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Evaluation of the impact sound insulation of an existing and refurbished wooden beam floor construction

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eines Diplom-Ingenieurs

unter der Leitung von

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ABSTRACT

This master thesis deals with the impact sound insulation of wooden beam floors in an old Viennese “Gründerzeit” house. The main objective was to deal with the issue of poor impact sound insulation of existing wooden beam floors, especially in the low frequency range below 100 Hz where their acoustical performance is rather problematic. Through the application of modern materials and techniques a wooden beam floor construction was refurbished step by step giving several variations, and their impact sound insulation was then compared to that of two existing non-refurbished constructions. The measurement test procedure followed to determine the impact sound insulation using sound pressure measurements was according to the EN ISO 16283-2:2013 for two impact sources operating on the floor: the standard tapping machine and the recently introduced heavy/soft rubber ball. At present, calculation procedures for a single number quantity exist only for the tapping machine method. Therefore rating the impact sound insulation of the floors was done according to the sound requirements set by the Austrian ÖNORM 8115-2:2006 standard. Furthermore, various impact sound insulation classification schemes with a number of quality classes proposed in the literature were applied to characterize the comfort level of each construction. Results demonstrate that it is possible to enhance the impact sound insulation of wooden beam constructions in such extend to reach low impact sound pressure levels, even for frequencies below 100Hz, and characterize them with a very high quality level.

Keywords

Impact sound insulation, impact sound pressure level, renovation, refurbished, wooden beam floor, building acoustics, “Gründerzeit” buildings

KURZFASSUNG

Die folgende Diplomarbeit befasst sich mit der Trittschaldämmung von Holzbalkendecken in einem Gründerzeithaus in Wien. Das Ziel war sich mit der schlechten Trittschalldämmung von Bestandsholzbalkendecken, vor allem im tieffrequenten Bereich unter 100Hz, auseinanderzusetzen. Durch die Anwendung von moderne Materialien und Techniken, wurde eine Bestandsholzbalkendecke Schritt für Schritt saniert und die Trittschaldämmung der Sanierungsvarianten wurde mit der von zwei bestehenden Holzbalkendecken verglichen. In der EN ISO 16283-2:2013 sind zwei Methoden zur Messung der Trittschalldämmung zu finden. Die eine Messung erfolgt mit einen Norm-Hammerwerk und die zweiter mit einem schweren/weichen Gummiball. Derzeit existiert nur für das Norm-Hammerwerk ein Bewertungsverfahren zur Berechnung einer Einzahlangabe. Deswegen die Bewertung der Trittschalldämmung von Holzbalkendecken erfolgte laut den Schallschutzanforderungen die in der ÖNORM 8115-2:2006 beschrieben sind. Außerdem wurden mehrere Trittschalldämmungsklassifikationsschemen für verschiedene Qualitätsklassen herangezogen um die schalltechnische Qualität einer Konstruktion zu beurteilen. Die Ergebnisse zeigen, dass es möglich ist die Trittschalldämmung von Holzbalkendecken so viel zu erhöhen, dass kleine Trittschalldruckpegel, auch für den Frequenzbereich unter 100Hz, erreichbar werden. Somit können sanierte Holzbalkendecken einen sehr hohem Schallschutz Komfort erreichen.

Schlagwörter

Trittschalldämmung, Trittschallpegel, Sanierung, Holzbalkendecken, Bauakustik, Gründerzeitgebäude

CONTENTS

1 INTRODUCTION

1.1 Motivation

Nowadays the population of cities is growing rapidly and Vienna's (Austria) population is one of the fastest growing among the metropolises of the world. This has as an immediate consequence on the demand for more housing. The availability of space is declining thereby raising the cost of land property. Hence, construction of new residential buildings alone cannot follow the growing demand for housing. A new development is the refurbishment of old buildings and the addition of storeys, after the roof removal, on top of the existing buildings. Among these dwellings, are the so called "Gründerzeithäuser" which were erected in the area of Vienna during the end of the 19th century and usually consisted of heavy masonry walls and wooden beam floors. Refurbishment of the various building elements, if not subject to preservation requirements, has to comply with the Viennese building law (Bauordnung für Wien). For every refurbished building element its constructional, thermal, fire protective and acoustical aspects have to fulfill the most recent ÖNORM (Austrian) standards and the OIB (Austrian Institute of Construction Engineering) guidelines.

From the above mentioned building aspects, in the refurbishment of old multifamily residences, one of the most common problems the planners encounter, is the sound insulation of its building elements. In Europe, where the standard of living has been rising year by year, the second most mentioned complaint, besides typical noise pollutants such as automotive, air and rail traffic, has been the noise heard from neighbor apartments in multifamily dwellings (Niemann et al. 2006). The issue is much more troublesome for the impact than the airborne sound.

The majority of the residents complain about the footstep noise or the impact sound produced by people walking, children jumping, falling objects or moving chairs from the upper to the lower floor. Modern Hi-fi and home theater systems have also been contributing to increasing protest. These sounds are identified by tenants with terms such as «buzzes», «bumps», or «thumps» (Blazier and DuPree 1994). The main factor of these complaints is usually found at the low-frequency end of the spectrum of the impulse response (transfer function) of the floor when exited by the above mentioned sources.

1.2 Objective

In the renovation of old Viennese "Gründerzeithäuser" buildings the sound insulation of the wooden beam floor is very problematic especially in the low frequency spectrum (Rabold et al. 2013). These structural elements, which comprise wooden beam constructions, require thorough planning at the design phase and careful execution during their construction (Hagberg et al. 2010). This thesis focuses on the analysis and evaluation, through a series of field measurements, of old wooden floor constructions, in order to get a better understanding how footfall noise is influenced, among others, by different materials and compositions. High quality acoustical design is a prerequisite for sustainable building design. Therefore, an attempt to develop, through the application of modern building materials and techniques, a wooden beam floor, to enhance its impact sound insulation in such extend to reach values much lower than the sound protection requirements of $\mathrm{L'}_{\mathrm{nT,w}} \leq 48\mathrm{dB}$ as described in the Austrian standard ÖNORMB 8115-2:2012 “Sound protection and room acoustics in building construction”. All the field experiments were performed at a “Gründerzeit” building in the 1st district of Vienna.

1.3 Background

1.3.1 Sound and Vibration

Sound in its physical form is any rapid change of even the smallest amount of pressure within a medium. Any medium that vibrates generates sound waves that transfer mechanical energy and therefore are characterized as mechanical waves. Although in reality a sound wave is a longitudinal wave where the wave flow follows the direction of the movement of energy, diagrammatically (see Figure 1) it is often represented as a sinusoidal wave, which represents the displacement of a vibrating particle of the medium from its mean position (equilibrium).

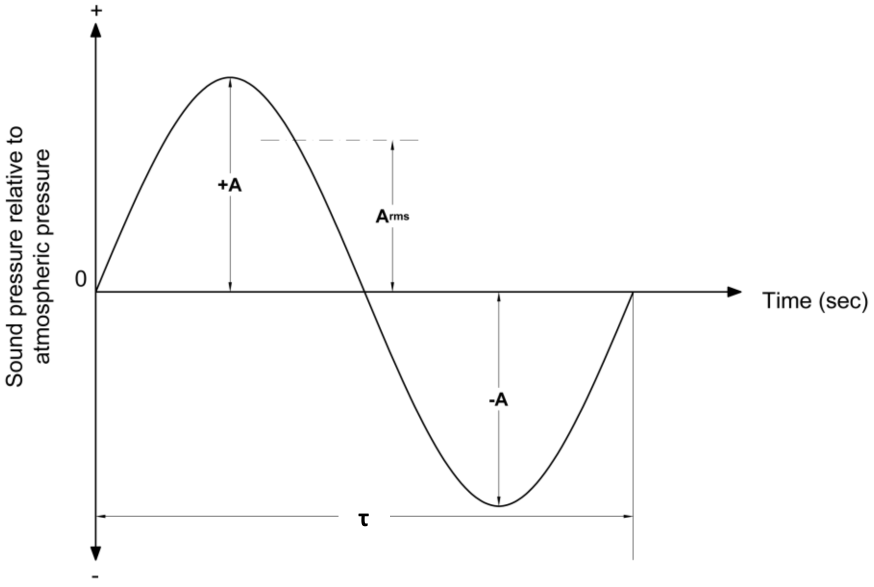


Figure 1. Sound wave of a pure tone (i.e. single frequency)

Relevant for this thesis properties of sound waves are:

- ±A is the wave amplitude which represents the loudness of the sound
- A_{rms}=0,707·|A|, is the square root of the average of the squared values of the wave form (with |A| being the absolute value of peak amplitude). The RMS value is proportional to the area under the curve.
- τ is the period or the length of time needed to complete one cycle of a wave
- f= 1/τ is the frequency in Hertz (the number of wave cycles that pass a single point in one second, moving at the speed of sound in the air approx. 340 m/s)
- λ is the wavelength

Audible sound is the brain's interpretation of sound waves detected by the ear. The sensation of very small and rapid changes in the air pressure above and below the atmospheric pressure of air (100.000 Pascal) is what humans perceive as audible sound. When these changes happen at the frequency between 16 Hz and 20 kHz (Fischer et al. 2008) sound is usually audible even though the pressure difference can be very low ($>>10^{-6}$ Pascal). The mechanical energy of a sound wave that is produced by these pressure differences is defined as sound energy and measured in dB (decibel). Because the sound pressure scale that humans perceive sound is very large, a more practical measure was introduced. This measure denoted as sound pressure level L_p (abbr. SPL in dB) is a logarithmic measure of the effective pressure of a sound relative to a reference value and is defined by equation (1):

Sound pressure level (SPL)

$$L_p = 20 \cdot \log\left(\frac{p}{p_0}\right)\ dB \tag{1}$$

Where:

p is the present sound pressure, in N/m²

p_0 is the reference sound pressure at the hearing threshold ($=2\cdot10^{-5}$ N/m²)

With the introduction of the Sound pressure level (SPL) the range between 0dB (hearing threshold) and 120dB (pain threshold) were defined. With decibels (dB) the sound pressure level is much easier expressed and in that way more reproducible. One 1 dB is approximately the smallest change in energy that the ear can detect (Hassan 2009).

Sound is measured with the assistance of a sound level meter or sound analyser, which is a compact electronic instrument with a microphone. For each change of acoustic pressure impacting on it, the microphone generates an electric voltage proportional to that change which is then measured and analysed by the electronic instrument. Sound level meters are filtering the sound in the so called A, B or C-weighted filters to take into account part of the differential frequency sensitivity. A-weighting filtering is to contribute for the feature of human hearing and therefore sound pressure levels acquired using this filter are referred as A-weighted and expressed by dB(A). In order to take a scientific measurement, the microphone is always calibrated (before and after the test) in accordance to a reference pressure. So its sensitivity is precise for each sound field measurement it is used (Hassan 2009, IEC 61672-1:2013).

1.3.2 Impact sound

As a physical measure, impact sound or footfall noise is almost always structure born and therefore appears when one body hits another, such as in the case of footsteps, jumping children, falling objects or pounding on a floor or a ceiling of a building. The energy caused by that collision propagates as a mechanical vibration almost unaffected through continuous and rigid structures, causing airborne sound to be emitted from structure to air, as seen in Figure 2. The impact sound transmission follows two paths, one direct and a flanking one, to reach the lower room (EN ISO 16283-2:2013).

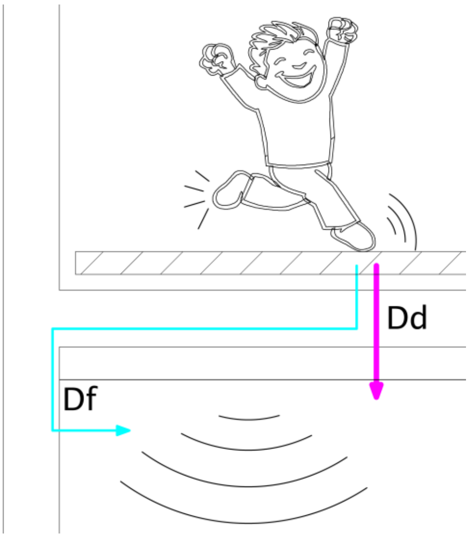


Figure 2. Footfall noise produced by a jumping child on a floor. Arrows show the impact sound transmission; direct transmission (path Dd) and flanking transmission (path Df)

When these sounds become bothersome for the residents of a dwelling they are characterized as noise. Troublesome noise over a long period of time can cause a series of problems such as loss of concentration, physical discomfort and stress (Goines and Hagler 2007). Noisy neighbours can be the main reason of complaints in multifamily residences and sometimes these sound sources can lead to unpleasant conflicts and restrained activity. In the case of footfall noise, it is often quoted by tenants of the lower apartments that they can hear where and when someone is walking on the upper floor which can negatively influence the privacy sphere in their apartments (Blazier and DuPree 1994, Hassan 2009). However, the way each individual experiences undesirable sound in his private sphere is a very subjective emotion. Each person reacts different to noises caused by impact sounds. Some people tolerate it more, ignore it or even get used to it but others are not able to do so and cannot relax, concentrate or accept it. Lang (2004) quotes, that «it will not be possible to make all activities unhearable and to protect tenants that are very sensitive to noise from every noise disturbance». The Austrian ÖNORM B 8115-2, in the Chapter "Scope of the directive" states the following: "In this standard requirements and standard values for the minimum sound protection are defined with the goal, to protect, for common behavior, normal-sensitive people form disturbing airborne and structure borne sound".

1.3.3 Impact sound insulation

The common approach to improve footfall noise is the so called sound insulation or isolation of the floor construction. In building acoustics insulation or isolation, although different terms, they are used to describe the same thing. By that it means that insulation or isolation is a way to prevent and block the biggest part of the produced impact sound energy to forestall it from reaching a receiving area (Hassan 2009). This can be achieved by the application of universally accepted design and construction methods as well as the right use of special materials. In the next sub chapter, an overview of existing knowledge to improve the impact sound insulation is presented.

Impact sound insulation is particular to floors and refers to the competence of a floor to lower the sound produced when an object strikes its walking surface. In building acoustics the frequency range of interest is between 50 and 3150 Hz. A universal in-situ testing method as described in EN ISO 140-7, now in the EN ISO 16283-2:2013 to rate the impact sound transmission through floors can be seen in Figure 3. A standardized tapping machine with five hammers that hit the floor with a total rate of several times per second is used to excite the horizontal partition (between source and receiving room). A microphone which is applied to a sound analyser in the receiving room measures the sound pressure levels in one-third-octave bands (100-3150 Hz). The resulting curve, after a correction for existing background noise and the reverberation time in the receiving room, is then fitted to a reference contour to obtain a single number quantity.

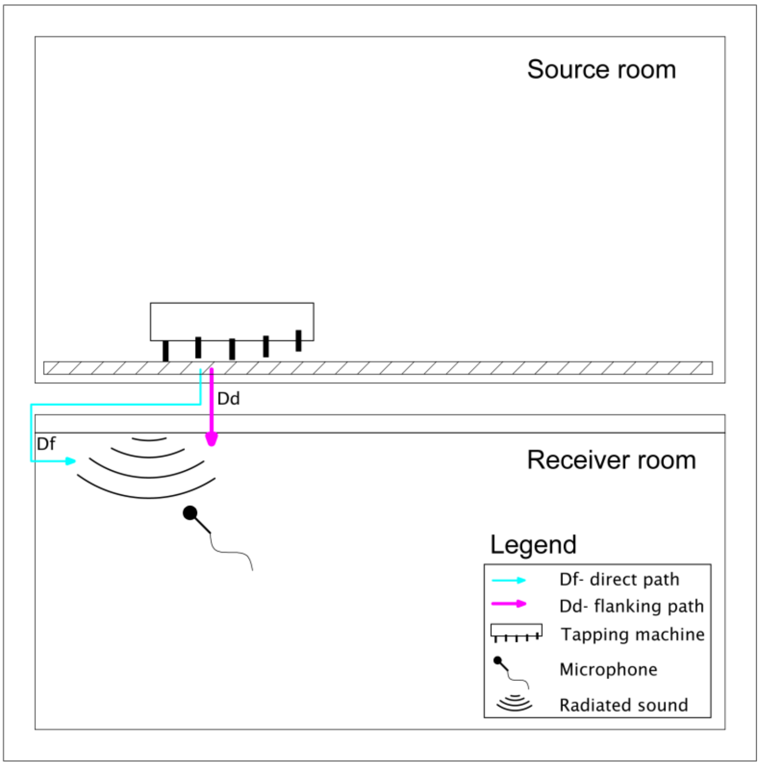


Figure 3. Impact sound insulation; field measurement setting

This single measured parameter is called weighted standardized impact sound pressure level $\mathrm{L'}_{\mathrm{nT,w}}$. It is evaluated from the standardized impact sound pressure (abbr. ISPL in dB) level $\mathrm{L'}_{\mathrm{nT}}$ by applying a weighting procedure specified in ISO 717-2:2013. $\mathrm{L'}_{\mathrm{nT}}$ is calculated with equation (2) according to the EN ISO 16283-2:2013. A good floor performance is indicated by a low $\mathrm{L'}_{\mathrm{nT,w}}$ value.

Standardized impact sound pressure level

$$L'_{nT} = L_i - 10\log\frac{T}{T_0}\ dB \tag{2}$$

Where:

L_i average impact sound pressure level in the receiving room, in dB,

T reverberation time in the receiving room, in seconds

T_0 reference reverberation time, in seconds; for a dwelling given as T_0 = 0,5 s

For field measurements alterative to the standardized impact sound pressure level $\mathrm{L'}_{\mathrm{nT}}$ and the weighted standardized impact sound pressure level $\mathrm{L'}_{\mathrm{nT,w}}$ following indicators can be used: the normalized impact sound pressure level $\mathrm{L'}_{\mathrm{n}}$ (corresponding to the reference equivalent sound absorption in the receiving room, see equation (3) and the weighted normalized sound pressure level $L'_{n,w}$ as evaluated from the normalized impact sound pressure level L'_{n} by applying the weighting procedure specified in the receiving in the ISO 717-2.

Normalized impact sound pressure level

$$L'_n = L_i - 10 \log \frac{A}{A_0}\ dB \tag{3}$$

Where:

L_i	average impact sound pressure level in the receiving room, in dB,
A	equivalent sound absorption area in the receiving room, in m²
A_0	reference absorption area, in m²; for a dwelling given as A_0 =10 m²

For laboratory measurements the following indicators are used: 1) normalized impact sound Pressure level L_n; 2) standardized impact sound pressure level L_{nT}; 3)Weighted normalized sound pressure level $L_{n,w}$; and 4) weighted standardized impact sound pressure level $L_{nT,w}$. In the scope of this thesis the weighted standardized impact sound pressure level was used to define the impact sound insulation of the floors.

However, the single number rating $L'_{nT,w}$ does not give an accurate indication for the sound insulation performance of wooden beam floors for sound sources that contain dominant low frequency or high frequency sound (Hassan 2009). Moreover, a practical method to address the important thematic of impact sound insulation has been a matter of debate and research for decades (Lang 2006). Other methods than that of the standardized tapping machine have been proposed multiple times to point out that the method to characterize the impact sound insulation should also describe sufficiently the damping of walking noise.

Such alternative methods include the Korean Bang Machine (according to KS F 2810-2), the heavy/soft impact ball (according to ISO 10140-5, Appendix F) and the modified standardized tapping machine (according to ISO 10140-5, Appendix F).

In a study conducted in 2006 (Jeon et al. 2006) to review the heavy/soft impact ball, the results pointed out that for composite floor structures with floor heating systems the noise from the impact ball is similar to that of children running and jumping, and that subjective responses correlate well with Zwicker's Loudness model (Zwicker et al. 1999) and the inversed floor impact sound pressure level $L'_{i,Fmax,AW}$ as defined in the JIS A 1419-2:2000.

The latest draft of the EN ISO 16283-2:2013 suggests that the maximum impact sound pressure ($L'_{i,Fmax,V,T}$) produced by the impact ball should be measured in the low frequency range, either in the octave bands (31.5-63-125-250-500 Hz) or in the 1/3 octave band filters (50-630 Hz), because the energy in that range is, due to the heavy-weight impact ball force spectrum, relatively greater than that of higher frequency range. But a study done in Japan (Ryu et al. 2010) in order to evaluate wood-framed floors, suggested that sound insulation in frequency bands up to 1 KHz are more effective to decrease annoyance than those in lower frequency octave bands for heavy-impact sound with inversed A-weighting curve spectrum (inverse A-weighted curves in IEC 61672-1).

Nevertheless, the method with the standardized tapping machine, because of its ease of use and the good repeatability of acquired values, was generally accepted in the International Standards and is widely used in most European countries including Austria (Rasmussen 2010). Other methods have not been approved in the ISO 717-2:2013, which makes it difficult to use them, with no requirements set to rate the impact sound insulation of a floor. According to the Austrian standard ÖNORMB 8115-2:2006, the standardized impact sound pressure level between apartments has to be $\mathrm{L'}_{\mathrm{nT,w}} \leq 48\mathrm{dB}$. According to a Danish survey, regarding the legal sound insulation requirements in 24 European countries, Austria has the strictest requirements for both impact and airborne sound insulation among them and probably the strictest requirements in the world (Rasmussen 2010).

However, the correlation between the subjective sensation of residents and the weighted standardized impact sound pressure level indicator $\mathrm{L'}_{\mathrm{nT,w}}$ is very poor. The $\mathrm{L'}_{\mathrm{nT,w}}$ descriptor does not take into consideration the individual noise peaks at low frequencies. Therefore many research projects were conducted (Hveem et al. 1996, Jeon et al. 2002, Warnock 2000, Scholl 2001, Burkhart 2002, Kühnet al. 2003) that addressed the above issue and showed clearly that there is no obvious relationship between the subjective sensation of residents and the $\mathrm{L'}_{\mathrm{nT,w}}$ indicators. To cope with this issue, in the ISO 717-2:1996 an adaptation term $\mathrm{C_I}$, see equation (4), was introduced which can also be applied for the wider frequency range down to 50 Hz ($\mathrm{C_{I,50-2500}}$; see equation (5)) was further researched.

Spectrum adaptation term (100-2500Hz)

$$C_I = \left(L'_{nT,sum} - 15 - L'_{nT,w}\right) dB \tag{4}$$

Spectrum adaptation term (50-2500Hz)

$$C_{I,50-2500} = \left(L'_{nT,sum} - 15 - L'_{nT,w}\right) dB \tag{5}$$

Logarithmic sum of the measurement results (for k frequency bands)

$$L'_{nT,sum} = 10 \cdot log \sum_{i=1}^{k} 10^{L'_{nTi}/10} \tag{6}$$

Where:

$L'_{nT,sum}$	is the logarithmic sum of the measurement results
$L'_{nT,i}$	is the standardized impact sound pressure for each position
$L'_{nT,w}$	is the weighted standardized impact sound pressure level

In a recent study (Rabold 2011) the correlation between the impact sound transmission of a walker and the standard tapping machine was investigated in the laboratory. For the evaluation of the walker an A-weighted (with a correction for the receiving's room reverberation time) $L_{AF,max,n}$ indicator was developed. For the data to be reproducible, a male walker, 75-85 kg, walking with socks 90-100 steps per minute in a circle and an eight shape was employed to excite the floor. This indicator was then compared with the $L_{n,w}$ from the impact sound excitation by the standard tapping machine in test facilities (DIN EN ISO 10140-5), which showed a rather poor link between them. The reason for that, as seen in Figure 4, is that by walking on the wooden beam floor the biggest part of the sound energy is transmitted at the frequencies under 100 Hz.

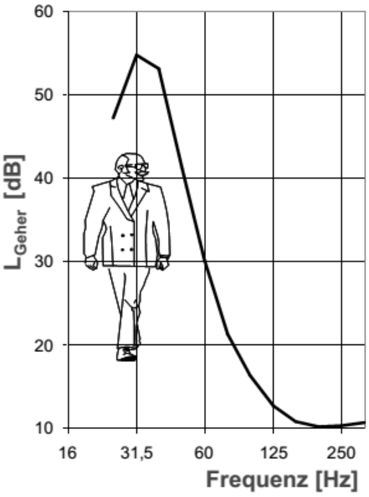


Figure 4. Frequency dependent illustration of the impact sound transmission by walking on a floor (Rabold.A ,"Trittschalldämmung richtig bewerten", p. 4 , 2011)

Therefore the $L_{AF,max,n}$ descriptor was compared with $L_{n,w} + C_{I,50-2500}$. The results showed a good correlation (R^2 =0.86, σ=2.9dB) of the two indicators. Furthermore $L_{AF,max,n}$ was compared with Zwicker's loudness, an objective method for measuring noise based on the use of 25 1/3 octave bands between 20Hz and 12500Hz (Zwicker et al. 1991), which also showed a good connection, for the walker excitation method. With the help of the sufficient correlation results new target values could be defined, e.g. $L_{n,w} + C_{I,50-2500}$ ≤ 53 dB or ≤ 46 dB, and relevant floor construction as "Demonstrators" developed.

An older study conducted in Austria (Lang 2004) researched the sound insulation of floor constructions for wooden beam slabs. Sixteen different flooring systems, on a normalized-wooden beam floor, were tested in laboratory facilities. The same sound measurement experiments were also done for the Heavy/soft Impact source (rubber ball) according to the ISO 140-11. The comparison between the standardized method and the rubber ball method showed that the impact sound transmission is predominant on the very low frequency spectrum (frequencies under 100 Hz). This spectrum is defined, by residents, as very annoying. Therefore Lang (Lang 2004) recommended that the impact sound measurements should be performed from down to 50 Hz and the requirements for the impact sound insulation should be applied according to the $\mathrm{L'}_{\mathrm{nT,w}} + \mathrm{C}_{\mathrm{I,50-2500}}$ indicator. This indicator does not change the requirements for massive (concrete or masonry) slabs, but is important to prevent acoustic discomfort for wooden slab floors, where residents tend consistently to complaint about the buzzing noise. Therefore, the requirements according to Lang (Lang 2006), of $\mathrm{L'}_{\mathrm{nT,w}}$ ≤ 48 dB should be extended to $\mathrm{L'}_{\mathrm{nT,w}} + \mathrm{C}_{\mathrm{I,50-2500}}$≤ 50 dB; higher requirements $\mathrm{L'}_{\mathrm{nT,w}} + \mathrm{C}_{\mathrm{I,50-2500}}$ ≤ 45 dB and very high (comfort) with $\mathrm{L'}_{\mathrm{nT,w}} + \mathrm{C}_{\mathrm{I,50-2500}}$≤ 40 dB (Lang 2006). The above requirements can be seen in the Table 1 as formulated by Lang (Lang 2006).

Table 1. Sound insulation requirements in 4 sound classes

	Class A "Music"	Class B "Komfort"	Class C "Extended"	Class D "Standart"
Impact sound insulation between apartments $\mathrm{L'}_{\mathrm{nTw}}$ + $\mathrm{C}_{\mathrm{I,50-2500}}$ (dB) *	≤ 40	≤ 40	≤ 45	≤ 50
Impact sound insulation inside an apartment $\mathrm{L'}_{\mathrm{nTw}}$ + $\mathrm{C}_{\mathrm{I,50-2500}}$ (dB) *	≤ 45	≤ 45	≤ 50	≤ 55
*for a transition period $\mathrm{L'}_{\mathrm{nTw}}$+ C_{I} around 2 dB lower				

Moreover a proposal for an acoustic classification scheme for housing, is being presented in the international European Project COST Action TU0901 (Rasmussen and Machimbarrena 2014). The specified class limits for impact sound pressure level in dwellings (see Table 2) are according to EN ISO 140-7, and the evaluation is expressed in the descriptor $\mathrm{L'}_{\mathrm{nT,50}} = \mathrm{L'}_{\mathrm{nT,w}} + \mathrm{C}_{\mathrm{I,50-2500}}$ as defined in the EN ISO 717-2. Similar to Lang (Lang 2006) this classification scheme (sound classes A-F as defined in Table 3) takes into account the low-frequencies. However it is noted that when applying this low-frequency rating, potentially disturbing high frequency sounds might not be rated appropriately. Because of that an additional criterion for $\mathrm{L'}_{\mathrm{nT,w}}$ is applied for the same limit value, while research is been done to find an improved weighting procedure that solves that problem sufficiently. As another option to $L'_{nT,50}$ the floor performance can be estimated by more common used descriptor $L'_{nT,100} = L'_{nT,w} + C_I$. For light-weight floors and composed elements with low frequency resonances this evaluation might not be adequate though. If $L'_{nT,100}$ is used the alternative frequency range 100-3150Hz can be optionally applied resulting in a class denotation X_{100}, e.g. B_{100}.

Table 2. Impact sound pressure level in dwellings. Class limits.(1),(2),(3) (Rasmussen and Machimbarrena 2014)

Type of Space	Class A $L'_{nT,50}$ (dB)	Class B $L'_{nT,50}$ (dB)	Class C $L'_{nT,50}$ (dB)	Class D $L'_{nT,50}$ (dB)	Class E $L'_{nT,50}$ (dB)	Class F $L'_{nT,50}$ (dB)
In dwellings from other dwelling	≤ 44	≤ 48	≤ 52	≤ 56	≤ 60	≤ 64

NOTES

(1) $L'_{nT,50}=L'_{nT,w}+C_{I,50-2500}$

(2) The same limit values are to be fulfilled by $L'_{nT,w}$

(3) As an alternative to $L'_{nT,50}$, the performance can be estimated for all types of constructions by the currently more common descriptor $L'_{nT,100} = L'_{nT,w} + C_I$, see Clause 3. If $L'_{nT,100}$ is applied, the class denotation is X_{100} , eg. B_{100}.

Table 3. Description in general terms of the quality of the different classes (Rasmussen and Machimbarrena 2014)

Class	General	Sound insulation judged poor
A	A quiet at quiet atmosphere with a high level of protection against sound	less than 5%
B	Under normal circumstances a good protection without too much restriction to the behaviour of the occupants	around 5%
C	Protection against unbearable disturbance under normal behaviour of the occupants, bearing in mind their neighbours	around 10%
D	Regularly disturbance by noise, even in case of comparable behaviour of occupants, adjusted to neighbours	around 20%
E	Hardly any protection is offered against intruding sounds	around 35%
F	No protection is offered against intruding sounds	50% or more

NOTE: the indicated percentages are just a global indication; the trend is rather well based in literature, but the absolute numbers depend very much on the setting and wording of the questionnaires used.

In another recent study, part of the Swedish AkuLite project, which was published and presented at the Internoise 2013 conference (Ljunggren et al. 2013), the correlation between measured sound and vibration parameters and the subjective annoyance of tenants in lightweight buildings was researched. AkuLite was a research project involving Swedish building industry and acoustic research groups which aimed to develop sound and vibration criteria that are consistent with people's perception in lightweight buildings. In this part of the study different impact sound pressure level indicators were applied and frequencies down to 20 Hz were included. The results from the comparison of the extensive field measurements and the subjective sensation of occupants (based on a new questionnaire drafted within the EUROPEAN network COST TU 0901 2012), for both commonly used impact sound descriptors $\mathrm{L'}_{\mathrm{n,w}}$ and $\mathrm{L'}_{\mathrm{n,w}} + \mathrm{C}_{\mathrm{I,50-2500}}$, showed very poor correlation (R^2 0.26 and 0.34 respectively). When considering frequencies down to 20Hz the R^2 for the $\mathrm{L'}_{\mathrm{n,w}} + \mathrm{C}_{\mathrm{I,50-2500}}$ indicator improves considerably up to 74%. The correlation improved even further to R^2 84% when a new adaptation spectrum $\mathrm{C}_{\mathrm{I,AkuLite,20-2500}}$ equation (7) was used. In comparison to the present adaption term $\mathrm{C}_{\mathrm{I,50-2500}}$ of ISO 717-2, where a uniform weighting of 15 dB is applied to all frequencies, the AkuLite adaption term (COST action TU 0901 2012) adjusted the weighting values from 20-50Hz to take into account the complaints of lightweight building residents without affecting concrete buildings and the values over 400Hz to include high frequency problems that might come across in concrete without affecting lightweight houses.

Adaptation term(20-2500Hz) according to the Akulite project

$$C_{I,AkuLite,20-2500} = \sum_{i} 10^{(L'_{ni} - FWC_i)} - L'_{n,w} \tag{7}$$

Table 4. Frequency weighting coefficients for (FWC) for $C_{I,AkuLite,20-2500}$ (Ljunggren et al. 2013)

f (Hz)	20	25	31.5	40	50-400	500	630	800	1000	1250	1600	2000	2500
FWC (dB)	-7	-9	-11	-13	-15	-14	-13	-12	-11	-10	-9	-8	-7

The findings are based on data obtained from 10 buildings objects, which is too few in order to get any statistically significant differences between the evaluated measurement parameters and the correlation to subjective annoyance. For some objects, measurements were taken only between limited numbers of rooms, because of difficulties when entering inhabited dwellings. The findings about the impact sound though, are in accordance with an independent listening test (Thorsson et al. 2013) and further research about the role of the lower frequency range in this situation is needed. In conclusion, multiple studies suggest using the lower frequency range as a suitable parameter for the evaluation of wooden floor damping properties.

1.3.4 Overview of existing knowledge to improve the impact sound insulation of wooden beam floors

As mentioned earlier, the issue with light weight floor constructions in general and hence with wooden beam floors is that they perform poorly in the low-frequency range (Lang 2006), below 100 Hz. This is the area where wooden beam floors have problems compared to heavy concrete floors, due to their light weight and perhaps their lower stiffness.

A typical Viennese wooden beam floor can be seen in Figure 5.

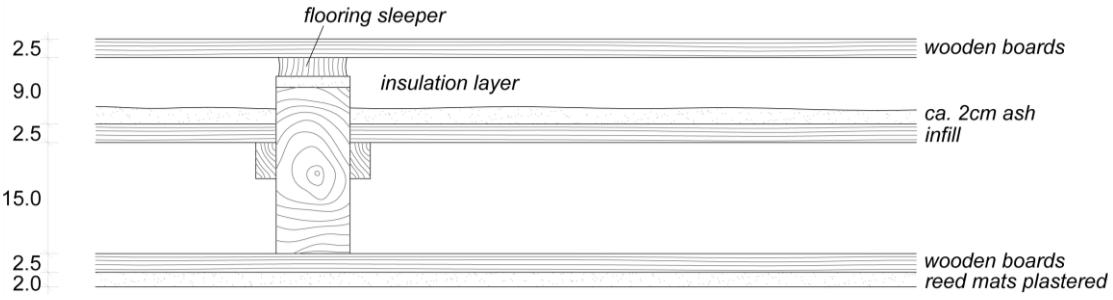


Figure 5. Typical Viennese wooden beam floor

One of the most influential parameters for the sound behavior of wooden beam floors is the area related mass (m’, in kg/m²). Therefore a common practical approach to increase the mass of the floor is:

- Partially filling the cavity with granular or particle type materials (such as dried sand, sawdust or fly ash)
- loading the section of the floor on the beam with a layer of gravel (or grit) topping or with a concrete or gypsum plate
- raising the mass of the plaster system on reed mats from the underside of the floor

In this way the response to the applied impact force is reduced and as a consequence the transmitted sound as well. In general, a heavier floor is less likely to vibrate when walked on and thus less likely to generate low frequency sound. But usually adding mass to the structure has a more positive effect insulating airborne sound, than in lowering impact noise (Holtz et al. 1999). However, in a publication about impact sound insulation of wooden beam floors-design guidance for building refurbishment projects (Rabold et al. 2013) the influence of area related mass in the void between the beams was studied. The findings illustrated that a raise of mass from 0 kg/m^2 to 120 kg/m^2 with an infill in the cavity can actually enhance the normalized sound pressure level $\mathrm{L}_{\mathrm{n,w}}$ about 3 dB and the $\mathrm{L}_{\mathrm{n,w}} + \mathrm{C}_{\mathrm{I,50-2500}}$ about 4 dB. On the other hand raising the mass of the plaster system on reed mats from 15 kg/m^{2}to 26 kg/m^2,enhanced the $\mathrm{L_{n,w}}$ about 4 dB and the $\mathrm{L_{n,w} + C_{I,50-2500}}$ about 1 dB.

Another way to enhance the impact sound insulation is the use of a floating floor on top of the wooden beam construction (Holtz et al. 1999). With this, both impact and airborne sound insulation are improved and at the same time the walking surface is getting harder. This also adds to the general stiffness of the floor. A floating floor construction forms a mass-spring-mass system, where the screed plate and the wooden beam slab are the mass and the resilient surface layer is the spring. For this system to be effective the resonance frequency ($\mathrm{f_0}$), is very important. It is calculated according to equation (8):

Resonance frequency

$$f_0 = 160 \cdot \sqrt{s' \cdot \left(\frac{1}{m'_1} + \frac{1}{m'_2}\right)} \tag{8}$$

where m'_1 and m'_2 are the area related masses (in kg/m^2) for the screed and the wooden beam floor respectively, s' is the dynamic stiffness of the resilient layer (in MN/m^3).

The floating floor is enhancing the impact sound insulating for all frequencies higher than the resonance frequency $\mathrm{f_0}$. The highest values are reached when the screed is heavy and the resilient layer very soft. The floating floor has to be seen as a system and therefore very soft resilient layers should not be used in the case of dry or melted asphalt screed because this layer serves as a load distributing layer and if overloaded can even break. There are different types of screed layers such as:

- Cement and anhydrite screed layers have a relative high area related mass (around 100kg/m^2),withstand very high loads, can reduce impact sound between 14 dB and 23 dB but are relative time-consuming to construct because they have to dry in order to walk on them.
- Melted asphalt screed has a lower area related mass (60-75 kg/m^2), cannot be used on top of soft resilient layers (s'>20 MN/m^3) but can comprehend for that through the inside damping, by absorbing part of the sound energy. It can reduce the impact sound up to 16 dB.
- Dry screed layers are either particle boards, OSB boards or gypsum fiber board with a width of 18-30mm and an area related mass between 10 and 30 kg/m^2. Because of their small flexural rigidity, rather stiff resilient layers have to be used (s'>16 MN/m^3), otherwise the tenant has the feeling that the floor is sinking ("forest floor effect"). In general dry screed layers have a lower impact sound insulation between

7 and 11 dB. A higher impact sound reduction can be achieved either with the combination of raising the mass of the wooden beam structure (as described in the previous paragraph) or by the so called “Elementierung” (Veres and Fischer 1992). With the term “Elementierung”, the loading on top of the resilient layer with more mass is meant. It should not be confused with the term of raising the area related mass of the wooden beam slab, because with “Elementierung” the weight of the floating floor itself is risen. Further measurements (Rabold and Buschbacher 1996) gave construction specifications such as: 1) the plates used for the “Elementierung” should be maximal 30x30 cm; 2) the mass of the plates should be more than that of the dry screed; 3) the “Elementierung” should be positioned without fixed connection (glued or screwed) with the dry screed. Three beneficial for the sound insulation goals are achieved by the use of this construction: the area related mass and the flexural rigidity of the screed are raised and the transmission of the impact sound throughout the wooden beam slab is lowered.

A different approach to achieve sound insulation is to refurbish the underside of the wooden beam slab (Rabold et al. 2013). This can be accomplished by following measures:

- Replacing the existing reed mats plaster system with a gypsum board or gypsum fiber board construction. The boards are either rigidly connected with battens or with resilient channels directly onto the beam. The exchange of the flexible plaster system with the batten connected gypsum boards leads to worse results and therefore should be avoided. An enhanced impact sound insulation is not reached until the old underside is exchanged with a decoupled mounting of the gypsum boards. A combination of decoupling the gypsum boards with resilient channels and raising their area related mass has a considerable normalized impact sound enhancement. A further enhancement in the low frequency bands can be achieved with a decoupled suspended ceiling which is filled with insulation in the cavity (such as in the case of a resilient hanger).
- Another method for a very efficient decoupling is also possible with a self-supporting underside. In this case a free spanning underside construction, without any direct contact to the beams, is mounted resiliently on the flanking walls. This top quality type of construction is especially advantageous when no other option to enhance the wooden beam construction form above is possible, due to lack of construction height or when the structural analysis does not allow supplementary measures.

Other parameters that can influence positively the low frequency spectrum damping are:

- completely filling (or, even overfilling) the cavity with mineral wool, especially for the cavity depths found in wooden beam floors (Sipari 2000, Hveem 1998)
- another suggested solution was separating the most dominant natural frequencies in the floor systems from the modes in the room, given by typical dimensions (Chung et al. 2006, Hveem 1998)
- Laying a soft resilient layer, such as a carpet, on top of the floor is a common way to improve impact sound transmission. By that the impact force is damped by the resilient layer which reduces the vibration energy that is transferred to the floor structure.

2 METHOD

2.1 Overview

All sound measurement experiments were executed in a “Gründerzeit” building, in Vienna. First, impact sound insulation measurements of existing wooden beam floor constructions in the building were conducted and analyzed to get an overview of their sound insulation quality. As a next step, the literature research was used as a guideline for finding possible refurbishment variants corresponding to impact sound insulation requirements of very high comfort (see Table 1 and 2). This led to the design of one wooden beam floor construction with a variation of undersides (further presented as non- and refurbished constructions (a) to (g)). Furthermore, the wooden beam floor to be analyzed was chosen and the source and receiving room were defined. For evaluating the impact sound insulation of the floor, the method with the standardized tapping machine and the alternative method with the impact ball (according to EN ISO 140-7 and EN ISO 16283-2:2013) were both applied. Finally the single number quantity $\mathrm{L'}_{\mathrm{nT,w}}$ with the adaptation term $\mathrm{C}_{\mathrm{I,50-2500}}$ was used as an indicator of the impact sound insulation of the floors.

2.2 Test case

The building, where the experimental measurements took place, is situated in the first district of Vienna. The area is rather quiet with a low volume of street traffic (see Figure 6).

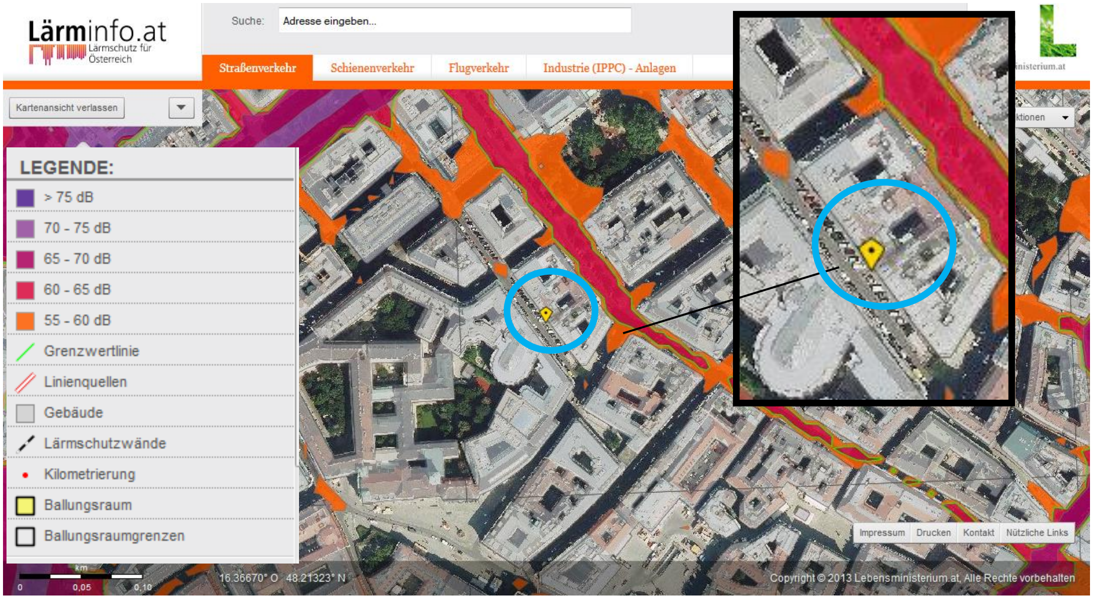


Figure 6. Noise map of the area around the building (www.Lärminfo.at)

The building was built around 1880 and is characterized as a typical “Gründerzeit” building of that time. The whole building is seven stories high (without the cellar level) consisting of the ground floor, mezzanine, first, second, third, fourth floor and the attic. In the second, third and fourth level all the floor area is constructed with the typical wooden beam slab of that time and heavy masonry walls.

Around 1990 the whole building was refurbished and its use turned to that of a bank. For office buildings it was a common technique at that time to construct raised floor systems. They have the advantages of easy and fast montage and offer enough space in the void to route mechanical services and cables, wiring and electrical supply (Figure 7).

Figure 7. The picture shows an opening of a raised floor system, Palais von Foerster

The rooms chosen for the experiment are positioned at the back side of the floor plan (see Figure 8 and 9) with their windows facing the inner courtyard. These specific rooms were chosen because they have almost the same floor area and similar floor plans.

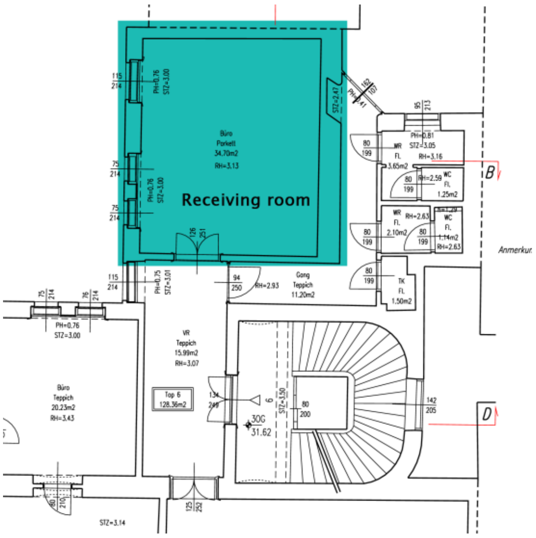


Figure 8. Floor plan 3rd level- Receiving room, Total floor area A=34,53m2, height H=2,81m, Volume V=97m3

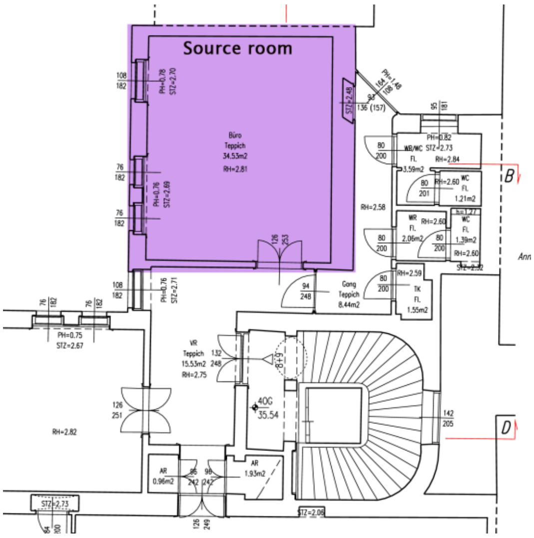
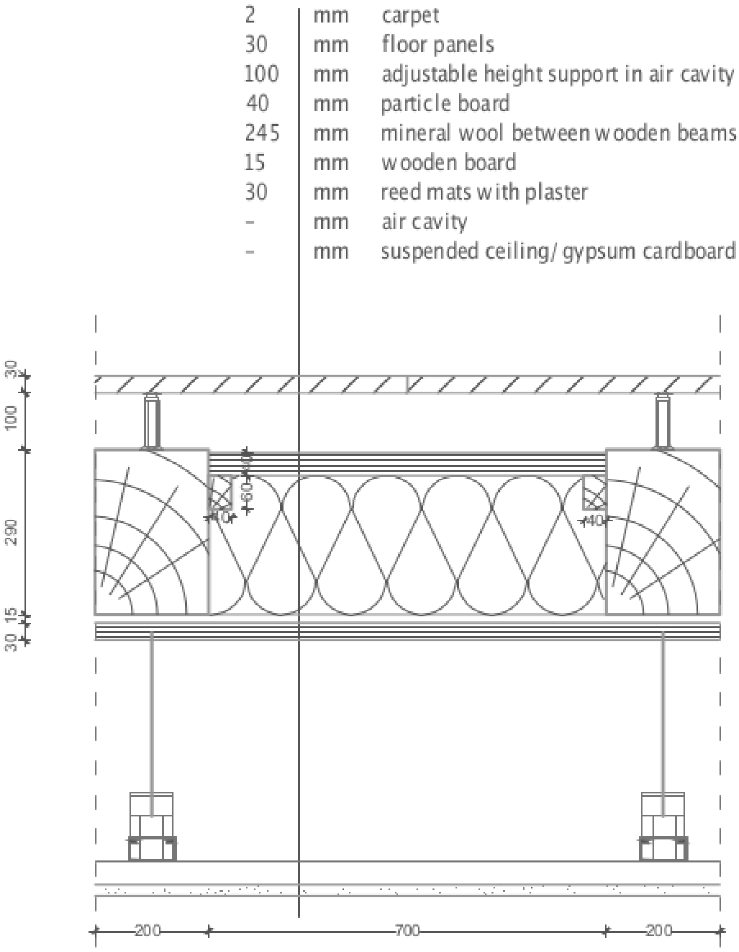


Figure 9. Floor plan 4th level- Source room, Total floor area A=34,7m2, height H=3,13m, Volume V=109m3

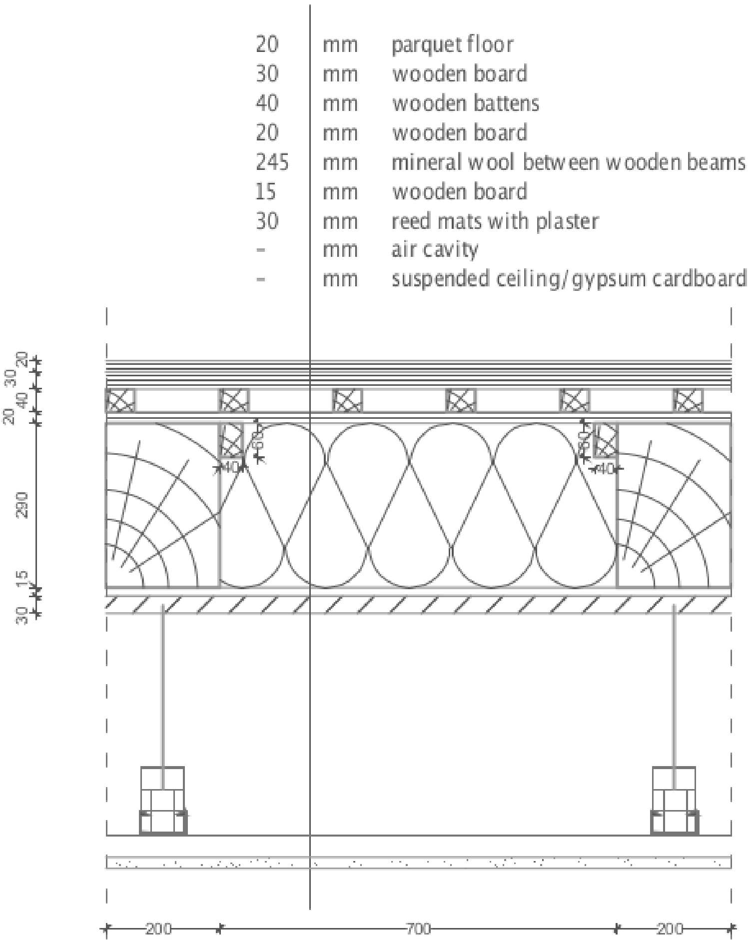
In Figure 10 the source room with the non-refurbished wooden beam floor construction (a) separating the 3rd and 4th level (Figure 11) and the receiving room with the non-refurbished wooden beam floor construction (b) separating the 2nd and 3rd level (Figure 12) can be seen.

Figure 10. Receiving room (left);Source room (right)



2	mm	carpet
30	mm	floor panels
100	mm	adjustable height support in air cavity
40	mm	particle board
245	mm	mineral wool between wooden beams
15	mm	wooden board
30	mm	reed mats with plaster
-	mm	air cavity
-	mm	suspended ceiling/ gypsum cardboard

Figure 11. Non-refurbished construction (a); wooden beam floor separating the 3rd and 4th level



20	mm	parquet floor
30	mm	wooden board
40	mm	wooden battens
20	mm	wooden board
245	mm	mineral wool between wooden beams
15	mm	wooden board
30	mm	reed mats with plaster
-	mm	air cavity
-	mm	suspended ceiling/gypsum cardboard

Figure 12. Non-refurbished construction (b); wooden beam floor separating the 2nd and 3rd level

2.3 Equipment for evaluation of impact sound insulation of the floors

The devices used in evaluating the impact sound insulation were chosen according to the EN ISO 140-7:1999 and EN ISO 16283-2:2013 standards and can be seen in Figure 13.

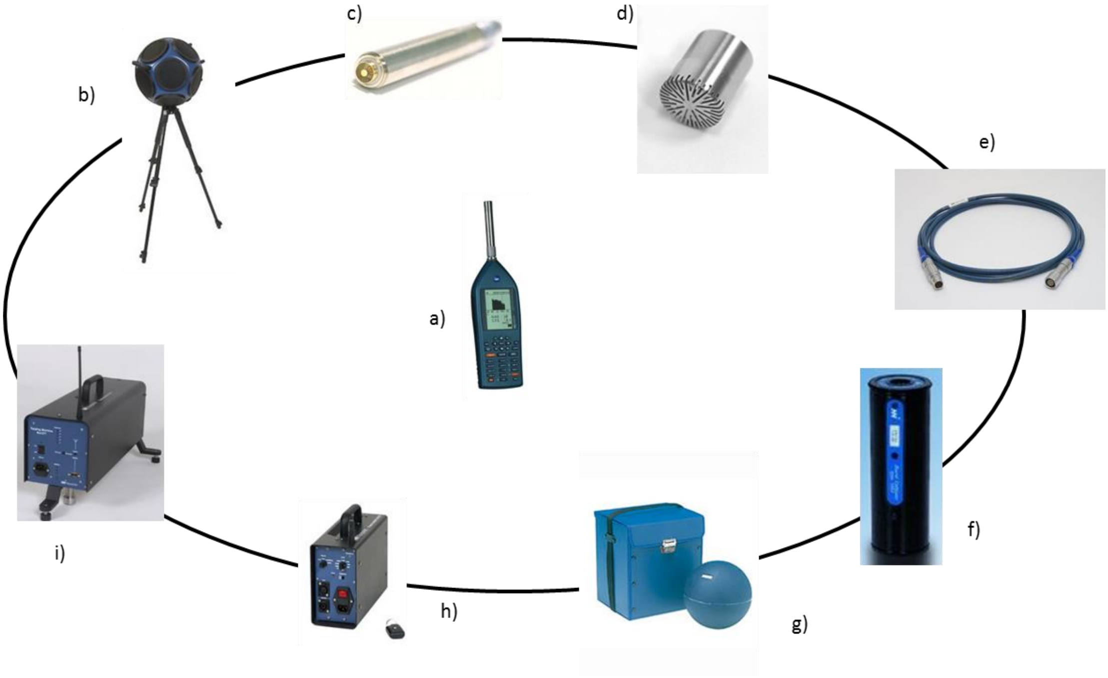


Figure 13. Overview of the various measurement equipment: a) sound analyzer, b) dodecahedron loud speaker, c) preamplifier, d) microphone, e) microphone preamplifier cable, f) calibrator, g) impact ball, h) power amplifier, i) standard tapping machine

For the first series of impact sound measurements, where the impact sound insulation of existing floors was evaluated, only mechanical equipment (standard method, see EN ISO 140-7:1999) was used. After refurbishment of the wooden beam floor, the impact ball (provided by the research center and laboratory for sound protection and building physics, TGM Wien) was used as an additional sound impact source (alternative method, see EN ISO 16283-2:2013).

2.3.1 Standard method with tapping machine

In order to measure the impact sound level of the floor and ceiling construction the following steps were made:

1. The Nor-277 tapping machine has been used for simulating the footfall noise in the source room. It uses five hammers each having a mass of 500 g and falling with a velocity equivalent to a free-drop height of 40 mm (adjustable). The hammers impact the testing surface of the floor with a tapping sequence of 10 impacts per

second, thus making the repetition frequency 10 Hz (each hammer operates at 2 Hz).

2. The logarithmic average sound pressure level in the receiving room was measured in the extended frequency range 50-5000 Hz with the sound analyzer Nor140.
3. In the receiving room the background noise was measured in order to test for any potential influence it might have in measurement accuracy. In the field it is required to filter the signal sound from the background noise. In practice, no correction is necessary if the difference between the measured noise and the background noise is more than 10 dB in each frequency band (50-5000Hz). In case the difference is between 6 and 10 dB a correction is necessary according to equation (9). If the difference is less than or equal to 6 dB in any of the frequency bands, 1.3 dB should be used for the correction, and clearly indicated in the report that the values are at the limit of the measurement.

   Adjusted signal level

   $$L = 10 \cdot log\left(10^{L_{sb}/10} - 10^{L_b/10}\right) \tag{9}$$

   where L the adjusted signal level in dB, L_{sb} is the level of signal and background noise combined in dB, L_b is the background noise in decibels.

4. Moreover, the reverberation time, which is the time that would be required for the sound pressure level to decrease by 60dB after the sound source has stopped, was measured in the receiving room using the interrupted noise method as described in ISO 3382-2. The time it takes for a sound to fade away after a noise source in the receiving room is switched off is defined as reverberation time. Then the receiving room sound pressure levels were adjusted to take into consideration the difference between the measured (in each third octave band) and reference reverberation time (t_0=0.5 sec) by calculating the equivalent sound absorption area of a room according to equation (10).

   Equivalent sound absorption area of a room

   $$A = \frac{0.16\,V}{T} \tag{10}$$

   Where V is the receiving room volume in m^3, T is the reverberation time in the receiving room.

5. Finally the standardized impact sound pressure level L'_{nT} (with a correction for the background sound, if necessary and reverberation time of the receiving room) is

calculated with the equation (2). The adaptation term $C_{I,50-2500}$ (see equation (5)) is also calculated as described in EN ISO 717-2:2013.

For a single pair of rooms and each individual horizontal partition, the above process is repeated. In Table 5 the number of microphone and impact sound positions for every sound test can be seen.

Table 5. Number of microphone and impact sound positions according (ISO 16283-2:2013, Table D.1)

Floor area of the source room, m^2	**Number of positions**	**Floor area of the receiving room, m^2**
		≤ 50
		Partition type 1[a]
35	Tapping machine	8
	Fixed or held microphone positions	4

[a] partition type 1: timber joist partitions

According to the EN ISO 16283-2 the distance of the tapping machine and the edges of the floor has to be at least 0.5 m. In case of the wooden beam floor (inhomogeneous floor construction) the hammer connecting line was orientated at 45° to the direction of the beams. In every impact sound test both source and receiving room were unfurnished and unoccupied; hence the operator of the sound analyzer was always outside the rooms. Only the microphone, which was mounted on a Tripod, was in the receiving room (Figure 10, left).

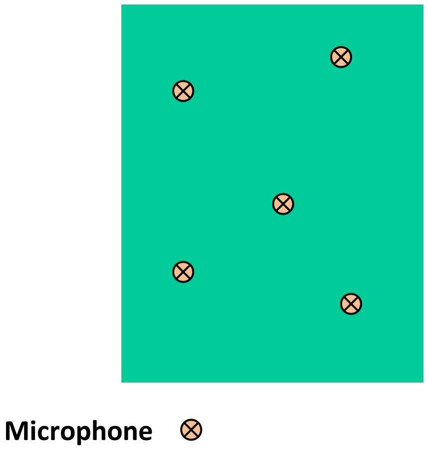


Figure 14. Level 3, floor plan with microphone positions (approximately)

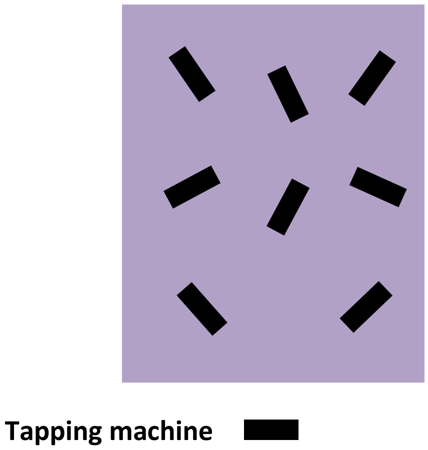


Figure 15. Level 4, floor plan with tapping machine positions (approximately

2.3.2 Alternative method with impact ball

Due to limited accessibility of the impact ball, the experiments on the wooden beam floor could only be performed after the refurbishment and for limited floor variants. For this type of method an impact ball made from silicon rubber with the following attributes was used:

a) Shape and size: hollow ball of 180 mm in diameter and with 30 mm thickness
b) Effective mass: (2,5±0,1) kg
c) Coefficient of restitution: 0,8±0,1

The impact ball was dropped vertically (see Figure 16) in a free fall from a height 100±1 cm measured from the bottom of the rubber ball to the surface of the floor under test. In order to avoid positional or structural effects during data collection, the rubber ball was left to fall from ten positions, where at least one position was above the beam and one in the middle of the floor. For each excitation by the rubber ball in the source room floor, the microphone was positioned at a random place in the receiving room. There the energy-average maximum impact sound pressure level $\mathrm{L_{i,Fmax}}$ was recorded with the Nor140 sound analyzer in one third octave bands with at least the following center frequencies (50, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630). For each ball position three microphone positions were used and their impact sound pressure levels were logarithmically averaged according to (equation (11)).

Figure 16. Impact ball positioned in a height of 100±1cm above the surface of the floor

$$L_{i,Fmax,j} = 10 \cdot \log\left(\frac{1}{m}\sum_{k=1}^{m} 10^{L_{i,Fmax,k}/10}\right) \tag{11}$$

Where:

$\mathrm{L_{i,Fmax,k}}$ is the maximum impact sound pressure level at the k microphone position (k= 1….m) in the receiving room.

Afterwards the impact sound insulation should be logarithmically averaged for the values obtained by the each impact position.

$$L_{i,Fmax} = 10 \cdot \log\left(\frac{1}{n}\sum_{j=1}^{m} 10^{L_{i,Fmax,j}/10}\right) \tag{12}$$

Where:

$\mathrm{L_{i,Fmax,j}}$ is the room average maximum impact sound pressure level for each rubber ball position j (j= 1…..n) according to equation (11).

Finally, the standardized maximum impact sound pressure level $L'_{i,Fmax,V,T}$ was calculated from the maximum impact sound pressure level, $\mathrm{L_{i,Fmax}}$, corrected for room volume, reverberation time and Fast time weighting using equations (13), (14) and (15), respectively.

Standardized maximum impact sound pressure level

$$L'_{i,Fmax,V,T} = L_{i,Fmax} + 10\log\frac{\mathrm{V}}{\mathrm{V_0}} - 10 \cdot \log\left[\frac{1 - C_0^{-1}}{1 - C^{-1}}\left(\frac{C^{(1-C)^{-1}} - C^{-(1-C)^{-1}}}{C_0^{(1-C_0)^{-2}} - C_0^{-(1-C_0^{-1})^{-1}}}\right)\right] \tag{13}$$

$$C_0 = \frac{T_0}{1{,}7275} \tag{14}$$

$$C = \frac{T}{1{,}7275} \tag{15}$$

Where:

T the reverberation time in the receiving room, in seconds,

$\mathrm{T_0}$ the reference reverberation time; for dwellings $\mathrm{T_0}$=0,5sec

V the receiving room volume in $\mathrm{m^3}$

$\mathrm{V_0}$ the reference receiving room volume; for dwellings $\mathrm{V_0}$=50$\mathrm{m^3}$

2.4 Hypothesis

2.4.1 First refurbished construction

For the refurbishment of the wooden beam floor, as a first step the layers on top of the wooden beam construction were removed (see Figure 17) and a possible rehabilitation solution was schemed.

Figure 17. Level 4, floor after removing the layers on top of the wooden beam construction

The challenge was to design a lightweight construction on top of the wooden beams with a height of approximately 130 mm, to solve the problem of the floor unevenness of the adjacent rooms to the staircase. In order to fulfil the structural and fire protection requirements, a floating floor based on lightweight dry screed layers was chosen to improve the impact sound insulation of the wooden floor. As mentioned before the disadvantage of such lightweight floating floor constructions is their small flexural rigidity (see 1.3.4), so that rather stiff resilient layers have to be used ($s' > 16\ MN/m^3$). This leads to lower impact sound insulation results. In order to compensate for this disadvantage the approach followed was similar to that of the "Elementierung" method (Veres and Fischer 1992, Rabold and Buschbacher 1996). Instead of using concrete plates, the so called Honeycomb acoustic system (FERMACELL®, Figure 18) was used to add more mass on top of the resilient layer, while keeping the construction height thickness under the required level.

Figure 18. Fermacell Honeycomb acoustic system

The FERMACELL®Honeycomb acoustic system consists of a Honeycomb insulation board (1500x1000x30 mm, “l x w x h”) which is laid wall to wall on top of the resilient layer and then filled with the special FERMACELL Acoustic infill (loose weight 1500kg/m^3, graded 1-4 mm). This technique allows the application of a softer resilient layer, such as the GetznerWerkstoffe Construction Mat with a dynamic stiffness s’<13 MN/m^3, which has a very high proportion of recycled PU (Polyurethan), shows very good impact sound insulation and has a high load bearing capacity. First, on top of the resilient layer one layered gypsum fibreboard is positioned to serve as a screwing ground for any installation tubes (heating, cables etc.) needed. Afterwards, the Honeycomb acoustic system is positioned. It is used as the installation plane for heating tubes and other cable (see Figure 19). The whole proposed refurbishment design with an area related mass of 145,22 kg/m² (see Table 6) and the position of the remaining layers can be seen in Figure 20. The height thickness is kept in that way under the required 130mm.

Table 6. Area related mass (kg/m²) for the new flooring system

Material	Thickness (mm)	Area related mass (kg/m²)
Fermacell- gypsum fibre board+wood fibre (Element 2E33)	35	31
Fermacell- honeycomb acoustic system	30	47
Fermacell - gypsum fibre board	10	12
GetznerWerkstoffe - construction Mat	16	2,67
Leveling compound	≈35	52,5
Trickle protection sheet	0,1	0,05

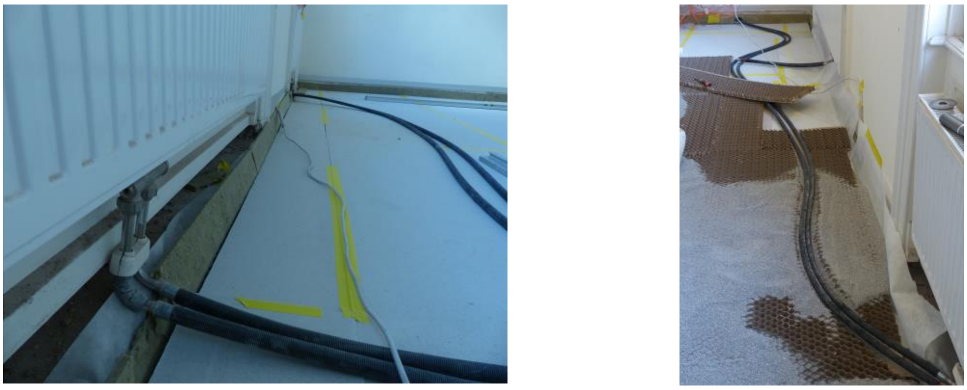


Figure 19. Gypsum fibre board serves as a screwing ground (left); Honeycomb acoustic system used as an installation plate (right)

2x12,5	mm	gypsum fibre boards
10	mm	wood fibre
30	mm	honeycomb acoustic system
10	mm	gypsum fibre board
16	mm	footfall sound insulation/polyurethane
35	mm	leveling compound for height compensation, in average 35mm
0,1	mm	trickle protection sheet
40	mm	particle board
245	mm	mineral wool between wooden beams
15	mm	wooden board
30	mm	reed mats with plaster
-	mm	air cavity
-	mm	suspended ceiling/gypsum cardboard

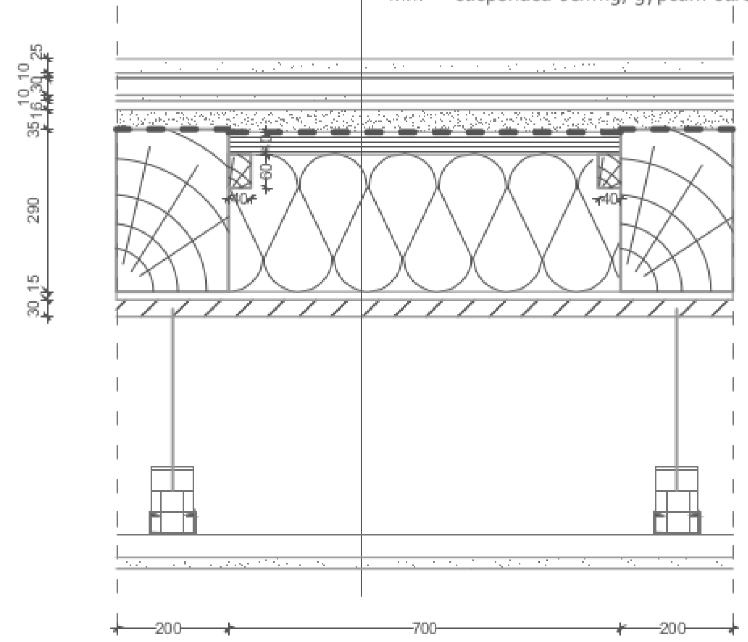


Figure 20. First refurbishment construction (c), new upper floor system on top of the wooden beam construction

The series of impact sound insulation tests will reveal whether this refurbishment design will show similar impact sound insulation qualities as a wet floating floor and hereby reach the "high comfort" requirements, set by the Austrian Standard ÖNORM B 8115-5:2012 "Schallschutz und Raumakustik im Hochbau - Teil 5: Klassifizierung", Lang 2006 and Rasmussen and Machimbarrena 2014 as seen in Table 7.

Table 7. Impact sound insulation requirements – Classification of impact sound insulation

Impact sound insulation		Class A	according to
		"High Comfort"	
to common rooms from rooms from adjacent utilization units	$L'_{nT,w}$	≤ 38	ÖNORM 8115-5
	$L'_{nT,w} + C_I$	≤ 43	ÖNORM 8115-5
	$L'_{nT,w} + C_{I,50\text{-}2500}$	≤ 48	ÖNORM 8115-5
	$L'_{nT,w} + C_{I,50\text{-}2500}$	≤ 40	Lang 2006
	$L'_{nT,50}=L'_{nT,w}+C_{I,50\text{-}2500}$	≤ 44	Rasmussen & Machimbarrena 2014

2.4.2 Second refurbished construction

As a second step, the whole suspended ceiling (see Figure 21) with all the mechanical equipment in the cavity, as well as the layer of reed mats with plaster was removed (Figure 22). This prelim step was done for two reasons: First, in order to investigate the influence of mass removal from the underside of the floor on the impact sound insulation. And second to prepare the construction for the next variant.

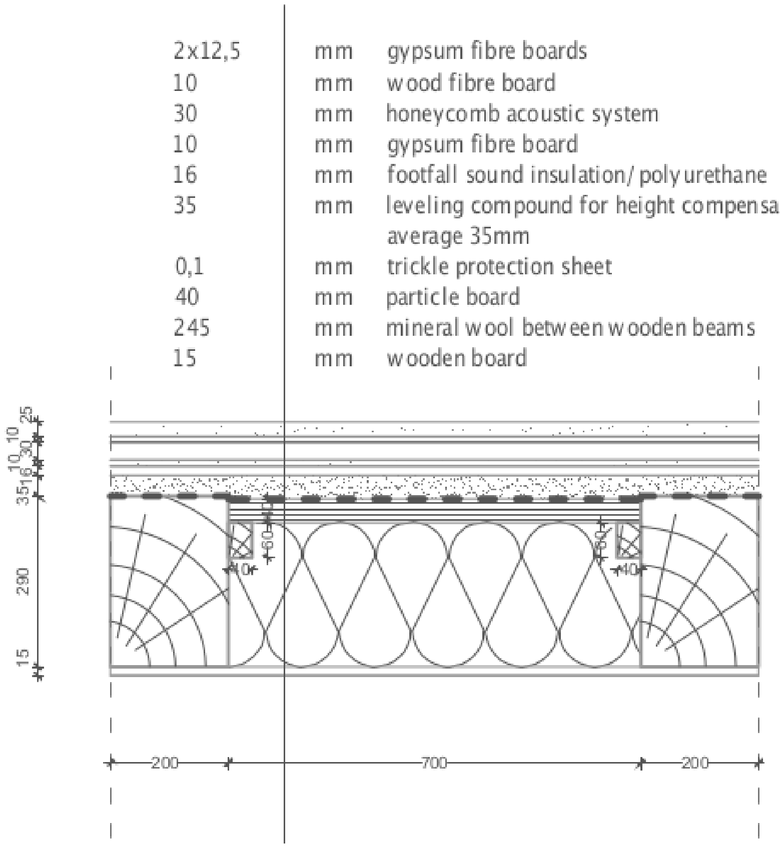
a.) Gypsum cardboard suspended ceiling

b.) Into the void

c.) After removal of gypsum cardboards

d.) Removing the last parts of the reed mats layer

Figure 21. Removing the suspended ceiling, mechanical equipment and the reed mats layer



2x12,5	mm	gypsum fibre boards
10	mm	wood fibre board
30	mm	honeycomb acoustic system
10	mm	gypsum fibre board
16	mm	footfall sound insulation/ polyurethane
35	mm	leveling compound for height compensation, in average 35mm
0,1	mm	trickle protection sheet
40	mm	particle board
245	mm	mineral wool between wooden beams
15	mm	wooden board

Figure 22. Second refurbished construction (d); where the whole underside up to the wooden board layer was removed

2.4.3 Third refurbished construction

As a third step, an attempt to make the construction more rigid was undertaken. Based on a statics calculation stiffening the existing wooden beam construction was achieved by mounting on the existing an additional 320cm X 16cm X 20 cm wooden beam (“stiffener”). These “stiffeners” were bold on them with 20 cm long screws (diameter of 6mm) as seen in Figure 23. This measure was taken to investigate if by making the beams stiffer, the whole floor construction would become more rigid and as a result enhance the performance of the resilient layer (construction) in the low frequency spectrum.

Figure 23. Third refurbished construction (e), wooden beam "stiffeners" bolted on the original wooden beam structure with 200x6 mm bolds every 150 mm.

2.4.4 Fourth refurbished construction

Finally, a very efficient measure to enhance the impact sound insulation of wooden beam floors is the construction of a fully decoupled self-supporting underside. In this case a free spanning underside construction of U-steel profiles was planned and mounted resiliently on the flanking walls without any direct contact to the beams (see Figure 24 and 25). The cavity between the "stiffening" wooden beams and the steel construction was filled with 12cm mineral wool. A single layer (12,5mm) of gypsum plaster board was used as the sealing layer.

Successively, a second layer of gypsum plaster board (12,5mm) was mounted on the first gypsum layer giving us the final wooden beam floor construction. With this method, the underside construction acts as a second ceiling which does not have any contact with the main floor construction. Thereby it is expected to enhance the impact sound insulation several fold, especially in the low frequency by the cavity mineral wool insulation.

Figure 24. Constructing the fully self-supported decoupled ceiling (left: mounting the U-steel profiles resiliently on the walls); (right: finished underside with double gypsum layer)

2x12,5	mm	gypsum fibre boards
10	mm	wood fibre
30	mm	honeycomb acoustic system
10	mm	gypsum fibre board
16	mm	footfall sound insulation/polyurethane
35	mm	leveling compound for height compensation, in average 35mm
0,1	mm	trickle protection sheet
40	mm	particle board
245	mm	mineral wool between wooden beams
15	mm	wooden board
300	mm	air cavity
120	mm	mineral wool between steel beams
25	mm	gypsum cardboard, double layer

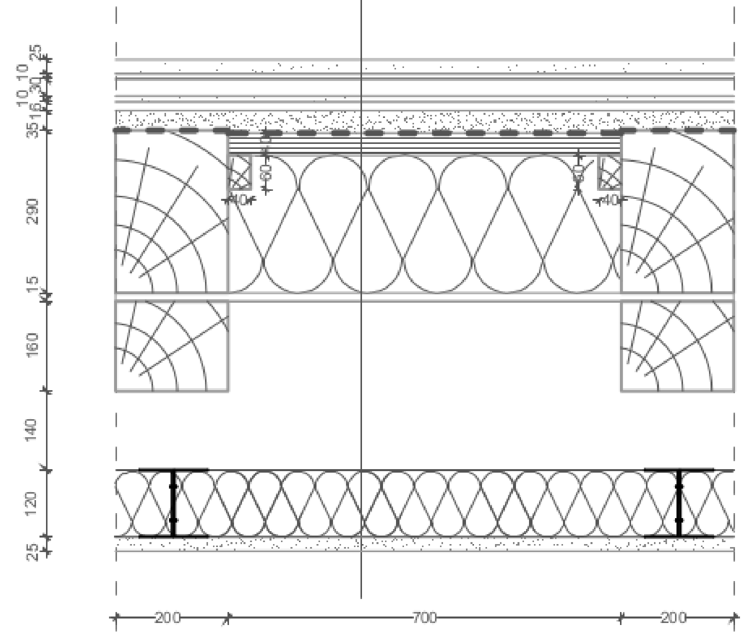


Figure 25. Fourth refurbished construction (g), new upper floor system, new free fully self-supported decoupled ceiling with double gypsum cardboard layer

3 RESULTS

3.1 Overview

The results are discussed following the sequence presented in the methodology, beginning with the results of the impact sound measurements of the non-refurbished constructions (a.) and (b.) between the 2nd-3rd level and 3rd-4th level, followed by the four constructions (c.) until (g.) of the refurbished floor between the 3rd-4thlevel according to the standard method as described in EN ISO 16283-2:2013 (see 2.3.1). Furthermore, the impact sound measurement results with the alternative method as described in the EN ISO- 16283-2:2013 (see 2.3.2), are presented for the first (c.) and second (d.) refurbished construction.

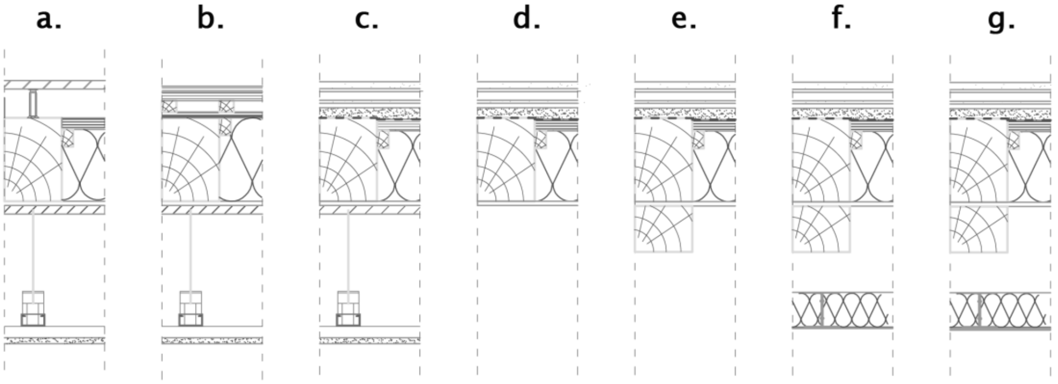
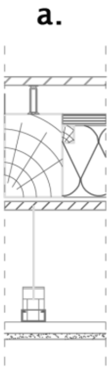


Figure 26. Overview of all constructions; ***a.*** *Non-refurbished construction, wooden beam floor between 3rd-4th level;* ***b.*** *Non-refurbished construction, wooden beam floor between 2nd-3rd level;* ***c.*** *First refurbished construction, wooden beam floor, new flooring system, non-refurbished underside;* ***d.*** *Second refurbished construction, wooden beam floor, new flooring system, removed suspended ceiling and reed mats with plaster;* ***e.*** *Third refurbished construction, wooden beam floor, new flooring system, removed suspended ceiling and reed mats with plaster, stiffened wooden beam construction;* ***f.*** *Fourth refurbished construction, new flooring system, stiffened wooden beam construction and new decoupled free spanning ceiling (single layer of gypsum cardboard);* ***g****. Fourth refurbished construction, wooden beam floor, new flooring system, stiffened beam construction and new decoupled free spanning ceiling (double layer of gypsum cardboard)*

3.2 Results for the non-refurbished wooden beam floor constructions

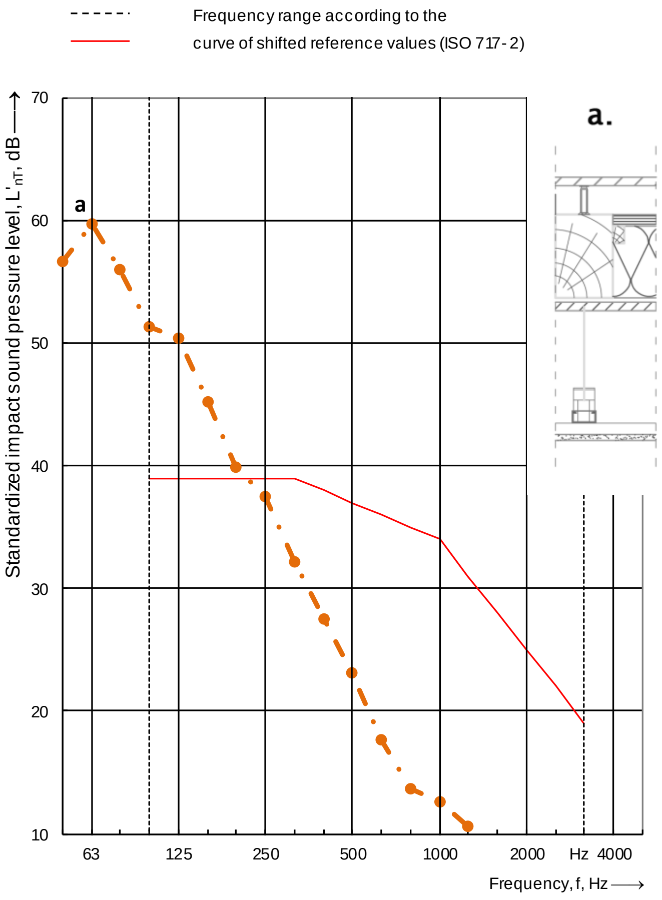
3.2.1 Non-refurbished construction; wooden beam floor separating the 3rd and 4th level



This non-refurbished construction consist of the raised floor with carpet, the particle board, mineral wool in the void, wooden laths, reed mats with plaster and the suspended ceiling. The first sound field test measurement was performed on the 19th of December 2013. The sound measurements values of the source room with a Volume of 97m^{3}and the receiving room with V=109m^3, were analyzed with the assistance of the NorBuild calculation software according to the EN ISO 16283-2, resulting in Table 8 and Figure 27. The weighted standardized impact sound pressure level is $L'_{nT,w}\,(C_I; C_{I,50-2500})$= 37 (3; 11) dB. In Figure 27 it is shown that the curve is reaching its maximum impact sound pressure level at 63 Hz and is decreasing thereafter.

Table 8. Standardized impact sound pressure level L'_{nT}

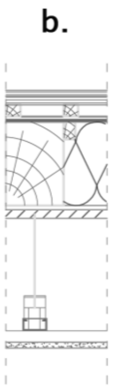
Frequency f [Hz]	L'_{nT} 1/3 octave [dB]
50	56,6
63	59,7
80	55,9
100	51,3
125	50,4
160	45,2
200	39,9
250	37,5
315	32,1
400	27,5
500	23,1
630	17,6
800	13,7
1000	12,6
1250	10,6
1600	7,6
2000	2,3
2500	2,6
3150	1,0
4000	0,8
5000	1,4



$$L'_{nT,w}\,(C_I)= 37(3)\ \text{dB} \qquad C_{I,50-2500}= 11\text{dB}$$

Figure 27. Standardized impact sound pressure level L'_{nT}; (a). Non-refurbished construction; raised floor system, suspended ceiling

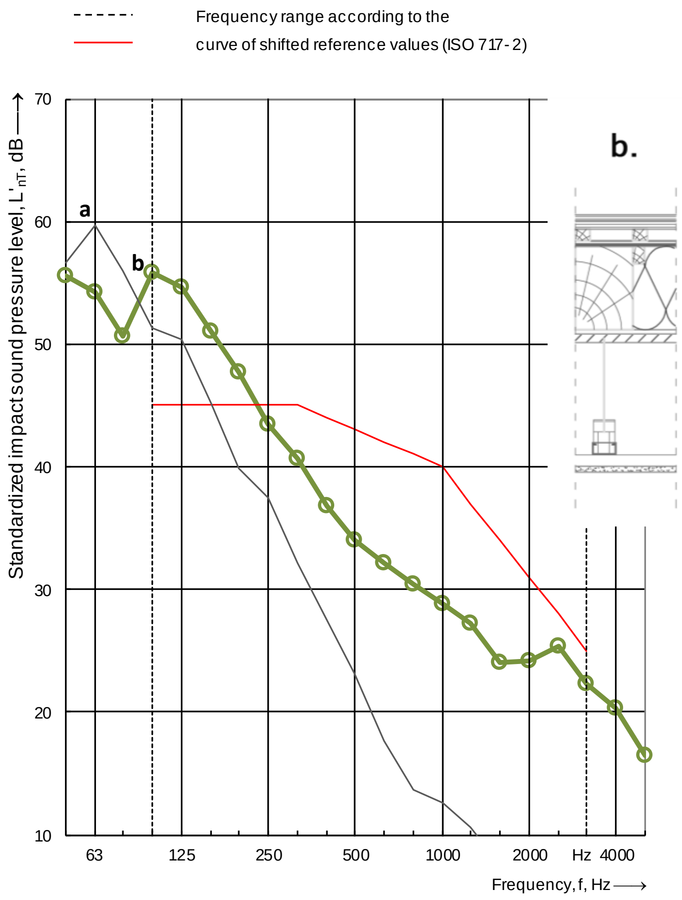
3.2.2 Non-refurbished construction; wooden beam floor separating the 2nd and 3rd level



This non-refurbished construction has the following layers (top to bottom): parquet flooring, wooden planking, wooden laths, wooden planking, mineral wool in the void, wooden boards, reed mats with plaster and the suspended ceiling with a layer of gypsum cardboard. This sound field test was performed on the 9th January 2014. The measurement values of the source room with a Volume of 109 m^3 and the receiving room with V=118,3 m^3, were analyzed with the NorBuild calculation software according to the EN ISO 16283-2, resulting in Table 9 and Figure 28. The weighted standardized impact sound pressure level is $L'_{nT,w}\left(C_I; C_{I,50-2500}\right)$= 43 (2; 4) dB.

Table 9. Standardized impact sound pressure level L'_{nT}

Frequency f [Hz]	L'_{nT} 1/3 octave [dB]
50	55,5
63	54,2
80	50,6
100	55,8
125	54,7
160	51,0
200	47,7
250	43,5
315	40,6
400	36,8
500	34,0
630	32,2
800	30,4
1000	28,8
1250	27,2
1600	24,0
2000	24,2
2500	25,4
3150	22,3
4000	20,3
5000	16,5



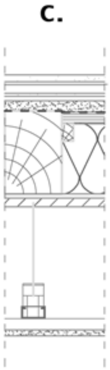
$L'_{nT,w}$ (C_I)= 43(2) dB $\quad$ $C_{I,50-2500}$= 4dB

Figure 28. Standardized impact sound pressure level L'_{nT}; (b). Non-refurbished construction; parquet flooring system, suspended ceiling; the curve denoted by (a) is from Figure 27 and plotted for comparison.

Figure 28 illustrates a 5dB drop of the impact sound pressure level between 50-80 Hz, a maximum of 55,8 dB at 125 Hz and declines until 1600 Hz where it rises shorty to reach another peak at 2500 Hz. The overall impact sound pressure level for the frequencies above 125 Hz is higher than construction (a). Especially in the middle to higher frequency range the difference reaches even 20 dB.

3.3 Results for the refurbished wooden beam floor separating the 3rd-4th level according to the standard method

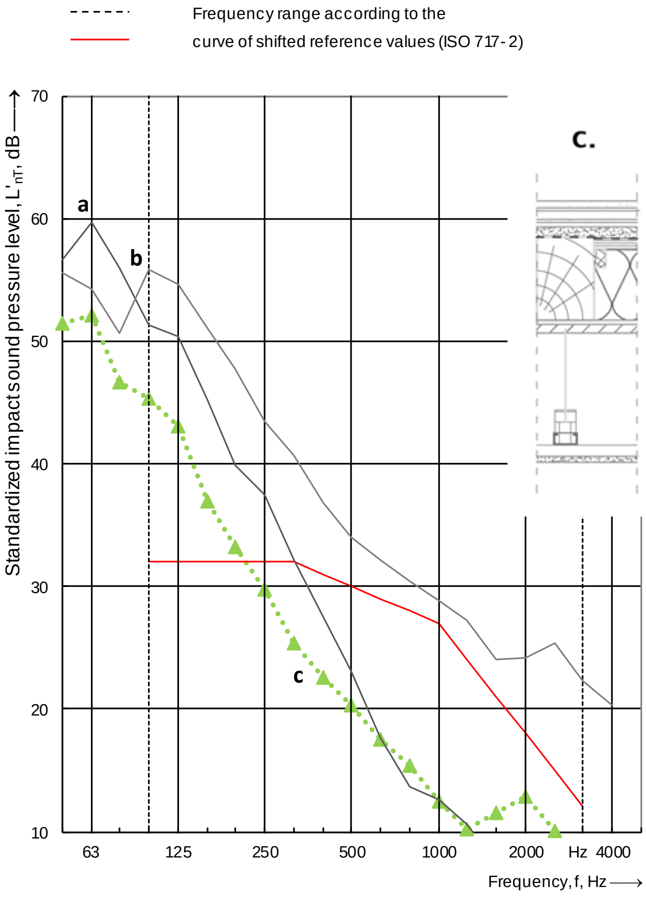
3.3.1 First refurbished construction



This construction consists of the new upper floor (gypsum fiber boards, wood fiber boards, honeycomb acoustic system, gypsum fiber board, footfall sound insulation, filling with grit for compensation height, trickle protection sheet) and the old suspended ceiling. As described in the Hypothesis after the realization of the refurbishment of the upper side of the construction, the third sound field test measurement was undertaken on the 2nd February 2014. The measurement values of the source room with a Volume of 109 m^3 and the receiving room with V=118,3 m^3, were analyzed with the NorBuild calculation software according to the EN ISO 16283-2. The results are presented in Table 10 and Figure 29. The weighted standardized impact sound pressure level is $L'_{nT,w}$ $(C_I; C_{I,50-2500})$= 30 (3; 11) dB. Not surprisingly the main peak of 52,1dB for curve (c) is found at 63Hz, same as the non-refurbished construction (a). Curve (c) drops between 3-8 dB in the low to middle frequency range down until 500 Hz in comparison to curve (c). Furthermore, above 500 Hz curve (c) shows higher values than curve (a).

Table 10. Standardized impact sound pressure level L'_{nT}

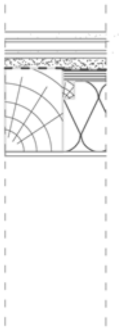
Frequency f [Hz]	L'_{nT} 1/3 octave [dB]
50	51,4
63	52,1
80	46,6
100	45,3
125	43,0
160	37,0
200	33,2
250	29,7
315	25,4
400	22,6
500	20,3
630	17,5
800	15,4
1000	12,4
1250	10,2
1600	11,5
2000	12,8
2500	10,1
3150	2,3
4000	-0,7
5000	-0,5



$L'_{nT,w}\ (C_I) = 30(3)$ dB $\qquad C_{I,50-2500} = 11$dB

Figure 29. Standardized impact sound pressure level L'_{nT}; (c). First refurbished construction; new upper flooring system, suspended ceiling

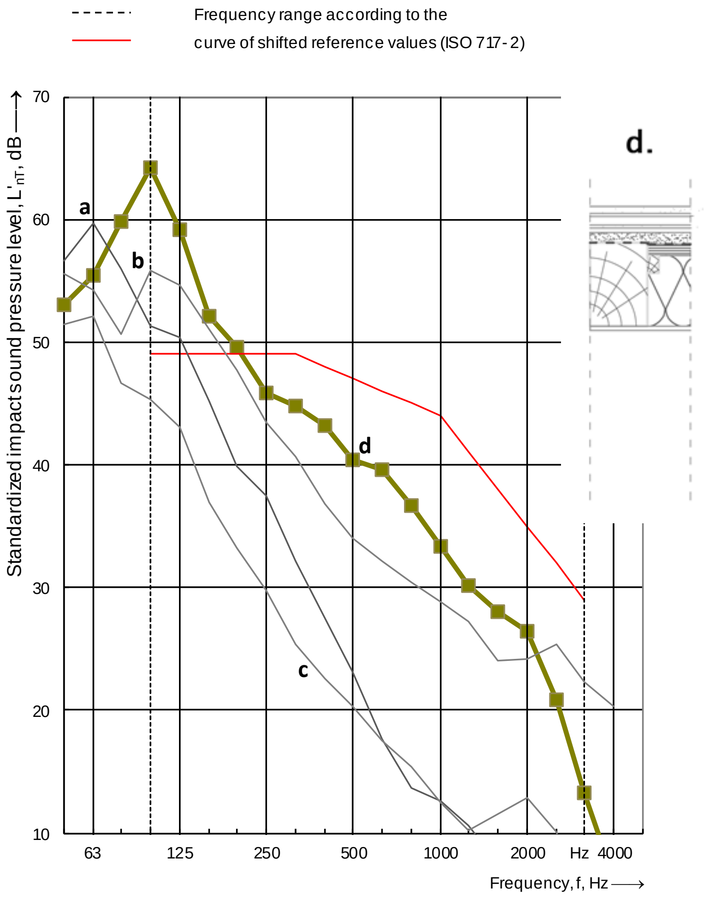
3.3.2 Second refurbished construction



This construction was tested after the removal of the suspended ceiling, the reed mats with plaster layer and the installations of the underside. The fourth test took place on 9th May 2014. The sound measurement values of the source room with a Volume of 106 m^3 and the receiving room with V=126 m^3, were analyzed with the NorBuild software according to the EN ISO 16283-2, resulting in Table 11 and Figure 30. The weighted standardized impact sound pressure level is $L'_{nT,w}\ (C_I; C_{I,50-2500}) = 47\ (4; 5)$ dB. As is obvious that the maximum impact sound pressure level of curve (d) shifted from 63Hz to 80Hz reaching a peak of 64,2dB, 10 dB higher in comparison to construction variant (c). It is remarkable that for frequencies below 63Hz curve (d) is illustrating lower values than curve (a). For the frequency range between 80-2000 Hz curve (d) shows the highest impact sound pressure level among all other constructions.

Table 11. Standardized impact sound pressure level L'_{nT}

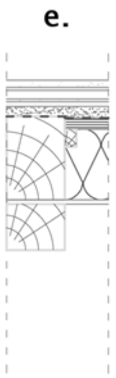
Frequency f [Hz]	L'_{nT} 1/3 octave [dB]
50	53,1
63	55,4
80	59,8
100	64,2
125	59,2
160	52,1
200	49,6
250	45,9
315	44,8
400	43,2
500	40,4
630	39,6
800	36,7
1000	33,4
1250	30,1
1600	28,0
2000	26,4
2500	20,8
3150	13,3
4000	6,4
5000	3,1



$L'_{nT,w}$ (C_I)= 47 (4) dB $C_{I,50-2500}$= 5dB

Figure 30. Standardized impact sound pressure level L'_{nT}; (d). Second refurbished construction; new upper flooring system, removed underside (without suspended ceiling)

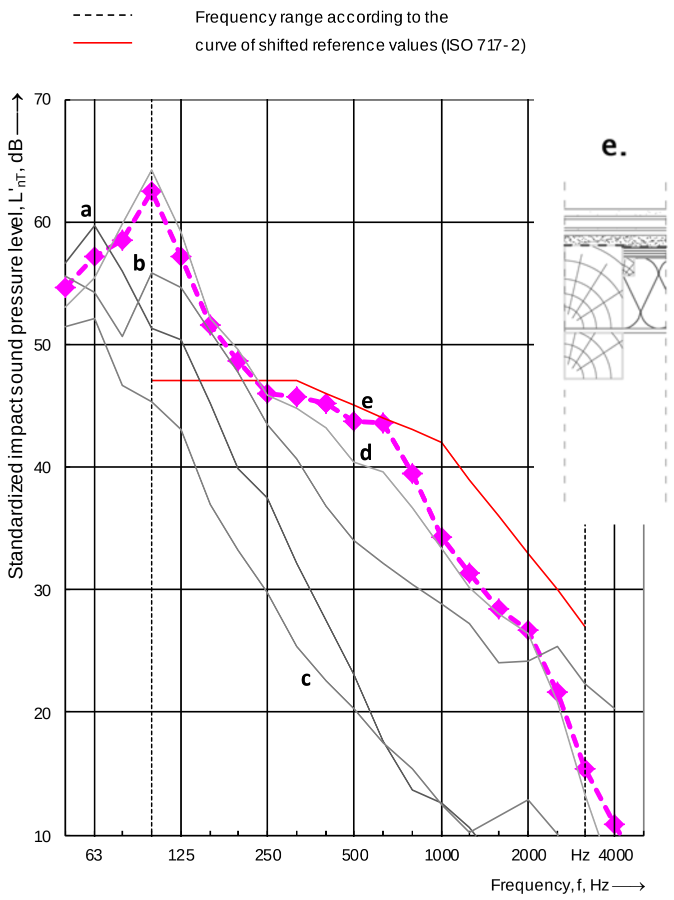
3.3.3 Third refurbished construction



This construction combines the new upper floor and the stiffened wooden beam underside. The fifth test was attempted on the 11th May 2014. The measurement values of the source room with a Volume of 106 m^3 and the receiving room with V=124 m^3, were analyzed with the NorBuild software according to the EN ISO 16283-2. The results can be seen in Table 12 and Figure 31. The weighted standardized impact sound pressure level is $L'_{nT,w}$ (C_I; $C_{I,50-2500}$)= 45 (4; 6) dB. Interestingly curve (e) shows a similar progression to curve (d) with small deviations for most of the low and high frequency range. Only for the middle frequency range from 250-1000 Hz the impact sound pressure level is higher.

Table 12. Standardized impact sound pressure level L'_{nT}

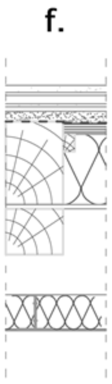
Frequency f [Hz]	L'_{nT} 1/3 octave [dB]
50	54,7
63	57,2
80	58,5
100	62,5
125	57,2
160	51,6
200	48,6
250	46,0
315	45,7
400	45,2
500	43,7
630	43,6
800	39,5
1000	34,3
1250	31,3
1600	28,4
2000	26,7
2500	21,7
3150	15,4
4000	10,8
5000	6,8



$L'_{nT,w}$ (C_I)= 45 (4) dB $C_{I,50-2500}$= 6dB

Figure 31. Standardized impact sound pressure level L'_{nT}; (e). Third refurbished construction; new upper flooring system, stiffened wooden beam construction

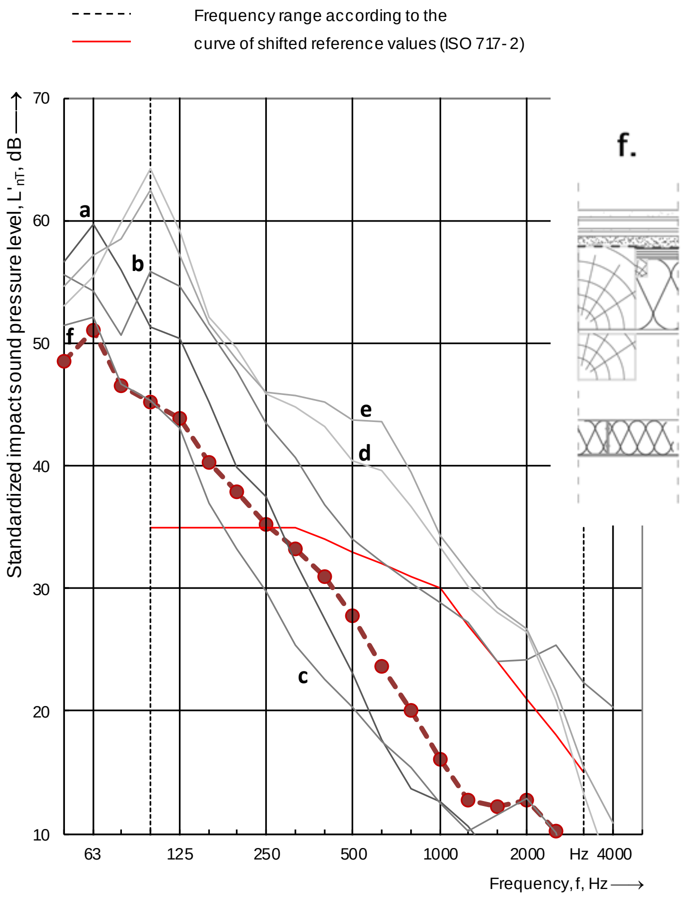
3.3.4 Fourth refurbished construction



As described in the Hypothesis after stiffening the construction a fully self-supported decoupled ceiling was mounted resiliently on the walls (single layer of gypsum cardboard) and the sixth test measurement was done on the 14th May 2014. The measurement values of the source room ($V=106\ m^3$) and the receiving room ($V=114\ m^3$), were analyzed with the NorBuild software according to the EN ISO 16283-2. The weighted standardized impact sound pressure level is $L'_{nT,w}\ (C_I; C_{I,50-2500})$=33 (1; 7) dB. The results can be seen in Table 13 and Figure 32. As illustrated in Figure 32, similarly to construction (a) and (c), the peak of curve (f) is shifted from 100Hz back to 63Hz. For the very low frequency range (50-100Hz) construction (f) presents lower impact sound pressure level values than all previous constructions. For frequencies above 125Hz floor (f) shows higher values than floor (c).

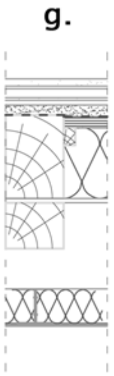
Table 13. Standardized impact sound pressure level L'_{nT}

Frequency f [Hz]	L'_{nT} 1/3 octave [dB]
50	48,5
63	51,0
80	46,5
100	45,2
125	43,8
160	40,2
200	37,9
250	35,2
315	33,2
400	30,9
500	27,7
630	23,7
800	20,0
1000	16,0
1250	12,7
1600	12,2
2000	12,7
2500	10,2
3150	4,2
4000	2,1
5000	1,9



$L'_{nT,w}\ (C_I)$= 33 (1) dB $C_{I,50-2500}$= 7dB

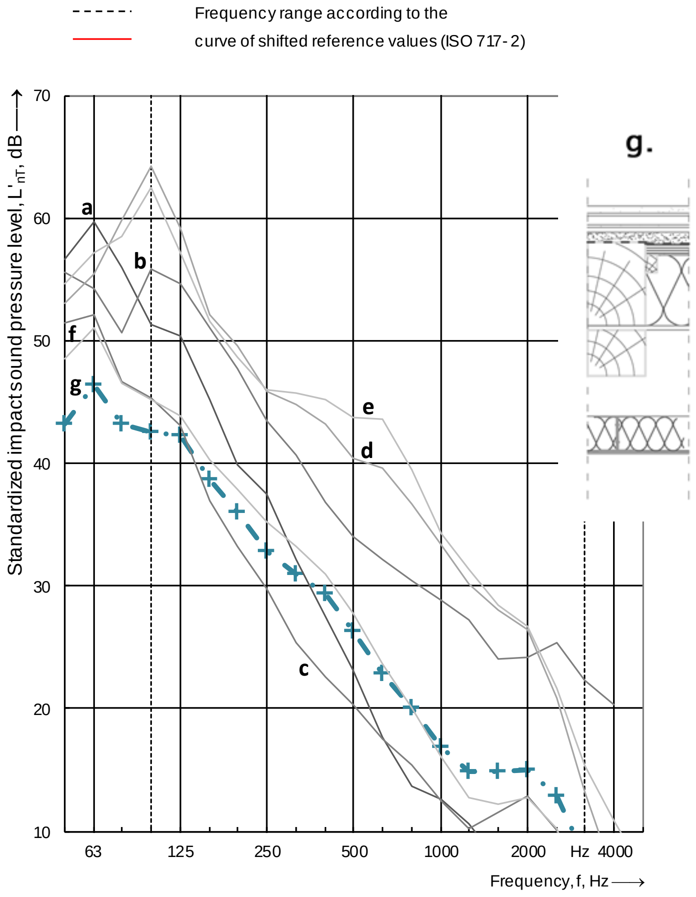
Figure 32. Standardized impact sound pressure level L'_{nT}; (f). Fourth refurbished construction; new upper flooring system, self-supported decoupled ceiling (single gypsum cardboard layer)



The last construction consists of the new upper floor and the new fully self-supported decoupled ceiling with a second gypsum cardboard layer mounted. This test measurement was done on the 15th May 2014. The measurement values of the source room with a Volume of 106 m^3 and the receiving room with V=113 m^3, were analyzed with the NorBuild software according to the EN ISO 16283-2, resulting in Table 14 and Figure 33. The weighted standardized impact sound pressure level is $L'_{nT,w}\,(C_I; C_{I,50-2500})$= 31 (1; 5) dB. As seen in Figure 33 curve (g) illustrates, in the low frequencies below 125 Hz, the lowest impact sound pressure level among all other constructions. Not surprisingly the maximum peak remains at 63Hz. Interestingly the impact sound pressure level drops about 2-5dB for frequencies below 125 Hz in comparison to curve (f). However, for the mid to high frequencies above 500Hz curve (g) illustrates higher values than curve (c)

Table 14. Standardized impact sound pressure level L'_{nT}

Frequency f [Hz]	L'_{nT} 1/3 octave [dB]
50	43,2
63	46,4
80	43,2
100	42,5
125	42,2
160	38,7
200	36,0
250	32,8
315	31,0
400	29,3
500	26,3
630	22,8
800	20,0
1000	16,8
1250	14,9
1600	14,8
2000	15,0
2500	12,9
3150	8,0
4000	4,5
5000	2,7



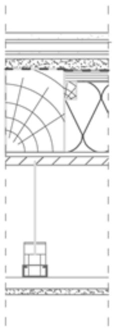
$L'_{nT,w}\,(C_I)$= 31 (1) dB $C_{I,50-2500}$= 5dB

Figure 33. Standardized impact sound pressure level L'_{nT}; (g). Fourth refurbished construction; new upper flooring system, self-supported decoupled ceiling (double layer gypsum cardboard layer)

3.4 Results for the refurbished wooden beam floor, separating the 3rd-4th level according to the alternative method.

3.4.1 First refurbished construction

c.



On 5th March 2014 a first attempt to carry out an impact sound measurement, according to the alternative method, using an impact ball to excite the floor took place. As described in the methodology (see section 2.3.2) the impact ball was left from a height of 100±1cm above the floor surface on a free fall to excite the construction. This was repeated for ten positions (3 times per position). A sketch of the approximate positions can be found in Figure 34 and the results of the impact sound pressure levels in Figure 35. As illustrated in Figure 35 the peak of the maximum impact sound pressure level is for most of the positions at 63 Hz. Only positions P1, P3, P4 and P5 show a rather inconsistent curve progression with their highest peaks at and supposedly below 50Hz. In the middle range frequencies all positons show many fluctuations and a rather inconsistent progression. The highest $L'_{i,Fmax,V,T}$ difference between the positions is about 20dB.

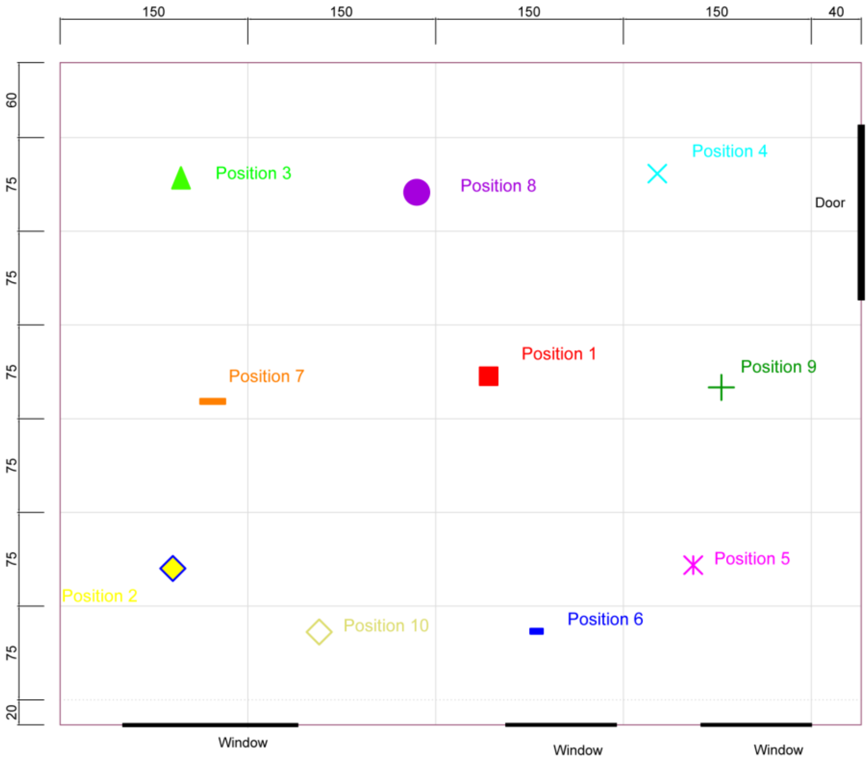


Figure 34. Sketch of the approximate impact ball positions

Finally, as pointed out in the EN ISO 16283-2:2013 for the frequencies over 630Hz, the impact sound pressure level results should be excluded from the calculation. However in the following figures they are presented for comparison reasons with the tapping machine method.

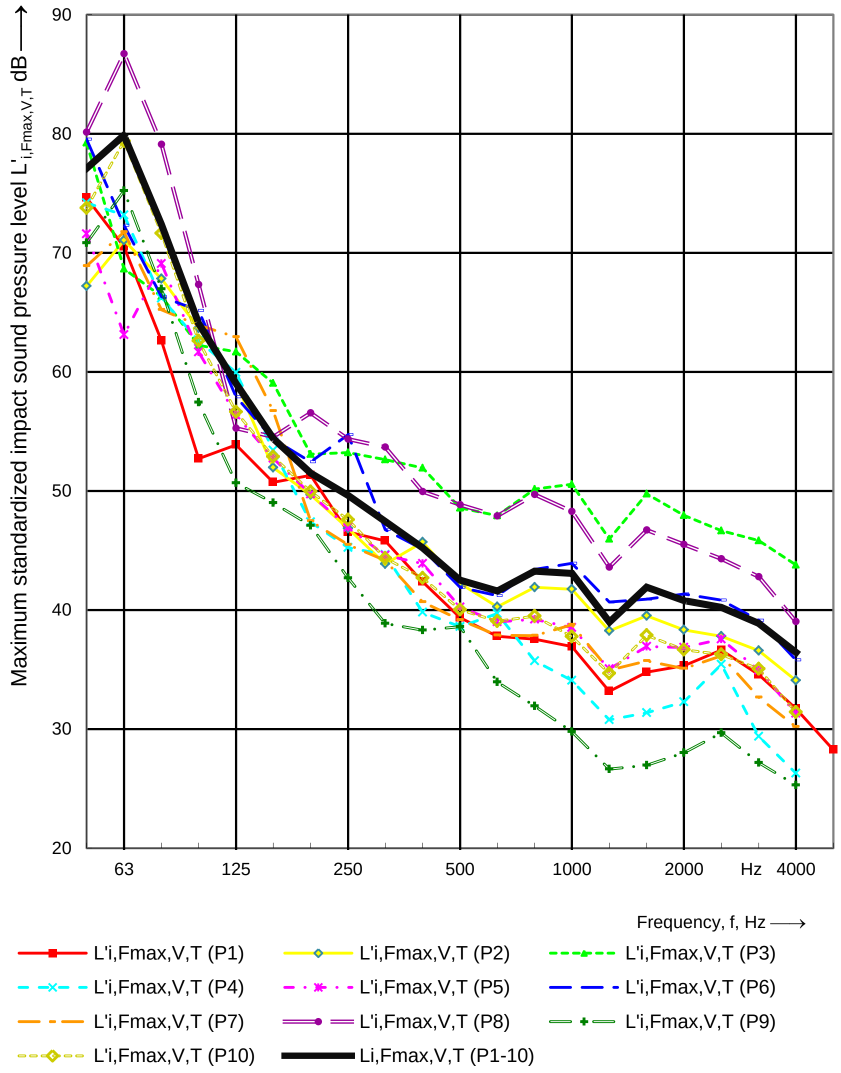


Figure 35. Graph showing the scattering of the maximum impact sound pressure level for each rubber ball position $L'_{i,Fmax,V,T}$ corrected for the Volume and the reverberation time and the standardized maximum impact sound pressure level $L'_{i,Fmax,V,T}$ of the 10 positions, corrected for the Volume and the reverberation time. (c) First refurbished construction; new upper flooring system, non-refurbished suspended ceiling

3.4.2 Second refurbished construction

d.

After the removal of the underside of the refurbished floor/ceiling system a second test based on the alternative impact sound measurement with the rubber ball was carried out. The results can be seen in Figure 36. The highest maximum impact sound pressure level can be seen for position P8, with almost 90dB. Positions P1, P4, P8 and P9 reach their highest peak at 63 Hz whereas positions P3, P5, P6 illustrate a rise at 63 Hz, followed by a drop at 80 Hz and finally reach their peak at 100Hz.

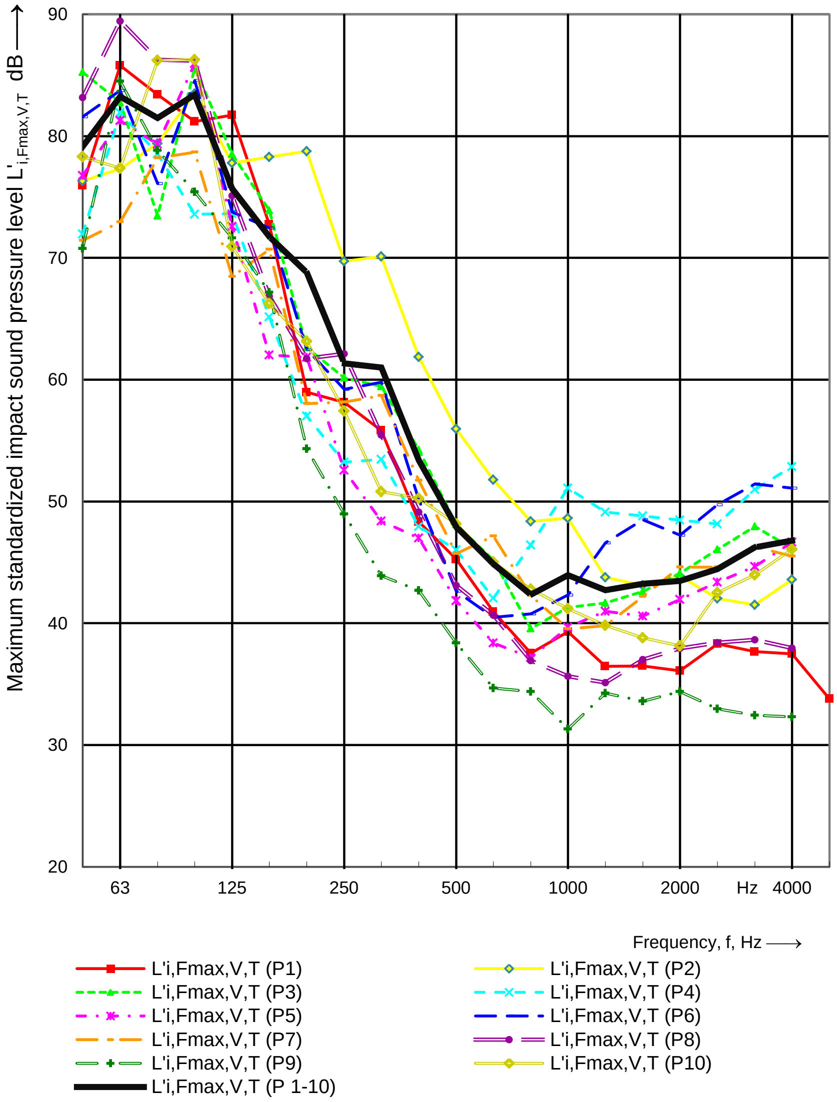


Figure 36. Graph showing the scattering of the maximum impact sound pressure level for each rubber ball position $L'_{i,Fmax,V,T}$, corrected for the Volume and the reverberation time and the standardized maximum impact sound pressure level $L'_{i,Fmax,V,T}$ of the 10 positions, corrected for the Volume and the reverberation time. (d) Second refurbished construction; new upper flooring system, removed underside (without suspended ceiling and reed mats layer with plaster)

On the other hand position P7 and P10 illustrate at 80 and 100 Hz very similar peaks. Interestingly P2 reaches its peak at 100Hz and for frequencies above 160 Hz illustrates the highest impact sound pressure level among all other positions. As stated in previously in 3.4.1, results for frequencies above 630 Hz should not be taken into account.

4 DISCUSSION

In this section the most important findings of the work are being presented. The structure follows that of the Results section and therefore is divided into the impact sound measurement results according to the standard method with the tapping machine and the alternative method with the rubber ball, as described in the EN ISO 16283-2:2013.

4.1 Standard method with tapping machine

As mentioned in the introduction, the acoustical properties of wooden beam floors are rather hard to estimate in comparison, for example, to those of a massive concrete floor, because this construction type is neither very heavy nor sufficiently rigid as a concrete slab. Depending on the construction type the various components might influence one another and lead to systems with several resonances (Fasold and Veres 2003).

However this is not the case for the non-refurbished construction (a). As seen in Figure 37, variant (a) reaches its maximum impact sound pressure level at the frequency of 63Hz (resonance f_0) whereas variant (b) shows two peaks, one in the very low frequency range where it drops almost 5dB between 50-80Hz to rise to its peak at 100Hz (resonance f_0) and fall again steadily with its second peak at the high ranged frequencies over 1250Hz. In both variants the raw ceiling including the underside is constructed in a very similar way but with a totally different upper side. The raised floor system (a), although not resiliently placed, is displaying a smoother impact curve than the rather inhomogeneous with a hard (less sound absorptive) connection between the parquet-planking-wooden lath flooring system (b) which creates more sound paths. The void of the raised floor which acts like a damper, the higher area-related-mass of the floor plates (37-71 kg/m²) and the carpet enhance the performance (for the frequencies above 100 Hz) of construction (a) in comparison to (b). The fact that construction (b) shows a better performance with a decreased maximum in the low frequencies below 100Hz might imply a higher overall stiffness of the upper floor finish. Finally the influence of the carpet for construction (a) might be the reason of the overall lower impact sound pressure level values for the middle to high frequency range.

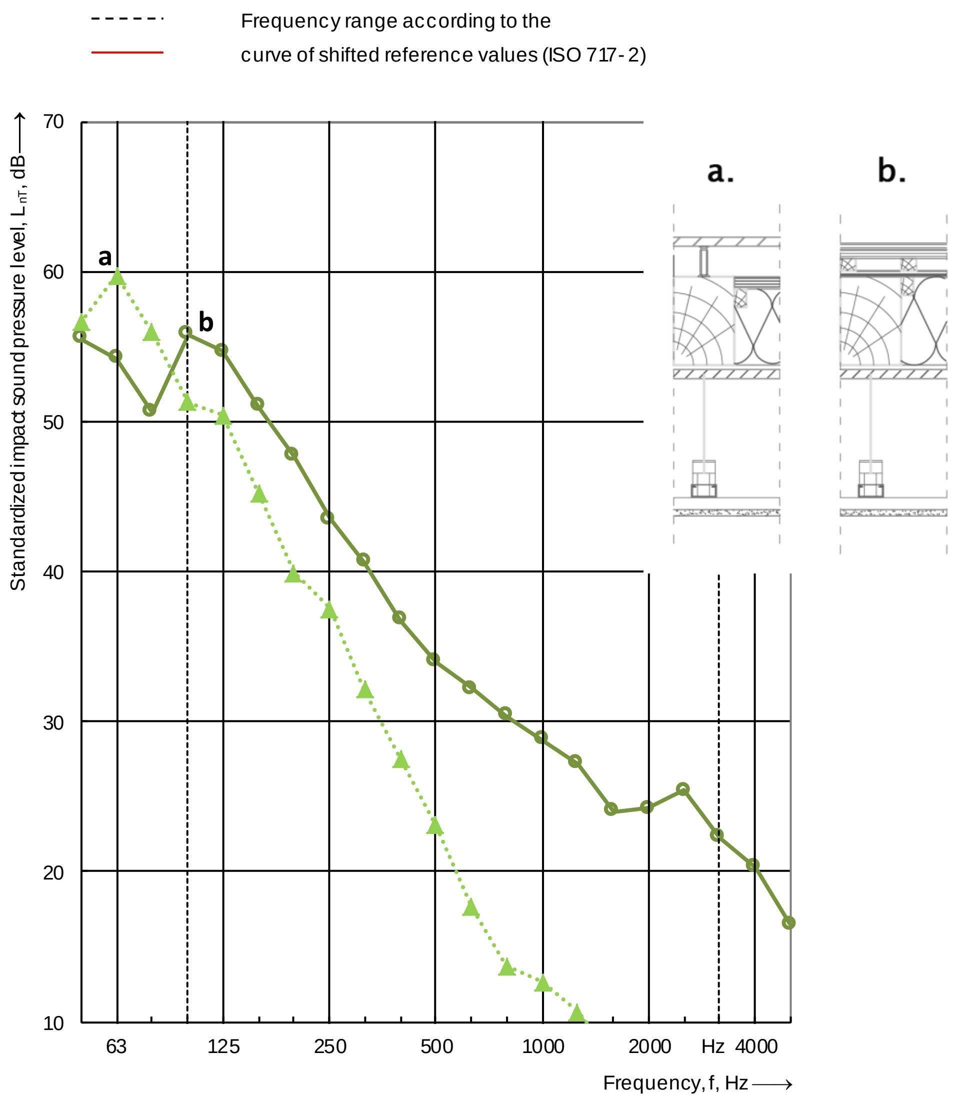


Figure 37. Standardized impact sound pressure level L'_{nT} for non-refurbished wooden beam floors

a	raised floor system (carpet) and suspended ceiling	$L'_{nT,w}(C_I) = 37\ (3)$ dB	$C_{I,50-2500} = 11$dB
b	Parquet floor and suspended ceiling	$L'_{nT,w}(C_I) = 43\ (2)$ dB	$C_{I,50-2500} = 4$dB

In Table 15 and Figures 38-40 summarizing results for the non-refurbished and refurbished wooden beam floors are presented.

As seen in Figure 38 the impact sound performance of construction (c) (new flooring system) in comparison to construction (a) is overall enhanced. Especially in the lower frequency range between 50-100Hz the impact sound pressure level (ISPL) decreases almost 10 dB, due to the floating floors higher area related mass (see 1.3.4). The new floating floor with its very resilient layer (dyn. stiffness of ≤13Mn/m³) and higher mass would be expected to

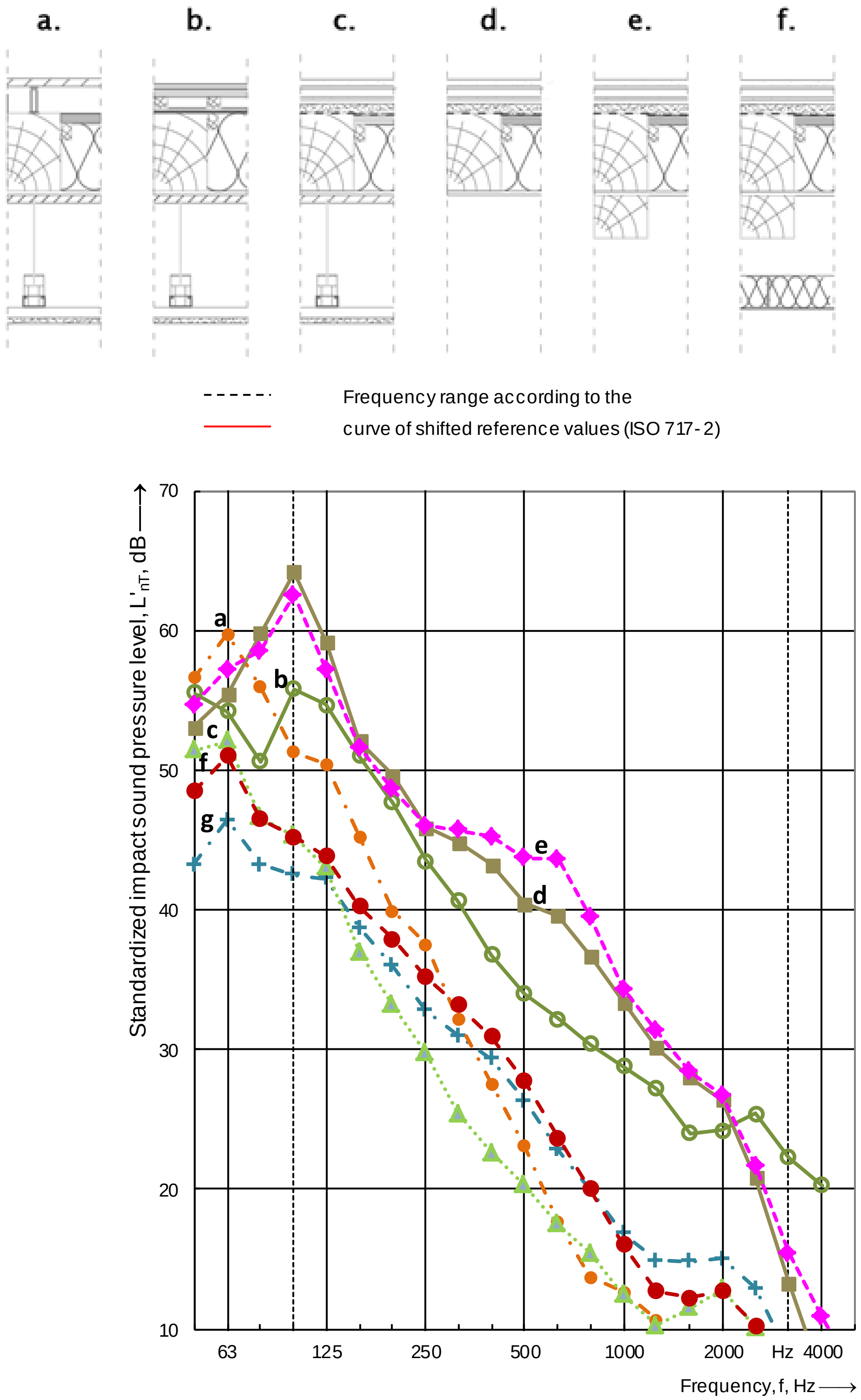


Figure 38. Standardized impact sound pressure level L'_{nT} of all constructions: a. Non-refurbished construction, wooden beam floor between 3rd-4th level; b. Non-refurbished construction, wooden beam floor between 2rd-3th level; c. First refurbished construction (new upper flooring system and non-refurbished suspended ceiling); d. Second refurbished construction (new upper flooring system and removed suspended ceiling); e. Third refurbished construction (new upper flooring system and stiffened wooden beam construction); f. Fourth refurbished construction (new upper flooring system,

stiffened wooden beam construction and fully self-supported decoupled ceiling with one gypsum cardboard layer); g. Fourth refurbished construction (new upper flooring system, stiffened wooden beam construction and fully self-supported decoupled ceiling with double gypsum cardboard layer)

activate the mass-spring-mass system (see 1.3.4) in a way to shift the resonance frequency in an even lower non audible spectrum. Interestingly, similar to construction (a), the peak of construction (c) remains unchanged at 63 Hz. It seems though that the dynamic stiffness of the enclosed air (in the cavity) of construction (a) dominates the mass-spring-mass behavior and therefore shows a similar resonance frequency at 63 Hz. As mentioned in the methodology, construction (a) is not the typical wooden beam floor found in old “Gründerzeit” buildings. After the conversion from an apartment to an office building, most of the wooden beam floors got a raised floor system with a carpet covering. This explains the rather good impact sound performance of construction (a). One could argue that the refurbished construction (c), when compared to non-refurbished construction (a), did not increase the floors impact sound insulation as expected. But the reduction of almost 10 dB in the lower and middle frequency spectrum (under 315 Hz) makes a clear difference in the audible spectrum and therefore enhances the overall impact sound insulation of construction (c) sufficiently.

Furthermore, the peak for construction (d), after the removal of the suspended ceiling, shifts to 100Hz with $\mathrm{L'_{nT}} = 65\mathrm{dB}$ which is logical according to the mass-spring-mass system (less mass in the underside). Surprisingly, the $\mathrm{L'_{nT}}$ between 50-63Hz is almost 5 dB lower to that of construction (a). But the absence of a suspended ceiling and the removal of the reed mats with plaster, as illustrated in Figure 38, worsened the insulation of the floor (d), especially at the middle to high frequencies (180-2000Hz). After stiffening the wooden beam construction (see construction (e)), a slight improvement of 1-2dB is illustrated in Figure 38 for the frequencies between 80-250Hz with the peak remaining at 100Hz. Another interesting point, similar to the analogy between floor (a) and (d), is that the stiffened construction (e) features 2dB higher ISPL in comparison to construction (d) in the frequencies below 63Hz. This could mean that a stiffer and inelastic construction like floor (e) is disadvantageous especially for the very low frequencies below 63 Hz and the middle to high above 250 Hz to a lighter and more flexible one like floor (d). Another interpretation might be that the lengthwise wooden beam stiffeners are not be the best way to get the desired stiffness. Instead lengthwise steel stiffeners or transverse stiffeners between the joists might be more appropriate and have better results.

As illustrated in Figure 38 floor (f), with the new fully self-supported decoupled ceiling with one gypsum cardboard layer, in comparison to floors (d) and (e) improves its impact sound insulation for the frequency range 80-2000Hz at about 15-20dB. The improvement in the low frequencies below 125Hz is rather similar to that of floor (c). Only at 50 Hz there is an obvious difference of almost 3dB, with floor (f) performing better than floor (c). This might imply that the mineral wool insulation of the decoupled ceiling, as a single measure, is not enough to really improve the low frequencies. For the middle to high frequencies above 125Hz and up to 500Hz the suspended ceiling of floor (c) is illustrating better insulating properties to the fully self-supported decoupled ceiling of floors (f) and even (g). Finally construction type (g) with the second gypsum cardboard layer, shows a great improvement of $\mathrm{L'}_{\mathrm{nT}}$ between 3-6dB at the low frequencies under 100Hz. The resonance frequency remains at 63Hz but with a value of 45dB decreased about 15 dB in comparison to the non-refurbished construction (a). It is worth mentioning that the second gypsum cardboard layer added more mass and made the sealing more pliable. The stiffened wooden beam construction made the structure more rigid and enhanced also the impact sound insulation of the whole construction by 1-2dB. These together with the damping (layer of mineral wool) of the resonance system (Stani et al. 2011), increased the insulation of the new ceiling, especially in the low frequencies, and enhanced the overall sound performance of the floor.

In Table 15 the values for the standardized impact sound pressure levels $\mathrm{L'}_{\mathrm{nT,w}}$ the adaptation terms $\mathrm{C_I}$ and $\mathrm{C}_{\mathrm{I},50-2500}$ are presented. According to Lang 2006, for wooden beam floors, the $\mathrm{C_I}$ adaptation term is usually in the range 0-4dB, which is also verified by the different construction variants in this thesis (see Table 15). The same goes for the adaptation term $\mathrm{C}_{\mathrm{I},50\text{-}2500}$ its range varies between 4-11dB which complies with the 1-13dB differences mentioned by Lang 2006. Although there has not been enough experience with the adaptation term $\mathrm{C}_{\mathrm{I},50-2500}$ in Austria and other countries (Stani et al. 2011, Rabold et al. 2013, Lang 2006) this term was used to characterize and quantify the results, because a reasonable correlation was found between subjective ratings of residents and the calculated and/or the measured standardized impact sound pressure level $L'_{nT,w}$ of their buildings (Rasmussen and Machimbarrena 2014). Using this adaptation term the frequency range down to 50Hz can be included in the evaluation method based on a single indicator.

Table 15. Table of the rated floors standardized impact sound pressure level $L'_{nT,w}$ and the adaptation terms C_I and $C_{I,50-2500}$.

	a.	b.	c.	d.	e.	f.	g.
$L'_{nT,w}$ [dB]	37	43	30	47	45	33	31
C_I [dB]	3	2	3	4	4	1	1
$C_{I,50-2500}$ [dB]	11	4	11	5	6	7	5

According to the ÖNORM 8115-2:2006, the minimum requirement for sufficient impact sound insulation between adjacent apartments is $L'_{nT,w}$ ≤48dB. As seen in Table 15 all the constructions are fulfilling the minimum requirement for this single indicator. However, according to Figure 38 and the analysis for the various wooden beam floors, the minimum requirement is not sufficient to meet the demand for high impact sound insulation quality in dwellings.

In Table 16 and Figure 39-40, the various classifications are presented for all wooden beam floors. To begin with, according to ÖNORM 8115-5 and classification (I), the limit of $L'_{nT,w} \leq 38$ is met by 3 out of 5 refurbished constructions (c), (f) and (g) and 1 out of 2 non-refurbished, construction (a). This is due to the new upper floor system and the existing or the new underside. The refurbished constructions (d) and (f) mainly due to the lack of a suspended or free hanging ceiling are far from being characterized as highly comfortable. Classification (II) implements the C_I adaptation term to include frequencies from 100Hz and above. Similar to (I) classification (II) fulfills the requirements for the non-refurbished constructions (a) and the refurbished constructions (c), (f) and (g).

Table 16. Classification of impact sound pressure level (according to ÖNORM 8115-5, Lang 2006 and Rasmussen and Machimbarrena 2014)

			I	**II**	**III**	**IV**	**V**	**Classification**
			$L'_{nT,w}$ [dB]	**$L'_{nT,w}$ + C_I [dB]**	**$L'_{nT,w}$ + $C_{I,50\text{-}2500}$ [dB]**	**$L'_{nT,w}$ + $C_{I,50\text{-}2500}$ [dB]**	**$L'_{nT,50}$ = $L'_{nT,w}$+$C_{I,50\text{-}2500}$ [dB]**	**Descriptor**
			ÖNORM 8115-5	**ÖNORM 8115-5**	**ÖNORM 8115-5**	**Lang 2006**	**Rasmussen & Machimbarrena 2014**	**Classification according to**
floor	**C_I [dB]**	**$C_{I,50\text{-}2500}$ [dB]**	**≤ 38**	**≤ 43**	**≤ 48**	**≤ 40**	**≤ 44**	**Class A - "High Comfort"**
a.	3	11	37	40	48	**48**	**48**	
b.	2	4	**43**	**45**	47	**47**	**47**	
c.	3	11	30	33	41	**41**	41	
d.	4	5	**47**	**51**	**52**	**52**	**52**	
e.	4	6	**45**	**49**	**51**	**51**	**51**	
f.	1	7	33	34	40	40	40	
g.	1	5	31	32	36	36	36	

Classification (III) which takes into consideration the impact sound pressure level from 50Hz and above is met by almost all the floor variants except from (d) and (e). However, the single indicators with values of 52dB and 51dB for floors (d) and (e) are not that far from the 48dB required to classify them as highly comfortable. This occurrence might rely on the fact that when applying this low-frequency rating, potentially disturbing high frequency sounds might not be rated appropriately (Rasmussen and Machimbarrena 2014) and therefore can lead to a wrong classification. Hence more research has to be done to find an improved weighting procedure that solves that problem sufficiently. The Akulite spectrum adaptation term (see 1.3.3) $C_{I,AkuLite,20-2500}$ might be a good alternative weighting procedure that could be applied and further investigated.

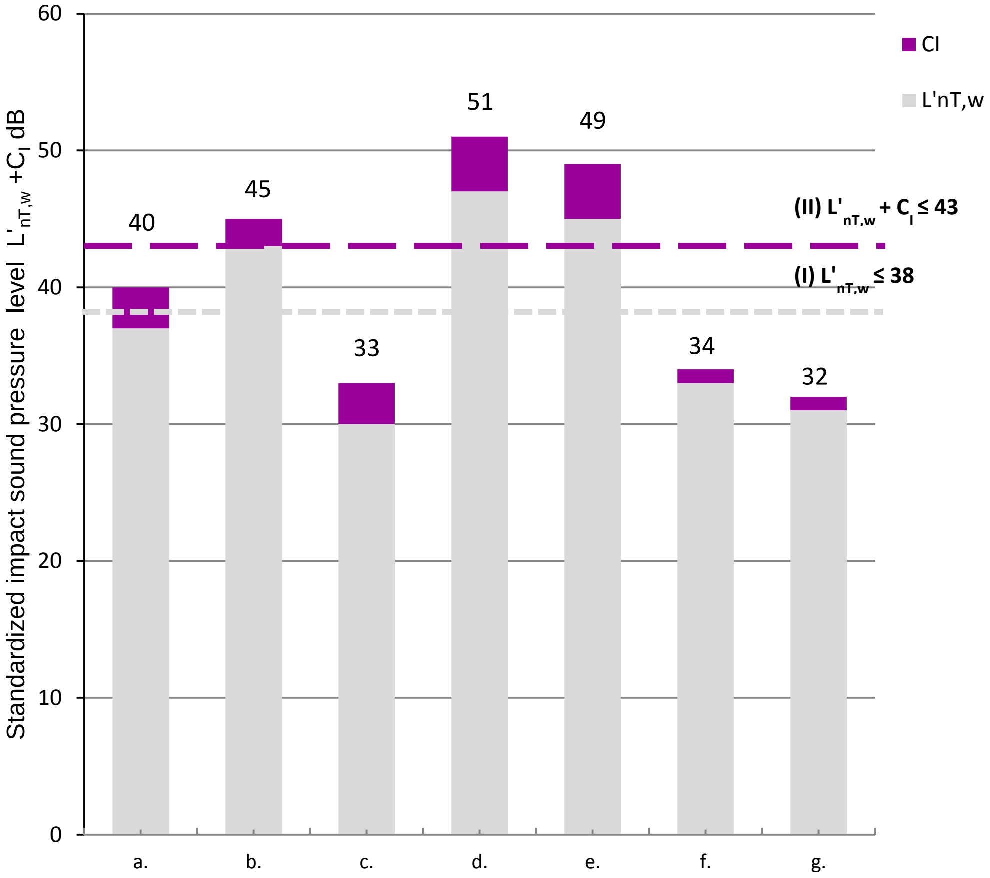


Figure 39. Sum of the standardized impact sound pressure level L’nT,w and CI spectrum adaptation term calculated at 1/3-octave bands from 100-2500 Hz [dB]. Horizontal lines showing the limits according to classification (I) and (II) (see Table 16)

Furthermore, Classification (IV), proposed by Lang (Lang 2006), has the strictest single value and can only be met for the last two floor variations (f) and (g). Moreover, Classification (V) according to (Rasmussen and Machimbarrena 2014) is fulfilled by the refurbished constructions (c), (f) and (g). Finally, among all constructions only the two last floor variations (f) and (g) could fulfill all the requirements, according to the various classification values (see Table 16), for the impact sound pressure level and reach a very high standard of comfort. This is also verified in Figure 38 where the curves for floor (f) and (g) highlight the lowest impact sound pressure levels for the frequencies below 100Hz.

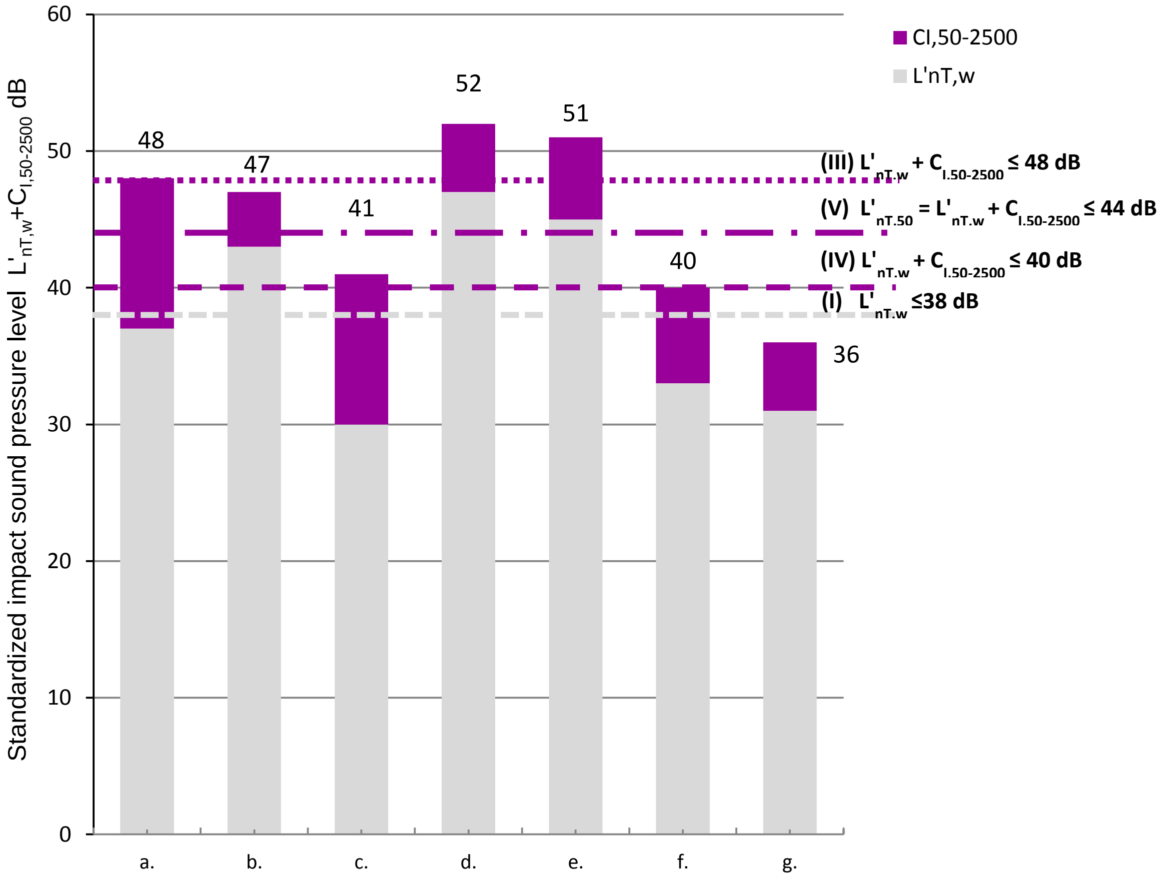


Figure 40. Sum of the standardized impact sound pressure level $L'_{nT,w}$ and $C_{I,50-2500}$ spectrum adaptation term calculated at 1/3-octave bands from 50-2500 Hz [dB]. Horizontal lines showing the limits according to classification (I), (III), (IV), (V) (see Table 16)

4.2 Alternative method with impact ball

As mentioned in section 2.3.2, due to limited accessibility of the impact ball, the experiments on the wooden beam floor could only be performed after the refurbishment and only for refurbished constructions (c) and (d). The limited number of tests makes it difficult to get any statistically significant results. Moreover, as stated in the EN ISO 16283-2:2013, at present, calculation procedures for obtaining a single descriptor do not exist in any ISO Standard. The impact ball is therefore used to assess heavy/soft impacts, such as from barefoot walkers or jumping children and to quantify absolute values that can be related to human disturbance in terms of a Fast Time - weighted maximum sound pressure level. Because no ISO standard evaluation method is available this method was not used to characterize the comfort quality of the floors. However an analysis of the measured sound pressure level results obtained by the rubber ball, according to EN ISO 16283-2:2013, was done and the standardized maximum impact sound pressure level $L'_{\mathrm{i,Fmax,V,T}}$ in comparison to the standardized impact sound pressure level L'_{nT} (tapping machine method) is presented in Figures 41-42.

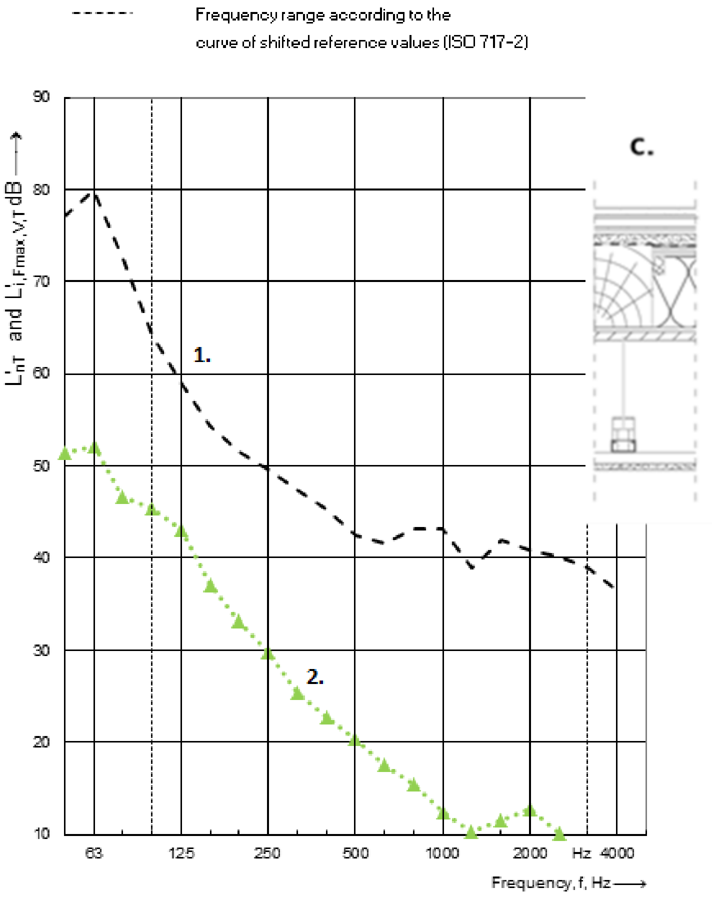


Figure 41. First refurbished construction (c); new upper flooring system, non-refurbished suspended ceiling; Graphic comparsion between the impact sound pressure level L'_{nT} (curve 2.) and standardized maximum impact sound pressure level $L'_{i,Fmax,V,T}$ (curve 1.) according to the two different measurement methods as described in the EN ISO 16283-2:2013 (see 2.3)

As seen in Figure 41, both curves illustrate similar progression from 50-630Hz, with the resonance frequency being clearly at 63Hz. It is obvious that the energy of excitation from the impact ball is significantly higher in the low frequency range compared to the method using the standardized tapping machine. The tapping machine produces a high frequency continuous tapping noise due to the hard but light metal hammers and the rubber ball test produces a much lower end instantaneous thud, which travels further through the solid parts of floors and walls. So at its peak it reaches almost 80 dB, about 30dB more than the impact sound pressure level generated by the tapping machine. For the method with the tapping machine, the weighted standardized impact sound pressure Level $L'_{nT,w}$ = 30 dB fulfills by far the minimum requirement of 48dB as set in the ÖNORM 8115-2:2006 standard.

Furthermore construction (c) reaches the high comfort standards for almost all Classification classes (I, II, III and V; see Table 16). Only Classification class IV as proposed by Lang (Lang 2006) is not met (see Table 16). However one could argue that this high comfort levels, especially for the indices taking into consideration the low frequencies over 50Hz (adaptation term $\mathrm{C}_{\mathrm{I},50-2500}$) still differ clearly to the rather high impact sound pressure levels generated by the impact ball. Even if plotting the sum of $\mathrm{L'}_{\mathrm{nT}} + \mathrm{C}_{\mathrm{I},50-2500}$ for the peak of 63Hz the value reaches about 63dB which differs still 17dB from the maximum ISPL value produced by the impact ball. As noted in many studies (Jeon et al. 2006, Ryu et al. 2010) the maximum ISPL produced by the rubber ball correlates well with real heavy impact sounds generated from adults waking or children jumping and running. Although the rubber ball method has been extensively used in Korea and Japan as the main method for evaluating the impact sound insulation of floors (wooden and concrete) produced by heavy weight impacts (JIS 1419-:2:2000, KS F 2863-3:2012), in other countries there has not been enough provided data and an evaluation scheme with the measurement result is still in discussions (Sato and Yoshimura 2014).

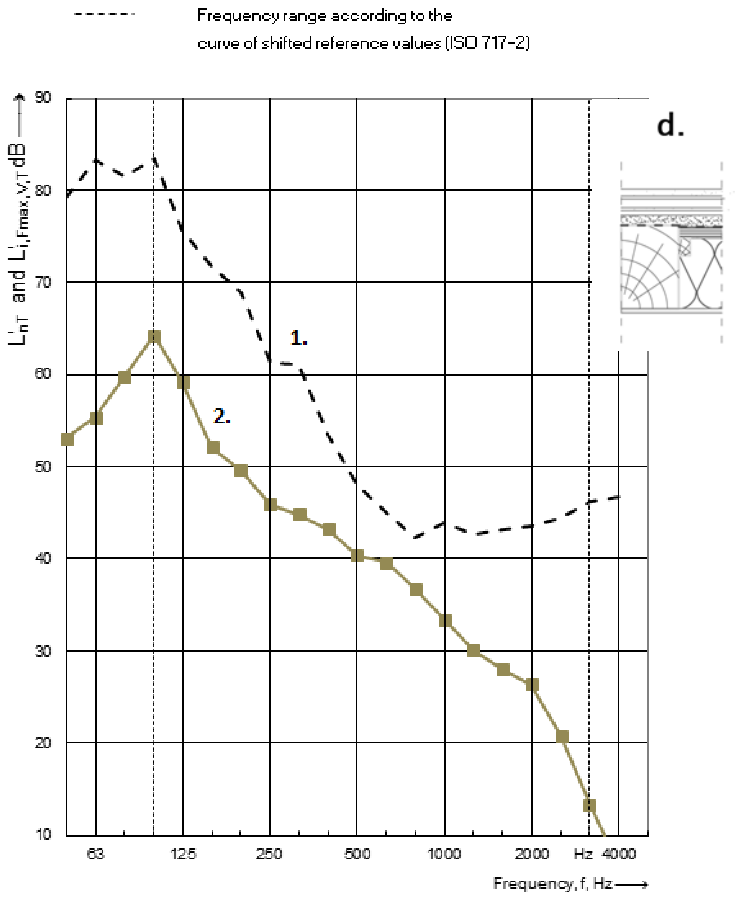


Figure 42. Second refurbished construction (d), new upper flooring system, removed underside (without suspended ceiling; Graphic comparsion between the impact sound pressure level L'_{nT} (curve

2.) and standardized maximum impact sound pressure level $L'_{i,Fmax,V,T}$*(curve 1.) according to the two different measurement methods as described in the EN ISO 16283-2:2013 (see 2.3)*

In Figure 42 the impact sound curve 1 for the rubber ball illustrates a rather inconsistent progress between 50-100 Hz compared to curve 2 for the tapping machine. The impact ball gives two, almost identical peaks at the frequencies of 63 and 100Hz which might be due to the many different rubber ball positions distributed to the whole floor surface. It is obvious as mentioned in 3.4.2 that there can be rather big fluctuations between the impact sound pressure levels produced from position to position. Therefore when the rubber ball impacts over a beam or in the middle of the room the impact sound propagates differently, resulting in varying impact sound pressure levels between each position and for each frequency.

4.3 Difficulties and Measurement uncertainty

In the renovation of old buildings many unexpected events might interfere with the refurbishment of the various components. In this thesis, we had to deal with problems, such as cracks in the wooden beams and the unevenness of the floor. At first these structural issues might not be obvious or of big importance, but as the implementation of the planning went on the unevenness of the floor proved to be very challenging. The choice of a dry screed system made it necessary to get an as even as possible underlay. Therefore to get the necessary compensation height for an even floor, high workmanship skills and careful execution were needed. In section 3.4, Figures 35 and 36 represent the maximum standardized impact sound pressure levels $\mathrm{L'_{i,Fmax,V,T}}$, for constructions (c) and (d), according to the impact ball method. They illustrate a rather inconsistent curve progression in the low frequencies and big fluctuations in the mid frequencies between the different impact ball positions (for approximate ball positions see Figure 34). These variations in the $\mathrm{L'_{i,Fmax,V,T}}$ results among the impacts positions could be due to the height differences of the leveling compound, which was applied to get an even floor. For floor areas with more leveling compound, as was the case on the right side of the room in Figure 34, the total area related mass (m', in kg/m²) was higher and therefore led to lower impact sound pressure levels and different frequency peaks. Other constructional differences on the existing wooden joists or in the cavity between the joists may have been further causes for result variations. The cracks at the wooden beams, for example, were according to the static calculation allowable, and thereby should have no negative influence on the structural performance of the construction. Nevertheless, the beams were stiffened in the progress of the refurbishment to research what influence would their higher stiffness have in the impact sound insulation of the floor.

A strict protocol for each measurement was followed to minimize possible mistakes at the analysis and evaluation of the measurement results. Moreover, during the site supervision a detailed photo documentation of each refurbishment step was done, to keep a record of the workmanship level and be able to understand and discuss potential issues that could influence the results.

The followed measurement method according to the EN ISO 16283-2:2013 contributes to the limitation of measurement uncertainties. To minimize the measurement uncertainties all tests were repeated in the same location by the same operator using the same equipment. As stated in the methodology, fixed microphone positions on a tripod were used for all the measurements in the receiving room. The averaging time at each individual microphone position was set to 15sec, because according to the EN ISO 16283-2:2013 longer averaging time is needed to include measurements down to 50 Hz.

5 CONCLUSION

This master thesis dealt with the impact sound insulation of wooden beam floors in an old Viennese “Gründerzeit” house. The main objective was to deal with the issue of poor impact sound insulation of existing wooden beam floors especially in the low frequency range below 100 Hz where their performance is rather problematic. Through the application of modern materials and techniques a wooden beam floor construction was refurbished step by step giving several variations, which were then compared to two non-refurbished constructions. The measurement test procedure followed was according to the EN ISO 16283-2:2013 for field measurements and the rating method according to the ÖNORM 8115-2:2006. Furthermore, various impact sound insulation classification schemes (proposed by ÖNORM 8115-5:2012, Lang 2006 and Rasmussen and Machimbarrena 2014) were applied to characterize the comfort level of each construction.

Based upon the results we can conclude that it is possible to obtain a very good impact sound insulation performance of refurbished wooden beam floors even for the low frequency spectrum if the correct combination of materials is applied thoughtfully. The fourth and final refurbished construction (g) with the new upper flooring system (gypsum fibre boards, wood fibre board, honeycomb acoustic system, construction Mat-impact insulation layer, gypsum fibre board, levelling compound, trickle protection sheet), the stiffened wooden beams and the new fully self-supported decoupled ceiling (mineral wool insulation, double U steel profiles, double gypsum cardboard layer) illustrates the highest impact sound insulation among all variants.

This construction reaches a weighted standardized impact sound pressure level of $\mathrm{L'}_{\mathrm{nT,w}} = 31\mathrm{dB}$ which is substantially lower than the 48dB required by the Austrian ÖNORM 8115-2:2006 standard. As a first step, the new floor created a mass-spring-mass system with sufficient mass to optimize the spring (resilient layer) and performed satisfactory also in the low frequencies under 100Hz. Next, the stiffened wooden beam construction made the structure more rigid and enhanced also the impact sound insulation of the whole construction by 1-2dB. Finally the fully self-supported decoupled ceiling, with the double gypsum cardboard layer damped the construction at the middle-high as well as the low frequencies resulting in a 45dB peak at 63 Hz. The descriptor $\mathrm{L'}_{\mathrm{nT,50}}$ (=$\mathrm{L'}_{\mathrm{nT,w}} + C_{I,50-2500}$ as defined in ISO 717-2, see Rasmussen and Machimbarrena 2014) equals to 36dB which fulfils all the classification requirements according to Table 16. Therefore the refurbished construction (g) is characterized with a very high quality level.

As mentioned before, the impact sound insulation of floors has been an intensive field of research for years. Especially the impact sound insulation of lightweight floors (e.g. wooden beam floors), where most complaints from residents are expressed, has been addressed by many recent and older studies. In the scope of this thesis, several impact sound insulation topics have been discussed and possible solutions to deal with the impact sound performance in the low frequency spectrum have been investigated. However further work needs to be done to get an even better understanding of the various parameters influencing the floor impact performance in the frequencies below 100Hz. For instance, the presented results showed some improvement of the impact sound insulation after raising the stiffness of the construction. However a different stiffening method, such as steel beams or transverse stiffeners might have a very different result. It would be interesting to research if and what kind of correlation, between the actual stiffness of the wooden beam construction and the damping properties of the floating floor with its elastic resilient layer, exists. First vibration measurements of the wooden beam joist and the floating floor should be done, to identify their fundamental natural frequencies (natural frequency is a frequency at which a structure will vibrate when displaced and then quickly released; the lowest natural frequency is called fundamental). To avoid felt vibration problems in wooden beam floors it is often stated that the fundamental frequency should be above 8Hz. These vibrations measurements could then be compared to the impact sound insulation measurements and try to investigate if any meaningful correlation between them exists. Furthermore, elastic layers such as polyurethane Construction Mat layer (used in this thesis), are usually applied as the sole resilient insulation layer for the floating floor construction. It is a fact that the more elastic a layer is, the lower its dynamic stiffness and the better the impact sound insulation of a floor gets. But elastic materials do not dissipate energy when a load is applied to them and then removed (as in the case of an impact sound). On the other hand, viscoelastic materials, which are mainly used for isolating vibration, dampening noise and absorbing shock, exhibit both viscous and elastic characteristics when undergoing deformation. Thereby, viscoelastic materials give off part of the energy absorbed as heat. Therefore, the impact sound insulation properties of viscoelastic materials (e.g. Sorbothane®, Sylomer® HD) instead of an elastic layer could be further researched. Moreover, the attempt to use the alternative method with the impact ball, which has been standardized in the ISO 10140-5 and EN ISO 16283-2, to examine the impact sound insulation of wooden beam floors proved to be straight forward, easy to use and did characterize the response of the floor to heavy/soft impact sufficiently. However, more experience is needed, at least in Europe, with this method especially in-situ measurements.

In Japan and Korea it is the sole method for evaluating heavy impact noises but until now, for this measurement method, no single number or any other evaluation method was standardized in any ISO.

INDEX

List of Figures

List of Tables

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