Acoustics in wooden buildings – Correlation analysis of subjective and objective parameters

Moritz Späh
Andreas Liebl
Philip Leistner

AcuWood Report 4
SP Report 2014:17

SP Technical Research Institute of Sweden
Box 857, 501 15 Borås, Sweden (headquarters)

SP Rapport 2014:17
ISBN 978-91-87461-67-5
ISSN 0284-5172

Fraunhofer-Institut für Bauphysik IBP

Forschung, Entwicklung,
Demonstration und Beratung auf
den Gebieten der Bauphysik

Zulassung neuer Baustoffe,
Bauteile und Bauarten

Bauaufsichtlich anerkannte Stelle für
Prüfung, Überwachung und Zertifizierung

Institutsleitung

Univ.-Prof. Dr.-Ing. Gerd Hauser
Univ.-Prof. Dr.-Ing. Klaus Sedlbauer

Project Report No. 4

Results of the project: correlation analysis of subjective and objective parameters (Translation of „Abschlussbericht AcuWood“)

WoodWisdom-Net: AcuWood – Acoustics in Wooden Buildings

Research project 033R056

The report comprises
69 pages of text
9 tables
35 figures

Moritz Späh, Andreas Liebl, Philip Leistner

Stuttgart, 24.10.2013

Project leader	Editor
Prof. Dr.-Ing. Philip Leistner	Dr. Moritz Späh

Fraunhofer-Institut für Bauphysik
Nobelstraße 12 · D-70569 Stuttgart
Telefon +49 (0) 711/970-00
Telefax +49 (0) 711/970-3395
www.ibp.fraunhofer.de

Institutsteil Holzkirchen
Fraunhoferstr. 10 · D-83626 Valley
Telefon +49 (0) 8024/643-0
Telefax +49 (0) 8024/643-366

Projektgruppe Kassel
Gottschalkstr. 28a · D-34127 Kassel
Telefon +49 (0) 561/804-1870
Telefax +49 (0) 561/804-3187

Contents

1 Introduction

Multi-storey apartment houses or office buildings are more often built in timber construction in Europe. The reasons for this development are the sustainability of timber as building material, the development towards industrial pre-fabrication of constructional parts, and the related cost reduction in building construction. In the last few years, the construction of multi-storey timber buildings was principally facilitated by the approving authorities. The essential problem of fire protection has been solved in the meantime so that the construction of multi-storey apartment houses in timber construction is now possible. Therefore, acoustical problems are nowadays principal and decisive obstacles for multi-storey timber constructions.

Current requirements of multi-storey residential construction are based on the experience of massive construction, since multi-storey timber construction was not possible due to the requirements of fire protection until recently. The acoustic perception in buildings in lightweight construction is different in comparison to massive construction. Especially the impact sound transmission in the low frequency range gives rise to complaints in timber construction [1].

The currently used rating system for airborne and impact sound transmission in buildings was developed in the 1950s aiming at assessing the usual building constructions. In the following years, the constructions of residential and office buildings changed remarkably. In 1996, spectrum adaptation terms for airborne and impact sound insulation were introduced in ISO 717 [2, 3] allowing a modified rating method and the extension of the weighted frequency range to 50 Hz by adequate spectrum adaptation terms. By introducing multi-storey residential timber construction it became obvious that the currently used rating method without spectrum adaptation terms cannot avoid increased annoyance especially caused by impact sound. Therefore, the application of spectrum adaptation terms (with a frequency range down to 50 Hz) became more and more urgent. No reliable information, however, was available until this project was started, which requirement values for the normalized impact sound pressure level with spectrum adaptation term $C_{I,50-2500\,Hz}$ shall be used. For a long time, it has been known that airborne sound transmission of timber floors is generally unproblematic, if impact sound insulation is sufficiently high. Therefore, the airborne sound insulation of the investigated floors was measured within the framework of the project, however, the focus and aims of the project were in the field of impact sound insulation. Special investigations of the vibration performance of floors were carried out in the affiliated project AkuLite in Sweden.

Thus, the project aim was to find improved technical rating methods for impact sound by correlating technical ratings with subjective ratings of impact sound. Accompanying questionnaires of residents of timber buildings were carried out to verify the statements of laboratory listening tests by field questionnaire results. In order to consider all currently used floor constructions a massive concrete floor with floating cement screed was included besides various timber floors. This provided an additional data set of a reference floor, with which the timber floor results could be compared.

1.1 Task

Since the problem of annoyance due to impact sound occurs primarily in multi-storey timber constructions, this project was aimed at developing rating methods for impact sound, which clearly better correlate with the subjective rating of impact sound in buildings. The rating methods proposed, however, should not only be suitable for timber construction but also includes massive and hybrid constructions.

The discrepancy between acoustic requirements in national standards and the subjective perception of residents is a general problem, which occurs especially to multi-storey timber construction and other multi-storey buildings in lightweight construction throughout Europe [1, 4, 5].

Although it was attempted to solve the problems of the weighted sound reduction index R_w [2, 6] and the weighted normalized impact sound pressure level $L_{n,w}$ [3, 7] by introducing the spectrum adaptation terms, this was not achieved so far [8]. The most significant problem in the field of sound insulation is the impact sound insulation of timber floors or lightweight floor constructions and additionally the airborne sound insulation of external building components like walls and roofs to a lower extent. Although a few investigations of sound transmission and subjective perception of impact and airborne sound in timber constructions were carried out, no extensive investigation of rating methods for impact sound insulation is available so far [9–13].

1.2 Condition of project work

The project AcuWood is a joint European project within the context of WoodWisdom.Net. It was applied for in the 2nd Joint Call 2009. The project partners are:

- Coordinator:
  SP Technical Research Institute of Sweden / SP Trätek, Sweden
- Peab, Industrial Partner, Sweden
- Fraunhofer Institut für Bauphysik IBP, Stuttgart, Germany
- Bundesverband Deutscher Fertigbau e. V. BDF Bad Honnef, Germany

- Deutscher Holzfertigbau Verband e.V. DHV, Stuttgart, Germany
- Lignum, Holzwirtschaft Schweiz, Zurich, Switzerland

The research project is divided into four work packages with the following contents:

- Work package A: coordination and project management, dissemination of the results
- Work package B: measurement of airborne and impact sound insulation by excitation of various technical and human noise sources, questionnaires and psychoacoustic investigations of sound perception in the laboratory and in the field
- Work package C: data analysis, variation and correlation of subjective and objective results, development of an enhanced impact sound source, definition of uniform rating criteria, validation of the developed method and criteria
- Work package D: development of an enhanced measurement and rating system, integration of the system in European standards, communication of the system to the outside world

The work packages were attributed to the partners as follows:

Work packages A and D: SP Trätek, Sweden

Work packages B and C: Fraunhofer IBP, Germany

In addition to the investigations carried out in Germany in the laboratory or in field constructions (AcuWood Report 1 [14]) further measurements in multi-storey timber buildings in Switzerland were conducted due to the support of Lignum (AcuWood Report 2 [15]). They were planned and coordinated by Lignum Holzwirtschaft in Switzerland and carried out by the Fraunhofer IBP with the support of Lignum. Moreover, the cooperation with Lignum also provided a questionnaire survey of residents of timber buildings in Switzerland. The data gained also added to the database of the AcuWood project allowing the determination of results for usual timber constructions of single-family houses as well as for multi-storey apartment houses. Insofar, the value of the data acquisition as well as the value of the results of the AcuWood project could be increased considerably. Our special thanks go to Lignum for their extensive support.

1.3 Planning and execution of the project

Planning and controlling the execution of the project rested with the project management of SP Trätek. The tasks within the work packages were carried out as described in the application. During the execution of work package B and C minor delays occurred at the IBP.They were eliminated in the course of the project so that it was completed according to the plan. During the project, 7 meetings took place so that all in all there was a project meeting approx. every 6 months, where all project partners were informed of the project progress. When necessary, additional meetings were conducted with industrial partners for information on their concerns regarding the progress of the project. All meetings are described in the half-year assessment reports for BMBF

This report primarily contains the description of the method and results of work packages B and C. The results of the total project AcuWood can be found in the reports of the AcuWood project, which are worked out by SP Trätek. The Fraunhofer IBP established reports in English on the AcuWood project, for detailed information see [14-16].

1.4 State of the art

1.4.1 Standardized rating method according to ISO 717

The objective rating of impact sound insulation is based on measurements in buildings by means of the standard tapping machine. The measurements are described in DIN EN ISO 140 [17] based on ISO 140 [18]. The requirement values vary within European countries by the hight of the requirements but also by the rating parameters.

A short survey of the development of the requirement values for airborne and impact sound insulation is given in [4]. The currently used rating method of ISO 717 [6, 7] is based on a German rating method and described for example in [19]. Since the sound insulation and the impact sound pressure level are dependent on the frequency, the values were arithmetically determined in Germany before the current method was developed. In the 1950s already it was known that single number value calculated in this way did not correlate with the subjectively perceived noise. Therefore, Cremer [20] suggested a rating method, where the measured sound insulation in the frequency range from 100 Hz to 3150 Hz was compared with a reference curve. These reference curves showed in principal the frequency spectrum of the sound insulation and impact sound pressure levels of common building components of that time. The rating curves were shifted so that the measuring curve to be rated only falls below a certain extent of the weighting curve (in case of airborne sound insulation) or does not exceed a certain extent (in case of the measurement of impact sound pressure level). A general validation of the method showed that this method reflected the subjective impression of building constructions, which were common at that time. A few rules to calculate the single number value were adjusted over the years [4], but the weighting curves were not modified and are still applied in ISO 717.

1.4.2 Extension of the frequency range

For a long time, the building acoustic frequency range has been used in third octaves from 100 to 3150 Hz to assess airborne and impact sound insulation [4]. ISO 717 issue of 1996 introduced spectrum adaptation terms, which extended the possible weighted frequency range from 50 to 5000 Hz. Since 1998, the frequency range for minimum requirements was extended to 50 Hz in Sweden [4], due to the experience with traditional lightweight constructions, particularly in the Scandinavian countries Norway and Sweden, but also Canada. For noise control criteria of higher noise control classes, ratings in the low frequency range to 50 Hz were carried out in Denmark, Sweden, Norway, Finland, Iceland and Lithuania in the last decade [4]. Frequencies below 100 Hz are essential for the subjective rating of impact sound insulation. Studies showed that frequencies down to 16 Hz may be necessary to achieve good correlation of subjective and objective rating of impact sound [21]. Unfortunately, the measurement of reverberation time at low frequencies is becoming increasingly difficult. Thus, the measurement range was limited to 20 Hz to 5000 Hz in this project.

Besides the extension of the frequency range to lower frequencies to 50 Hz and to higher frequencies up to 5000 Hz the introduction of the spectrum adaptation terms also caused a modification of the rating method. The spectrum adaptation term alone does not describe the building component but is only reasonable in the context of the single number value determined by the conventional method by means of the shifted weighting curve, the normalized impact sound pressure level or the standardized impact sound pressure level. The reason is that the sum from normalized impact sound pressure level and spectrum adaptation term represents the sum of the A-weighted third octave values in the specified frequency range. To achieve the spectrum adaptation term the normalized impact sound pressure level is subtracted from the sum. Since the sum from normalized impact sound pressure level and spectrum adaptation term represents the sum of the A-weighted third octave band values, the introduction of the spectrum adaptation terms means the adaptation of another rating method, whereby the calculation of the single number value by means of the shifted weighting curve is no longer necessary. This becomes more obvious, if the drafts of ISO 16717 [22] and [23] are taken into consideration, which is meant to replace the currently valid ISO 717 in the future.

1.4.3 Further rating methods

The rating methods described refer to the application of the standard tapping machine, which has been introduced for impact sound measurements for a long time. Since this source and the principal rating method by shifting the weighting curve have been introduced, criticism occurred based on the poor correlation of the weighted impact sound pressure level and the subjective perception. From time to time proposals were made to modify the rating method or to leave the method as it is but modify the weighting curve in form and frequency range. Among these proposals are those of Fasold [24] and Gösele [19], but also of Bodlund [25] and Hagberg [26]. The latest proposals are derived from the AkuLite project, which is the Swedish preceding project of the AcuWood project [27, 28]. In addition, rating methods for the standard tapping machine are described in the Japanese standard JIS A 1419-2 [29] and in the Korean standard KS F 2863-2.

The Japanese standard JIS A 1419-2 [29] and the Korean standard KS F 2863-2 describe rating methods for the Japanese rubber ball developed by Tachibana [30]. All these and some other rating methods were applied in the AcuWood project. They are described in chapter 2.

1.4.4 Subjective rating of impact sound

Within the context of the AkuLite project a comprehensive literary study was carried out in Sweden on the annoyance of noise in buildings, the subjective perception of impact sound by footstep noise and a survey of various methods of listening tests in work package 1 [31]. Moreover, the method applied in the AkuLite project is reported. The subjective rating in the AkuLite project is based on the analysis of Thorsson [31]. To carry out the listening tests in this project another method was selected. Instead of recording the vibration velocity of the floor during the measurement and playing back by a loudspeaker at the ceiling of the listening room, recording in the AcuWood project was done by an artificial head. The Play-back in the listening test was performed by adjusted headphones. The adjustment procedure is described in AcuWood Report No. 3 [16]. The binaural playback by headphones allowed the localization of the impact sound source in the listening test, similar to the set–up in the AkuLite project. The impact of the localization of the source on the subjective rating was investigated in a first listening test within the context of the AcuWood project. It was found that the localization had an influence on the subjective rating. Thus, all recordings for the main listening tests in the AcuWood project were performed by means of the artificial head.

The disadvantage of the selected method is that the room acoustics of the receiving room in the construction has an impact on the recorded signal. This impact is reduced in the AkuLite project. To reduce the impact of room acoustics on the recordings, almost all measurements were carried out in rooms with similar dimensions and volume. In addition, by using sound absorbers in the receiving room it was attempted during the measurements to achieve similar room acoustic conditions. The result was reverberation times similar to those in occupied rooms and close to 0.5 s. Deviations were accepted primarily in construction measurements, if the rooms were unoccupied. The measured reverberation times are described in Report No. 1 [14] and Report No. 2 [15]. Further information on the listening tests is described in Report No. 3 [16].

2 Rating methods for technical assessment

2.1 Method

The technical rating of impact sound is performed by a standardized technical impact sound source in the source room exciting the floor between source room and receiving room. The transmitted impact sound pressure level is measured in the receiving room and assessed by a rating method. This assessment achieves that a so-called „single number value“ and is determined from a frequency-dependent spectrum describing the impact sound transmission and thus the quality of the floor structure concerning the impact sound excitation. The currently used standardized impact sound source is the standard tapping machine, and the assessment and determination of the single number value is done according to ISO 717-2 [7]. This rating method has been criticized since it was introduced. Thus, there have always been proposals to modify the rating method, whereby most methods referred to a modification of the weighting curve of ISO 717-2. The essential proposals from literature were integrated and applied in this project. Moreover, other rating methods were used, which seemed to be reasonable. To assess the Japanese rubber ball the Japanese standard JIS A 1419-2 [29] and the Korean standard KS F 2863-2 were applied. This project was not aimed at developing a own suggestion for a rating method.

2.2 Rating methods used for the standard tapping machine

The rating methods used to obtain a single number value from the frequency-dependent measured impact sound pressure level are described in the following.

2.2.1 Weighted standardized impact sound pressure level $L'_{nT,w}$ referring to DIN EN ISO 717-2

DIN EN ISO 717-2 [5] describes the method to determine the weighted normalized impact sound pressure level $L'_{n,w}$ or the weighted standardized impact sound pressure level $L'_{nT,w}$. The rating procedure for both single number values is similar.

The requirements of DIN 4109 [32] refer to the weighted normalized impact sound pressure level $L'_{n,w}$. This standard is reviewed at present so that it is not clear on which of the two previously described values of $L'_{n,w}$ or $L'_{nT,w}$ the future requirements of the new DIN 4109 will be referred to. The latest guideline of VDI 4100 [33] gives requirements referring to the weighted standardized impact sound pressure level $L'_{nT,w}$. This seems to be reasonable, since the requirements are then no longer given for the partition building element but for the building situation. Thus, the evaluation in this project was essentially related to reverberation-corrected spectra including $L'_{nT,w}$. The influence of the reverberation time correction on the correlation coefficient and the evaluation results in chapter 3 is relatively small.

The standardized impact sound pressure level L'_{nT} is calculated according to:

$$L'_{nT} = L'_i - 10\log\left(\frac{T}{T_0}\right) \text{ [dB]} \tag{1}$$

with:

L'_i: measured sound pressure level in the receiving room in dB (These values are described in both AcuWood reports [14, 15] for all measurements carried out in the project.)

T: measured reverberation time in the receiving room in s

T_0: reference reverberation time of 0.5 s

The standardized impact sound pressure level L'_{nT} can also be calculated from the normalized impact sound pressure level L'_n.

$$L'_{nT} = L'_n - 10\log(V) + 15 \text{ [dB]} \tag{2}$$

L'_n: normalized impact sound pressure level in dB

V: Volume of receiving room in m³

Due to the reference curve method of DIN EN ISO 717-2 [7] the single number value $L'_{nT,w}$ is determined from the measured third octave spectrum. In the procedure, a given weighting curve for the frequency range from 100 to 3150 Hz is shifted in a way that the sum of exceeding third octave band frequency values of the measuring curve above the weighting curve is as high as possible, but not higher than 32 dB. Hereby, only the exceeding frequency values in the frequency range from 100 to 3150 Hz are taken into account. The single number value $L'_{nT,w}$ is the value of the shifted weighting curve at 500 Hz. According to DIN EN ISO 7171-2, the reference curve is shifted in 1 dB steps. Therefore, the uncertainty of the single number values is higher than for single number values with one digit after the decimal point. The shifting of the weighting curve was therefore defined in 0.1 dB steps in this report. Figure 1 shows the reference curve and the measured values L'_{nT} of the timber floor without screed and floor covering as example of the determination of the standardized impact sound pressure level $L'_{nT,w}$.

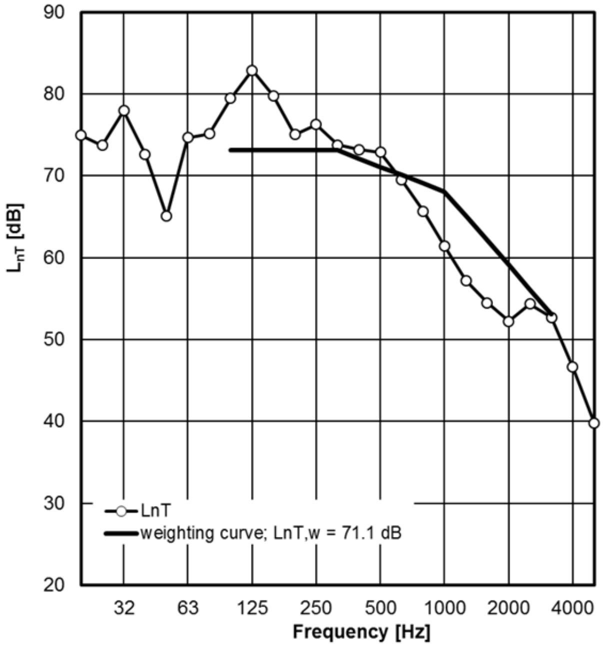


Fig. 1: weighting curve of DIN EN ISO 717-2 and measured values of the standard tapping machine on the timber floor without screed and floor covering in test facility P8 of the IBP.

The diagram shows that the unfavorable exceeding third octave values for the floor occur at low frequencies from 100 to 500 Hz. The characteristics of the measuring curve below 100 Hz are not taken into account.

2.2.2 Weighted standardized impact sound pressure level $L'_{nT,w}$ with spectrum adaptation term C_I

The spectrum adaptation term C_I was introduced by the reviewed DIN EN ISO 717-2 [3] 1997. This additional value shall contribute to a better rating of the excitation by the standard tapping machine in regard to the real footstep noise, and to a better adjustment of the single number value to the human perception of impact noise. The sum from the weighted standardized impact sound pressure level $L'_{nT,w}$ and the spectrum adaptation term C_I can be calculated by:

$$L'_{nT,w} + C_I = L'_{nT,sum} - 15 \tag{3}$$

where:

$L'_{nT,sum}$: sum of the third octave band values of the defined frequency range in dB.

$L'_{nT,w}$: weighted standardized impact sound pressure level in dB

The sum of the third octave band values of the standardized impact sound pressure level is determined by:

$$L'_{nT,sum} = 10\log\left(\sum_{i=1}^{k} 10^{\frac{L'_{nT,i}}{10}}\right) [\mathrm{dB}] \tag{4}$$

$L'_{nT,i}$: standardized impact sound pressure level in third-octave band i in dB. Hereby, the frequency range from 100 to 2500 Hz or from 50 to 2500 Hz is taken into consideration. The frequency range used is described by an index of C_I ($C_{I,100\text{-}2500}$ or $C_{I,50\text{-}2500}$).

k: number of frequency bands

The spectrum adaptation term is calculated by a conversion of the equation (3):

$$C_I = L'_{nT,sum} - 15 - L'_{nT,w} \tag{5}$$

As it can be seen from the equations, the calculation of the spectrum adaptation term is a different rating method than the assessment by the shifted weighting curve. Since the spectrum adaptation term is only meaningful in combination with the normalized or standardized impact sound pressure level, the explicit calculation of the normalized or standardized impact sound pressure level is no longer necessary. This would also make the rating method with the shifting of a reference curve unnecessary. This is taken into consideration in the draft of ISO 16717 [23], which shall replace the current DIN EN ISO 717 in the future.

2.2.3 Weighted standardized impact sound pressure level $L'_{nT,w}$ according to Gösele

In 1965, K. Gösele [19] suggested the definition of an ideal weighting curve for impact sound rating. In his opinion the ideal weighting curve shall rate the impact sound adjusted to the sensitivity of the human hearing, and shall reduce the differences between real noises of impact sound noise and those of the standard tapping machine. Gösele found that the A-weighted scale better accounts for the frequency-dependent sensitivity of human hearing and also better rates the impact sound. The standard tapping machine is very loud in comparison with walking noise or other living noise, and in contrast to the walking noises it is clearly higher in frequencies. Nevertheless, according to Gösele the ideal weighting curve shall be optimized and not the tapping machine. He also wanted to consider other noises of impact sound, which are higher in frequency then walking, for example the dropping of objects. „If both cases are taken into consideration, an averaged curve can be searched, whereby the frequency of annoyance of the one or the other source can both be regarded. It is, however, more useful to take both kinds of excitation into consideration by taking the stricter of the two requirements as a basis.“ Due to these considerations he suggested the weighting curve represented in Figure 2.

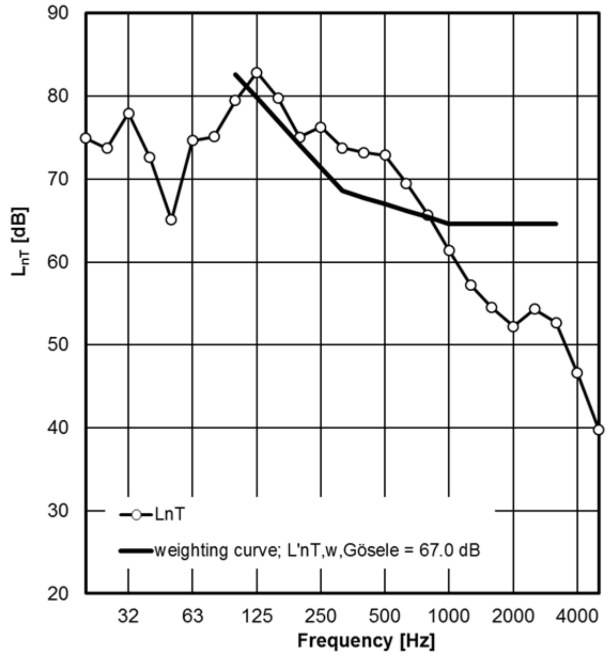


Fig. 2: weighting curve according to Gösele [19] and measured values of the standard tapping machine on a timber floor in the test facility P8 of the IBP.

The weighting curve of Gösele increases towards low frequencies and possesses a shape opposite to the ISO 717 weighting curve. The weighted frequency range is with 100 to 3150 Hz the same. The rating methodology is similar to ISO 717.

2.2.4 Weighted standardized impact sound pressure level $L'_{nT,w}$ according to Fasold

In 1965, Fasold [24] also published a suggestion for a weighting curve. In his opinion the essential tasks of rating were the definition of a minimum requirement for noise control as well as the fact that the results should correlate well with the subjective acoustical impression.

To define the weighting curve a „reasonable noise“ was determined, which residents must tolerate, if noise is audible from adjacent apartments. In a second step, the „mean annoying living noise“ was determined composed by various noises within apartments. The weighting curve was defined by means of the two processes. Subsequently, the suitability of the derived curve was to be investigated or verified by calculations of loudness and subjective measurements.

The weighting curve of Fasold [24] was adjusted to the frequency response of the „mean annoying living noise“ and simultaneously observes the characteristics of the standard tapping machine.

To derive the weighting curve Fasold applied the following method:

To the reasonable noise in one-third octave bands, 5 dB were added so that octave levels were achieved. This curve gave usual living noise with distinctively lower levels than those of the standard tapping machine. The difference between standard tapping machine level and the level of the „reasonable noise“ were added to the level of the „reasonable noise “. The impact sound pressure level L_T was converted by

$$\mathrm{L_N} = \mathrm{L_T} - 10\left(\lg \frac{\mathrm{A_0}}{\mathrm{A}}\right)[\mathrm{dB}] \tag{6}$$

with

L_T: impact sound pressure level in dB

A: sound absorption area from averaged living rooms in m²

A_0: equivalent sound absorption area of 10 m²

Tohe normalized impact sound pressure level L_N and defined as weighting curve. The intensification of the weighting curve in the range from 800 Hz to 3150 Hz was to consider the increased annoyance of this frequency band for human hearing. The weighting curve proposed by Fasold is shown in Figure 3.

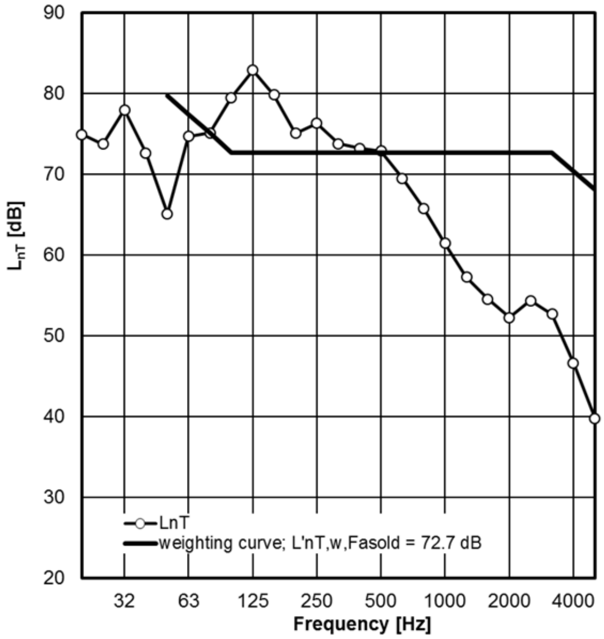


Fig. 3: weighting curve according to Fasold [24] and measured values of the standard tapping machine on the timber floor in test facility P8 of IBP.

The weighting curve according to Fasold shows a different gradient in comparison to the curve of ISO 717. The curve has a constant value within the building acoustic measurement range from 100 to 3150 Hz. It is essential that the weighted frequency range reaches from 50 to 5000 Hz. The curve increases below 100 Hz up to 50 Hz and decreases at high frequencies from 3150 Hz to 5 kHz. The rating methodology is similar to ISO 717.

2.2.5 Weighted standardized impact sound pressure level $L'_{nT,w}$ according to Bodlund

K. Bodlund describes in [25] three fundamental options to solve the problem of rating impact sound. One solution would be to introduce a new technical impact sound source, which best reproduces the real impact sound, or to modify the rating methods to determine the single number value. He also considered using both options simultaneously. In his work, he decided to modify the rating method, since the standard tapping machine had already been established as technical impact sound source.

In his investigations he also found out that the spectrum of the standard tapping machine does not cover the spectrum of living impact sound in the low-frequency range and that the weighting curve of DIN EN ISO 717-2 [7] weights the mean and higher frequencies considerably stronger than the low frequencies.

By correlation investigations between the subjective assessment of residents in buildings and the single number parameters determined from a variety of different weighting curves, Bodlund [25] defined his reference curve. A large-scale study was carried out in Sweden for this purpose. Sound measurements were carried out in various apartment houses in timber and massive construction, and in discussions with apartment owners the subjective auditory impression with regard to impact sound was inquired. The weighting curve derived by Bodlund [25] is shown in Figure 4.

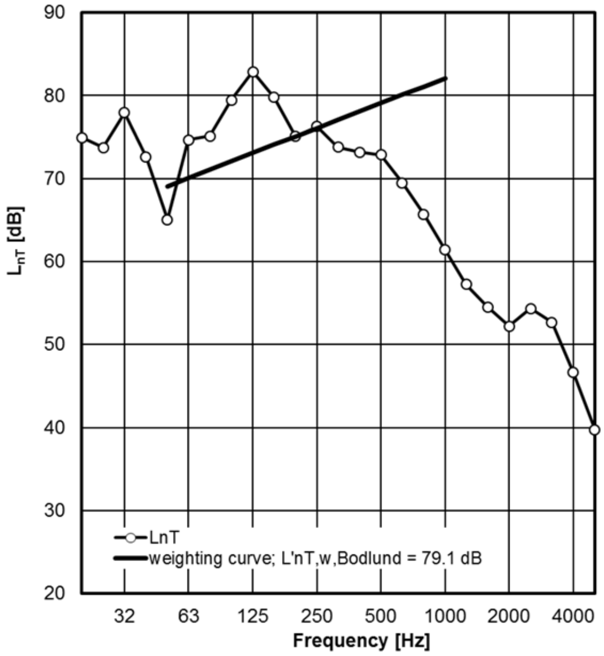


Fig. 4: weighting curve according to Bodlund [25] and measured values of the standard tapping machine on the timber floor of test facility P8 of IBP.

The weighting curve covers a frequency range from 50 to 1000 Hz. Frequencies higher than 1000 Hz are not considered which is adequate for the usual impact sound of living noise. The curve shows a straight line with positive increase of 1 dB per one-third octave. Thus, the low frequencies are clearly stronger weighted then higher frequencies. The reference curve shifting procedure and the maximum sum of 32 dB as well as the determined single number parameter by the value of the shifted reference curve at 500 Hz is similar to DIN EN ISO 717-2.

2.2.6 Weighted standardized impact sound pressure level $L'_{nT,w}$ according to reversed A-weighting

In his publication of 1999, P. Sipari [34] continues an idea of Gösele [19] by using the reversed A-weighting as reference curve to determine the single number value. This is equivalent to subtracting the A-weighting from the standardized impact sound pressure level and using a weighting curve equal over all frequencies. This idea of rating is applied in this project. The method of shifting the weighting curve and of the maximum sum of 32 dB was maintained from the ISO 717 method. The reference curve of the reversed A-weighting is shown in Figure 5.

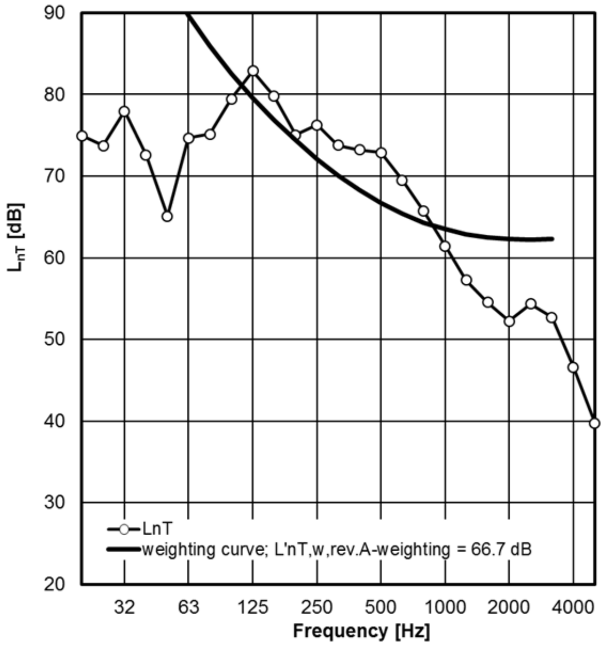


Fig. 5: weighting curve according to reversed A-weighting and measured values of the standard tapping machine on the timber floor in test facility P8 of IBP.

Hereby, the extended building acoustic measurement range from 50 to 3150 Hz is considered. The curve shows that the rating is performed rather at the mid frequencies due to the increase of the weighting curve towards low frequencies.

2.2.7 Weighted standardized impact sound pressure level $L'_{nT,w}$ according to Hagberg

Hagberg‘s considerations in [26] from 2010 are based on Bodlund’s investigations [25]. In the process, he takes up the results and extends them by carrying out further measurements and questionnaires on the subjective auditory impression of inhabitants. As Bodlund did he also carried out correlation analyses by comparing the subjective parameters with the measured standardized single number values and others, achieved by different rating methods.

In his investigations he found that the reference curve must be plane in the mid and high frequency range. Only in the low-frequency range he suggests a decrease of 5.5 dB / third-octave of the curve towards low frequencies to 50 Hz, so that low frequencies between 50 and 100 Hz are clearly increasingly weighted to low frequencies. From 100 Hz on upwards his curve has frequency independent values.

Hagberg varied the inclination of the curve in the low frequency range for evaluation until the correlation coefficient between technical rating and subjective assessment was greatest. The great inclination below 100 Hz weights the higher annoyance effect in the low frequency range, if for example walking noise occurs or children are jumping around. In contrast to Bodlund, Hagberg defines his curve up to 3150 Hz, since he assumes that also high frequency excitations might results in annoyance in buildings. Hagberg denotes this weighting curve in [26] new,03. It is shown in Figure 6.

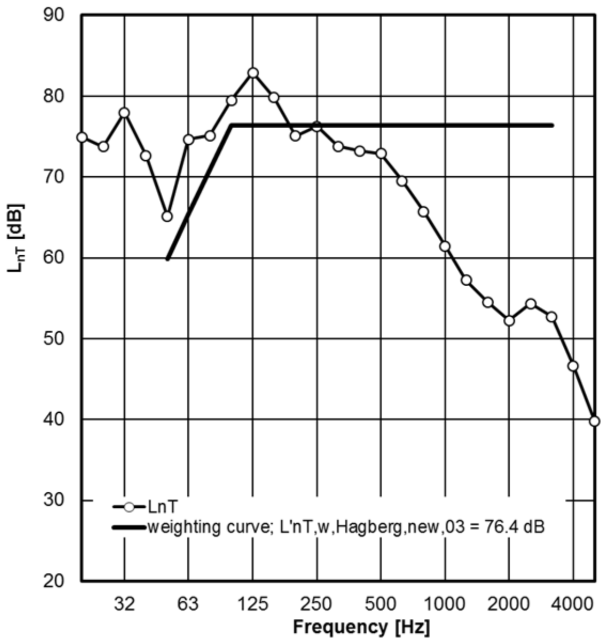


Fig. 6: weighting curve according to Hagberg new,03 [26] and measured values of standard tapping machine on the timber floor in test facility P8 of IBP.

The rating method is performed similar to the ISO 717 method.

In his further considerations, Hagberg suggested that the plane curve should decrease with a defined inclination in the high frequency range, since not only timber floors should be covered by the method but also massive floors with hard floor coverings. In this context, high frequencies caused by other sources of excitation, for example the dropping of hard objects, could cause problems. Without any further investigations he defined a decrease of 1 dB / one-third octave above 315 Hz and developed weighting curve new,04, which is shown in Figure 7.

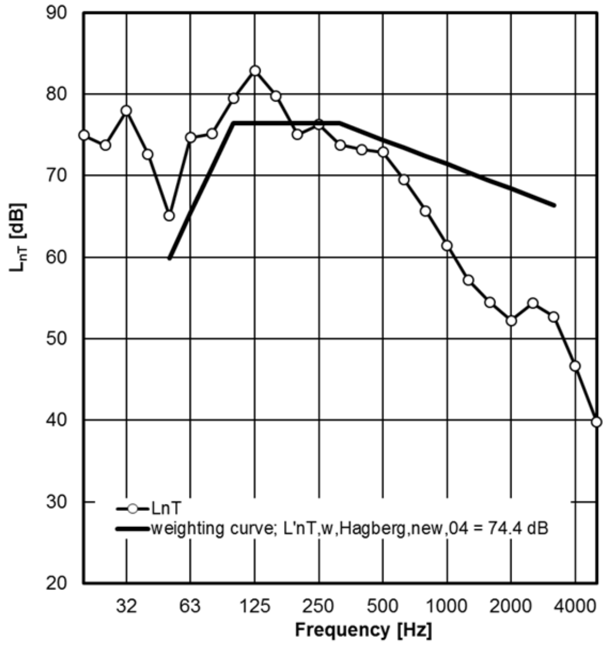


Fig. 7: weighting curve according to Hagberg new,04 [26] and measured values of standard tapping machine on the timber floor in test facility P8 of IBP.

The graphs of the weighting curves in Figure 6 and 7 show that the exceeding values for the shown measuring curve occur at the same frequencies. Thus, both methods should give similar single number values. However, for method new,04 it is by 2 dB lower than for method new,03, since the value of the shifted weighting curve at 500 Hz is by 2 dB lower. The different value of the single number parameter, however, is not significant, since this difference occurs for all measuring curves.

2.2.8 Weighted standardized impact sound pressure level $L'_{nT,w}$ according to the hearing threshold

The hearing threshold was defined in DIN EN ISO 389-7 [35] and describes the „sound pressure level, at which a person correctly gives perception of a presented signal in half of the causes under certain conditions and after several repetitions“. Therefore, the hearing threshold gives the limit of human hearing. The idea to use the hearing threshold as weighting curve is based on the consideration that any exceeding of the hearing threshold can cause annoyance for the person affected. A certain acceptable exceeding is included in the sum of 32 dB, as in the ISO 717 rating method. The hearing threshold is thoroughly safeguarded and standardized for the total relevant frequency range from 20 to 5000 Hz. The question, however, is whether the application of the hearing threshold for noise of the tapping machine is suited to assess noise from impact sound. This question is answered by the evaluation of chapter 5.

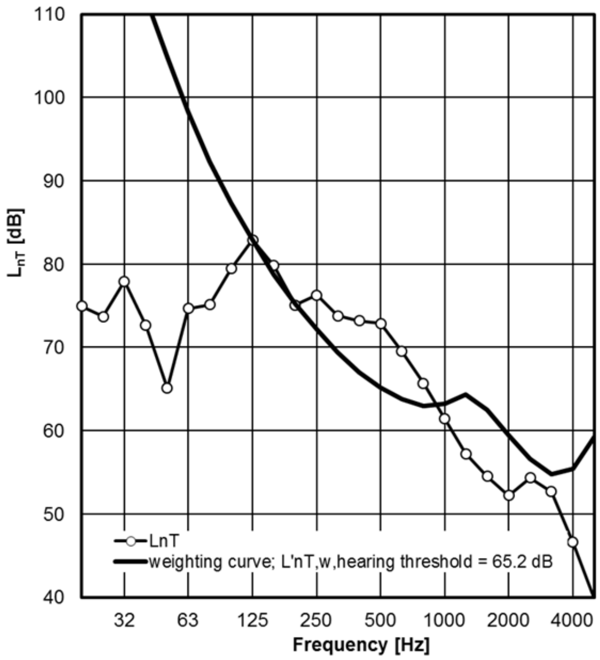


Fig. 8: weighting curve of hearing threshold according to DIN EN ISO 389-7 [35] and measured values of the standard tapping machine on the timber floor in test facility P8 of IBP.

The inclination of the weighting curve is very steep in the low frequency range and reaches the lowest point at approx. 4000 Hz before increasing to higher frequencies. The total frequency range from 20 Hz to 5000 Hz is taken into consideration for rating. Here again, the sum of the unfavorable deviations (exceeding values) of the measuring curve in comparison to the weighting curve smaller than 32 dB is used. Figure 8 shows that rating for this measurement is decisive in the average frequency range between 200 and 1000 Hz, caused by the shape of the measurement curve and the fact that the weighting curve steeply increases at low frequencies.

2.2.9 Weighted impact sound pressure level according to JIS A 1419-2

The standard to rate impact sound reduction in Japan is JIS A 1419-2 [29]. Various rating methods are described there for the standardized tapping machine and the Japanese rubber ball. The first method complies with DIN EN ISO 717-2. Three additional methods are also described which can also be used to determine impact sound insulation. In contrast to DIN EN ISO 717-2, octave levels are considered in these other methods.

Conversion from on-third octave to octave levels $L'_{n,1/1}$ is calculated as follows:

$$\mathrm{L'}_{\mathrm{n,1/1}} = 10\log\left(\sum_{\mathrm{i=1}}^{3} 10^{\frac{\mathrm{L'}_{\mathrm{n,1/3,i}}}{10}}\right) [\mathrm{dB}] \quad (7)$$

$L'_{n,1/3,i}$: impact sound pressure level of one-third octaves in the related octave band

A correction of the reverberation time is not applied for the additional rating methods in JIS A 1419-2. These methods are described in the following.

2.2.10 JIS A 1419-2 method 2: weighted impact sound pressure level $L'_{i,r}$

This rating method is based on a family of reference curves comprising the frequency range from 63 to 2000 Hz. The individual octave band levels of the reference curves are listed in tables in the standard. The distance of the individual curves is 5 dB. The reference curves incline to low frequencies continuously and have the same gradient. The reference curves are shown in Figure 9.

The octave band values, which are calculated by means of equation 7 from the measured one-third octave values, are entered in the diagram of the reference family of curves. The highest curve of the reference curves is taken as weighting curve, which is exceeded by a maximum of one octave band level by not more than 2 dB. If one octave level exceeds the reference curve by more than 2 dB or several octave levels exceed the reference curve, the next higher curve will be used for rating. The single number parameter is determined by the value of the reference curve used at 500 Hz. The result is whole-number single number values in steps of 5 dB. The reference family of curves and the measuring curve of the timber floor is shown in Figure 9.

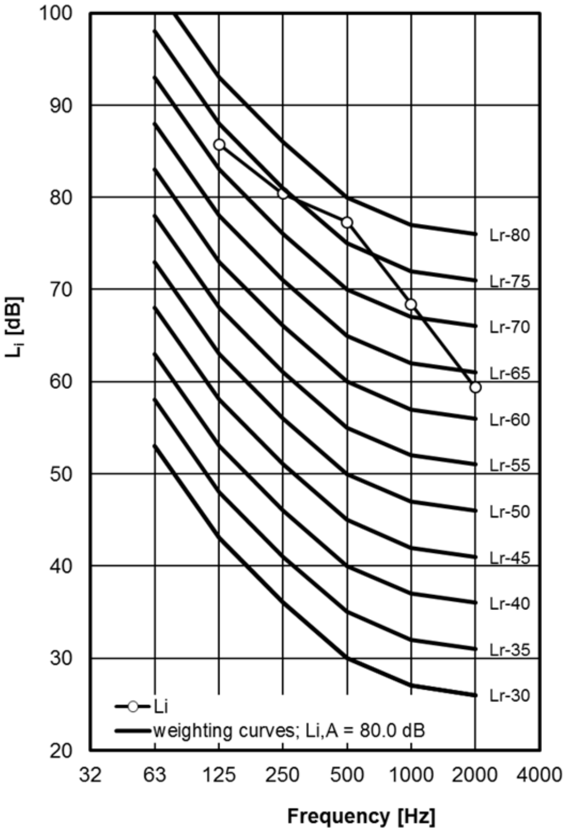


Fig. 9: family of curves of rating method JIS A 1419-2 method 2 and measured values of standard tapping machine on the timber floor in test facility P8 of IBP.

2.2.11 JIS A 1419-2 method 3: weighted impact sound pressure level $L'_{i,A}$

To determine the single number value of the weighted impact sound pressure level $L_{i,A}$ each level of the different microphones is A-weighted and energetically added up over the frequency range from 20 to 5000 Hz:

$$L'_{i,A,e} = 10\log\left(\frac{1}{k}\sum_{i=1}^{k} 10^{\frac{L'_{i,A,i}}{10}}\right) \text{ [dB]} \tag{8}$$

With:

$L'_{i,A,i}$: A-weighted measured impact sound pressure level in the one-third octave band i

k: number of frequency bands

The derived single number values of the impact sound pressure level $L'_{í,A,e}$ are summarized by arithmetic averaging of the microphone positions to the value:

$$L'_{i,A} = \left(\frac{1}{n}\sum_{i=1}^{n} L'_{i,A,e,i}\right)\ [dB] \tag{9}$$

$L'_{i,A,e,i}$: energetically averaged impact sound pressure level for each microphone position i

n: number of microphone positions

2.2.12 JIS A 1419-2 method 4: weighted impact sound pressure level $L'_{i,AW}$

In method 4 of JIS A 1419-2 the reference curve method is used, which is similar to that described in DIN EN ISO 717-2. A reference curve is defined, which must be shifted. Specifications for the reference curve and for the measured values are based on octave band levels. The reference curve rates the octave band levels in the frequency range from 125 to 2000 Hz for the standard tapping machine. The curve declines to higher frequencies. The reference curve is shifted in 1 dB steps until the sum of exceeding octave band values reaches a maximum but is smaller than 10 dB. The impact sound pressure level $L'_{i,A,w}$ which is assessed from this is determined by the value of the shifted reference curve at 500 Hz. The shifted reference curve and the measured values of the timber floor in octaves are given in Figure 10.

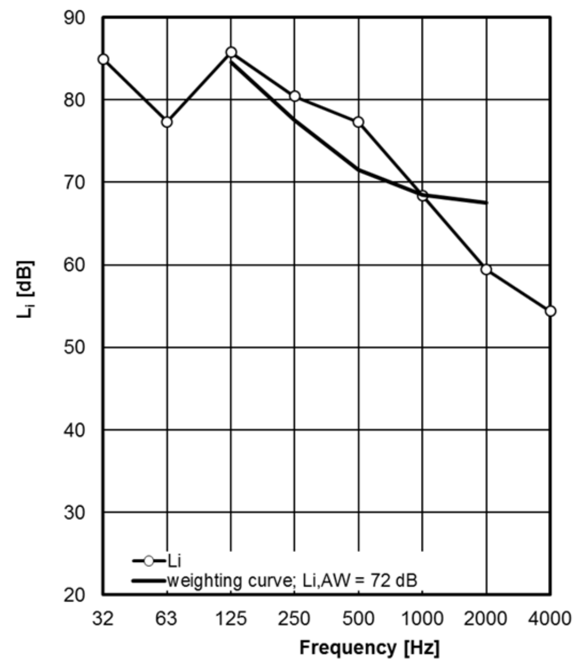


Fig. 10: shifted reference curve of the rating method JIS A 1419-2 method 4 and measured values of the standard tapping machine on the timber floor in test facility P8 of IBP.

2.2.13 A-weighted standardized sum of impact sound levels L'$_{nT,A,sum}$

The sensitivity of human hearing with regard to the perceived levels of loudness of the noise is frequency-dependent. Sounds of similar sound pressure are perceived as being more silent at low frequencies than at high frequencies. The A-weighting considers this characteristic for sounds with low sound pressure levels. There are also other weighting curves, for example B-, C- and D-weighting, which are valid for higher loudness levels. The A-weighting is generally mostly used and is even partially applied for loud noises, where other weighting curves would be more appropriate. The weighting curves can be realized by filters or can be added on the one-third octave or octave band spectra. The tabulated values of the A-weighting are given in DIN EN 61672-1.

The standardized sum of the impact sound pressure level L'$_{nT,A,sum}$ is achieved by the energetic addition of the A-weighted one-third octave values in the defined frequency range:

$$\mathrm{L'}_{\mathrm{nT,A,sum}} = 10\log\left(\sum_{\mathrm{i}=1}^{\mathrm{k}} 10^{\frac{\mathrm{L'}_{\mathrm{nT,A,i}}}{10}}\right)\ [\mathrm{dB}] \qquad (10)$$

$L'_{nT,A,i}$: A-weighted standardized impact sound pressure level for one-third octave band i

k: number of frequency bands

Since primarily the low frequencies are decisive for the noise and annoyance of impact sound and the essential sound transmission takes place in the frequency range below 2500 Hz in the measurements performed, the frequency range from 50 to 2500 Hz was considered for the first single number value. Another single number value was added in the extended frequency range from 20 to 2500 Hz, since A-levels for timber floors can be decisive even at frequencies below 50 Hz for the sum of the A-weighted third octave band values. Since these very low frequencies can be perceived as very annoying, it was expected that the sum of the A-weighted third octave band values with an extended frequency range could result in a better correlation to the subjective rating. The frequency range used is marked by denominating the frequency range in the index of the single number value. Results for the correlation analysis are given in of chapter 5.

2.2.14 Rating method according to AkuLite $C_{I,AkuLite,20\text{-}2500}$

The Swedish research project AkuLite [27, 28], designed as previous project of the AcuWood project also investigated the correlation of objective and subjective ratings of impact sound. This investigation, however, was carried out in Sweden, and the subjective assessment was based on paper questionnaires filled out and returned by the residents, the results were correlated to the measured values of the same buildings. A technical rating method was proposed as a result of the analysis in this project, which better correlated with the subjective assessment in the AkuLite project. Consequently, this rating method was also used in the AcuWood project.

The rating according to AkuLite is based on the method according to DIN EN ISO 717 by integrating the spectrum adaptation term C_I. The calculation of C_I is carried out according to DIN EN ISO 717 by

$$\mathrm{C_I} = \mathrm{L'_{n,sum}} - 15 - \mathrm{L'_{n,w}}. \tag{5}$$

The rating by C_I was extended to the frequency range from 20 to 2500 Hz in the AkuLite project:

$$\mathrm{C_{I,20-2500}} = \mathrm{L'_{n,sum,20-2500}} - 15 - \mathrm{L'_{n,w}} \tag{11}$$

Equation (11) can be converted by consideration of equation (4) in

$$C_{I,20-2500} = 10\log\left(\sum_{i=1}^{k} 10^{\frac{L'_{n,i}-15}{10}}\right) - L'_{n,w} \qquad (12)$$

with

k: 22 for all one-third octave bands from 20 to 2500 Hz

In a second step, the constant of 15 dB, which is subtracted in calculating the sum (eq. 11), is modified for the one-third octave bands used. Hereby, a frequency-dependent component is introduced in the summation, which takes into consideration the subjective assessment. Thus the rating proposed in the AkuLite project is given by:

$$C_{I,AkuLite,20-2500} = 10\log\left(\sum_{i=1}^{k} 10^{\frac{L'_{n,i}+W_I}{10}}\right) - L'_{n,w} \qquad (13)$$

The weighting function W_I is represented in Table 1.

Table 1: Frequency weighting of rating method $C_{I,AkuLite,20-2500}$.

Frequenz	W_I
20	-7.0
25	-9.0
31.5	-11.0
40	-13.0
50	-15.0
63	-15.0
80	-15.0
100	-15.0
125	-15.0
160	-15.0
200	-15.0
250	-15.0
315	-15.0
400	-15.0
500	-14.0
630	-13.0
800	-12.0
1000	-11.0
1250	-10.0
1600	-9.0
2000	-8.0
2500	-7.0

The weighting function of AkuLite shows that the low frequencies as well as the high frequencies are stronger weighted by a lower subtrahend. The stronger weighting at high frequencies is aimed at potential excitation by living noise, for example the dropping of hard objects etc. The stronger weighting at low frequencies, however, takes into consideration the higher annoyance effect of walking noise in this frequency range. More detailed information on the weighting method can be found in [28].

2.2.15 Rating method according to AkuLite $C_{I,AkuLite,20\text{-}2500,Sweden}$

Another variation of the AkuLite rating was also investigated in the AcuWood project. It is given in the Swedish regulation (Swedish standard SS 25267), where the calculatory room volume is limited to 31 m³, meaning that for all rooms with lower volume than 31 m³ $L'_{n,w}$ is used, for all rooms above a volume of 31 m³ $L'_{nT,w}$ is applied. (At a room volume of 31 m³ $L'_{n,w}$ and $L'_{nT,w}$ are equal).

2.3 Rating method for the modified tapping machine

The modified tapping machine was proposed by Scholl [36] as excitation source adapted to walking noise. It is based on using the standard tapping machine equipped by an additional resilient interlayer between the hammers of the tapping machine and the floor to be measured. In the process, the impedance of the tapping machine for the floor is modified in a way that it is similar to the impedance of the human foot. No rating methods are available for the modified tapping machine. The rating method of ISO 717-2 can probably be applied to the impact sound pressure levels measured by the modified tapping machine. Since the weighting curve used, however, was not developed for this source this method does not seem to be reasonable. Therefore, the sum of the A-weighted third octave band values was used as single number parameter in the AcuWood project.

2.3.1 A-weighted standardized sum impact sound levels $L'_{nT,A,sum}$

The modified tapping machine is designed as technical substitute source of walking noise due to its construction. Thus it is obvious to characterize it by the standardized sum of impact sound levels as single number parameter. This rating method is described in chapter 2.2.13 and calculated according to equation (10).

2.4 Rating method for the Japanese rubber ball

The Japanese rubber ball was developed by Tachibana in Japan [30]. Excitation is performed by dropping the ball from a height of 1 m on the floor to be measured. In Asia, the Japanese rubber ball is used as impact sound source, therefore rating methods had been developed in Japan. These rating methods are generally described in JIS A 1419-2 [29]. The rating methods are applied for the standard tapping machine as well as for the Japanese rubber ball. Since the frequency ranges applied are partially different, the methods for the rubber ball are explained in the following. The significant difference between the rubber ball and the standard tapping machine is that the rubber ball generates an impulse-like excitation, the standard tapping machine, howevergenerates a quasi-constant sound. Therefore, the maximum spectrum $L_{i,Fmax}$ of the ball is generally considered by fast weighting (τ=125 ms) in the rating of the Japanese rubber ball. A reverberation correction of the measured levels is not applied in JIS A 1419-2 for the rubber ball.

2.4.1 JIS A 1419-2 method 1: rating according to DIN EN ISO 717-2

The rating method 1 of JIS A 1419-2 complies with the rating according to DIN EN ISO 717-2. It was developed for the standard tapping machine and therefore it was not applied for the Japanese rubber ball.

2.4.2 JIS A 1419-2 method 2: weighted impact sound pressure level $L'_{i,Fmax,r}$

Method 2 of JIS A 1419-2 can be transferred to the rubber ball. The reference family of curves for the rubber ball is the same as for the standard tapping machine and the regulations to determine the single number value are identical. Figure 11 shows the reference curves and measured values of the Japanese rubber ball on the timber floor.

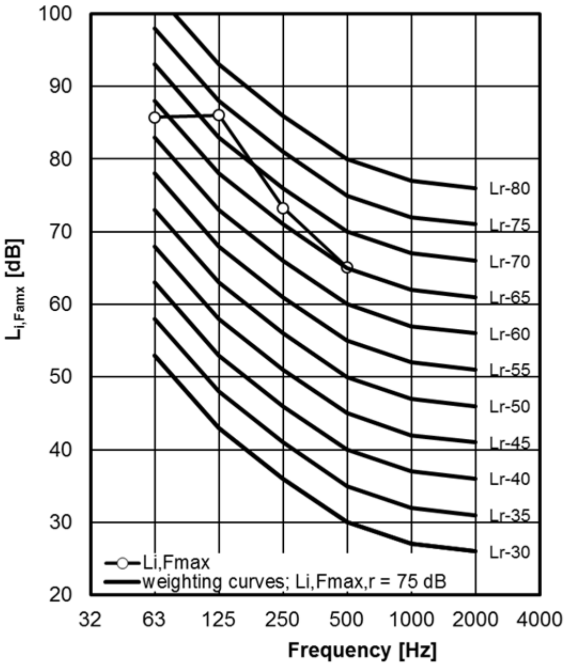


Fig. 11: reference family of curves of rating method JIS A 1419-2 method 2 and measured values of the Japanese rubber ball on the timber floor in test facility P8 of IBP.

2.4.3 JIS A 1419-2 method 3: weighted impact sound pressure level $L'_{i,A,Fmax}$

Already described in chapter 2.2.11, method 3 of JIS A 1419-2 is also valid for the rubber ball with its maximum levels $L_{i,Fmax}$, which must be A-weighted for this method.

The single number value is energetically added over the frequency range from 20 to 5000 Hz:

$$L'_{i,A,Fmax,e} = 10\log\left(\frac{1}{k}\sum_{i=1}^{k} 10^{\frac{L'_{i,A,Fmax,i}}{10}}\right)\ [dB] \tag{11}$$

with

$L'_{i,A,Fmax,i}$: A-weighted measured impact sound maximum level in the one-third octave band i

k: number of frequency bands

The derived single number values of the impact sound level $L'_{i,A,Fmax,e}$ are summarized by arithmetic averaging of the microphone positions to a value of:

$$L'_{i,A,Fmax} = \left(\frac{1}{n}\sum_{i=1}^{n} L'_{i,A,Fmax,e,i}\right)\ [\mathrm{dB}] \qquad (12)$$

$L'_{i,A,Fmax,e,i}$: (over several excitations) energetically averaged impact sound level for each microphone position i

n: number of microphone positions

2.4.4 JIS A 1419-2 method 4: weighted impact sound pressure level $L'_{i,Fmax,AW}$

The reference curve method 4 for the Japanese rubber ball is the same as described in chapter 2.2.12. It is, however, applied to the measured maximum level $L_{i,Fmax}$ for the rubber ball. Another difference is that the weighting curve for the octaves 63 to 500 Hz is defined and that the maximum exceeding of the weighting curve must not exceed 8 dB. The shifted reference curve and the measured values of the Japanese rubber ball on the timber floor in octaves are represented in Figure 12.

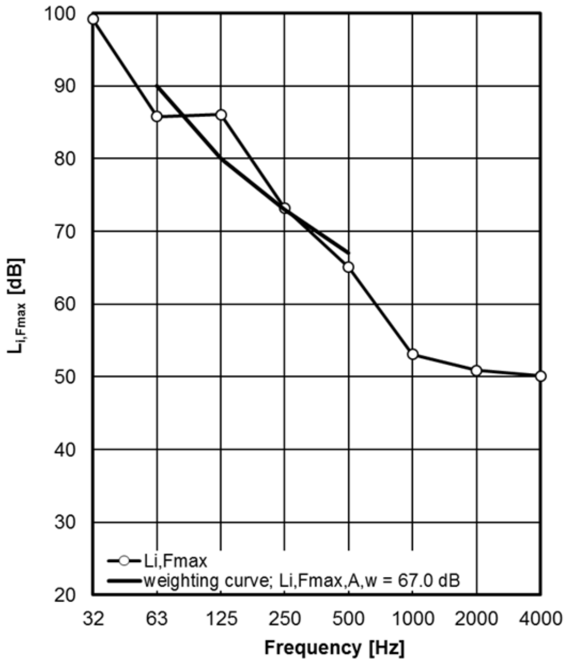


Fig. 12: shifted reference curve of rating method JIS A 1419-2 method 4 and measured values of the Japanese rubber ball on the timber floor in test facility P8 of IBP.

The single number value of this method is again the value of the shifted weighting curve at 500 Hz.

2.4.5 KS F 2863-2 method 1: weighted impact sound pressure level $L'_{i,Fmax,AW,H}$

The method of the Korean standard KS F 2863-2 [37] to rate the Japanese rubber ball complies with method 4 of JIS A 1419-2 [29] described in chapter 2.4.4.

2.4.6 KS F 2863-2 method 2: weighted impact sound pressure level $L'_{i,avg,Fmax,(63\text{-}500Hz)}$

The rating is performed by arithmetic averaging of the measured maximum octave levels in the frequency range from 63 to 500 Hz. The measured levels have no reverberation time correction and are not A-weighted.

The arithmetic averaging is performed as follows:

$$L'_{i,avg,Fmax,63-500Hz} = \left(\frac{1}{k}\sum_{i=1}^{k} L'_{i,Fmax}\right)\ [\mathrm{dB}] \qquad (13)$$

with:

$L'_{i,Fmax}$: energetically averaged maximum impact sound level for each octave band i

k: number of octave bands

2.4.7 A-weighted standardized maximum sum level $L'_{nT,A,F,max,sum}$

The Japanese rubber ball is also designed as a substitute source for walking noise. In contrast to the modified tapping machine the excitation is impulse-like. Therefore, the maximum spectrum $L_{i,Fmax}$ of the ball is generally considered with fast weighting (τ=125 ms) for the rating of the Japanese rubber ball. The standardized maximum sum level is calculated from it as single number value. This rating method is described in chapter 2.2.13 and calculated according to equation (10).

3 Results: Correlation of subjective and objective parameters

The significant results of the project are explained in the following two chapters. In this context, the correlation of the subjective and objective rating represents the main method to assess the technical impact sound sources, the rating methods and the basis to give requirement values for the rating methods. The questionnaires of residents of timber constructions serves to verify the subjective ratings determined by laboratory listening tests, and thus to verify the results of the project. The results of the questionnaires of the residents are described in chapter 4.

3.1 Representative impact sound source

The noise produced by the standard tapping machine for impact sound measurements is clearly different from the noise of impact sound from real footsteps. The standard tapping machine produces a different excitation spectrum to walking as well as to other living noises. Therefore, the standard tapping machine represents real living noise rather poor. This different excitation spectrum is only partially compensated by the rating method of ISO 717. With the modified tapping machine and the Japanese rubber ball further technical sources are investigated in the AcuWood project, which were specifically developed with regard to walking noise caused by footsteps. The three technical sources were investigated with regard to representing living noise.

The most important impact sound source regarding the annoyance in apartment buildings is walking noise. Thus, real walkers were employed in the AcuWood project, and the sound pressure levels of their footsteps was recorded or measured in the receiving room. The laboratory measurements refer to a male walker with shoes and a male walker wearing socks as well as a female walker wearing shoes. Due the conditions of the measurements in buildings the sound level of only one male walker with shoes and with socks was measured. The walkers in the laboratory were different male and female persons, who produced relatively similar excitation while walking. For the measurements in the buildings, always the same person was employed as walker always using the same shoes. In a preliminary study for walking described in [38] a greater number of walkers was investigated as impact sound sources. Therefore, the male walker employed in the AcuWood project can be characterized to give an average excitation spectrum. A detailed description of the walkers can be found in [14]. The subjective annoyances of the different walkers determined by the listening test were arithmetically averaged for the same floor to obtain a subjective annoyance value for each floor.

The moving of a chair was investigated as a further living noise. Generally, this living noise is relatively loud and can be very well reproduced by using the same chair. The selection of the chair and the method of moving the chairs are described in [14]. In evaluating the results of the moving of the chair it must be mentioned that the noise of the moving of the chair is not representative for all kinds of chairs, but specifically valid only for this type of chairs. This is also true for the results of the listening test.

3.1.1 Representative impact sound source for walking (footstep noise)

An essential question in the AcuWood project was, how representative the technical impact sound sources are for the real footstep noise. The subjective annoyance of the noise assessed in the listening test served as the criterion. The reason is that the subjective annoyance of the noise is suggested to be the cause of complaints on noise due to impact sound. The subjective loudness of noises was also investigated in the listening test. The correlation of subjective loudness and subjective annoyance was very high for all investigated sources. The determination coefficient R^2 was at 0.99 for footstep noise, at 0.97 for noise from moving chairs, and at 0.98 for the Japanese rubber ball. Thus is can be assumed that primarily loudness determines the annoying effect of the investigated noises.

By comparing the subjective annoyance of the technical source and the subjective annoyance of the real source, a linear regression analysis was carried out for all measured floors. The various floor constructions in the figures have different colors and are differently marked. The various measuring points result from laboratory measurements of different floor coverings, see also [14]. By the measurements in the buildings, different floor constructions were analyzed [14, 15]. The analysis of data was based on a linear correlation. The determination coefficient R^2 of the linear regression was determined as the most important criterion for good agreement of the linear correlation. Figure 13 shows the comparison of subjective annoyances of the standard tapping machine and walking on various floors.

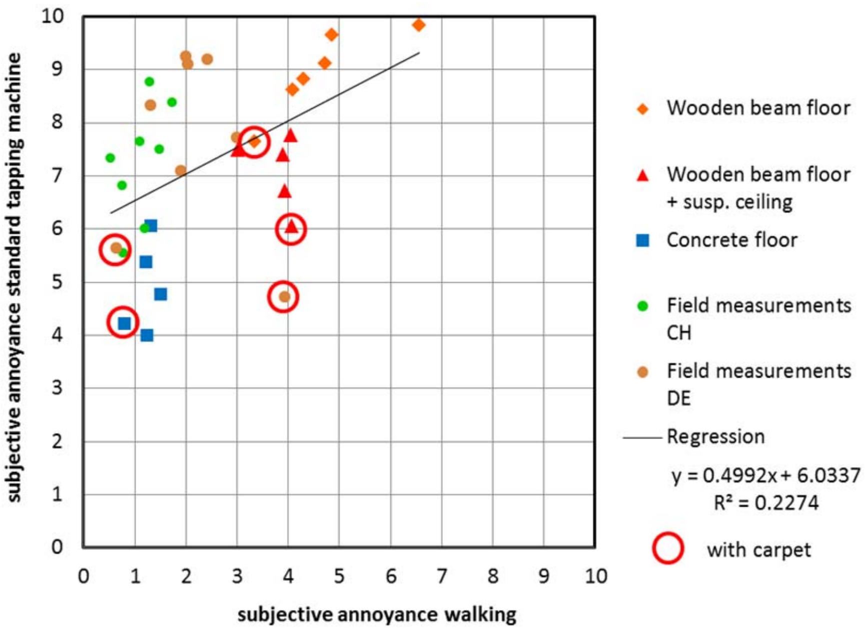


Fig. 13: comparison of the subjective annoyance of standard tapping machine and the subjective annoyance of walking.

The comparison of the subjective annoyance of the standard tapping machine and the subjective annoyance of the walking is given in Figure 13, showing the total shift of the values to a high annoyance of the standard tapping machine. This was to be expected, since the standard tapping machine is clearly louder than the footstep noise. It is evident, however, that similar subjective annoyances occur for the different floor constructions, for example the massive floor and the timber floor from measurements in buildings in Switzerland (measurements in buildings CH) produced by walkers. The annoyance of the standard tapping machine, however, occurs systematically different for the two types of floors and with clearly greater scattering. It must be noted that the reproducibility itself of the standard tapping machine is higher than that of the walkers (As already previously mentioned, the subjective annoyances of walking are mean values of different walkers).

The values of the laboratory measurement of the timber floor with suspended ceiling show a similar behavior. In this case, 4 floors show almost the same subjective annoyance of walking (the exception is the measurement with carpet with a subjective annoyance of walking of 3), the subjective annoyance of the standard tapping machine, however, shows a scattering of values from 6 to 8.

It must be mentioned that the measurements on floors with carpet are also included in the comparison. In general, all coverings should be included in the analysis. This was generally obeyed in this project. The application of the standard tapping machine on carpeted floors, however, results in a modification of the excitation source, since the standardized drop height of the hammers is not achieved, especially for deep-pile carpets. Thus, the drop height and the excitation are altered for the tapping machine on carpet. Similarly, the application of the modified tapping machine on carpeted floors leads to a different excitation then intended. .

Therefore, Figure 13 shows the measurements on carpet, which are marked by circles around the measured values. It is obvious that the floor with carpet clearly reduces the subjective annoyance of the standard tapping machine, the annoyance due to walking, however, is almost without any influence by the carpet.

The essential statement of the comparison in Figure 13 , however, can be derived from the determination coefficient R^2 of the linear regression. This value is $R^2=0.23$, meaning that the subjective annoyance of walking can only be insufficiently explained by the subjective annoyance of the standard tapping machine for the investigated floors. The correlation of the two parameters is very low. This is certainly due to the clearly different spectra of the sources, resulting in the insufficient correlation on the different floor constructions with various frequency-dependent characteristics. Therefore the standard tapping machine represents walking noise insufficiently.

The subjective annoyance of the modified tapping machine is compared to the subjective annoyance of walking in Figure 14 .

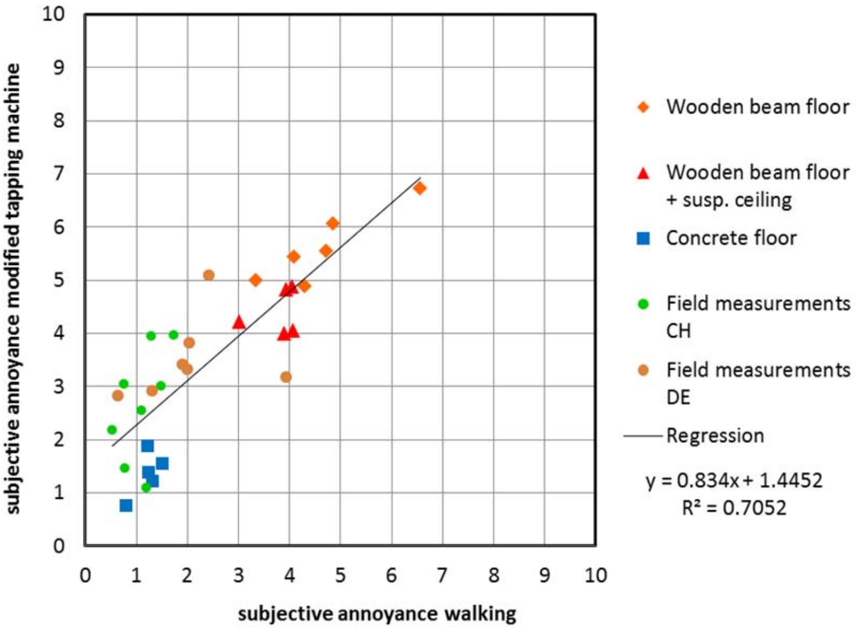


Fig. 14: comparison of the subjective annoyance of the modified tapping machine and the subjective annoyance of walking.

The comparison in Figure 14 shows that the correlation of the two parameters is clearly better for the modified tapping machine. Not only the values for the floors with carpets are closer to the linear regression, but also the scattering of the subjective annoyances on the same floors become more homogenous and show less scattering. All in all, the shifting of the measured values and thus the shifting of the linear regression toward higher values is clearly reduced, the modified tapping machine is perceived to be only slightly more annoying (and louder) than the footstep noise. The better correlation of the values is documented by a clearly higher determination coefficient of R^2=0.71. Therefore, the modified tapping machine represents footstep noise obviously better than the standard tapping machine.

The subjective annoyance of the Japanese rubber ball is compared to the subjective annoyance of walking in Figure 15.

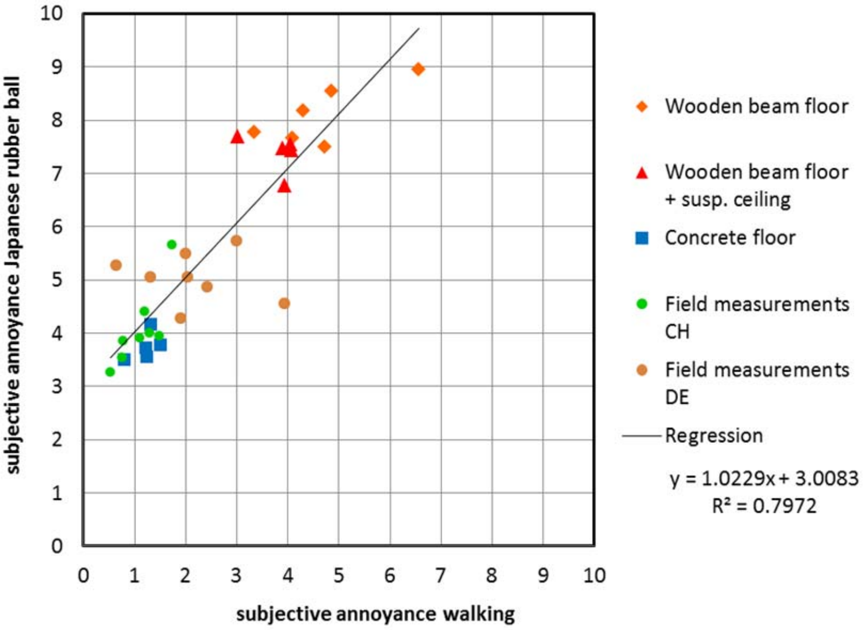


Fig. 15: comparison of the subjective annoyance of the Japanese rubber ball and the subjective annoyance of walking.

Again, there is a shift towards higher values in the comparison of the subjective annoyance of the Japanese rubber ball with the subjective annoyance of walking. The reason is certainly that the ball is clearly louder than walking. The scattering of the measured values, however, is clearly lower so that a determination coefficient $R^2=0.80$ is achieved here. Thus, the Japanese rubber ball represents best of all three technical excitation sources the walking noise with regard to the subjective annoyance.

3.1.2 Representative impact sound source for the moving of chairs

As in case of walking noise the three technical sources could also be used for the investigation of the moving of chairs with regard to the correlation of the subjective annoyance. The comparison of subjective annoyance is represented in Figure 16 for the standard tapping machine.

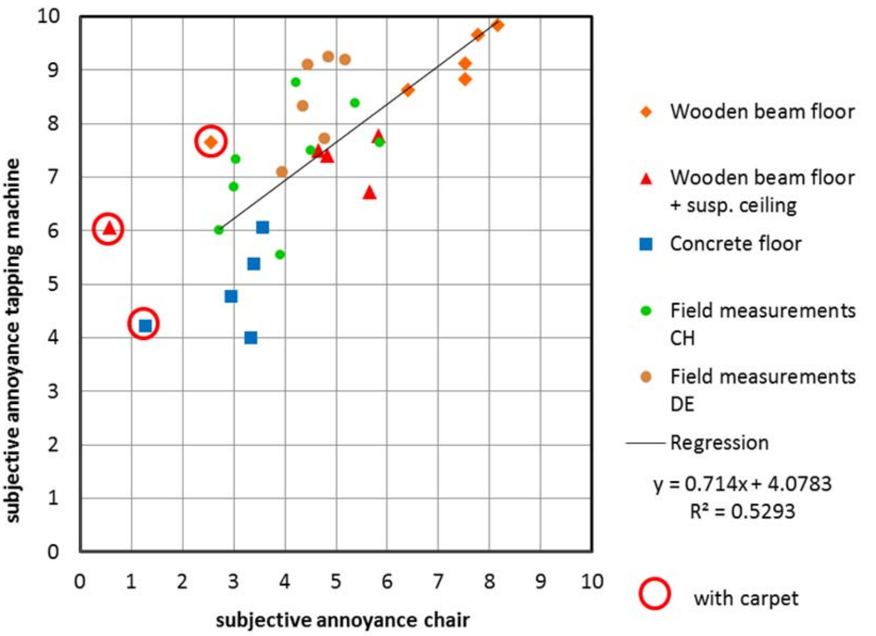


Fig. 16: comparison of the subjective annoyance of the standard tapping machine and the subjective annoyance of the moving of the chair.

As in case of the walking noise the subjective annoyance of the standard tapping machine is clearly higher in case of the moving of the chair. The scattering of the measured values, however, is lower, what can be ascribed to the fact that the measurements of the moving of the chair was frequently repeated and that the same source was used for all floors (For the walking mean values of various walkers were used so that part of the scattering can be explained by the different sources on different floors). If the individual floor types are considered, for example the massive floor, the scattering of the subjective annoyance of the standard tapping machine was clearly higher than the subjective annoyance of the moving of the chair. The lowest value of the subjective annoyance of the moving of the chair was achieved by the carpeted floor. The low value can be explained by the fact that the excitation of the chair is clearly modified on a carpeted floor. This is more obvious than in case of the standard tapping machine. The stick-slip effect of the moving of the chair across the floor is almost eliminated on carpeted floors so that the excitation of the source is strongly modified. Therefore, no measurements on carpeted floors were carried out in buildings. This is why the measured values on carpeted floors were excluded in the linear regression analysis in Figure 16. The determination coefficient R² achieves a value of 0.53 in Figure 16. It can be concluded that the standard tapping machine better represents the noise of moving of the chair than the walking noise.

The comparison of the subjective annoyance of the modified tapping machine and the moving of the chair is represented in Figure 17.

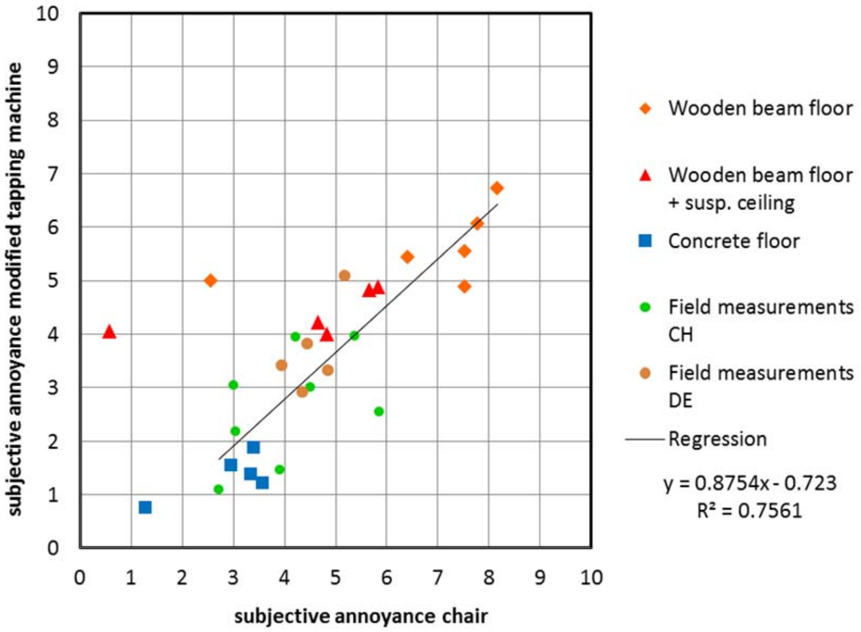


Fig. 17: comparison of the subjective annoyance of the modified tapping machine and the subjective annoyance of the moving of the chair.

The comparison in Figure 17 shows that the moving of the chair is perceived as being more annoying, since the values are shifted to higher annoyances. The three discrepant values by the laboratory measurement on carpeted floors are clearly visible and were not taken into account in the linear regression. With $R^2 = 0.76$ the modified tapping machine represents the moving of the chair better than the standard tapping machine.

Figure 18 shows the comparison of the subjective annoyance of the Japanese rubber ball with the subjective annoyance of the moving of chairs.

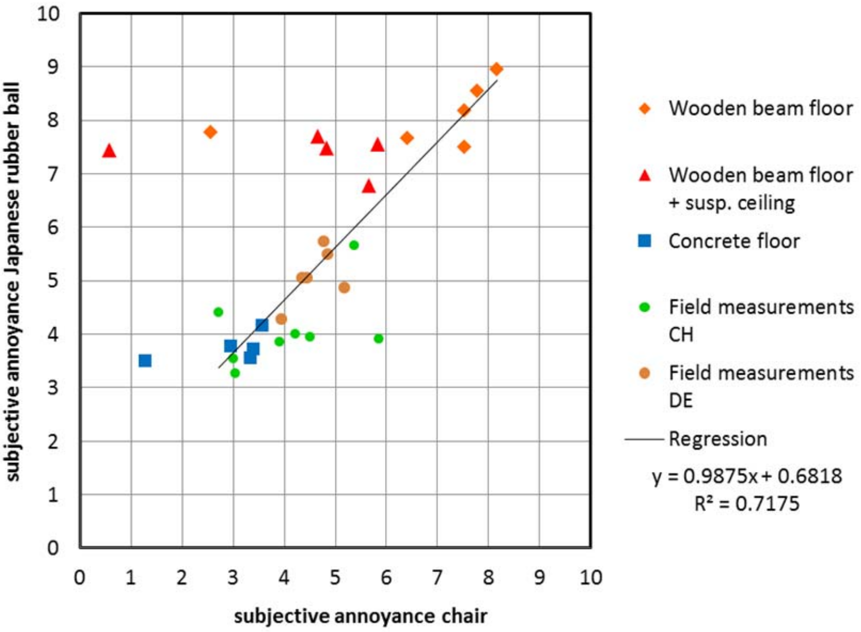


Fig. 18: comparison of the subjective annoyance of the Japanese rubber ball and the subjective annoyance of the moving of chairs

The measured values of the carpeted floors, which appear as three discrepant values in Figure 18 were not taken into consideration for the regression analysis. The subjective annoyance of the rubber ball is perceived to be higher than the subjective annoyance of the moving of the chair. Especially for the measured values on the timber floor with suspended ceiling, higher deviations of the measured values from the regression line occur. The reason is that this floor transmits low and very low frequencies below 50 Hz due to the suspended ceiling tuned to very low frequencies. The Japanese rubber ball can excite these frequencies, the moving of chairs however is a rather high frequency source. Moreover, a higher deviation from the regression straight line can be observed in the measurements in Switzerland. The cause of this could not be clarified. All in all, a value of $R^2 = 0.72$ is achieved, which is slightly lower than in case of the modified tapping machine.

It can be concluded that the standard tapping machine is the most insufficient technical source of the three investigated sources to represent living noises such as walking and the moving of the chair. The two sources which were developed for walking noise, the modified tapping machine and the Japanese rubber ball, achieve clearly better results in the analysis and represent the investigated living noises better. The Japanese rubber ball achieves a higher determination coefficient R^2 in case of the walking noise, whereas the modified tapping machine has a higher determination coefficient R^2 in case of the moving of the chair.

The question which of the two sources developed for walking noise is advantageous with regard to the subjective annoyance cannot be answered immediately. The investigation in the AcuWood project, however, shows two essential advantages of the Japanese rubber ball.

The Japanese rubber ball has a much louder excitation, resulting in higher annoyance values in the previously described analyses. The decisive advantage for the practical use of the Japanese rubber ball is the higher signal-to-noise ratio. This is most evident in the measurements in buildings carried out in the AcuWood project. It can be said from experience that only the ball is suited for „usual“ measurements in buildings, the modified tapping machine, however, is too silent for usual ambient noise during the measurements.

The second essential argument for the Japanese rubber ball is that it can be used on all floor coverings including carpeted floors. The low efficiency of carpeted floors for walking noise is adequately reproduced by the Japanese rubber ball. Measurements by the modified tapping machine, however, seem to be less useful and less practicable, since the low excitation is additionally reduced in this case.

3.2 Optimized rating method

Besides the application of the excitation source the rating method is also of significant importance. Only a rating method can achieve a single number value from a measured frequency spectrum, expected to make a statement on the impact sound insulation or impact sound transmission. Therefore, different rating methods were used for the technical excitation sources applied. The derived single number values are compared with the subjective annoyances of the real living noises (walking noise and noise caused by the moving of the chair). By correlation, it can be determined which rating method (of the excitation source used) can be in good agreement to the subjective assessment of living noises. The rating methods used are described in chapter 2.

A new rating method, based on the measured data of the AcuWood project was not developed. A variety of suggested rating methods is available for the standard tapping machine, based partly on the analysis of the subjective assessments [25, 26, and 28]. It did not seem to be useful to develop a rating method optimized for the data set of the project, which would achieve an especially high correlation in the application of the data, but is probably less suitable for other data. For a new suggestion, the data base seemed to be too small. Other promising ideas, however, were tested besides rating methods suggested in the literature. Single number values, which were obvious and seemed to be simple from the acoustical point of view, were generated for the Japanese rubber ball and the modified tapping machine.

3.2.1 Rating method for the standard tapping machine

The majority of the suggested methods in the literature is aiming for the standard tapping machine, described in chapter 2. Therefore, only the most relevant correlation analyses between single number value and the subjective annoyance are described here.

The most relevant rating method for the standard tapping machine is the normalized impact sound pressure level $L'_{n,w}$ used in standardization at present. It was calculated for the measurements in this project and compared with the subjective annoyance of walking as shown in Figure 19.

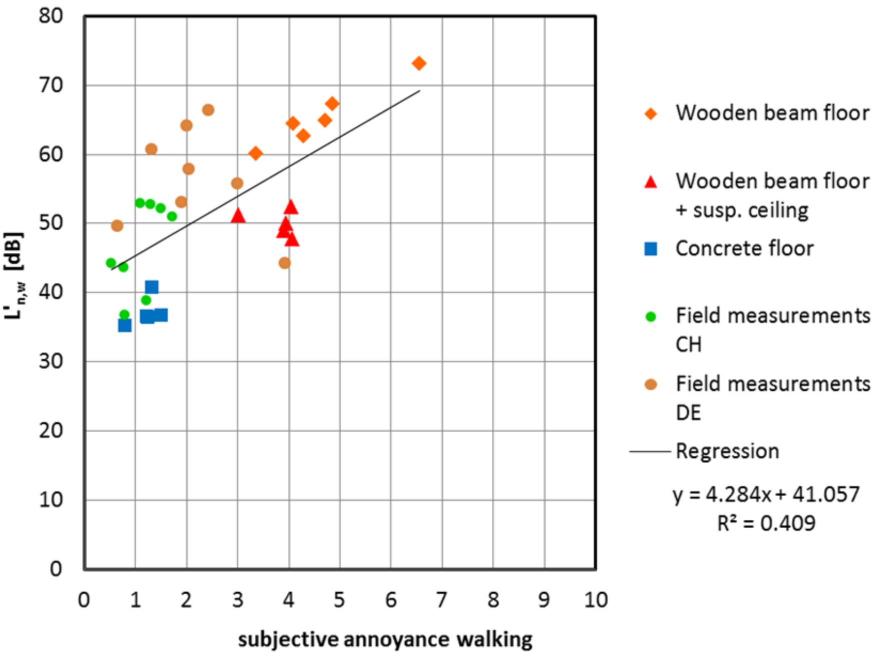


Fig. 19: comparison of the measured normalized impact sound pressure level $L'_{n,w}$ and the subjective annoyance of walking.

The representation and regression in Figure 19 includes the measurements on carpeted floor. In the cases of timber floors with and without suspended ceiling and massive floors the carpeted floors gave the lowest normalized impact sound pressure levels. In the case of the measurements in buildings in Germany (measurement in buildings D) again these are the two data points with the lowest $L'_{n,w}$ values. In case of the measurements in Switzerland (measurement in buildings CH) no floor was covered by carpet. Since in all cases the floors were equipped by floating screed, the measured values on carpeted floor are not extremely lower than those of other floor coverings of the same floors in the laboratory. It is noticeable that the normalized impact sound pressure levels are clearly different in case of similar subjective annoyance of walking, for example in measurements of the massive floor and in the measurements in Switzerland. The average difference amounts to almost 10 dB. With the exception of two floors in Switzerland, all other Swiss floors are clearly worse assessed by the normalized impact sound pressure level with similar subjective annoyance of the noise. Consequently, the coefficient of determination of the regression R² = 0.41 was relatively low.

The result is of the correlation analysis is quite similar, if instead of the normalized impact sound pressure level the standardized impact sound pressure level is considered. It is recommended as assessment criterion in the current VDI 4100 [33] and was already proposed as assessment criterion in the drafts of the new DIN 4109. Figure 20 shows the comparison of the standardized impact sound pressure level L´$_{nT,w}$ with the subjective annoyance of walking.

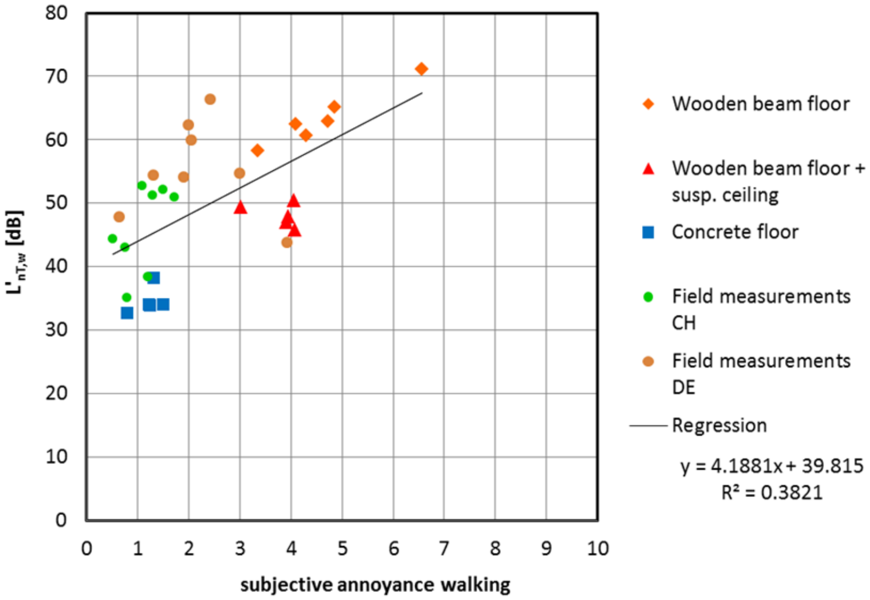


Fig. 20: comparison of the measured standardized impact sound pressure level L´$_{nT,w}$ and the subjective annoyance of walking.

Again the measured values for the same subjective annoyance of walking are high. Again, most timber floors achieve a higher single number value in comparison to the massive floor, at similar subjective annoyance. The value R² = 0.38 is still slightly lower than for L´$_{n,w}$.

If the spectrum adaptation term $C_{I,50-2500}$ is added to L´$_{nT,w}$, the following correlation occurs between single number value and subjective annoyance, shown in Figure 21.

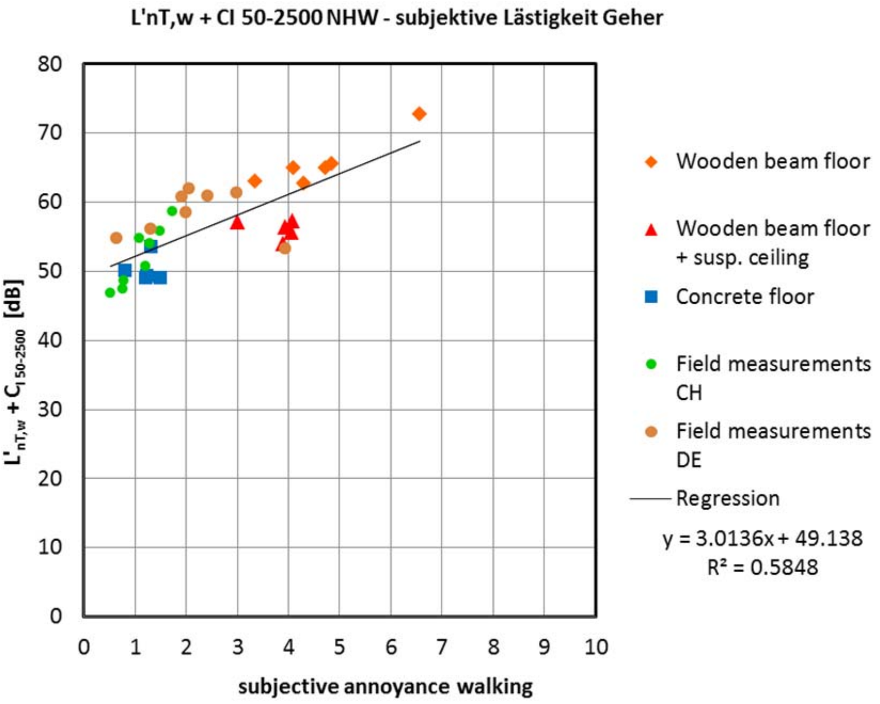


Fig. 21: comparison of the measured standardized impact sound pressure level $L'_{nT,w}$ $+C_{I,50\text{-}2500}$ and the subjective annoyance of walking.

The application of $L'_{nT,w}$ $+C_{I,50\text{-}2500}$ achieves a clearly better correlation of the single number value with the subjective annoyance. Especially the measured values at low subjective annoyance of the measurements in buildings in Switzerland and the laboratory measurements on the massive floor approach each other, so that they have similar single number values at similar subjective annoyance ratings. Nevertheless, the more precise consideration shows that especially the measurements in buildings in Germany in single-family houses in timber construction tend to be higher than the regression line.All values for the timber floor with suspended ceiling are lower than the regression line. This can be explained by the suspended ceiling, which is tuned to low frequencies in the laboratory. If the spectra of these measurements are taken into consideration, the loudest one-third octaves of the standardized impact sound pressure level were lower than 50 Hz. These frequencies are not considered in the single number value but perceived, thus causing higher subjective annoyance. The determination coefficient of the correlation analysis in figure 21 is $R^2 = 0.58$, and that is a clear enhancement in comparison to $L'_{n,w}$ and $L'_{nT,w}$. Insofar, the investigation clearly supports experts to extend the weighting frequency range towards low frequencies.

All rating methods described in chapter 2 were applied for the standard tapping machine and a linear correlation to the subjective annoyance of walking was carried out. The correlation analysis results are listed in Table 2.

Table 2: Determination coefficient R² of the linear regression of different rating methods of the standard tapping machine and the subjective annoyance for walking noise.

Rating method	R²	Rating method	R²	Rating method	R²
$L'_{nT,w}$ ($L'_{n,w}$)	0.38 (0.41)	$L'_{nT,Fasold}$	0.56	$L'_{nT,hearing\ threshold}$	0.31
$L'_{nT,w}+C_{I,100–2500}$ ($L'_{n,w+}C_{I,100–2500}$)	0.48 (0.51)	$L'_{n,w}+C_{I,AkuLite,20\text{-}2500}$	0.56	JIS $L_{i,A}$	0.35
$L'_{nT,w}+C_{I,50–2500}$ ($L'_{n,w}+C_{I,50–2500}$)	0.58 (0.61)	$L'_{n,w}+C_{I,AkuLite,20\text{-}2500,hf}{}^{*}$	0.56	JIS $L_{i,A,F}$	0.29
$L'_{nT,Hagberg03}$	0.63	$L'_{n,w}+C_{I,AkuLite,20\text{-}2500,Sweden}{}^{**}$	0.57	JIS $L_{i,A,w}$	0.29
$L'_{nT,Hagberg04}$	0.62	$L'_{nT,Gösele}$	0.36	$L'_{nT,A\ 20\text{-}2500}$	0.36
$L'_{nT,Bodlund}$	0.58	$L'_{nT,reversed\ A\text{-}weighting}$	0.36	$L'_{nT,A\ 50\text{-}2500}$	0.36

The values presented in Table 2 demonstrate which rating method of the standard tapping machine achieves a good correlation between the single number value and the subjective annoyance rating. The highest value for R² is achieved by the rating according to Hagberg, new,03, with R² = 0.63. This method covers the frequencies from 50 Hz to 3150 Hz and includes a very high increase of rating from 100 Hz towards 50 Hz, see chapter 2.2.7. The comparison of the single number value according to Hagberg 03 and the subjective annoyance of walking are shown in Figure 22.

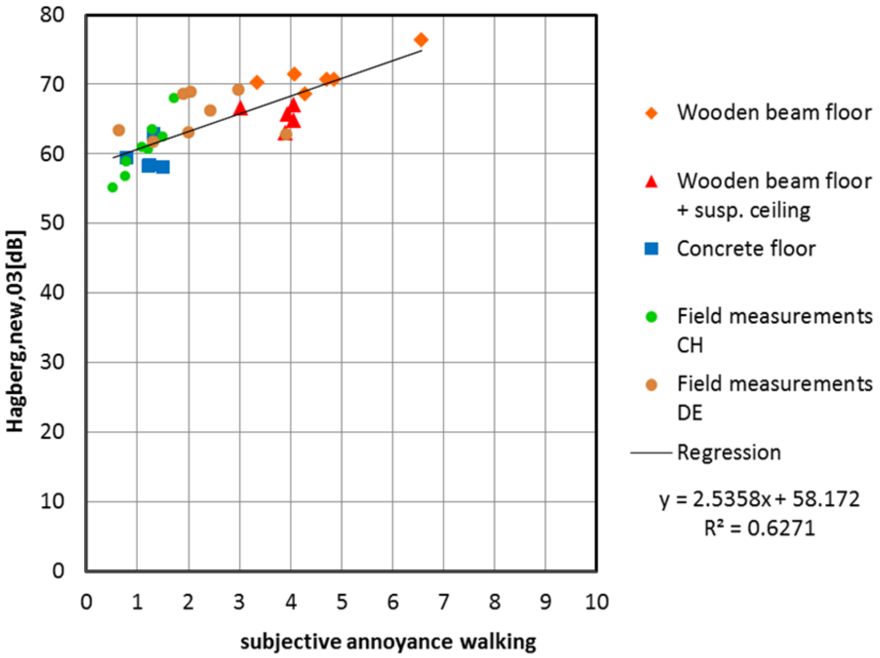


Fig. 22: comparison of the single number value $L'_{nT,Hagberg,new,03}$ and the subjective annoyance of walking.

For the same subjective annoyance, the single number values are very similar for the rating according to Hagberg, new,03. Therefore, $R^2 = 0.63$ is slightly higher than for $L'_{nT,w} + C_{I,50\text{-}2500}$. However, it is still evident that the single number values for the timber floor with suspended ceiling are still below the regression line, showing that rating from 50 Hz upward is insufficient for this floor structure, which has the highest A-weighted impact sound level for walking noise below 50 Hz. In this case, a rating involving the frequencies below 50 Hz would be more favorable.

The value for Hagberg, new,04 shown in Table 2 is only slightly lower than for Hagberg,new,03. The difference occurs due to the modification of rating at high frequencies, and is only relevant for the measurements in Germany. The different rating at high frequencies cannot be interpreted here. Therefore, both methods are taken as equivalent within the framework of the AcuWood project.

The rating methods according to Bodlund, Fasold and AkuLite have values of R^2 between 0.58 and 0.56. They and are relatively similar and within the range of $L'_{nT,w} + C_{I,50\text{-}2500}$, whereby only the methods according to AkuLite assess the very low frequencies from 20 Hz upwards. All other rating methods, particularly the Japanese standard JIS A 1419-2 provide very low values of the regression analysis. The reason is that the rating methods proposed in the Japanese standard were probably developed for the Japanese rubber ball, but are also being applied on the standard tapping machine.

The rating by the sum level $L'_{nT,A,20\text{-}2500}$ and $L'_{nT,A,50\text{-}2500}$ was also very low for both frequency ranges, with $R^2 = 0.36$. This was to be expected, since the spectrum of the standard tapping machine is very different to the spectrum of the walkers and thus the standard tapping machine is less suitable as representative source for walking noise. These low values confirm the statements of chapter 3.1.1.

It can be concluded that the method according to Hagberg achieves the best correlation, the standardized impact sound pressure level with spectrum adaptation term $L'_{nT,w}+C_{I,50\text{-}2500}$, however, is equal to the other better rating methods and the currently suggested method of AkuLite. The normalized impact sound pressure level $L'_{n,w}+C_{I,50\text{-}2500}$ achieves a slightly higher value for R^2, based on the available data and compared to the AkuLite rating method. $L'_{n,w}+C_{I,50\text{-}2500}$ is useful, since it has already been introduced internationally by ISO 717-2 for a long time, and is used as basis for requirement values in some European countries in the meantime.

3.2.2 Rating method for the modified tapping machine

This report suggests the standardized sum of the impact sound pressure level $L'_{nT,A,sum}$ as single number value for the modified tapping machine. Two frequency ranges from 50 to 2500 Hz and from 20 to 2500 Hz are considered. The comparison of the sum of the impact sound pressure level $L'_{nT,A,50-2500}$ of the modified tapping machine with the subjective annoyance of the walking is shown in Figure 23.

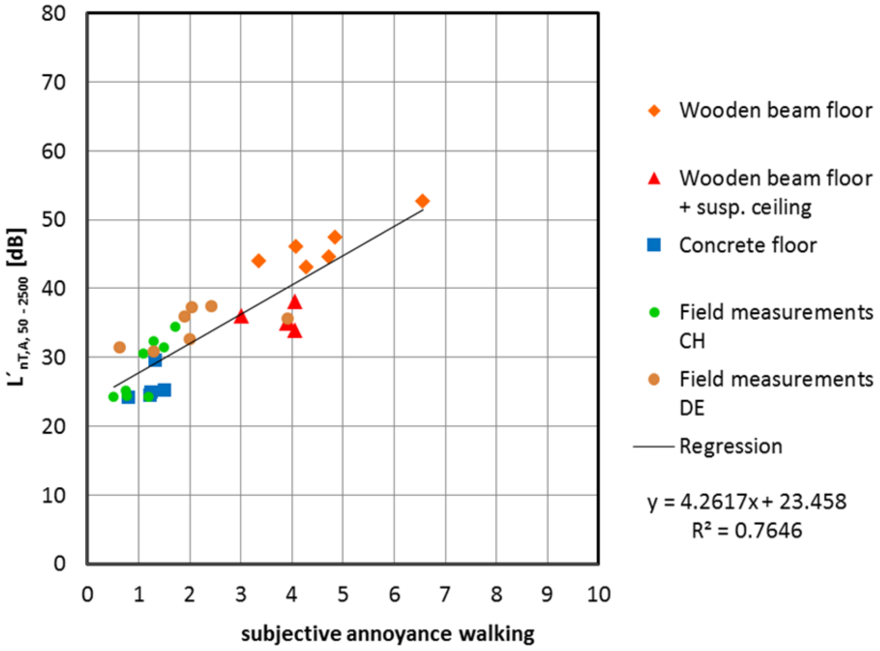


Fig. 23: comparison of the single number value $L'_{nT,A,50-2500}$ of the modified tapping machine and the subjective annoyance of walking.

Figure 24 shows the comparison of the sum of the impact sound pressure level $L'_{nT,A,20-2500}$ of the modified tapping machine and the subjective annoyance of walking.

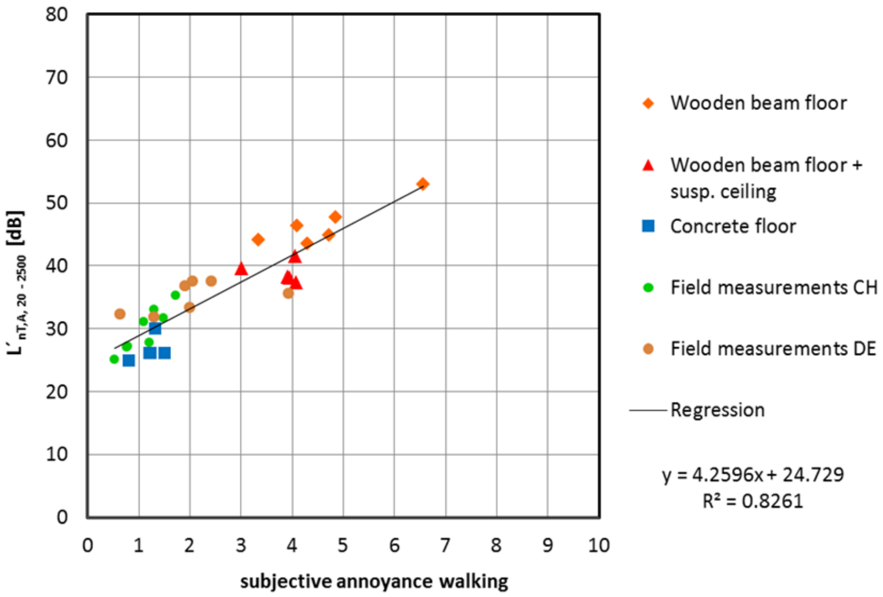


Fig. 24: comparison of the single number $L'_{nT,A,20\text{-}2500}$ of the modified tapping machine and the subjective annoyance of walking.

In case of the modified tapping machine, which is very similar in spectrum and in the sound pressure level to the walkers, the sum level $L'_{nT,A,20\text{-}2500}$ better correlates with the subjective annoyance of walking than the sum level $L'_{nT,A,50\text{-}2500}$. The determination coefficient R^2 amounts to a value of 0.83 in comparison to 0.77. The difference of the single number value for floors with the same subjective annoyance of the walking noise is relatively low. considering the single number values of the timber floor with suspended ceiling the single number values are better positioned on the regression straight line for $L'_{nT,A,20\text{-}2500}$. Therefore, it is favorable to consider the frequencies below 50 Hz for floors with suspended ceilings tuned to very low frequencies.

3.2.3 Rating method for the Japanese rubber ball

The Japanese standard JIS A 1419-2 gives rating methods for the Japanese rubber ball. The Korean standard KS F 2863-2 also suggests two rating methods. Method 1 of KS F 2863-2 corresponds to method 4 of JIS A 1419-2. In addition, this paper suggests the A-weighted maximum sum level as single number value.

The best correlation of the Japanese and Korean rating methods was achieved by rating $L_{i,A,Fmax}$, method 3 of JIS A 1419-2, chapter 2.4.3. The comparison of the rating with the subjective annoyance of walking noise is represented in Figure 25.

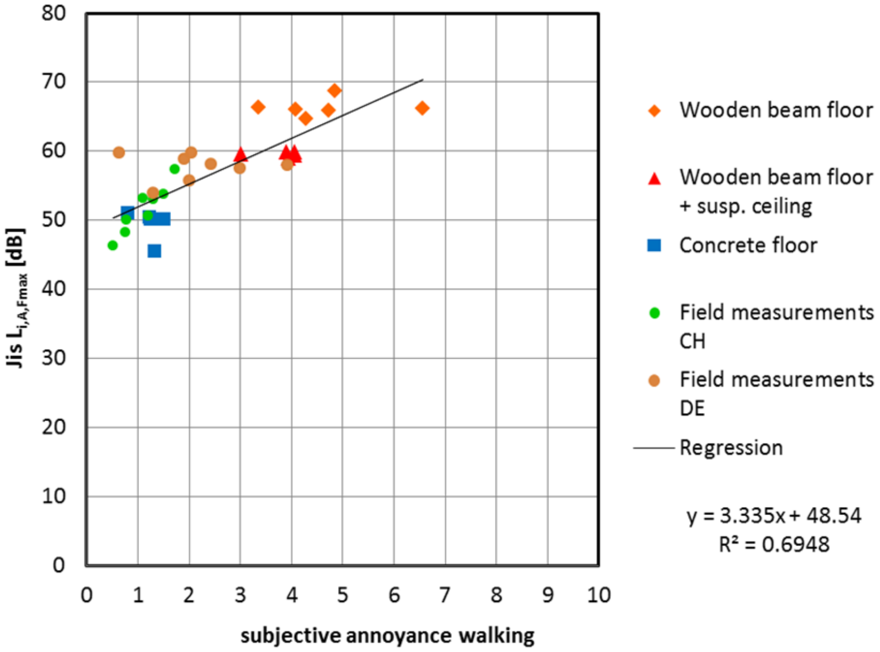


Fig. 25: comparison of the single number value $L_{i,A,Fmax}$ (JIS 1419-2) of the Japanese rubber ball and the subjective annoyance of walking.

The correlation of both parameters is relatively high for the Japanese rubber ball, but does not achieve the values of the modified tapping machine with a determination coefficient R^2 von 0.69. The best rating method for the Japanese rubber ball is the standardized maximum sum level $L'_{nT,A,F,max,20-2500}$ which is compared in Figure 26 with the subjective annoyance of walking noise.

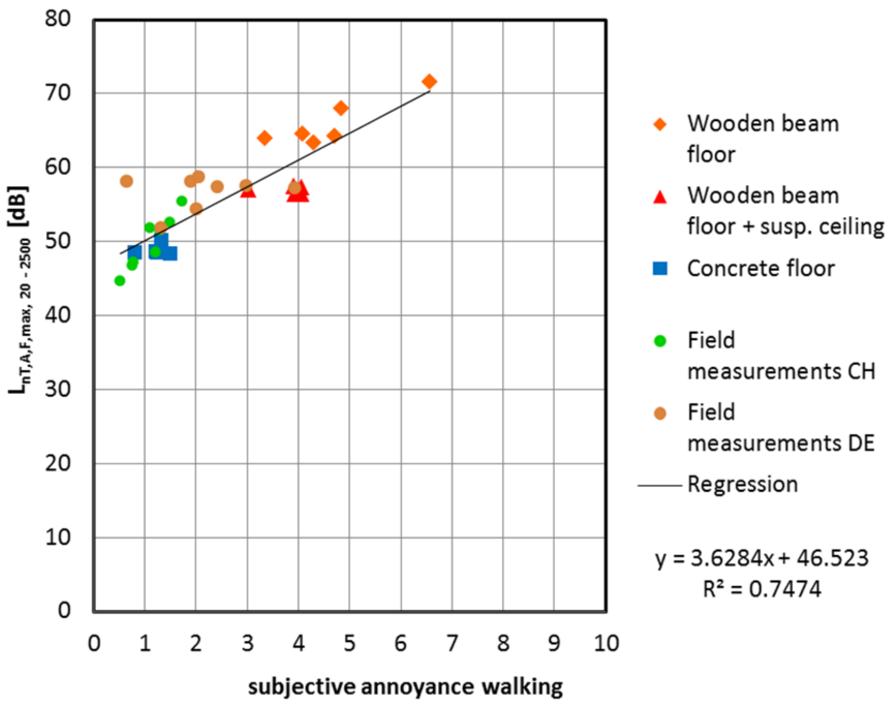
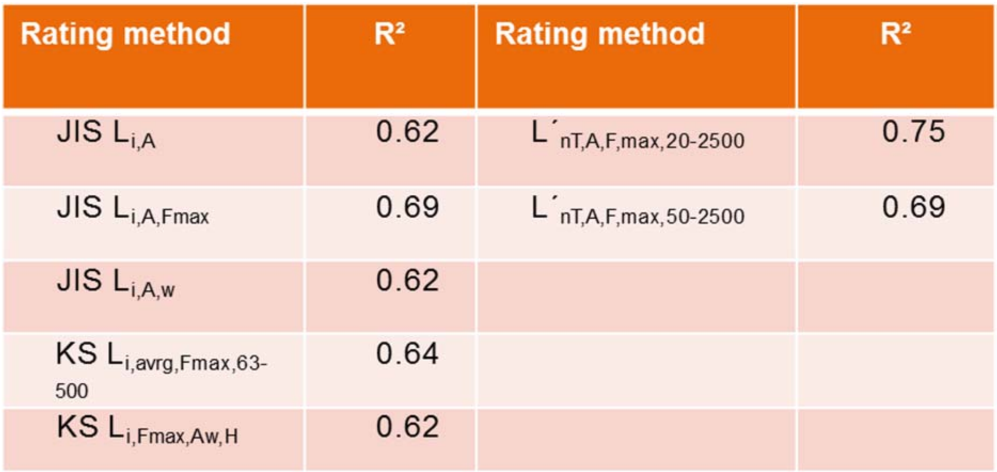


Fig. 26: comparison of the single number value of the standardized maximum sum level $L'_{nT,A,F,max,20-2500}$ of the Japanese rubber ball and the subjective annoyance of walking noise.

The best correlation with the subjective annoyance of walking noise with $R^2=0.75$ for the Japanese rubber ball is achieved by the A-weighted standardized maximum sum level $L'_{nT,A,F,max,20-2500}$ according to chapter 2.4.7. This value is slightly lower than that of the modified tapping machine, but the excitation of the rubber ball is clearly louder, the values of the standardized maximum sum level of the ball are approx. 20 dB higher than those of the modified tapping machine. Therefore, this source is clearly better suited for practical use to characterize living noise, since it has a clearly better signal-to-noise ratio (with regard to the background noise in buildings) than the modified tapping machine.

The determination coefficients R^2 of the linear correlations of all rating methods for the Japanese rubber ball in relation to the subjective annoyance of walking noise are listed in Table 3.

Table 3: Determination coefficient R² of the linear regression of different rating methods for the Japanese rubber ball and the subjective annoyance of walking noise.



Rating method	R²	Rating method	R²
JIS $L_{i,A}$	0.62	$L'_{nT,A,F,max,20-2500}$	0.75
JIS $L_{i,A,Fmax}$	0.69	$L'_{nT,A,F,max,50-2500}$	0.69
JIS $L_{i,A,w}$	0.62		
KS $L_{i,avrg,Fmax,63-500}$	0.64		
KS $L_{i,Fmax,Aw,H}$	0.62		

The results in Table 3 show that the method of the sum level from 20 to 5000 Hz achieved the highest determination coefficient. Also method, JIS $L_{i,A,Fmax}$, which considers the total frequency range with no correction to reverberation time, is relatively high with R²=0.69. This value can be directly measured by means of a simple sound level meter.

3.3 Requirement values

Suggestions for requirement values can be deduced from the listening tests in a further step. Besides the subjective assessment of annoyance on an 11-stage scale according to ISO/TS 15666, it was also questioned by a yes/no answer, whether the noise was assessed as annoying. Details can be found in AcuWood report No. 3 [16]. The answers to this question allow an assessment of the annoyance scale for the investigated noise. The correlation is very high between the answers on annoyance and the number of persons annoyed by walking noise and also for the moving of the chair. A similar linear correlation (with a similar gradient and similar determination coefficient R²) is determined for walking noise and moving of the chair, so that results for both kinds of noise are shown together in Figure 27.

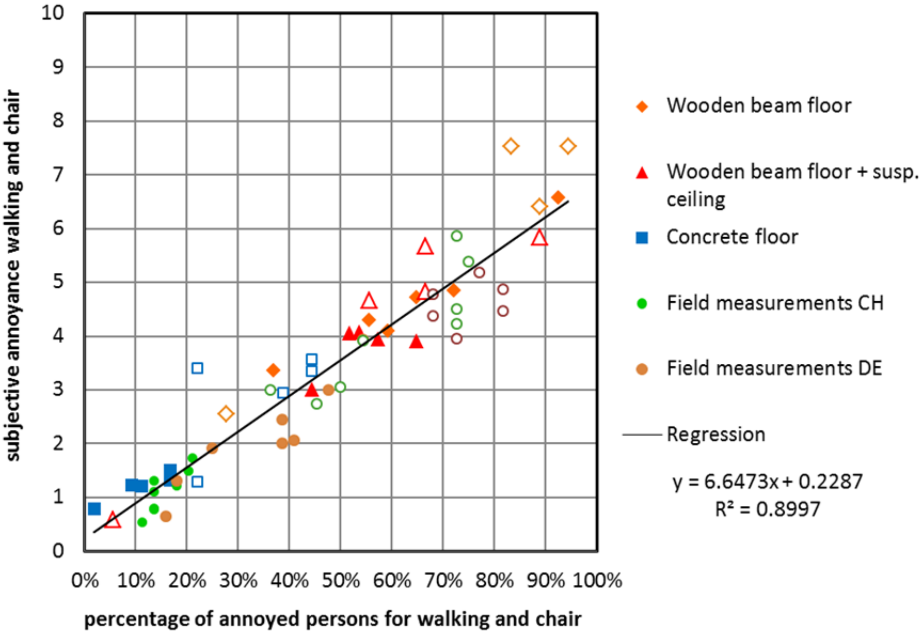


Fig. 27: Comparison of the percentage number of annoyed persons and the subjective annoyance. The filled marks are data pairs for walking noise, unfilled marks are data pairs for the moving of the chair.

The graph in Figure 27 shows a linear correlation between subjective annoyance and percentage number of persons annoyed with a determination coefficient $R^2=0.90$ including both kind of noises. It is interesting to find that 50% of the percentage number of persons annoyed is achieved at a subjective annoyance rating of 3.6 and not at a mean subjective annoyance of 5, as probably expected.

With the given data, requirement values can be directly deduced from the percentage number of persons annoyed. Moreover, given requirement values as defined in DIN 4109, VDI 4100 or other standards and guidelines can now be analyzed in regard to the percentage number of persons annoyed. The direct correlation of requirement values in dB with the number of persons annoyed provides for the first time insight to the significance of the requirement values also for acoustic laymen.

3.3.1 Requirement values for the standard tapping machine

Requirement values as minimum requirement are defined for the normalized impact sound pressure level according to DIN 4109 [32] with $L'_{n,w}$=53 dB for floors of apartments. In the supplementary sheet 2 of DIN 4109 [39] $L'_{n,w}$=46 dB is suggested as enhanced requirement for floors of apartments.

The normalized impact sound pressure level compared to the percentage number of persons annoyed by walking noise is shown in Figure 28.

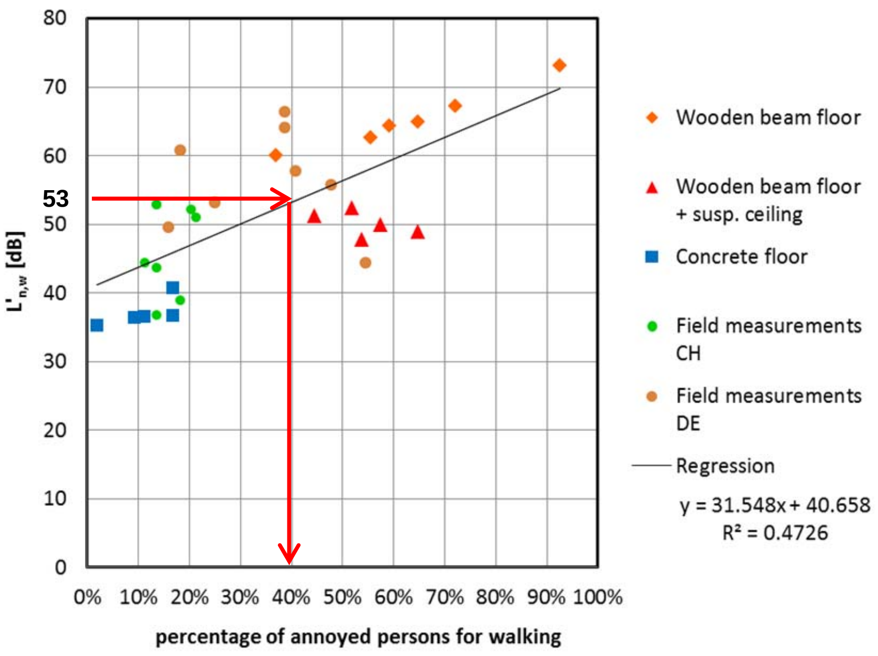


Fig. 28: comparison of the normalized impact sound pressure level $L'_{n,w}$ of the standard tapping machine and the percentage number of persons annoyed by walking noise.

The comparison demonstrates a correlation between technical single number value and subjective rating, which is easy to understand. This correlation is easier to understand than the correlation of the single number value with the subjective annoyance, since the scale of the percentage number of persons annoyed by the sound is intuitively understood. Even acoustic laymen are able to comprehend the importance of acoustic requirement values. In the field of assessing thermal comfort in buildings, the description by the percentage of persons dissatisfied has been familiar for a long time by the PMV-PPD model (predicted mean vote und predicted percentage dissatisfied) according to Fanger.

The requirement values of DIN 4109-89 [32] and the suggestion for enhanced noise control of DIN 4109 Bbl.2 [39] and the corresponding percentage of persons annoyed are given in Table 4. The determination of the percentage value of persons annoyed for the minimum requirement of DIN 4109 is shown in Figure 28 graphically.

Table 4: minimum requirement and suggestion for enhanced noise control of DIN 4109 and corresponding percentage value of persons annoyed by walking noise.

DIN 4109-89	**L´$_{n,w}$**	**Percentage value of persons annoyed by walking noise y = 31,5*x + 40.7; R² = 0,47**
Minimum requirement	53 dB	39%
Suggestion for enhanced noise control supplementary sheet 2	46 dB	17%

The comparison for the standardized impact sound pressure level is represented in Figure 29.

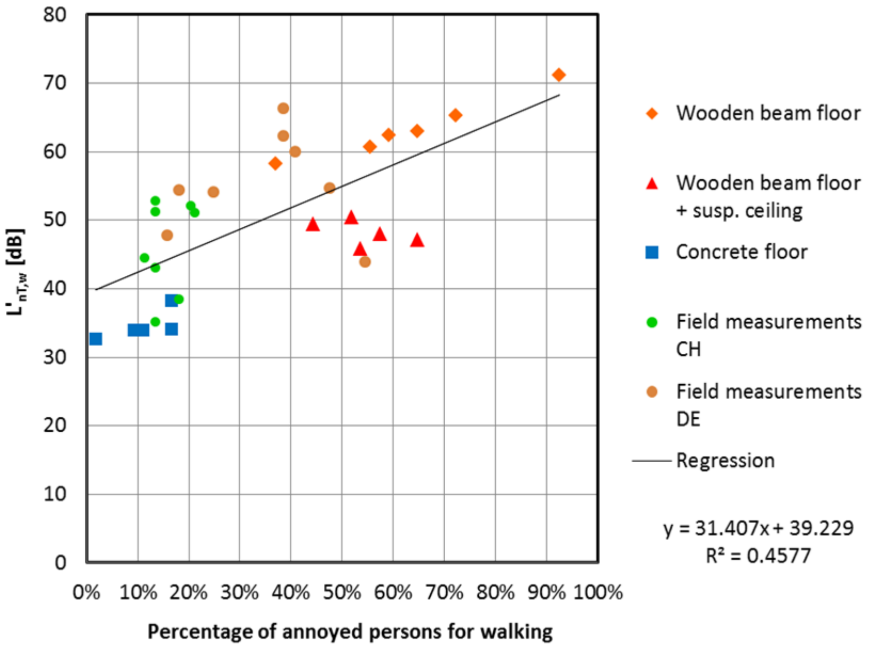


Fig. 29: comparison of the standardized impact sound pressure level L´$_{nT,w}$ of the standard tapping machine and the percentage of persons annoyed by walking noise.

Both linear correlations of the normalized and the standardized impact sound pressure level and the percentage of persons annoyed show a clear scattering of the single number values. It is evident that the measurements of the massive floors in comparison to the floors in Switzerland show clearly lower single number values, although the percentage of persons annoyed is very similar. The determination coefficient is similarly low as in the comparison of the single number values with the subjective annoyance.

Values for the noise control classes I to III are also defined in the latest version of VDI 4100 [32] for the standardized impact sound pressure level $L'_{nT,w}$. These are represented in Table 5 by the corresponding percentage values of persons annoyed by walking noise.

Table 5: minimum requirement and suggestion for enhanced noise control of VDI 4100 and corresponding percentage value of persons annoyed by walking noise

VDI 4100 (2012)	**$L'_{nT,w}$**	**Percentage of per-sons annoyed by walking noise $y = 31,4*x + 39.2$; $R^2 = 0,46$**
SST I	51 dB	38%
SST II	44 dB	15%
SST III	37 dB	-7%

*negative percentage value calculated from the linear regression in Figure 29.

As with annoyance ratings, the results for the standardized and the normalized impact sound pressure level with spectrum adaptation term $C_{I,50-2500}$ are clearly better. The correlation for the normalized impact sound pressure level with spectrum adaptation term is represented in Figure 30, and for the standardized impact sound pressure level $L'_{nT,w}+C_{I,50-2500}$ the comparison is given in Figure 31.

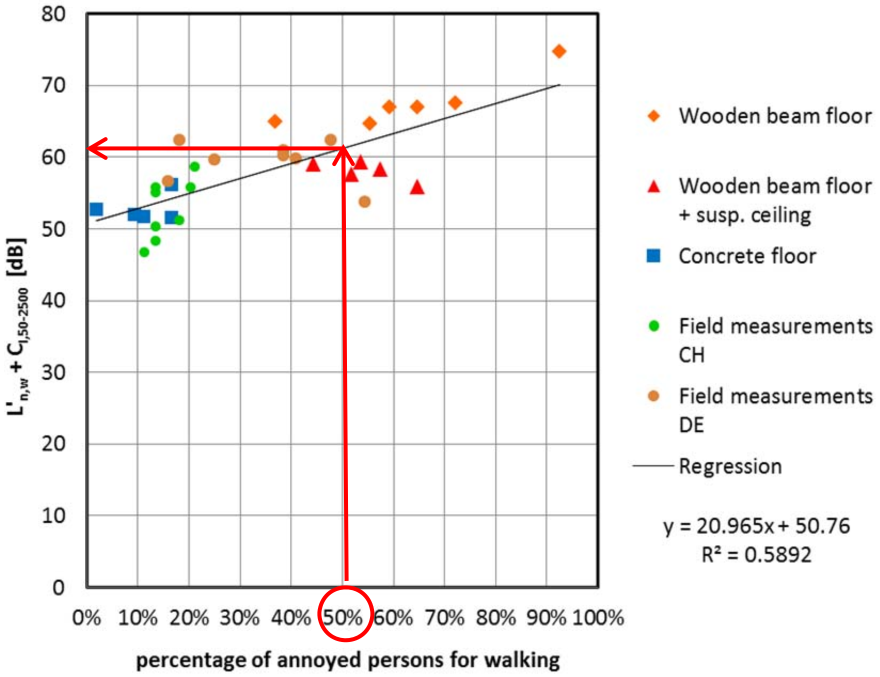


Fig. 30: comparison of normalized impact sound pressure level $L'_{n,w}$ + $C_{I,50\text{-}2500}$ of the standard tapping machine and the percentage of persons annoyed by walking noise.

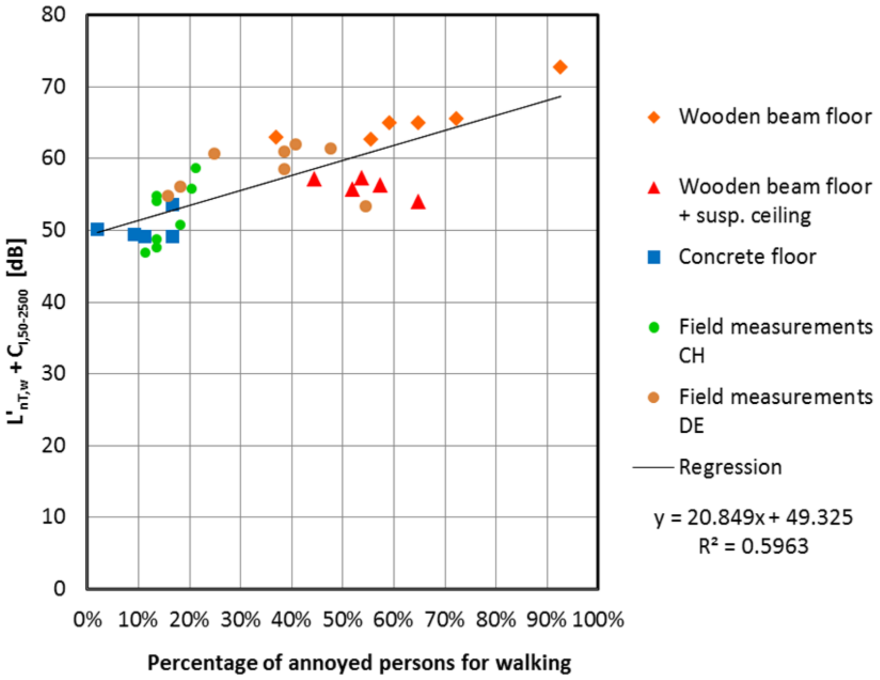


Fig. 31: comparison of the standardized impact sound pressure level $L'_{nT,w}$ + $C_{I,50\text{-}2500}$ of the standard tapping machine and the percentage value of persons annoyed by walking noise,

The determination coefficient R^2 is clearly higher with values of 0.59 and 0.60 for the normalized and the standardized impact sound pressure level with spectrum adaptation term $C_{I,50\text{-}2500}$. Requirement values can be deduced from the equations of the regression line based on the percentage value of persons dissatisfied. The example of stages of 40%, 20% and 0% of persons dissatisfied is proposed here for a three-stage requirement system similar to VDI 4100. These requirement values are represented in Table 6.

Table 6: three-stage requirement values determined by the percentage value of the persons annoyed by walking noise.

Rating	Percentage of persons an-noyed by walk-ing noise	$L'_{n,w} + C_{I,50\text{-}2500}$ $y = 21 \cdot x + 50,8$; $R^2 = 0,59$	$L'_{nT,w} + C_{I,50\text{-}2500}$ $y = 20,8 \cdot x + 49,3$; $R^2 = 0,60$
stage I	40 %	59 dB	58 dB
stage II	20 %	55 dB	53 dB
stage III	0 %*	51 dB	49 dB

The requirement values according to Hagberg [26], which have been included in SS 25267 in the meantime, are given in Table 7 for comparison.

Table 7: three-stage requirement values according to Hagberg [26]

Rating	Requirement values according to Hagberg for $L'_{n,w} + C_{I,50\text{-}2500}$ and for $L'_{n,w}$
stage I	56 dB
stage II	52 dB
stage III	48 dB

The requirement values of Hagberg are slightly lower than the deduced requirement values in Table 6. Only one floor of the measured floor constructions in Switzerland achieves stage III according to Hagberg, with a value of 46.7 dB. Based on the data of the measured constructions in this project the requirement values of Hagberg seem to be a little too ambitious. There is, however, a potential for optimization in the investigated floor constructions, which had not yet been used. By means of the investigations carried out within the framework of the AcuWood project, this optimization can be performed in a clearly more adequate and targeted way, since it is known now, which assessment parameters must be used for rating and which values should be achieved. Thus, it seems worth considering requirement values similar to those of Hagberg.

3.3.2 Requirement values for the modified tapping machine

For the first time it is additionally now possible to define requirement values for the modified tapping machine by means of the available database as for the standard tapping machine. Figure 32 shows the correlation of the best single number value $L'_{nT,A,20\text{-}2500}$ (with the highest determination coefficient of $R^2 = 0.82$) and the percentage of persons dissatisfied.

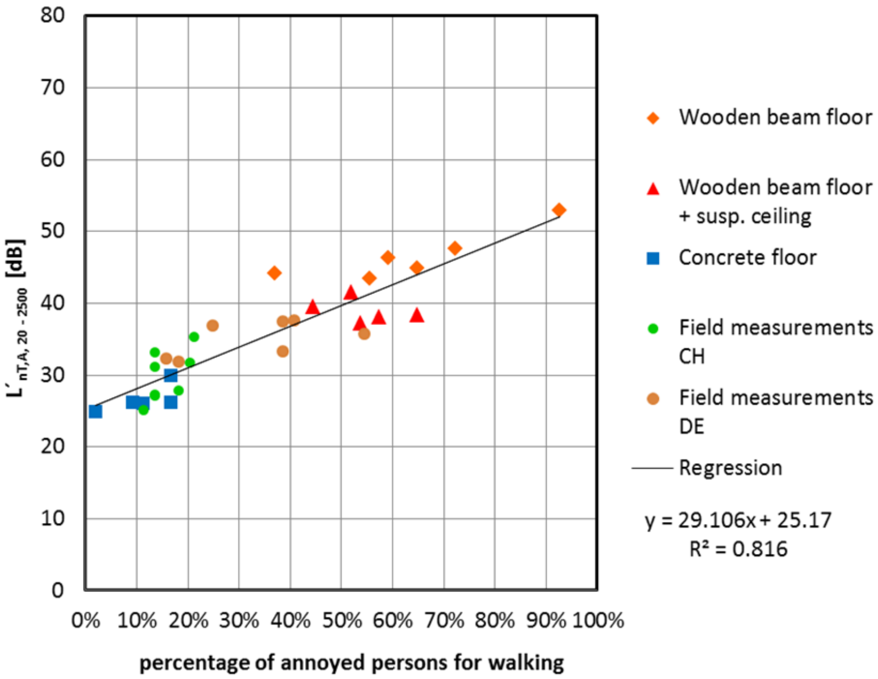


Fig. 32: comparison of the sum of standardized impact sound pressure levels $L'_{nT,A,20\text{-}2500}$ of the modified tapping machine and the percentage of persons annoyed by walking noise.

Figure 33 shows the standardized sum level $L'_{nT,A,50\text{-}2500}$ for comparison.

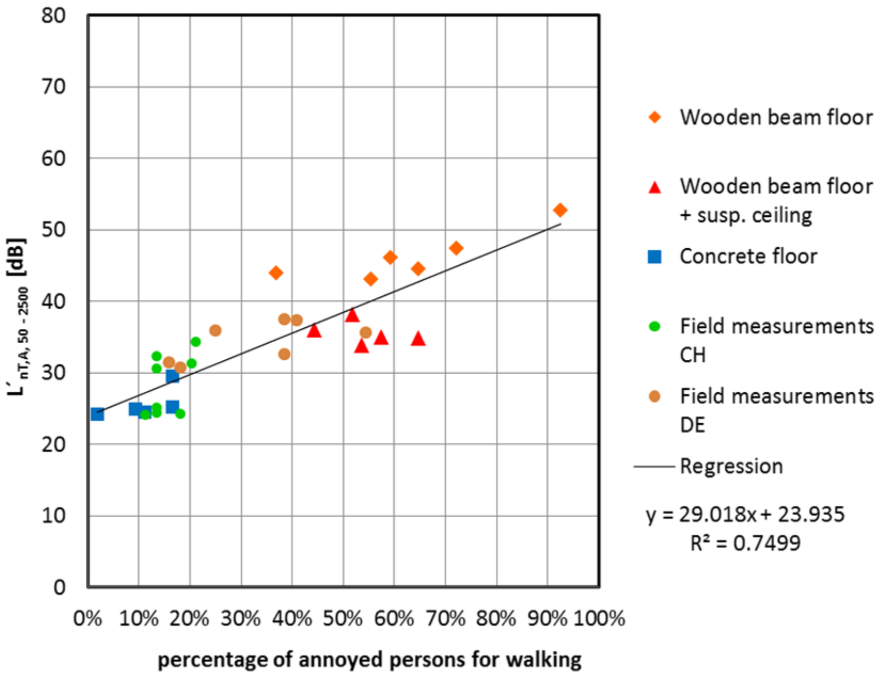


Fig. 33: comparison of the standardized sum level $L'_{nT,A,50\text{-}2500}$ of the modified tapping machine and the percentage value of persons annoyed by walking noise

The comparison of Figure 32 and 33 shows that the summation from 50 Hz to 2500 Hz results in a lower determination coefficient of $R^2 = 0.75$ compared to $R^2=0.82$, exclusively caused by a greater deviation of the measured values at the timber floor with suspended ceiling from the regression line. The frequencies down to 20 Hz should also be taken into account in forming the sum level for this floor construction. If requirement values are deduced in three stages for the modified tapping machine as for the standard tapping machine, the values given in Table 8 are achieved.

Table 8: three-stage requirement values for the modified tapping machine determined by the percentage of persons annoyed by walking noise

Rating	Percentage of persons an-noyed by walk-ing noise	$L´_{nT,A,20-2500}$ $y = 29{,}1*x + 25{,}2$; $R^2 = 0{,}82$	$L´_{nT,A,50-2500}$ $y = 29*x + 23{,}9$; $R^2 = 0{,}75$
stage I	40 %	37 dB	36 dB
stage II	20 %	31 dB	30 dB
stage III	0 %*	25 dB	24 dB

3.3.3 Requirement values for the Japanese rubber ball

Requirement values can also be deduced for the Japanese rubber ball in the same way. The correlation between the best single number value and the percentage of persons annoyed by walking noise is represented in Figure 34 and 35.

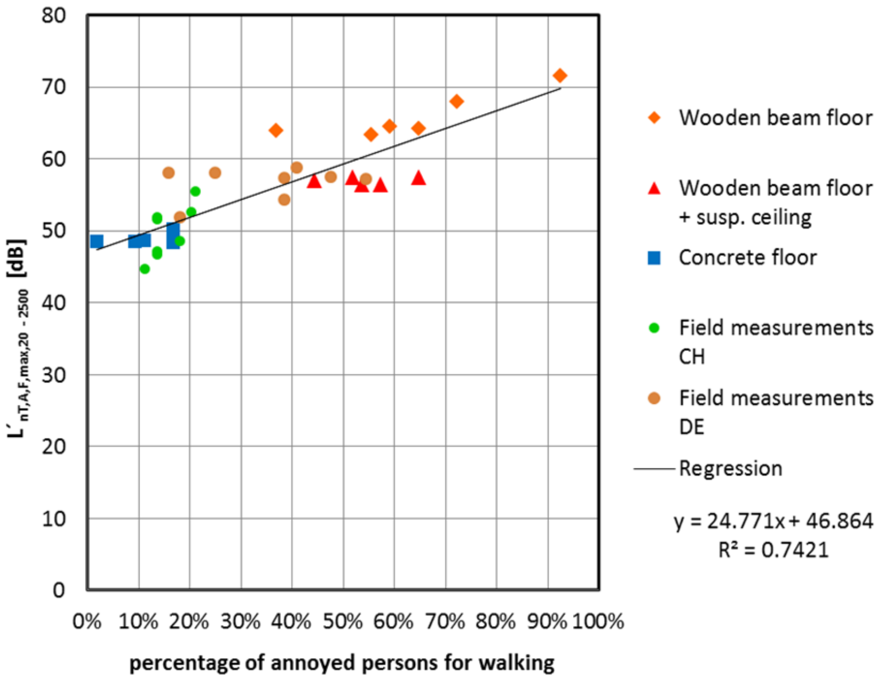


Fig. 34: comparison of the standardized maximum sum level $L´_{nT,A,F,max,20-2500}$ of the Japanese rubber ball and the percentage of persons annoyed by walking noise.

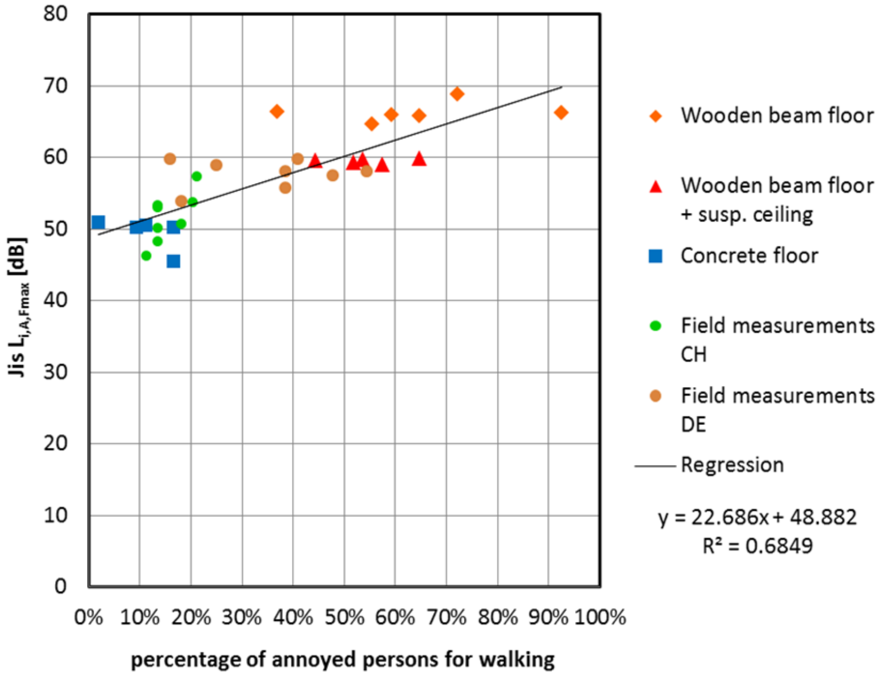


Fig. 35: comparison of the single number value JIS $L_{i,A,F,max}$ of the Japanese rubber ball and the percentage of persons annoyed by walking noise.

Table 9 gives an overview of the requirement values deduced for the Japanese rubber ball.

Table 9: three-stage requirement values for the Japanese rubber ball determined by the percentage of persons annoyed by walking noise.

Rating	**Percentage of persons annoyed by walking noise**	**$L'_{nT,A,F,max,20-2500}$ y = 24,8*x + 46,9; R² = 0,74**	**$L'_{nT,A,F,max,50-2500}$ y = 27,6*x + 44,3; R² = 0,69**	**JIS $L_{i,A,F,max}$ y = 22,7*x + 48,9; R² = 0,68**
stage I	40 %	57 dB	55 dB	58 dB
stage II	20 %	52 dB	50 dB	53 dB
stage III	0 %*	47 dB	44 dB	49 dB

The highest requirement values for the rating according to JIS are achieved for the single number value $L_{i,A,F,max}$. The values for the sum level from 20 to 2500 Hz are slightly lower, and still lower by approx. 2 dB for the sum level of the frequency range from 50 to 2500 Hz. The reason is that a lower sum level occurs for floor constructions with a resonance frequency below 50 Hz, if the frequency range of the sum level only starts from 50 Hz. This particularly applies to the timber floor with suspended ceiling. The result is a linear regression, which generates a slightly lower level but also shows a lower determination coefficient.

4 Results: Subjective rating of residents by a questionnaire-based field study

The questionnaire-based field survey reveals that the overall ratings by the residents may be considered as very satisfying. Ratings with regard to annoyance caused by noise are quite low. However, walking noise caused by neighbors raises the highest complaint compared to other noise sources. It can also be shown that building and floor construction types differ with regard to perceived acoustic annoyance caused by walking noise. Ratings of residents in single-family houses differ from ratings of residents in multi-family houses. In this sample floor constructions made from wood are not rated worse compared to floor constructions made from concrete. However, this only holds true, if wood-concrete composite floors are included in the group of wooden floors. Within the group of floor constructions made from wood, the different types of floors clearly differ from each other with regard to perceived acoustic annoyance caused by walking noise. This result from the survey is in accordance to the listening tests and the measurement results in the building when using an appropriate single number descriptor. In general it can be stated that the questionnaire used in this field-survey may be applied for post occupancy evaluation and identification of construction problems in wooden buildings.

5 Summary

The results of the investigations in the AcuWood project are based on laboratory measurements at altogether 16 different floors and 16 floors in buildings. They are divided in to 4 floors in massive construction (concrete floor with floating cement screed and four different commercial floor coverings), 4 uncovered timber floors, 4 timber floors with floating dry screed, and 4 floors with floating dry screed and suspended ceiling. Eight floors were measured in single-family houses in timber construction in Germany. All these floors had floating cement or anhydride screeds. Eight floors were measured in multi-family houses in timber construction in Switzerland, two of which with different and currently usual floor constructions (wooden hollow box floor with ballast, wood-concrete composite floor, solid wood floor and ribbed floor of glued laminated timber with ballast). All buildings in Switzerland had floating screed floors.

Moreover, the results are based on two laboratory listening tests, where altogether 218 different kinds of noise were assessed. In the listening tests the individual sensitivity to noise was asked on an 11-point scale as well as the annoyance of the noise on an 11-point scale, the loudness of the noise on a 51-point scale and the annoyance by assuming permanent sound exposure while reading was asked to answer by yes/no. The recording of the sounds was performed by an artificial head and the sound reproduction by headphones.

Furthermore, the results are based on two Internet based questionnaires of residents with regard to the annoyance of a variety of sounds. In this context, the questionnaires in Germany were carried out primarily in single-family houses, in Switzerland primarily in multi-family houses. The text of the interviews was almost identical in both countries, only differences characteristic for the country were observed in questioning (for example ß is not used in Switzerland etc.).

The results for walking noise can be summarized as follows. Since the moving of the chair in buildings was not mentioned in the interviews as an essentially annoying source, and since the chair used was an object, which cannot be regarded as representative for all kinds of chairs, the results are given in brackets. The significance of the statement is not modified by considering this source. The results are

- The Japanese rubber ball represents walking noise in buildings best. This is confirmed by the good correlation of subjective annoyance of the rubber ball with the subjective annoyance of the walking noise with a determination coefficient of R = 0.80 (moving of chairs: $R^2 = 0.72$). This statement also includes the fact that the rubber ball is suitable for field measurements, as it provides a sufficiently high signal-to-noise ratio. The measurement with the rubber ball can be carried out on all kinds of floor coverings (including carpet). The single number value $L'_{nT,A,F,max,20-2500}$ reproduces the subjective assessment of walking noise best and shows good correlation with the annoyance of the walking noise with $R^2 = 0.75$ (moving of chairs: $R^2 = 0.82$). Moreover, this single number value can be simply determined by adequate measuring equipment.

- The modified tapping machine represents walking noise in buildings just as well, but with a determination coefficient (correlation of the subjective annoyance of the modified tapping machine with the subjective annoyance of walking noise) of $R^2 = 0.71$ (moving of chairs: $R^2 = 0.76$) has a less favorable correlation (The influence of background noise could not be avoided in the subjective assessment in several measurements). The modified tapping machine generates a sound level, which is similarly in level to the walking noise. Therefore, excitation is too low in most cases to carry out measurements in buildings (with higher background noise). Moreover, the effect of the modified tapping machine on soft and flexible floor coverings, on carpeted floors in particular, are clearly different from the effect of walking noise. Thus, application of the modified tapping machine cannot be recommended on carpeted floors. The correlation between the single number value $L'_{nT,A,20-2500}$ and annoyance of walking noise was highest of all technical sources investigated with $R^2 = 0.83$ (moving of chairs: $R^2 = 0.82$).

- The correlation of the subjective annoyance of the standard tapping machine with the subjective annoyance of walking noise is low, the determination coefficient is $R^2 = 0.23$ (moving of chairs: $R^2 = 0.53$). Regarding the rating methods to determine the single number value, the method according to Hagberg $L'_{nT,Hagberg,new,03}$ with $R^2 = 0.63$ was best (moving of chairs: $R^2 = 0.65$), the method according to ISO 717 with the best correlation is the single number value of $L'_{nT,w} + C_{I,50-2500}$ with a determination coefficient of $R^2 = 0.58$ (moving of chairs: $R^2 = 0.72$). This single number value represents a rating method for the standard tapping machine, showing an acceptable correlation with the subjective assessment of living noises.

- of the analysis to reveal the best single number values showed that walking noise can excite low frequencies below 50 Hz (the moving of chairs, however, excites slightly higher frequencies). If floor constructions are assessed, which have resonance frequencies below 50 Hz (for example the timber floor with suspended ceilings in the test facility), the very low frequencies down to 20 Hz should be taken into account in the ratings (single number value). It is also significant, whether the technical source can excite low frequencies. The standard tapping machine excites very low frequencies less than higher frequencies so that the rating down to 20 Hz is not beneficial (see rating by the AkuLite method). In contrast, the Japanese rubber ball can excite very low frequencies very well so that a better correlation is achieved by taking into consideration the frequencies down to 20 Hz. With a normative rating of the frequency range only down to 50 Hz, for example by using the standard tapping machine and the rating by $L'_{nT,w} + C_{I,50-2500}$ the risk arises that constructions with a resonance frequency below 50 Hz are assessed distinctively better, than the subjective assessment, as the frequencies between 20 and 50 Hz are not considered. Therefore, the application of the Japanese rubber ball as technical source and a rating down to 20 Hz is recommended.

- The question in the listening tests, whether the noise is assessed as annoying, (answered by yes or no) allows the determination of the percentage value of persons annoyed. Very good correlation was achieved between this percentage of persons annoyed by walking noise and the moving of the chair and the subjective annoyance, with $R^2 = 0.90$ for both noises.

- Therefore, the correlation of the percentage value of persons annoyed with the technical single number values (see above) was very similar to the correlation of the subjective annoyance with the same single number values. Already existing requirement values could be converted by the appropriate regression analysis in the percentage value of persons annoyed. Vice versa, requirement values can be defined on the basis of the percentage value of persons annoyed. The suggested requirement values are specified in 3 stages (similar to VDI 4100 [33]) with a percentage value of persons annoyed of 40%, 20% and 0%.

- Work within the framework of the AcuWood project allowed for the first time the definition of requirement values for the Japanese rubber ball and the modified tapping machine.

- The direct correlation of the percentage of persons annoyed with the requirement values is very valuable, since a transparent and easily understandable description of the requirement values is possible for the first time. Thus, even acoustical laymen like real estate sellers and buyers, judges or politicians etc. will able to comprehend the significance of requirement values based on the percentage of persons annoyed.

- The results for the moving of the chair are relatively similar to the results for walking noise. It must, however, be mentioned that the moving of the chair had a higher frequency spectrum. Therefore the standard tapping machine as representative source did not show a similar low determination coefficient as for walking noise. The Japanese rubber ball, however, as representative source for the moving of the chair lead again to a better correlation (with higher determination coefficient R^2) than the standard tapping machine.

- The subjective assessment of the questionnaire in Switzerland showed that the walking noise was assessed to cause the highest annoyance of all noise occurring in apartment houses. This complies with previous investigations and confirms the approach to investigate primarily the annoyance caused by walking noise in this project.

- The subjective assessment of the listening tests and the subjective assessment in multi-family houses in Switzerland resulted in very similar values (The same scale for annoyance was used in the listening tests and in the questionnaires). Unfortunately, only for two buildings there was enough questionnaire data available for the comparison to the listening test data. Therefore there is strong evidence but no proof that the assessment of the annoyance due to permanent sound exposure in buildings could also be reproduced by the short-term laboratory investigations.

6 References

[1] Forssen, J., Kropp, W.e.a.: Acoustics in wooden buildings. State of the art 2008. Vinnova project 2007-01653, Stockholm (2008)

[2] DIN: DIN EN ISO 717-1 (1997): Akustik - Bewertung der Schalldämmung in Gebäuden und von Bauteilen. Teil 1: Luftschalldämmung. Beuth Verlag GmbH(DIN EN ISO 717-1) (1997).

[3] DIN: DIN EN ISO 717-2 (1997): Akustik - Bewertung der Schalldämmung in Gebäuden und von Bauteilen. Teil 2: Trittschalldämmung (1997).

[4] Rasmussen, B.: Sound insulation between dwellings – Requirements in building regulations in Europe. Applied Acoustics 71(4), 373–385 (2010)

[5] Lang, J.: Zur Erweiterung des bauakustischen Frequenzbereichs bis 50 Hz. WKSB 62, 19–32 (2009)

[6] DIN: DIN EN ISO 717-1 (2006): Akustik - Bewertung der Schalldämmung in Gebäuden und von Bauteilen - Teil 1: Luftschalldämmung (ISO 717-1:1996+AM1:2006). Beuth Verlag GmbH(717-1 (2006)) (2006). [7] DIN: DIN EN ISO 717-2 (2006): Akustik - Bewertung der Schalldämmung in Gebäuden und von Bauteilen - Teil 2: Trittschalldämmung (ISO 717-2:1996 + AM1:2006). Beuth Verlag GmbH(717-2 (2006)) (2006).

[8] Hagberg, K.: Acoustic development of light weight building system. In: Proc. EURONOISE 2009.

[9] Rindel, J.: Acoustic Quality and Sound Insulation between Dwellings. In: Proc. Conference in Building Acoustics Dublin 1998.

[10] Scholl, W.M.W.: Impact Sound Insulation of Timber Floors: Interaction between Source, Floor Coverings and Load Bearing Floor. Building Acoustics 6(1), 43–61 (1999).

[11] Scholl, W.: Impact Sound Insulation: The Standard Tapping Machine Shall Learn to Walk! Building Acoustics 8(4), 245–256 (2001).

[12] Jeon, J.Y., Jeong, J.H.: Objective and Subjective Evaluation of Floor Impact Noise. Journal of Temporal Design in Architecture and the Environment 2(1) (2002).

[13] Brunskog, J., Hwang, H., Jeong C.-H: Subjective response to foot-fall noise, including localization of the source position. In: Proc. INTER-NOISE 2011.

[14] Späh, M. Liebl, A., Leistner. P.: Project Report No. 1: Measurement in Laboratory and Single Family Houses. WoodWisdom-Net: AcuWood - Acoustics in Wooden Buildings.

[15] Späh, M. Liebl, A., Leistner. P.: Project Report No. 2: Field Measurements in Multi-Storey Buildings. WoodWisdom-Net: AcuWood - Acoustics in Wooden Buildings.

[16] Liebl A., Späh, M., Leistner, P.: Project Report No. 3: Listening Tests and Questionnaires. WoodWisdom-Net: AcuWood - Acoustics in Wooden Buildings.

[17] DIN: DIN EN ISO 140-4 (1998): Akustik - Messung der Schalldämmung in Gebäuden und von Bauteilen. Teil 4: Messung der Luftschalldämmung zwischen Räumen in Gebäuden (ISO 140-4: 1998). Beuth Verlag GmbH(140-4 (1998)).

[18] ISO: ISO 140-4 Acoustics- Measurement of sound insulation in buildings and of building elements. Part 1 to 18, Geneva, Switzerland(ISO 140).

[19] Gösele, K.: Evaluation of sound reduction in building structures by means of rating curves. Zur Bewertung der Schalldämmung von Bauteilen nach Sollkurven (1965).

[20] Cremer, L.: Schallschutz von Bauteilen (1960).

[21] Thorsson, P.: Subjective evaluation of footsteps noise on lightweight structures - Design of laboratory experiments. In: Proc Forum Acusticum 2011 Aalborg, pp. 1817–1822.

[22] International Organization for Standardization ISO: ISO 16717-1 Acoustics - Evaluation of sound insulation spectra by single numbers. Part 1: Airborne sound insulation, NA 062-02-31 AA N 1199 (16717-1) (2012).

[23] International Organization for Standardization ISO: ISO 16717-2 Acoustics - Evaluation of sound insulation spectra by single numbers. Part 2: Impact sound insulation(16717-2) (2011).

[24] Fasold, W.: Untersuchungen über den Verlauf der Sollkurve für den Trittschallschutz im Wohnungsbau. Acustica 15, 271–284 (1965).

[25] Bodlund, K.: Alternative Reference Curves for Evaluation of the Impact Sound Insulation between Dwellings. Journal of Sound and Vibration 102(3), 381–402 (1985).

[26] Hagberg, K.: Evaluating Field Measurements of Impact Sound. Building Acoustics 17(2), 105–128 (2010).

[27] Ljunggren, F., Simmons, C., Hagberg, K.: Findings from the AcuLite project: Correlation between measured vibro-acoustic parameters and subjective perception in lightweight buildings. In: Proc. INTER-NOISE 2013

[28] Simmons, C., Ljunggren, F., Hagberg, K.: Findings from the AcuLite project: New single number for impact sound 20-5000 Hz based on field measurements and occupant´s survey. In: Proc. INTER-NOISE 2013

[29] Japanese Standards Association: JIS A 1419-2 (200): Acoustics - Rating of sound insulation in buildings and of building elements - Part 2: Floor impact sound insulation (JIS A 1419-2) (2000).

[30] Tachibana, H., Tanaka H., Yasuoka, M., Kimura, S.: Development of new heavy and soft impact source for the assessment of floor impact sound insulation of buildings. In: Proc. INTER-NOISE 1998, pp. 825–828.

[31] Thorsson, P., Larsson, P.: Literature study WP1 AkuLite (2011).

[32] DIN: DIN 4109 Schallschutz im Hochbau Anforderungen und Nachweise. Beuth Verlag GmbH(4109) (1989).

[33] VDI: VDI 4100 (2012): Sound insulation between rooms in buildings - dwellings - Assessment and proposals for enhanced sound insulation between rooms. VDI(4100) (2012).

[34] Sipari, P.: Sound Insulation Of Multi-Storey Houses - A Summary Of Finnish Impact Sound Insulation Results. Building Acoustics 7(1), 15–30 (2000).

[35] ISO: ISO 389-7 (2005):Acoustics - Reference zero for the calibration of audiometric equipment - Part 7: Reference threshold of hearing under free-field and diffuse-field listening conditions, Geneva, Switzerland (389-7) (2005).

[36] Scholl, W.: Das Normhammerwerk muß laufen lernen. In: Proc. DAGA 2001.

[37] Korean Standard: KS F 2863-2: Rating of floor impact sound insulation for impact source in building and of building elements. Part 2: Floor Impact sound insulation against heavy impact source (KS F 2863-2).

[38] Fabian Spinner: Trittschallminderung von Unterdecken unter Verwendung praxisgerechter Trittschallquellen. Bachelorthesis, Hochschule für Technik - University of Applied Sciences (2012).

[39] DIN: Beiblatt 2 zu DIN 4109 Schallschutz im Hochbau Hinweise für Planung und Ausführung. Beuth Verlag GmbH(BBl 2 zu DIN 4109) (1989).

AcuWood – Acoustics in wooden buildings

AcuWood is a project within the WoodWisdom-Net Research programme and running 2010-2013. It is performed in cooperation with research and industry partners from Germany, Sweden and Switzerland and coordinated by SP Wood Technology.

The main objectives are to find objective criteria for acoustic quality that is independent of the type of building system, to increase the knowledge base for future development and to increase the competitiveness of lightweight structures. The project is run in close contact with international R&D and standardization.

Stockholm • Borås • Skellefteå • Växjö
Tel: +46 10 516 50 00 • www.sp.se/tratek

SP Report 2014:17