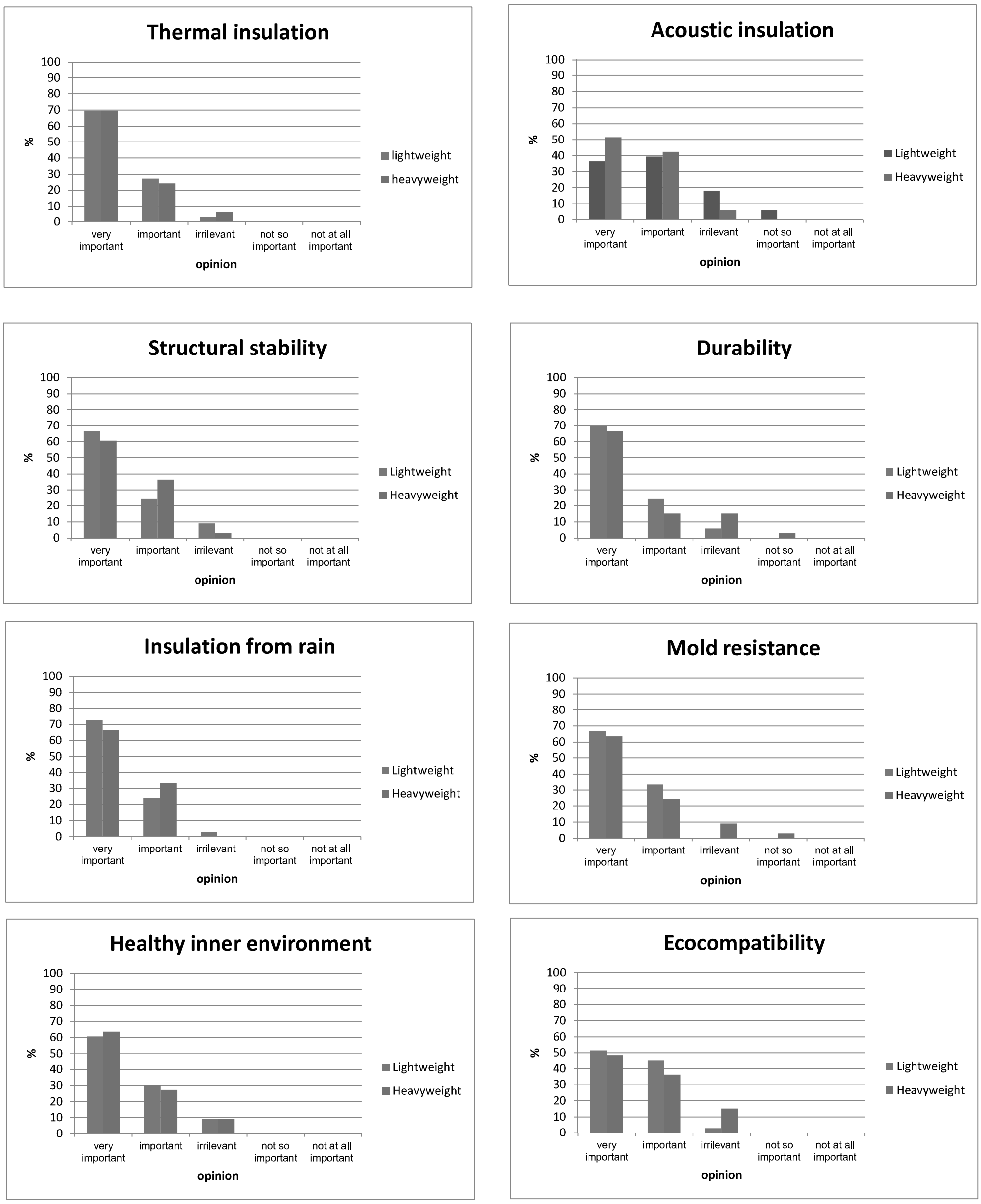


Figure 15 –International results. General topic

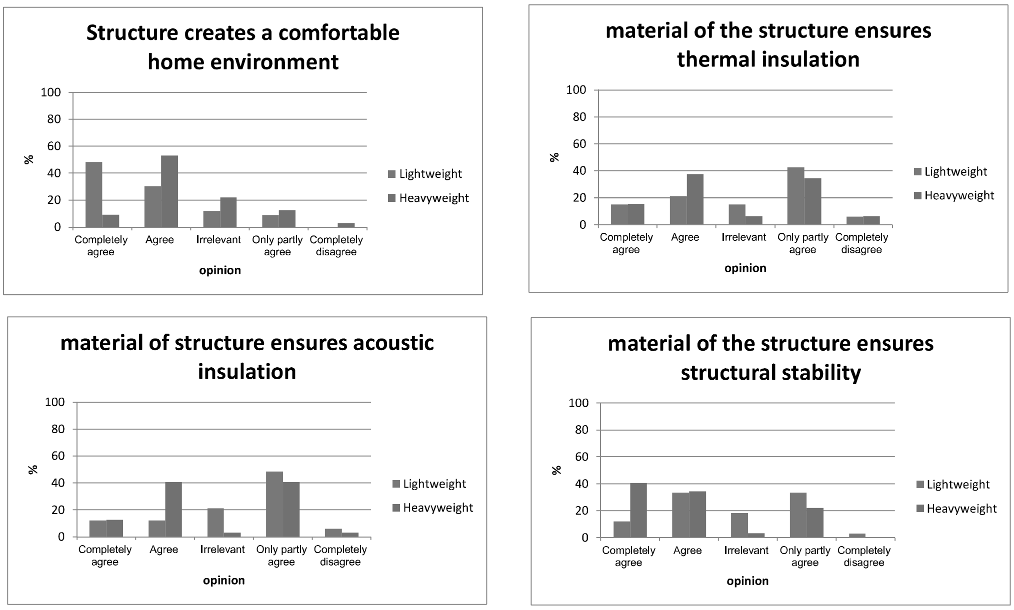


Figure 16 – International results. Influence of materials

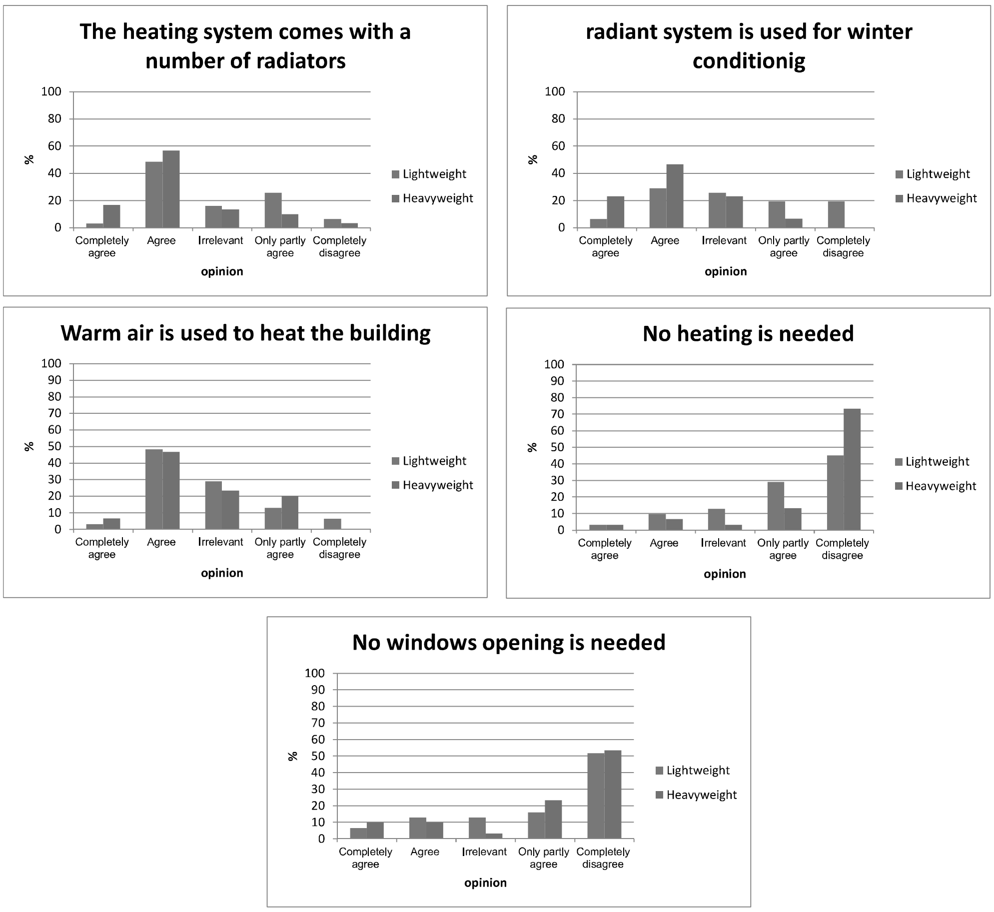


Figure 17 – International results. Influence of conditioning system

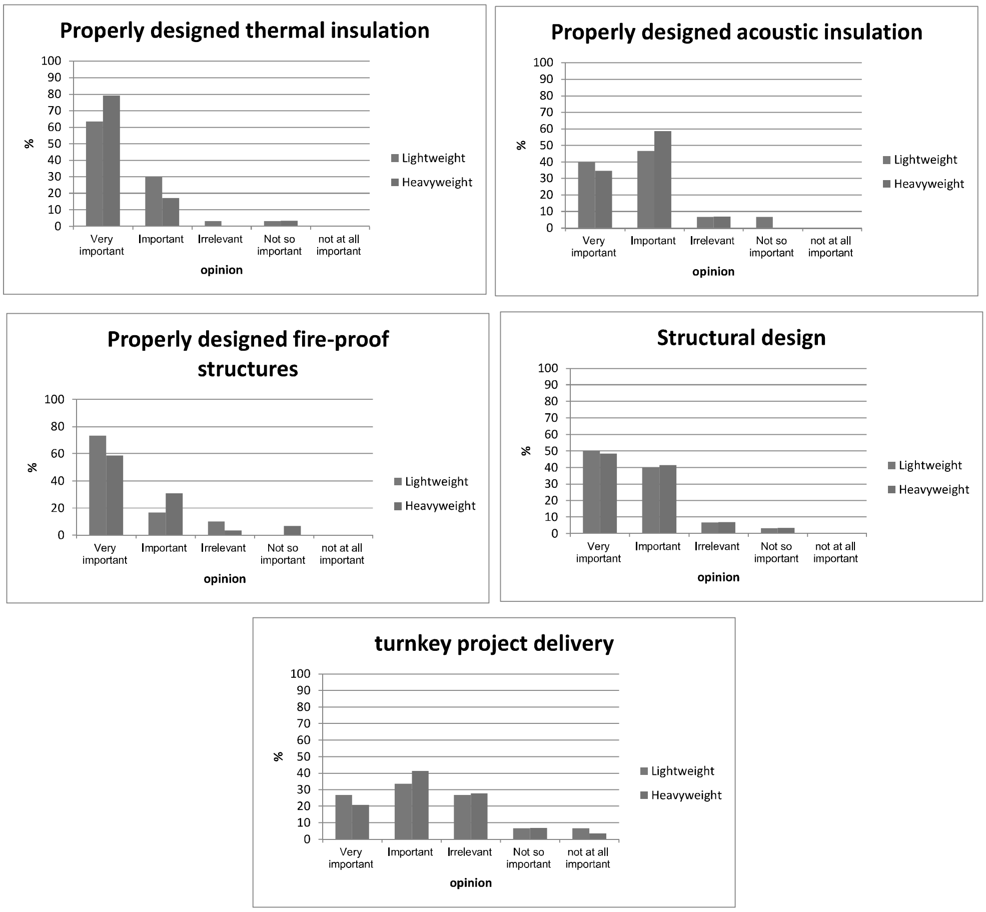


Figure 18 – International results. Influence of proper design

7.5 Open day results

The open day answers to the survey are reported below. Starting from Figure 19 the general requirements are described. For thermal and acoustic insulation it is evident how people have two different approaches: for the first one, almost everyone thinks that is very important for both technologies and it slightly improve after the visit whether for acoustic insulation only half of them behave that it is real significant aspect for lightweight type. After the open day the opinion double their presence on lightweight so, as demonstrated before, education plays a paramount role.

In Figure 20 the influence of the open day is highlighted once more. Nevertheless, here communication failed since people understood that the structure ensures the thermal and acoustic insulation as well as the good home environment.

In Figure 21 the influence of the conditioning systems is reported. Since the open day edifice had a warm air system, it is interesting to note how this typology became, after the visit, the favourite one. The bigger change (also in comparison to previous results for Italian and international web-based questionnaire) could be seen in question related to “no conditioning” and to “windows opening”. Here, the difference induced by the education effect is clearly evident.

In Figure 22 the effect of proper design is reported. Once more the guided visit effect are evident in all aspects.

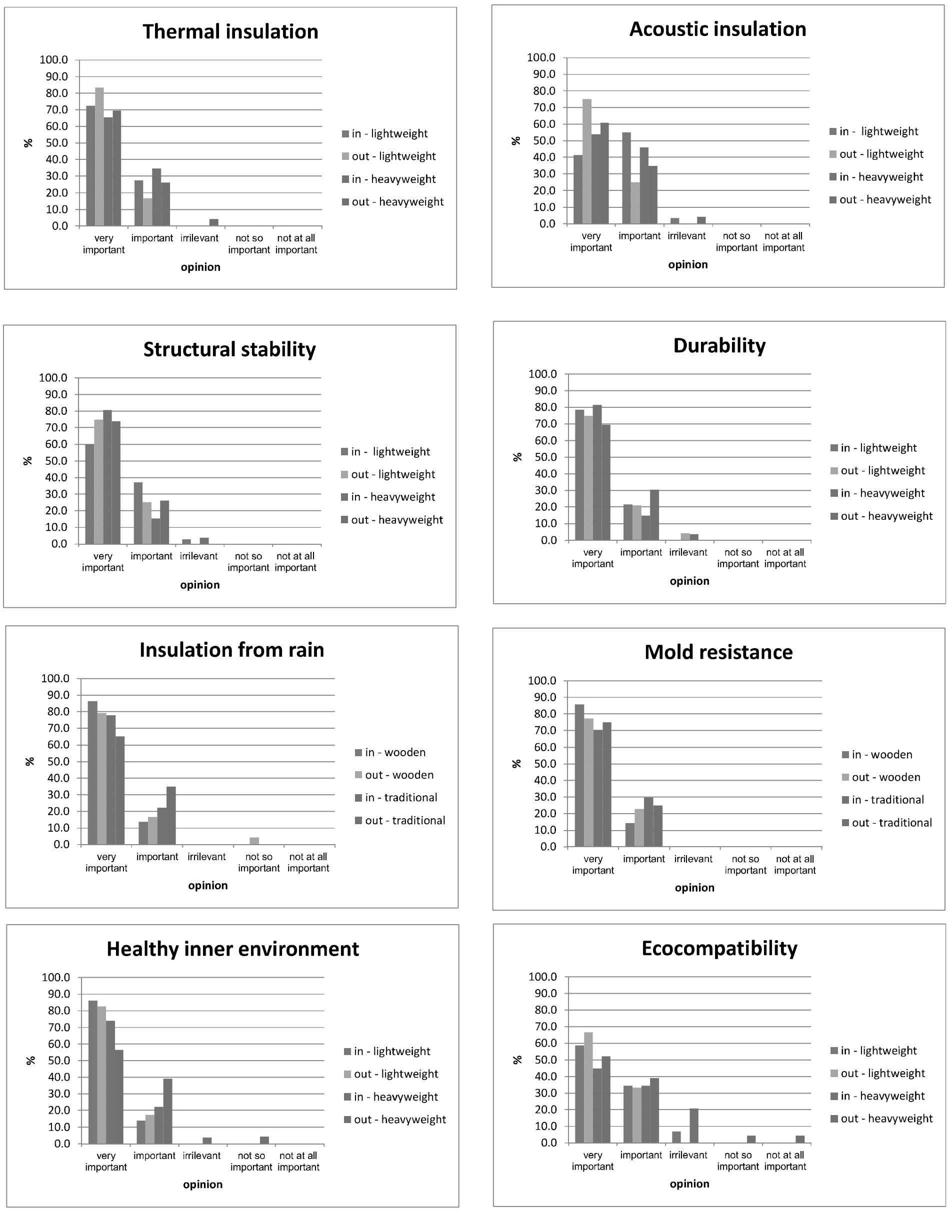


Figure 19 – Open-day results. General topics.

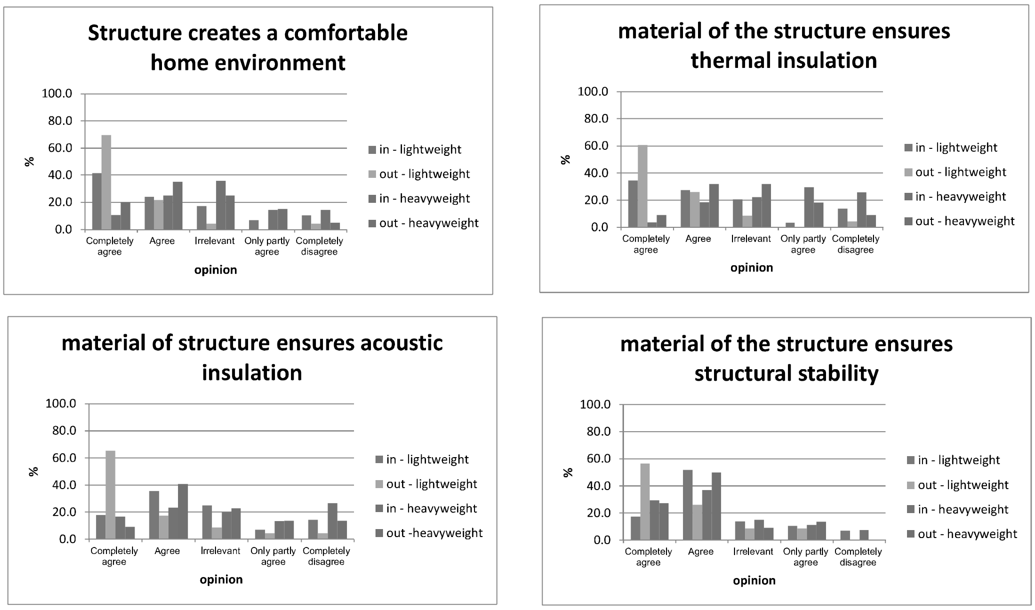


Figure 20 – Open-day results. Influence of materials

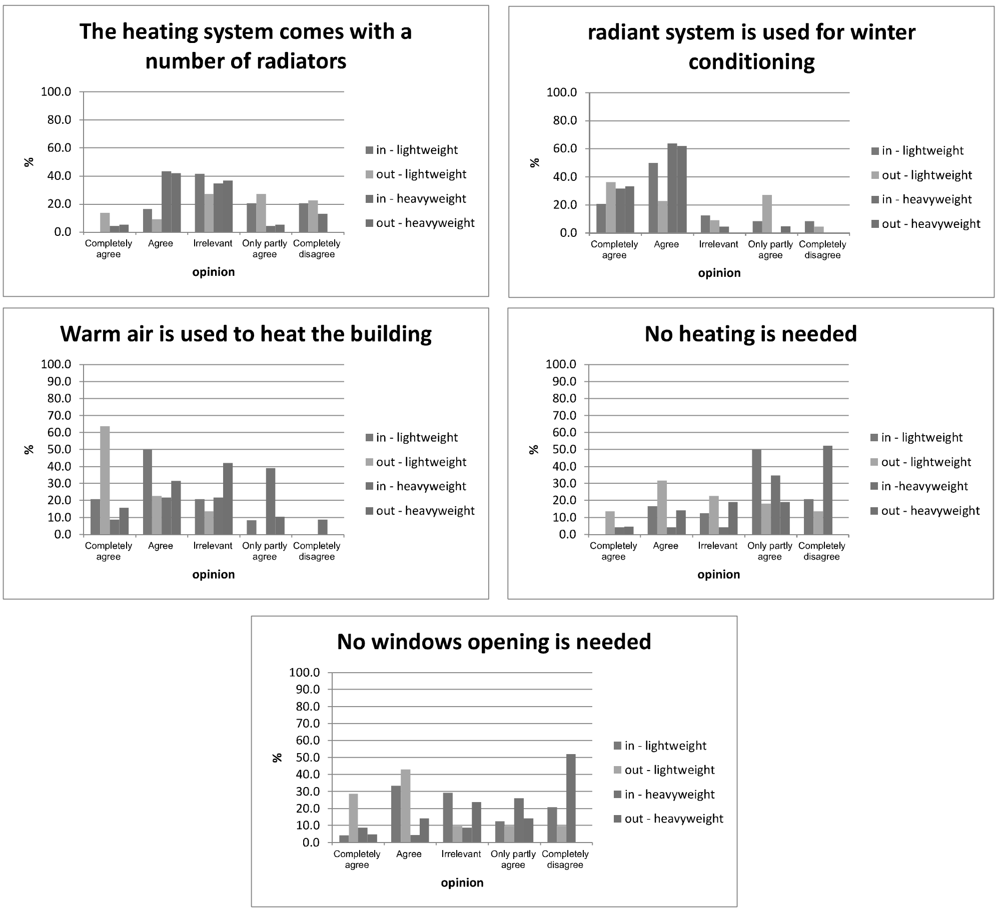


Figure 21 – Open-day results. Influence of conditioning system

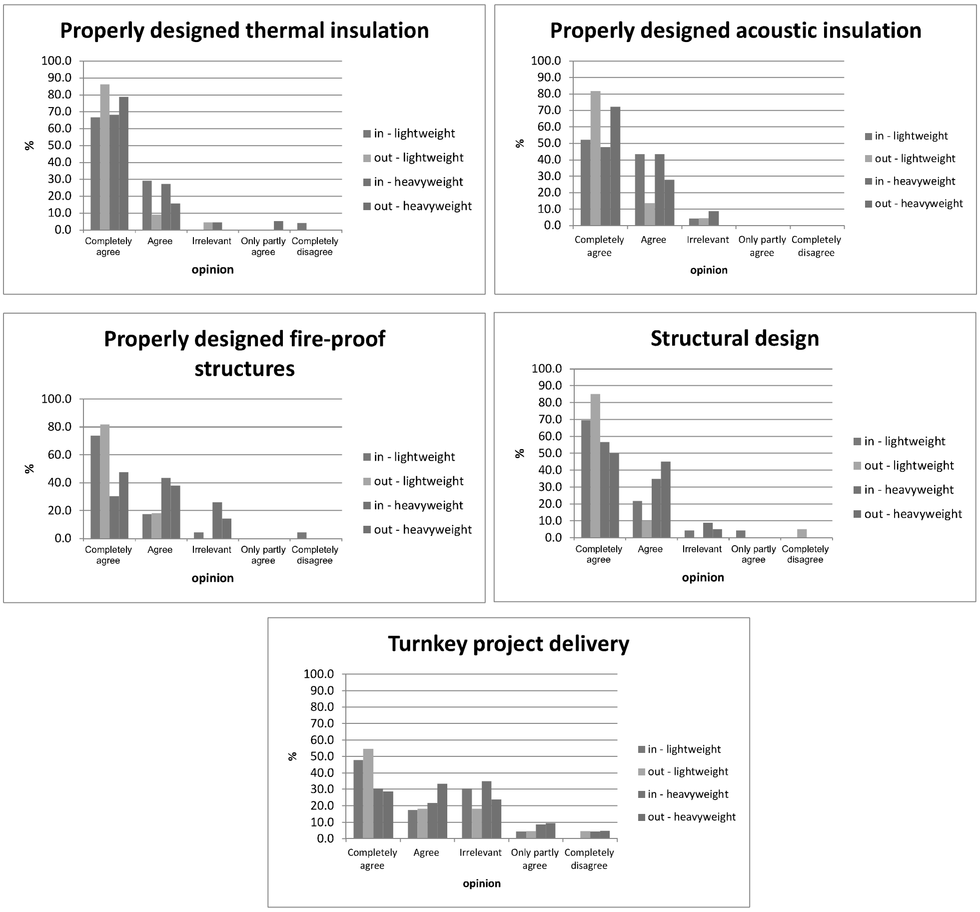


Figure 22 – Open-day results. Influence of proper design

7.6 Discussion

An international web-based survey was realized and used to understand what lay people expect from both heavyweight and lightweight timber buildings. Then during a timber construction open day it was asked to complete the same questionnaire both before and after the visit.

The results showed how almost everyone has the stereotype of the timber building: high energy performance, fire hazard and sustainability whether for heavyweight ones no particular stereotype was found.

Lay people trust timber building as they are felt like a perfect building to live in and where every traditional issue is solved. On the other hand, there is no deep distrust in traditional constructions, even if their rates are poorer and the attention on the design step is higher.

Real thermal insulation as well as proper design are the most rated parameters, whether acoustic issues are very far from being a principal interest. This fact is in contrast with real timber constructions performance, since nowadays thermal insulation reached its maximum values but acoustic insulation is the most complained issues [11],[12].

At the same time the structural wood is believed to perform almost every issue from good inner comfort to thermal or sound insulation, as well physical stability and durability. This belongs to the stereotype that "timber provides warm environment and good feelings" and so everything is ok with it. Physics demonstrate that these parameters depend from case to case to single components. As an example thermal insulation depends on external protection layer which could be (and is often) realized using mineral wool as well as polystyrene.

From the acoustic point of view, wood is not a good sound insulator since its poor mass and its periodicity of beam installation provide a reduced comfort at low frequency ranges. Furthermore, the impact noise is very difficult to reduce, because of typical timber structures configurations.

7.7 Conclusion

An international web-based survey was realized and used to understand what lay people expect from both heavyweight and lightweight timber buildings.

The results showed how almost everyone has the stereotype of the timber building: high energy performance, fire hazard and sustainability whether for heavyweight ones no particular stereotype was found.

Furthermore, the use of an open day guided tour permitted to provide results before and after the visit. What was found is that the influence of the education better change people's mind in almost all questionnaire fields.

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8. Assessment criterion for indoor noise disturbance in the presence of low frequency sources

8.1 Introduction

The existing and consolidated assessment methods of annoyance inside dwellings are widely based on the A-weighted sound pressure level measurement (L_{Aeq}). Nevertheless this parameter leads to an underestimation of the influence of mid and low frequencies [1, 2, 3].

Noise disturbance has increased hugely in the last 15-20 years. Even if traffic noise is generally considered as the first cause of disturbance, both for annoyance or sleep problems, in many cases the source is related to music, people speaking or external noisy machinery. In particular, concerning the first source, weekends have become a very difficult period for inhabitants living close to venues such as clubs, discotheques and pubs. Furthermore, these activities have usually powerful external HVAC, increasing the noise problems at low frequencies.

Moreover, at night the residual noise is generally lower than during the daytime and consequently the disturbance is increased. In many countries, the existing regulations do not provide an objective method able to determine whether music, HVAC or other sources create annoyance in relation to a given moment or period.

Often, the criteria used are fully based on A-weighted sound pressure levels. The A-weighting is based on the peculiar perceptions of the human ear. So using L_{Aeq} level as a mean value or as the difference with background or residual noise could lead to a misinterpretation of the results, as explained below.

The background noise is defined as the L_{90} value; on the other hand the residual noise is the result of a measurement where the noise sources are turned off.

Several measurements throughout the years have shown that the A-weighted sound pressure level was misleading in determining noise disturbance [4, 5, 6, 7]. Distorted results are possible and could depend on many reasons:

a. underestimation of structural transmissions at low frequencies,

b. time of day or night when the noise appears

c. receiver exposure time.

As a matter of fact, if the residual noise is not characterised by low frequencies, the presence of sources with these components leads to a stronger perception [8], especially at night. Therefore it is evident that the single A-weighted sound pressure level cannot be a reliable indicator, suitable to assess whether the disturbance exists or not.

In this paper a selected number of noise assessment criteria are tested in order to understand and compare their results. Moreover a proposal for a harmonised criterion is established by combining methods supplied in the literature with those established by the Italian legislation. The proposed method is to be used in lawsuits, disputes or whenever an objective evaluation is needed. In this study, noise disturbance is considered both as annoyance and sleep disturbance.

8.2 Literature review

8.2.1 General studies and soundscape approach

In the last decades many authors have described the sound pressure level risks [9] both outside and inside dwellings. Miedema and Oudshoorn [10] connected annoyance with noise, focusing on transportation noise using DNL and DEN values. Even if this is a very good method, it requires very long measurements and only works for transportation sources. Indeed, it is difficult to apply it to disco pubs, people speaking, HVAC, etc.

More recently, the COST TUD action TD 0804 collected a large number of results obtained by different participants worldwide. Within the published e-book [11], many issues are presented in order to investigate noise and soundscape. The definition of soundscape, using the standard ISO 12913-1:2014 [12], is as follows: "acoustic environment as perceived or experienced and/or understood by a person or people, in context".

In particular, Kang et al. [11] report that over 30 % of the EU population is exposed to noise levels above the WHO recommendation; Drever [13] studied the effect of ultra-rapid "ecological" hand dryer on vulnerable groups; Ortiz et al. [14] focused on quite zones; Lercher et al. [15] studied the noise effects on children; Prodi et al [16] studied the impact of noise on intelligibility in classrooms; Hiramatsu [17] connected noise and soundscape. These studies were very important in order to understand the subjective effect on receivers, but it does not supply an objective method to assess the disturbance.

Soundscape studies approach noise as a "resource" rather than "waste" [9]. In lawsuits or disputes, however, this approach is never used. In addition, it requires people to complete questionnaires regarding their positive or negative feelings towards sounds and noise. In a dispute, these results become difficult to use, as the different parties are not interested in soundscapes, but rather in winning the case.

None of these methods takes into account the façade, airborne and impact sound insulation in buildings because disturbance is measured in the context in which it takes places (noise propagation, time of day and night, etc). Therefore, in order to evaluate the annoyance of the intruding noise, its characteristics are more important than the way in which it enters the dwelling. Clearly, the sound insulation performance of the building can affect the final perception of the intruding noise [18], even at low frequencies or in the case of impact noise [19, 20]. Nevertheless, this relates only to the rating of the buildings [21, 22] and not to the evaluation of the intruding noise. In order to reduce disturbance, when necessary, sound insulation can be improved or the noise level of the source can be reduced.

8.2.2 Single value: L_{Aeq} based techniques

8.2.2.1 International method: WHO guidelines

The WHO guidelines [23] are frequently used in the acoustical community. They propose health-based limits for night noise exposure stating that noise nuisance exists when the measured L_{Aeq} value inside a dwelling at night exceeds 30 dB(A), with higher limits when short-term measurements or maximum values are considered. Furthermore, it is specified that an external level below 30 dB(A) does not create negative effects on the health of the dwellers, including vulnerable groups such as children. This limit is to be considered as a long-period equivalent level. Interim levels of 40 dB(A) and 55 dB(A) were also proposed where the 30 dB(A) ultimate target cannot be achieved in a short period.

The WHO approach sets maximum thresholds for both inner and outer levels. Noise levels exceeding these thresholds are deemed to disrupt sleep. It was mainly created for traffic noise and it is based on overall levels (L_{Amax} and L_{Aeq}) only. This makes measurements and post-elaboration fairly easy, but does not take into account the mid-low frequencies contribution.

8.2.2.2 Regional methods: Italian methods

As an example, Italian methods are presented, the first is required by the applicable legislation [24] and the second is an agreed but not codified "comparative" system adopted when the actual conditions do not allow the use of the mandatory method. It is sometimes used in court if required by the judge.

The first method consists of the L_{Aeq} measurement and third octave bands analysis with a minimum sampling rate of 125 ms. This is necessary for the investigation of tonal or impulsive events in the measured signal.

The final values need to comply with the mandatory requirements specifying separate limits for daytime and night time. These limits take into account both external and internal acoustic conditions. The outer (*absolute*) values are not to be exceeded and are based on equivalent levels over the whole day or night periods. The inner values (*differential*) are evaluated considering the difference between the environmental and the residual noise (noise source switched off). If the measured L_{Aeq} is greater than the residual noise by 5 dB during the day and 3 dB during the night, then the measured noise is regarded as disturbance. The measurements are based on short-term periods, with the disturbing source on and off.

There are lower minimum limits for the applicability of this method: the disturbing noise has to be greater than 50 dB(A) during daytime and 40 dB(A) during night time within the dwelling with

open windows and 35 dB(A) and 25 dB(A) within the dwelling with closed windows. The differential limits do not apply to any type of traffic sources.
The mid-low frequency effect is taken into account only for tonal phenomena (a noise in which a frequency is predominant) but not for broadband. The very high sampling definition requires the acquisition of a lot of data. As a consequence, measurements and post processing are difficult, and expensive sound level meters are needed.
The "comparative method", is sometime used in lawsuits, but it has no scientific bases. As a consequence no robust results are supplied.

8.2.3 Frequency analysis based methods

8.2.3.1 Polish criterion

The Polish criterion is robust and detailed [6] and its use was made a legal requirement. It establishes two control conditions for the definition of indoor noise disturbance: the 1/3 octave band L_{eq} spectrum needs to exceed the given threshold and the measured value needs to exceed the background noise by 6 dB. Background noise is defined as the noise measured when no disturbing and thus measurable source is active (i.e. residual noise). The noise constitutes a nuisance if both of the above conditions are met in any 1/3 octave band between 10 Hz and 250 Hz. No measurement guidelines are given.
This method is based on both clinical and acoustical evidence and it is the only method taking into account residual noise and considering a wide frequency range (up to 250 Hz).

8.2.3.2 Danish criterion

This method [5] focuses on the 10 Hz – 160 Hz bandwidth and uses a logarithmic summation of these 1/3 octave bands. Its application is required by the law . The obtained value, named $L_{pA,LF}$, must not be greater than $L_{pA,LF}$ = 20 dB during night time inside dwellings. A maximum value of L_{pG}= 85 dB(G) (using G-weighting) is required for infrasound, splitting the low frequency domain. The measurements must be performed in three different positions and the final value is obtained by averaging the measurements. This method combines measuring guidelines and an assessment of vibration and refers to the background noise measured when the noise source is turned off (residual noise).

8.2.3.3 Australian criterion (I)

This method [25] is almost equal to the Danish method, but the limit is reduced by 5 dB in the event that the source is disco music.

8.2.3.4 German criterion

This is the only standardised method within DIN 45680:1997 [26]. This German standard was reviewed in 2011 and 2013 [27] and two unapproved drafts are currently being discussed.

A first check is made on the measured noise: if L_{Ceq} is 20 dB (15 dB in the 2011 and 2013 drafts) higher than L_{Aeq} , then the disturbance can be evaluated. To do so, the exposition period and the rating time must be assessed. The residual noise must be 6 dB below the disturbing noise. The standard requires measurement with linear weighting.

Once the above steps have been completed, the linear L_{eq} is weighted with high penalising k_{ai} coefficients derived from the EN 60651 standard [28]. The final value is compared with daytime, evening and night time limits. Then, a logarithmic summation of 8 Hz to 100 Hz 1/3 octave bands is required, but only for those that are higher than the threshold indicated for the disturbance. The 2011 and 2013 DIN 45680 drafts use the ISO 226 [29] threshold, while the DIN 45680:1997 version is based on the threshold provided by the same standard.

8.2.4 External noise criterion

This criterion is used in the Australian method II [30]. According to this system, the noise is measured outside the building using a C weighting curve. The measurement procedure is simple (no need to access the dwellings by night, no need to arrange measurement time and day etc.).

Nevertheless, neither the noise source within the same receiver building nor structural transmission (through substructures etc.) are taken into account.

8.3 Application in real-life cases

In recent years, several measurements were carried out by the authors with different types of sources and different situations for the receiver.

For discotheques, pubs etc. the noise disturbance can be divided in two categories:

1) People speaking outside;
2) Music source from live concerts, disc-jockeys, karaoke, HVAC etc.

The first case has already been discussed in [31], with both environmental health officers and researchers/engineers arriving to the same conclusions while using different methods. In the second case, different assessment methods lead to different results.

In the following paragraphs, the results of the application of different methods for any of the different types of sources, are shown. In the following figures, the general definition of “level (dB)” reported in y axes, refers to what the specific paragraph is concerning about.

8.3.1 Live concerts

In the following example, the indoor noise disturbance in a residential apartment came from the live concert inside a music pub (blues/jazz/pop music). The disturbed room was located on the second floor of the building and the pub was located on ground floor of the same building.

8.3.1.1 German criterion

The first step is to verify the 20 dB (or 15 in the drafts) threshold between L_{Ceq} and L_{Aeq}. Figure 1 shows the comparison between 100 ms sampling and 1 second sampling rate. The change of sampling clearly affects the assessment method. Furthermore, the 20 dB threshold is very difficult to reach. No indication is given of whether a single excess in an individual sample is enough to move on to the next steps, or whether the whole measurement has to exceed the threshold to continue the assessment.

The second step provides a comparison between the 1/3 A weighted octave bands ($L_{terz,r}$) and the DIN 45680 threshold (Figure 2).

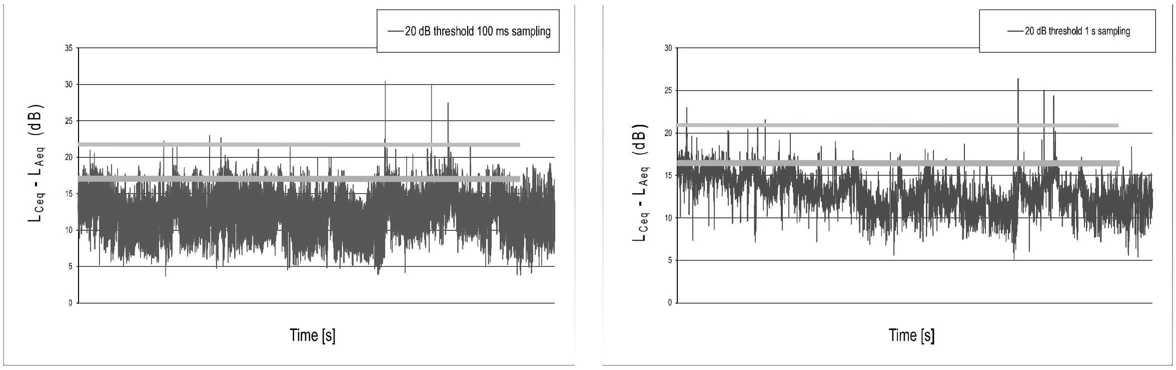

Figure 1 – Operability threshold (20 dB yellow line, 15 dB green line) according to DIN 45680.

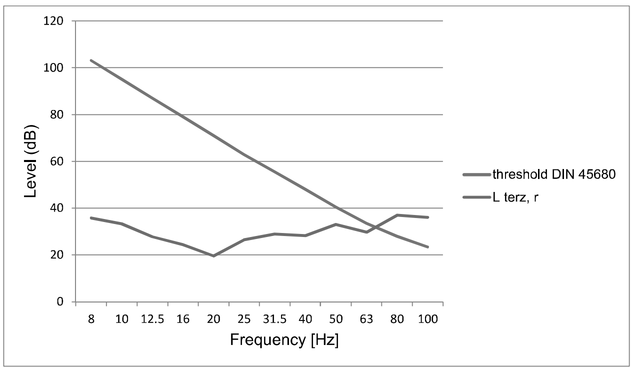

Figure 2 – comparison between the 1/3 A weighted octave bands ($L_{terz,r}$) and the DIN 45680 threshold

In this case, the 80 Hz and 100 Hz bands exceed the limit. Using the corrections of k_{ai} coefficients provided in Annex 1 of the DIN 45680, the obtained overall value of the noise inside the room is 18.9 dB(A). According to the night time limits provided (25 dB(A)), no disturbance is found.

8.3.1.2 Polish method

Figure 3 (a) shows a comparison between the noise level L_{Aeq} and A weighted background noise; the threshold curve L_{A10} is also reported. Figure 3 (b) shows the difference between L_{Aeq} and the threshold values (ΔL_1) and between L_{Aeq} and background level (ΔL_2). In the first case the disturbance is verified for $\Delta L_1>0$; in the second one the disturbance is verified for $\Delta L_2>6$ dB.

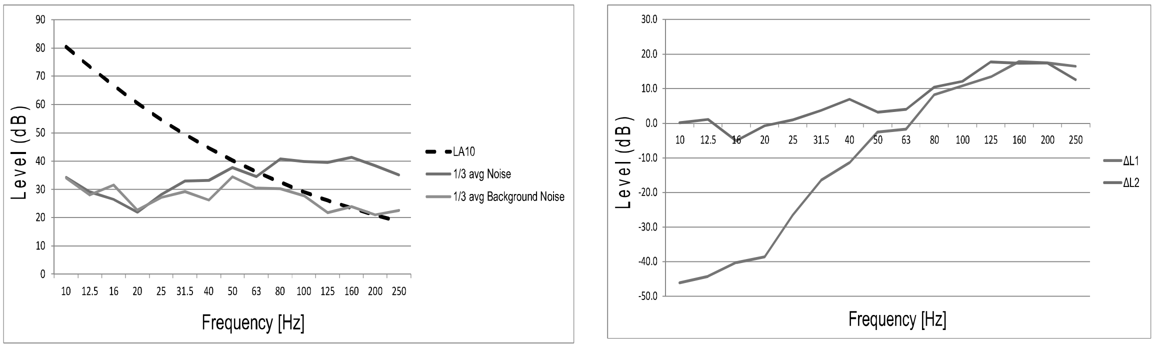

Figure 3 – Polish method trends, (a) noise and threshold; (b) defined parameters

The presence of disturbance between 80 Hz and 250 Hz is evident, as it is when applying the German method (before k_{ai} weighting).

8.3.1.3 Danish method

Here the comparison between A-weighted sound pressure level for low frequencies ($L_{pa,LF}$) within 1/3 octave bands 10 Hz to 160 Hz range and G-weighted for infrasound (L_{pG}) and given daytime and night time limits is reported. For the latter period these are $L_{pa,LF}$ = 20 dB(A) maximum and L_{pG} = 85 dB(G) maximum. Table 1 shows the final measured values.

The noise disturbance is present at low frequencies but not in the infrasound range.

Table 1– noise trends $L_{pa,LF}$ and L_{pG} parameters

Frequency [Hz]	$L_{pa,LF}$ (dB(A))	L_{pG} (dB(G))
10.0	-36.2	34.2
12.5	-34.2	33.2
16.0	-30.4	34.0
20.0	-28.6	30.9
25.0	-16.5	31.9
31.5	-6.4	29.0
40.0	-1.4	21.2
50.0	7.5	17.7
63.0	8.3	6.5
80.0	18.2	4.7
100.0	20.8	-4.1
125.0	23.4	-12.5
160.0	27.9	-18.7
overall	30.2	40.4

8.3.1.4 Australian method (I)

This method is very similar to the Danish method, but for impulsive sources like disco music the given limit is 5 dB(A) lower. This penalisation has not been applied in the case analysed here (live music). Noise assessment with the Australian method produced exactly the same results as with the Danish method.

8.3.2 Karaoke and piano bar

In this case the measurements were carried out inside a dwelling during a piano bar and karaoke night; the disturbance came from both inside and outside the pub.

8.3.2.1 German method

Figure 4 shows the difference between L_{Ceq} and L_{Aeq} represented with 100 ms sampling; both thresholds (15 and 20 dB(A)) are exceeded. The comparison between the 1/3 A weighted octave bands ($L_{terz,r}$) and the DIN 45680 threshold is then provided.

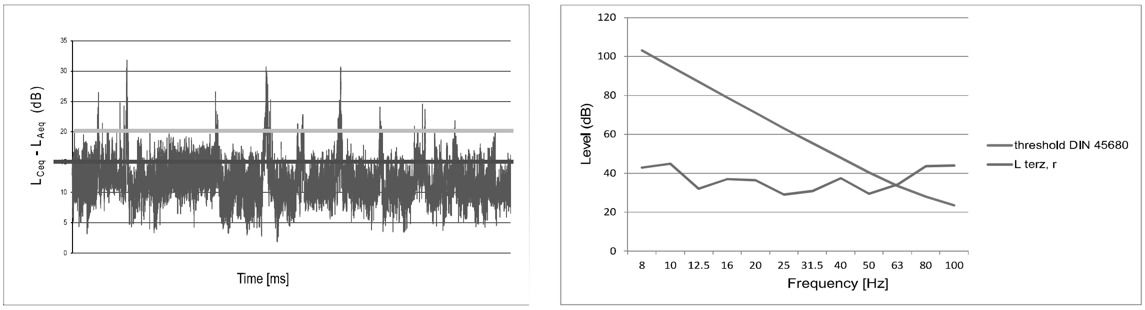

Figure 4 – first step (a) and 1/3 octave band assessment (b)

The noise disturbance is found from 80 Hz. Nevertheless, if k_{ai}-weighting is applied the final value is 16.2 dB(A). Since the night limit is 25 dB(A), no disturbance can be ascertained.

8.3.2.2 Polish method

Figure 5 shows a comparison between the noise level L_{Aeq} and residual noise and the difference between L_{Aeq} and the threshold values (ΔL_1) and between L_{Aeq} and residual level (ΔL_2). This method shows a wider noise disturbance range (from 80 Hz to 250 Hz).

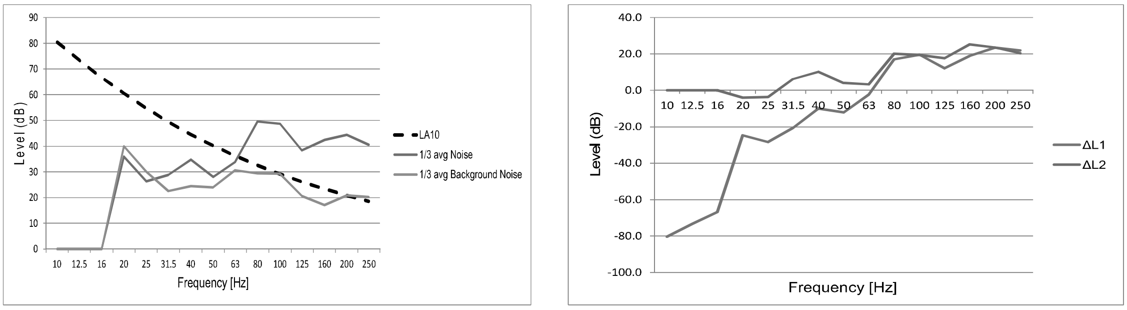

Figure 5 – Polish method trends, (a) noise and threshold; (b) defined parameters

8.3.2.3 Danish and Australian (I) method

According to both of these methods there is a noise disturbance, but not in the infrasound range.

8.3.3 Far disco music

Here, the indoor noise disturbance comes from a club 70 meters away . The sources are both disco music and a live concert, often playing with open windows and doors.

8.3.1.3 German method

Figure 6 shows the difference between L_{Ceq} and L_{Aeq} represented with 100 ms sampling; both thresholds (15 and 20 dB(A)) are exceeded. The comparison between the 1/3 A weighted octave bands ($L_{terz,r}$) and the DIN 45680 threshold is then provided.

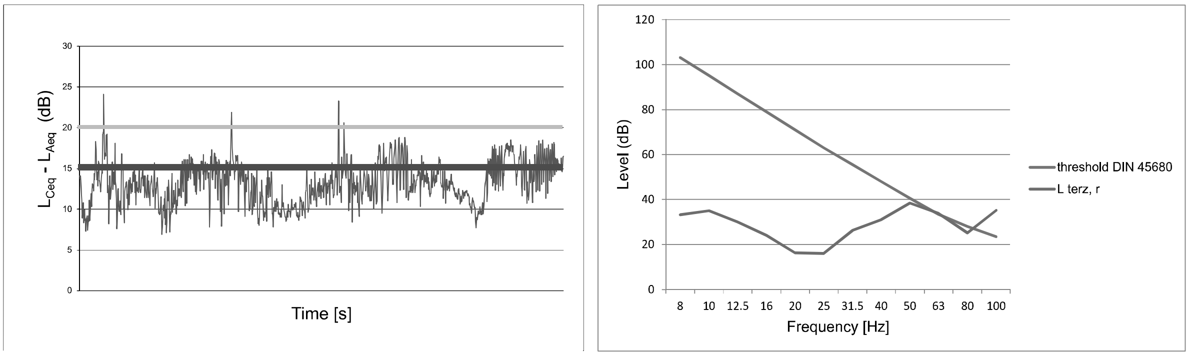

Figure 6 – first step (a) and 1/3 octave band assessment (b)

The noise disturbance is found from 100 Hz. This is due to the absence of structural transmissions. Nevertheless, applying the k_{ai}-weighting, the final value is 16.2 dB(A). Since the night limit is 25 dB(A), no disturbance is confirmed.

8.3.1.4 Polish method

Figure 7 shows a comparison between the noise level L_{Aeq} and residual noise and the difference between L_{Aeq} and the threshold values (ΔL_1) and between L_{Aeq} and residual level (ΔL_2). This method evidences a noise disturbance range from 100 Hz.

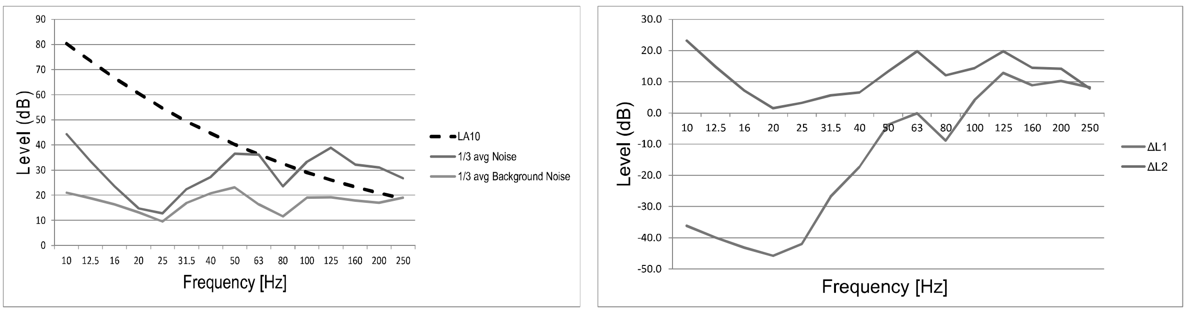

Figure 7 – Polish method trends, (a) noise and threshold; (b) defined parameters

8.3.1.5 Danish and Australian (I) methods

A noise disturbance is identified using both of these methods, but not in the infrasound range.

8.3.2 Disco music coming from the same building

The measurements were carried out inside a block of flats, in the apartment belonging to a family who complained about the noise from a disco club.

8.3.2.1 German method

Figure 8 shows the difference between L_{Ceq} and L_{Aeq} represented with 100 ms sampling; both thresholds (15 and 20 dB(A)) are exceeded. The comparison between the 1/3 A weighted octave bands ($L_{terz,r}$) and the DIN 45680 threshold is then provided.

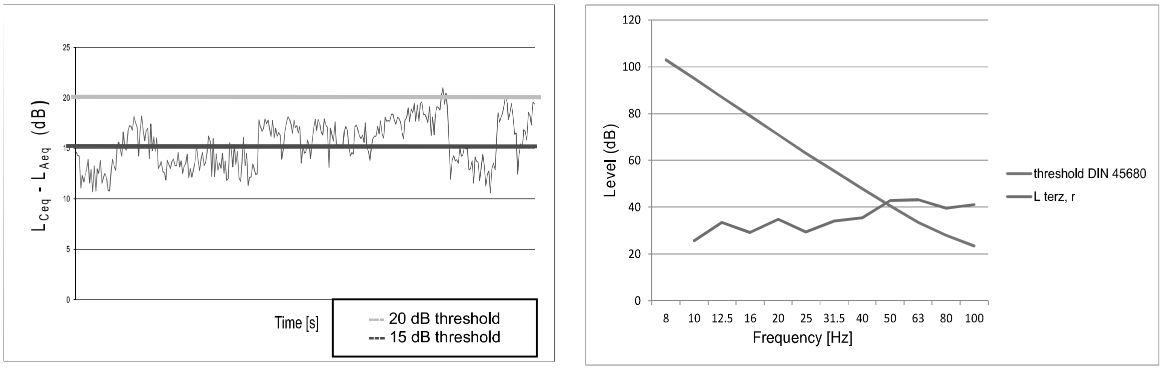

Figure 8 – first step (a) and 1/3 octave band assessment

The noise disturbance is found from 50 Hz, highlighting the structural path as predominant. Nevertheless, applying the k_{ai}-weighting, the final value is 24.4 dB(A). Since the night limit is 25 dB(A), no disturbance is confirmed.

8.3.2.2 Polish method

In figure 9 a comparison between the noise level L_{Aeq} and residual noise and the difference between L_{Aeq} and the threshold values (ΔL_1) and between L_{Aeq} and residual level (ΔL_2) is shown. This method evidences a noise disturbance range from 80 Hz.

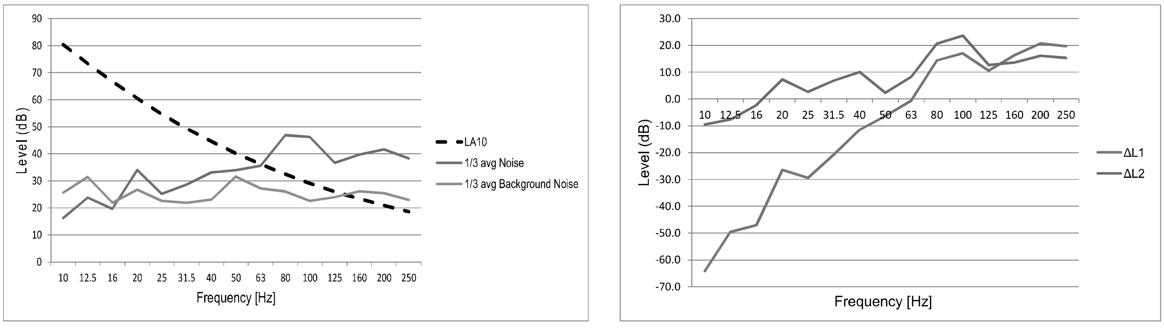

Figure 9 – Polish method trends, (a) noise and threshold; (b) defined parameters

8.3.2.3 *Danish and Australian (I) methods*

The Danish method does not confirm disturbance, while the Australian one does.

8.3.3 Large HVAC

In this case, the noise came from a large (4x2x2 meters) HVAC system for winter and summer air and water conditioning unit located at a distance of 1 meter from the receiver windows. It had in-built silencers and noise barriers.

8.3.3.1 German method

Figure 10 shows the difference between L_{Ceq} and L_{Aeq} acquired with a 100 ms sampling rate, where only the 20 dB(A) threshold is exceeded. The comparison between the 1/3 A weighted octave bands ($L_{terz,r}$) and the DIN 45680 threshold is then provided.

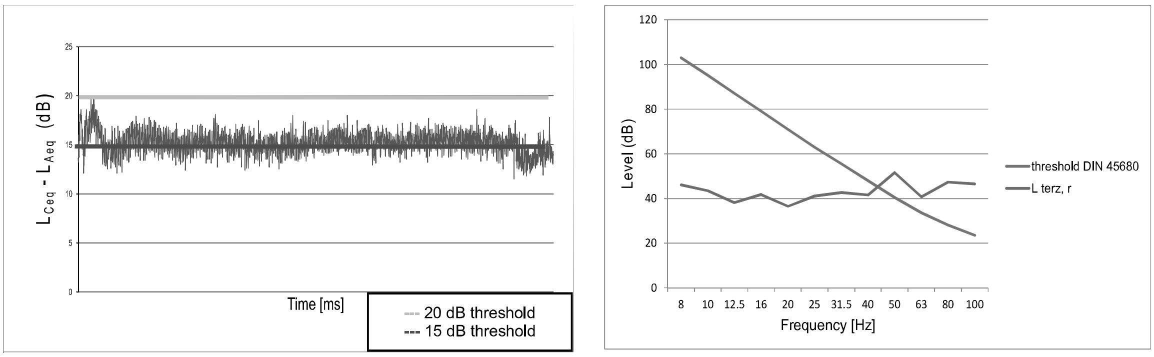

Figure 10 – first step (a) and 1/3 octave band assessment

The disturbance cannot be assessed as the $L_{Aeq} – L_{Ceq}$ check never exceeds 15 dB. Nevertheless, if the standard method is used, the output values exceed the threshold starting from 50 Hz and by applying the k_{ai}-weighting the final value is 29.5 dB(A), which confirms the disturbance.

8.3.3.2 Polish method

Figure 11 shows a comparison between the noise level L_{Aeq} and residual noise and the difference between L_{Aeq} and the threshold values (ΔL_1) and between L_{Aeq} and residual level (ΔL_2). This confirms a disturbance at 50 Hz and from 160 Hz.

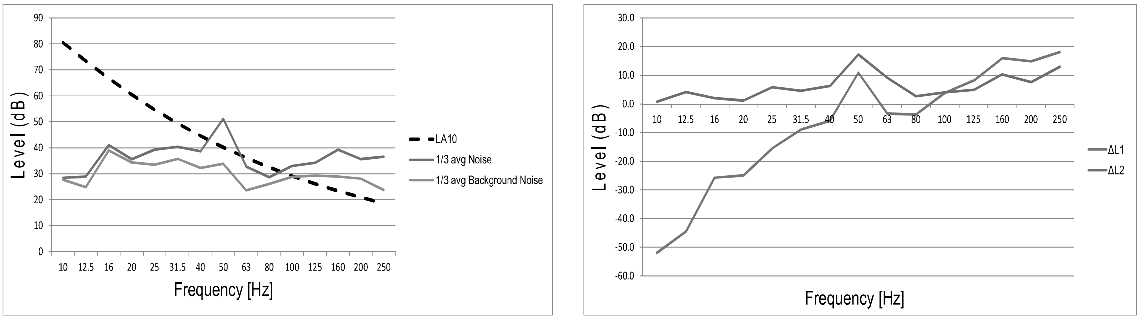

Figure 11 – Polish method trends, (a) noise and threshold; (b) defined parameters

8.3.3.3 Danish and Australian (I) methods

Neither method confirms the noise disturbance.

8.3.4 Traditional HVAC

The measurements are carried out inside an apartment located on the 4th floor of a building; the indoor noise disturbance comes from a traditional (air cooling 1x0.8x0.4 m) HVAC system located in the courtyard.

8.3.4.1 German method

Figure 12 shows the difference between L_{Ceq} and L_{Aeq} acquired with a 100 ms sampling rate; both thresholds (15 and 20 dB(A)) are exceeded. The comparison between the 1/3 A weighted octave bands ($L_{terz,r}$) and DIN 45680 threshold is then provided.

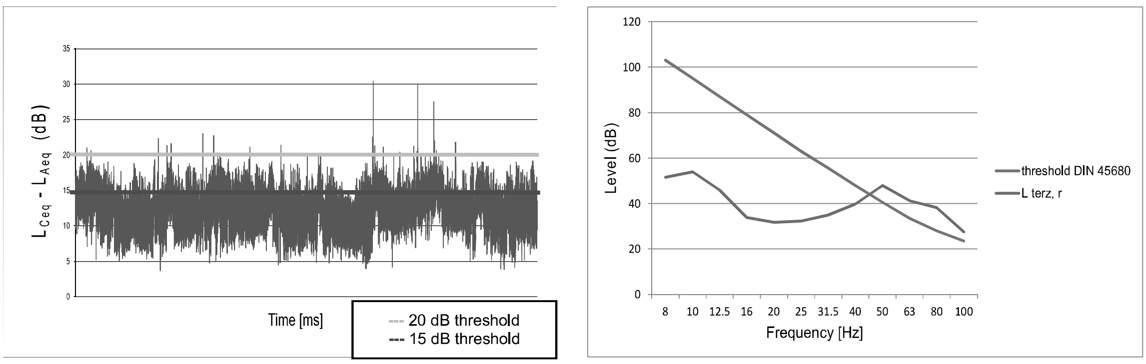

Figure 12 – first step (a) and 1/3 octave band assessment

The noise disturbance is found starting from 50 Hz. Nevertheless, if the k_{ai}-weighting is applied, the final value is 16.4 dB(A). Since the night limit is 25 dB(A), no disturbance is ascertained.

8.3.4.2 Polish method

Figure 13 shows a comparison between the noise level L_{Aeq} and residual noise and the difference between L_{Aeq} and the threshold values (ΔL_1) and between L_{Aeq} and residual level (ΔL_2) . No disturbance is ascertained.

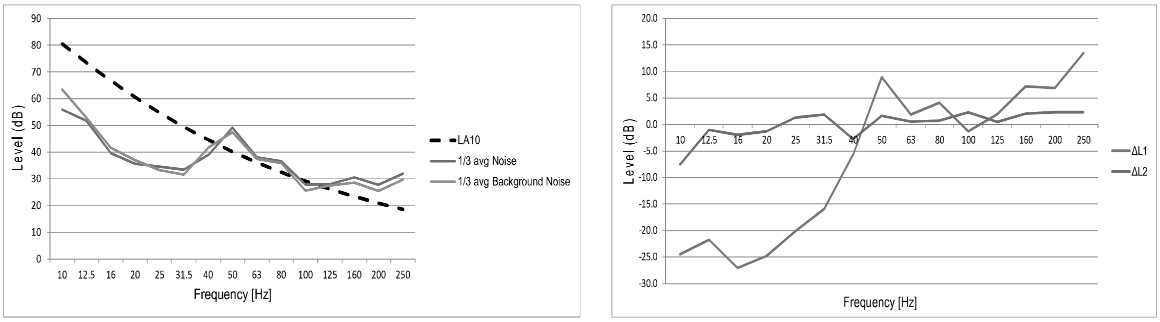

Figure 13 – Polish method trends, (a) noise and threshold; (b) defined parameters

8.3.4.3 Danish and Australian (I) methods

Neither of these methods confirms the existence of a noise disturbance.

8.4 Discussions of results

All methods require the 1/3 octave band frequency analyses and provide specifications on background noise conditions. Some of them contain measurement specifications and only one introduces a penalty depending on the disturbance occurring by day or by night.

The German method does not confirm the existence of the disturbance at any time while the Danish/Australian methods, in most cases, do. No method considers the frequency trend of the source, nor the influence of multiple sources, nor the sampling measurement step.

Some processes require multiple measurements and supply hearing or disturbance thresholds. Finally, the different frequency ranges are investigated and no importance is attached to the windows being open or closed.

If the measure is slightly over the threshold changing receiver positions, sampling, etc. can affect the final result regardless of the chosen method.

If no strict rules are imposed on the measurement and parameters methodology, the results cannot be compared and disturbance cannot be clearly and objectively assessed.

8.5 Proposal for a harmonised assessment criterion

Since measuring subjective disturbance is impossible as each individual has is sensitive to noise in a different way, no universal threshold can and will ever be established. Despite the use of subjective interviews for example in soundscapes [11], in the cases described here the noise is considered a disturbing source and never a positive contribution. Subjective evaluations, particularly in the case of legal disputes, are not a reliable form of measurement.

Nevertheless, several studies have been carried out over the years in many different countries using laboratory subjective tests in order to obtain a hearing/disturbance threshold [2,3,5,6,11]. Determining a new threshold using subjective tests therefore makes little sense.

The aim of this work is to determine an objective method to assess the noise disturbance (considered both as annoyance and sleep disturbance) in the usual conditions and for the average individual, taken for granted that this is the only way to include as many people as possible. So it makes sense to calculate the average of the hearing thresholds included in standards/literature as presented in figure 14 and table 2, since they come from different authors who have used different techniques and operate in different part of the world and since these thresholds are average themselves. In a way, this represents the "average of the averages".

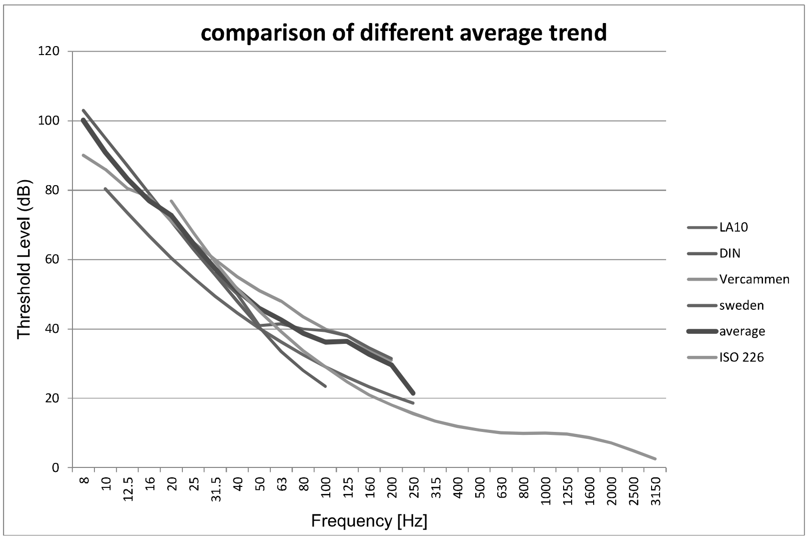

Figure 14 – literature standard and average of the averages trends

Hz	dB
8	100.2
10	90.9
12.5	83.3
16	76.9
20	72.7
25	64.5
31.5	57.3
40	51.1
50	45.9
63	42.6
80	38.7
100	36.2
125	35.2
160	31.5
200	28.5
250	21.5

Table 2 – average values

After all this case history, the present study suggests the following steps in order to assess disturbance:

1) Noise should be measured both inside the dwelling where the disturbance is higher and at the source. If the source signal is stable enough, then this measurement can be carried out

separately. If the 1/3 octave bands trend of the former is comparable with the latter (also a composition of frequencies due to many sources), then this method can be used, according to [7].
The source(s) measurements have to be carried out at a distance of 1 meter from the highest emitting point. If the noise source is composite (industrial plant) then the receiver should be placed in a spot equally distant from the different sources in a normal direction starting from the focal point of the overall surface. If this is not possible (close walls, irregular shape) the instrument needs to be placed closer to the surface, remaining in a normal direction starting from the focal point.

2) The residual noise (source(s) off) should be measured in the same period of the day and week before or after the noise source is used.

3) The residual noise should be compared and contrasted with the disturbing noise. If the difference (in 1/3 octave band analysis) is higher than 6 dB according to [6], the disturbance can be evaluated using following steps.

4) The measured disturbing noise within the dwellings should be compared and contrasted with the average threshold. If the former exceeds the latter two different scenarios must be considered:

a. If it is night time (from 22 to 7 h); if the receivers are children up to the age of 3 or people with serious illnesses (all day long); if the receivers are in hospitals or schools or buildings where silence is needed (all day long), then the excess of the threshold confirms the existence of the disturbance.

b. If none of the above conditions applies, the excess has to be equal to or higher than 3 dB according to [23] in any 1/3 octave band.

Measurement guidelines:

1) A minimum of three different 15-minute measurements are to be averaged. If the noise is shorter, then the use of multiple receivers is needed (3 minimum) with at least 1 minute measurement time each. The microphone(s) need to be 50 cm away from each other.
If the noise source(s) is not constant (e.g. concert, short and repeated HVAC cycle etc.) and the related residual noise is shorter than 2 minutes, then the measures have to be post-processed in order to compute the disturbing noise only and exclude the residual noise. The minimum sampling step is set to 1 second.

2) At the same time an instrument must be placed near the source(s) in order to acquire the frequency trend. If the signal is stable enough, then this measurement can be carried out separately (before or after those in the dwelling).

3) No other person except the engineer(s) must be present during the measurements. All the external acoustic events are to be taken into account and post-processed to avoid any outer interference.

4) All doors and windows must be closed.

5) The measurements must be carried out in closed rooms such as dining room, living room, bedroom, etc. No corridors, storerooms, bathrooms smaller than 8 square meters (minimum area for repeatable measurements, taking in to account furniture, room shape etc.) should be considered.

When providing results:

1) Report measurement methodology

2) Identify irrelevant acoustic events during occurring during measurement operation and do not factor them in while assessing the disturbance

3) Report name, type and certification of the instrumentation

4) Describe the source type and report the frequency and trend.

5) Attach pictures of the measurements and of the sources

6) Report the 1/3 octave band assessment trend and indicate if and where the presence of a noise disturbance is confirmed

7) Propose possible solutions

8.6 New method application

The 6 cases discussed above were used to test, analyse and assess the methods proposed in the literature, to understand their rationale and identify potential issues. Lessons were in this way learned and translated into a new method meant to provide an objective assessment of noise disturbance, which was obviously not available when the 6 cases above were initially assessed and could therefore not be applied. Following its creation, chances arose to apply the new method in 2 of the above discussed situations:

1) Disco music coming from the same building (paragraph 3.4). Here the noise was measured by night and no receivers listed in 4) sub a) with no receivers as described in point 4) sub a) in the building

2) Large HVAC (paragraph 3.5). Here the noise was measured by night and no receivers listed in 4) sub a) with no receivers as described in point 4) sub a) in the building

In 1) the methods provided in the literature produced very diverging results. Those who dwelt inside the building while the measures were in progress nevertheless unanimously reported the presence of a noise disturbance (first step, fig. 15). The proposed approach also confirmed the existence of the disturbance. The source was subsequently modified (by means of a limiter and a

DSP analyser) and the disturbance was measured by 2 different teams. The new method was used in addition to the old method in order to contrast results.

By using the methods proposed in the literature, the 2 teams once again obtained diverging results, owing to unspecific measurement procedures and uncertainty as to which threshold should be applied in which case.

By using the new method, the 2 teams obtained comparable results and concluded that there was no disturbance (second step, fig. 15), which was in line with the subjective perception of the police, present in the building, and the owners of the building

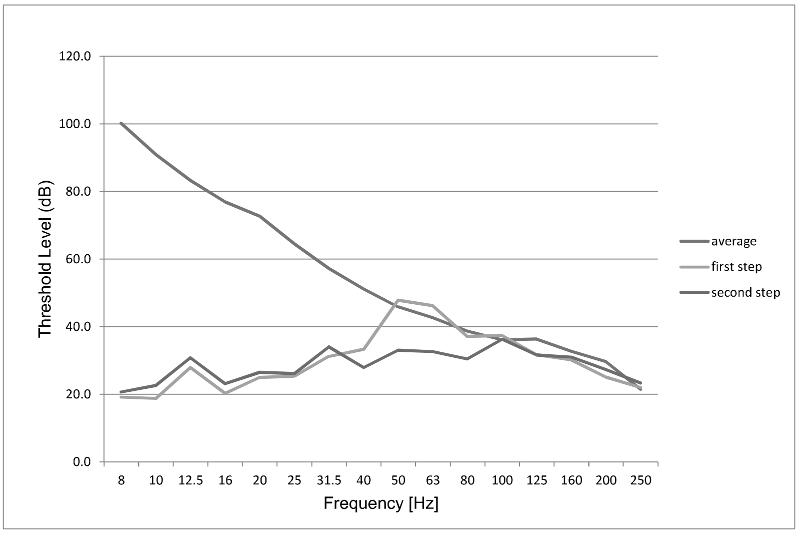

Figure 15 – the new method applied in real-life circumstances (see paragraph 3.4)

In 2), the results obtained using the methods provided in the literature are at utter variance, although all those who dwelt inside the building while the measures were in progress agreed that the disturbance was there (first step, fig. 16). The disturbance could also be identified using the new method. The source was then modified by applying the appropriate silencer and the new method was used along the old method to assess the disturbance, so that the results could be contrasted.

And again, using the methods proposed in the literature, the team obtained diverging results, owing to unspecific measurement procedures and uncertainty as to which threshold should be applied in which case

By using the new method, the team concluded that there was no disturbance (second step, fig. 16), which was in line with the subjective perception of the police, present in the building, and the owners of the building

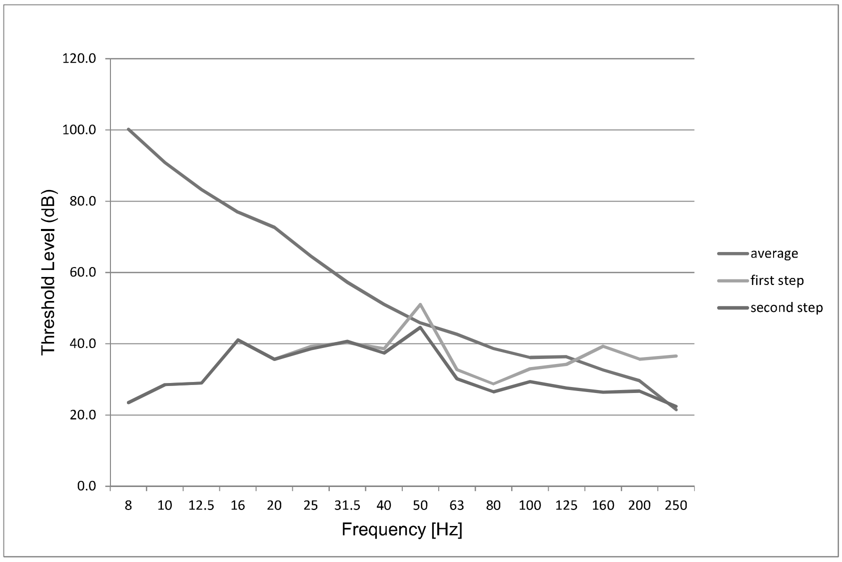

Figure 16 – – the new method applied in real-life circumstances

8.7 Conclusions

Sound measurements inside dwellings are commonly used to understand noise and sleep disturbance. As a consequence, many researchers worldwide have tried to determine objective methods to assess whether a disturbance is present or not. Some countries use the discussed criteria and have made their use compulsory. Each method focuses on some features, leaving possible interpretations to the engineers, which may cause misunderstandings. The goal of this paper is to inform stakeholders in the drafting of new standards or legislation, or in the integration of existing legal requirements by proposing an objective method built on robust and scientific criteria that should replace the current, unreliable but widely used procedures and their subjective interpretation.

To this end, an in-depth analysis of different disturbance assessment methods was carried out. Six different traditional sources were analysed and measured and results were compared and contrasted. Pros and cons were highlighted and a new assessment criterion was proposed and successfully tested combining, were possible, the different approaches and standards discussed in the literature. A new average threshold is supplied which simplifies the procedures in case of low-frequency components, but which could be used for any situation. This is complemented with new and well defined measurement steps and guidelines.

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