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Subjective and Objective Evaluation of Impact Noise Sources in Wooden Buildings

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ABSTRACT

Multi-storey timber buildings up to 6 and more floors are increasingly built in many European countries. The challenge with these buildings can be that with traditional intermediate floor constructions in timber it can be difficult to fulfill the standard requirements and even when they are met, low frequency transmission can still cause complaints. Additionally it is difficult to develop appropriate light weight floor constructions since it is well known that the correlation between the standardized evaluation methods using the tapping machine and the human perception of impact noise can be poor, especially in buildings with light weight structures. In the AcuWood project, measurements and recordings on different intermediate timber floor constructions in the laboratory and the field were performed covering a wide range of modern intermediate timber floor constructions. Additionally, one intermediate concrete floor with different floor coverings was included in the study. Besides the standardized tapping machine, the modified tapping machine and the Japanese rubber ball and "real" sources were employed. Subjective ratings from listening tests were correlated to many technical single number descriptors including the standardized descriptors and non-standardized proposals. It was found that the Japanese rubber ball represents walking noise in its characteristics and spectrum best, taking into account the practical requirement of a strong enough excitation for building measurements. The standardized tapping machine, with an appropriate single number descriptor, $L'_{\mathrm{nT,w}} + C_{\mathrm{I,50\text{-}2500}}$ or slightly better, $L'_{\mathrm{nT,w\ Hagberg\ 03}}$, leads also to an acceptably high determination coefficient between the descriptor and the subjective ratings. Additionally, the study delivered data, from which proposals for requirements for the suggested single number ratings are deduced, based on the subjective ratings.

Keywords: Impact Noise, Correlation, Listening test, Single number rating, Annoyance, Requirements, Timber Construction, Low Frequencies, Residential Buildings.

1. INTRODUCTION

Multi-storey residential buildings with up to 6 and more floors in timber are becoming more and more popular in Europe. Driving forces are new building regulations (based on extensive research on fire safety), better sustainability and the development towards industrialization of building elements and with that cost reduction, excellent construction-accuracy and unbeaten short construction time. However, noise and vibration disturbances experienced by residents are often an issue within these buildings even if the building code requirements are fulfilled. Therefore, sound and vibration issues might become the hindrance for further development of multi-storey timber buildings.

The current acoustic requirements of residential buildings are based on experience in heavy weight massive constructions, since these structures have dominated the European market historically and timber multi-storey buildings were uncommon in Europe until 10-15 years ago. The perceived acoustic quality in lightweight buildings can be different to heavy weight buildings. In particular, low frequency sound transmission impact sound sources can lead to complaints in timber buildings [1].

The currently applied single number ratings for building acoustics were developed in the 1950's for massive constructions used at that time. In 1996 the introduction of the spectrum adaptation terms according to ISO 717 [2], enabled ratings that include low frequencies down to 50 Hz. Until today low frequency spectrum adaptation terms have been mandatory in national requirements only in one European country, namely Sweden, and used in national classification schemes in only a few European countries [3].

In the AcuWood project the main aim was to find technical descriptors for different impact sound sources taking several European countries (building traditions, cultural differences etc.) into account [4]. The methodology used was to correlate technical descriptors of different floor constructions to subjective ratings, gained by listening tests, similar to methods used to evaluate sound quality [5]. A graph of the approach is shown in figure 1.

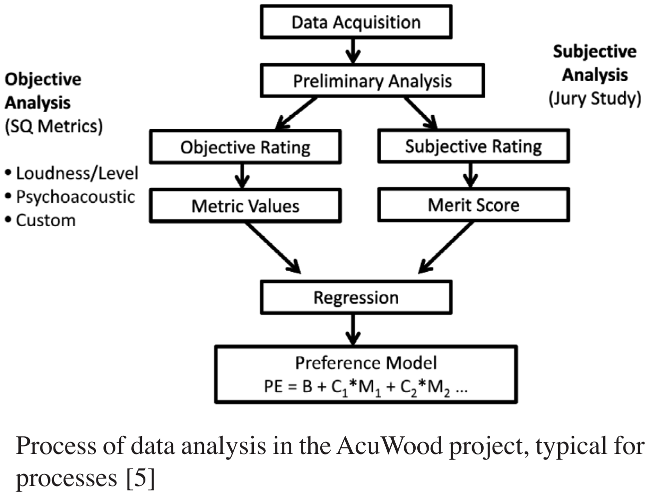

Figure 1: Process of data analysis in the AcuWood project, typical for sound quality processes [5]

2. MEASUREMENTS

Microphone recordings of impact noise measurements were conducted in different floor testing facilities of the Fraunhofer IBP and in the field in both Germany ("DE") and Switzerland ("CH"). For the measurements different impact noises sources were employed. In the laboratory different floor coverings were used. In parallel, binaural recordings with a dummy head were conducted in the receiving rooms. All recordings with the dummy head were made in a similar position in all receiving rooms near a corner of the room at a height of 1.2 m, representing a sitting person. The binaural recordings were then used for the listening tests. From the microphone recordings third-octave band values were extracted, on which the evaluation of the technical descriptors are based.

2.1 Impact Noise Sources

Different impact noise sources were examined in all described measurements. First of all, the standardized tapping machine according to ISO 10140-5 [7] annex E was used. The measurements were conducted in the laboratory according to ISO 10140 and in the field according to ISO 140-7 [8]. The number of microphone positions in the receiving room was 6. In general, four excitation positions on the floor were measured, giving a number of 24 independent measurements in the receiving room. The levels of the 6 microphones were energetically averaged. Some deviations from the standards were necessary in two field measurements, where the distance of microphones to the surrounding walls was reduced. In one of the field measurements the sending room was very small (10 m^3) and the number of excitation positions was accordingly reduced. In addition, the modified tapping machine according to ISO 10140-5 annex F1 method b was applied. This was performed by using the standardized tapping machine placed on 12.5 mm thick elastic pads. The hammers were falling onto elastic interlayers of 12.5 mm thickness, as described in ISO 10140-5. The measurements were conducted at the same positions and with the same procedure as for the standardized tapping machine. Additionally, the Japanese rubber ball described in ISO 10140-5 annex F2 was used. The ball was dropped from a height of 1 m, according to the standard. Here the $L_{F,max}$ value was evaluated in third octave bands from the recordings. The ball drop was repeated in the laboratory and in the field measurements from Switzerland ("CH") 10 times, and in the German field measurements ("DE") the number of ball drops was reduced to 5. The same positions as for the standardized tapping machine were excited by the ball.

Furthermore, "real" sources (walking persons with different footwear) were examined. In all field measurements the same male walker was engaged with the same footwear (shoes and socks). In the laboratory measurements, not always the same walking persons were engaged, giving differences in the walking styles and excitation etc. In the laboratory on all floors three walking persons were engaged, a male walker with normal shoes, a male walker on socks and a female walker with hard heeled shoes. The walkers were walking in a circle across the four excitation positions of the tapping machine; the frequency of steps was about 2 Hz. The walking noise was recorded for 60 s. In cases of background noise during recordings, parts with high background noise were excluded in the analysis of the data.

The second “real” source in all measurements was a chair drawn across the floor. The chair was a four-leg modern chair with plastic seat and backrest. The chair was drawn by a rope for a length of approximate 1 m, giving a signal of about 5 s in the receiving room. The excitation was repeated in the laboratory and the Swiss field measurements (“CH”) 10 times. In the German field measurements (“DE”) the number of iteration was reduced to 5. The same positions as for the standardized tapping machine were excited. The main excitation mechanism of the chair is the stick-slip effect of the feet on the floor. In the measurements of floors with carpet, this source mechanism changed, so that the chair became essentially a different source with much less energy input into the floor and with a different excitation spectrum. This has to be kept in mind when analysing the results of the chair.

2.2 Laboratory Measurements

Two building acoustics test facilities were used to perform the measurements. Both of them are located in IBP (called P8 and P9) and comply with the requirements of ISO 10140-5. Laboratory P8 is used to test intermediate timber floor constructions. It consists of concrete walls and floors and contains a frame where lightweight floors are installed. Laboratory P9 is a concrete construction with a 140 mm thick concrete floor. In both laboratories linings in the sending and receiving room with resonance frequency between 60 and 80 Hz reduce flanking transmission between sending and receiving room at frequencies above approximately 100 Hz.

The laboratory P8 was equipped with a standardized intermediate timber floor according to ISO 10140-5 (Appendix C floor C1). This floor is a lightweight wooden beam floor with a weighted sound reduction index R_w = 45 dB and a weighted normalized impact sound pressure level $L_{n,w}$ = 74 dB. This floor represents a basic floor construction not found in modern buildings with wooden floors. Therefore, further measurements were conducted on the floor equipped with a standard dry floating floor consisting of 18 mm thick gypsum fibre board laminated on 10 mm thick wood fibre board for impact insulation. The bare floor combined with the dry floating floor had a R_w = 54 dB and a $L_{n,w}$ = 68 dB. Additionally, different floor coverings were installed on the dry floating floor in the laboratory to simulate real floor situations. The floor coverings are described in Table 1.

Table 1. Floor coverings used in the laboratory

Number	Floor covering	Interlayer	DLw [dB]
1	7 mm laminate	ribbed foam	20
2	13 mm parquet	foam interlayer	15
3	8 mm tiles + 2 mm tile adhesive	decoupling layer	16
4	4 mm standard carpet	none	23

For practical reasons all floor coverings were not glued to the floating floor and covered only parts of the floor area. The influence of the additional floor coverings on the airborne sound reduction was considered to be low. As the measurements were conducted in laboratories with homogeneous heavy weight flanking walls and linings, the correction of the impact noise levels by airborne sound transmission was not necessary.

As an additional measure in order to increase the acoustic performance of intermediate timber floors, elastically suspended ceilings are often installed. Therefore, the above described floor of laboratory P8 was altered by removing the lowest sheet of gypsum board and replacing it by a suspended ceiling with 40 mm spacers and elastic interlayer and additional 2 x 12.5 mm gypsum boards. On top of the intermediate floor the dry floating floor remained. For this floor construction the measured weighted sound reduction index was R_w = 63 dB, and the weighted normalized impact sound pressure level of the floor was $L_{n,w}$ = 53 dB. Again, for this floor similar measurements were conducted as before on the bare floor and with the same floor coverings described in Table 1.

The measurements in the laboratory P9 were included in this study to give a benchmark for homogeneous heavy weight concrete floors. Additionally, including concrete floors in the correlation analysis was necessary as the proposal for an adequate rating system should comprise all building constructions, including light weight, massive and hybrid constructions. The intermediate floor of P9 measured was a homogeneous floor slab of 140 mm concrete according to ISO 10140-5. Additionally, a standard floating floor with a 50 mm concrete screed on 25 mm mineral wool impact sound insulation (dynamic stiffness $s' \leq 9$ MN/m^3) was installed. For this intermediate floor the weighted sound reduction index was R_w = 64 dB, the weighted normalized impact sound pressure level was $L_{n,w}$ = 41 dB. Again, similar measurements as on the standardized intermediate timber beam floor were conducted with the same floor coverings described in Table 1. This floor does not represent modern heavy weight concrete floors any more. Nowadays, normal concrete floors have a thickness between 200 and 240 mm and are therefore much heavier than the one considered. Nevertheless, the floating floor installed is up to date for German building constructions. It is assumed that the intermediate concrete floor with floating floor considered in this study has mainly a similar frequency spectrum compared to contemporary intermediate concrete floors, however the level of the impact noises are slightly higher (approximately 3-5 dB) than for contemporary intermediate concrete floors.

2.3 Field Measurements

The field measurements were conducted in a manner similar to the laboratory measurements. The measurements comprised modern Swiss multi-storey and multi-family residential timber buildings where the intermediate floors have to fulfill increased legal requirements. Additionally, modern German two-storey single family houses with typical intermediate floors were measured.

The investigated timber buildings in Switzerland comprised four popular intermediate timber floor constructions. In detail: 1. a hollow box floor with ballast and floating floor (height of floor h_f = 269 mm, mass of unit area $m_f' \approx 208$ kg/m^2, impact insulation mineral wool of thickness d_i = 30 mm and dynamic stiffness $s' < 9$ MN/m^3 with a floating floor made of calcium sulphate screed with thickness d_s = 55 mm and m_s' = 110 kg/m^2); 2. a timber-concrete composite floor with floating floor (h_f = 220 mm,

$m_f' = 308$ kg/m^2, impact insulation mineral wool, $d_i = 17$ mm and $s' < 9$ MN/m^3 with a floating floor made of cement screed with $d_s = 80$ mm and $m_s' = 176$ kg/m^2); 3. a solid timber floor (Brettstapel) with ballast and floating floor ($h_f = 245$ mm, $m_f' \approx 220$ kg/m^2, insulation EPS, $d_i = 40$ mm and $s' > 30$ MN/m^3 with a floating floor made of cement screed with $d_s = 85$ mm and $m_s' = 180$ kg/m^2); 4. a ribbed wooden floor of glulam timber with ballast, floating floor and suspended ceiling ($h_f = 337$ mm, $m_f' \approx 81$ kg/m^2, impact insulation mineral wool, $d_i = 40$ mm and $s' < 9$ MN/m^3 with a floating floor made of calcium sulphate screed with $d_s = 60$ mm and $m_s' = 115$ kg/m^2, suspended ceiling with space of 45 mm, partly filled with mineral wool and 2x15 mm gypsum boards with $m'= 26.4$ kg/m^2). All measured intermediate floors had a floor covering of parquet. In all Swiss buildings two floors (rooms) in the same flat with the same build-up but different surface sizes where measured to investigate any differences due to workmanship etc.

The field measurements in Germany were mainly conducted in exhibition houses of prefabricated house companies. All houses were recently erected, therefore they reflect modern single family houses with up to date constructions, thermal insulation etc. One of these timber houses was individually planned and built. In this building two intermediate floors of different sizes were measured. In all other houses one intermediate floor situation was measured. Four of the houses were equipped with intermediate timber beam floors with 240 mm beams and mineral wool filling; two houses had solid timber intermediate floors with 240 mm and 140 mm thickness respectively. One of the intermediate floors with timber beams was additionally equipped with ballast with $m' = 64$ kg/m^2. All houses had floating floors of anhydride or cement with a thickness of the screed between 50 and 65 mm. In most cases impact insulation material was installed underneath the floating floor, in one case it was much stiffer thermal insulation material. The measurement results showed in some cases higher high-frequency impact noise levels, suggesting problems in the proper installation of the floating floor (possibly with sound bridges via installations etc.). Therefore they include results of a wide range of modern floors in buildings.

3. LABORATORY LISTENING TESTS

The laboratory listening tests were conducted for all above described floors in a series of two tests with similar procedure and technique (n=18; n=22). The signals of a length between 5 and 20 s were recorded by dummy head and played to the subjects by calibrated headphones. To confirm the comparability of the two listening test results, the set of one of the field measurements was included in both listening tests. Statistical analysis showed that the answers of both series were comparable and therefore could be combined. The listening tests included questions to the individual noise sensitivity on an 11 point rating scale from “not at all” to “extremely”, the subjective annoyance of the signals on a 11 point rating scale according to ISO/TS 15666 [9], the subjective loudness on a 51 point rating scale according to ISO 16832 [10]. Additionally the question was asked if the signal would be judged annoying when imagine reading a newspaper, magazine or book (answer yes or no). Details and more information on the listening test are described by Liebl [11]. In addition to the listening tests described, questionnaire surveys in single family houses in Germany and in multi-family houses in Switzerland were performed. Because of practical reasons, the questionnaires were not performed in the same houses as the measurements, except two multi-family houses in Switzerland. Results of the questionnaire surveys are reported by Liebl [11].

4. SINGLE NUMBER RATINGS

For the technical description of the measured impact spectra there are numerous single number ratings available. Besides the standard weighted single number ratings for the standardized tapping machine $L_{n,w}$ and $L_{nT,w,}$ including the spectrum adaptation terms $C_{I,\ 100\text{-}2500}$ and $C_{I,\ 50\text{-}2500}$ according to ISO 717, a number of different ratings have been proposed in the past. Most of them are based on the ISO 717 rating method, with a different rating curve in terms of slope and frequency range. Lately, proposals have been made in the AkuLite Project in Sweden [12, 13], but also by Hagberg [14]. Other proposals were given by Bodlund [15], Fasold [16] and Gösele [17]. Additional methods are described in the Japanese Standard JIS A 1419-2 [18] and the Korean Standard KS F 2863-2 [19]. As single number value for all applied impact noise sources the A-weighted standardized sound pressure level $L_{nT,A}$ with a reference to a reverberation time of 0.5 s in the receiving room was calculated from the third octave band spectrum values. This was calculated for two different frequency ranges of $L_{nT,A,50\text{-}2500\ Hz}$ and $L_{nT,A,20\text{-}2500\ Hz}$. For the Japanese rubber ball this was altered to $L_{F,max,nT,A,50\text{-}2500\ Hz}$ and $L_{F,max,nT,A,20\text{-}2500\ Hz}$. Furthermore, two additional single number rating methods were tested in the correlation analysis. Both are based on the standard method of ISO 717, altering only the reference curve. First the reversed A-weighting curve from 50 to 3150 Hz was used as reference curve. Additionally, the hearing threshold curve of ISO 389-7 [20] for a diffuse sound field, was applied as a reference curve. The frequency range from 20 to 5000 Hz was used for this reference curve.

5. CORRELATION ANALYSIS

With the correlation analysis of subjective and objective parameters for the given dataset, three questions can be answered:

- Which of the technical sources is most appropriate to represent walking noise and chair moving noise?
- Which single number descriptor for the given technical source correlates best with the subjective annoyance of the analyzed real sources?
- What requirement levels can be proposed based on the subjective ratings for walking noise?

In this study two “real sources” were investigated, walking person and moving of a chair. For the walking noise signals, different persons were engaged and the levels and the subjective ratings on the same intermediate floor (with the same floor covering) were averaged. As technical sources the standardized tapping machine, the modified tapping machine and the Japanese rubber ball were used. The results of the listening tests showed a high correlation of the loudness and the annoyance judgements. Therefore, loudness and annoyance analysis give essentially similar results. The following analysis is based on the annoyance ratings.

5.1 Representative Sources

In order to clarify which of the technical sources is the most representative for walking noise a correlation between the subjective rating of the technical sources and the subjective rating of walking noise was made. The result for the standard tapping machine is shown in figure 2.

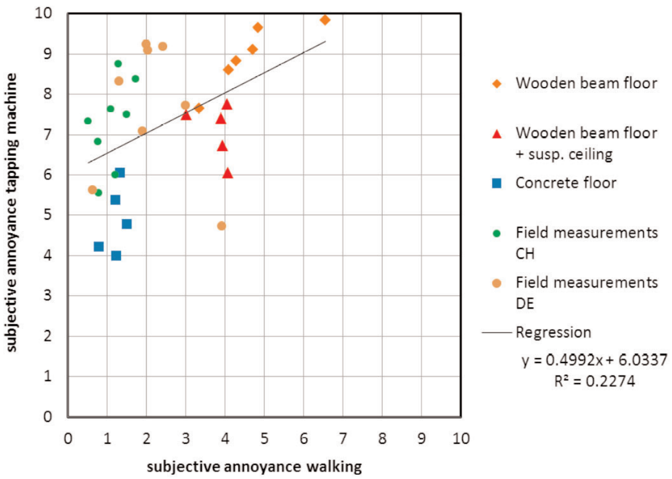

Figure 2: Correlation of the subjectively rated annoyance of the standardized tapping machine with the annoyance of walking noise

For the correlation a linear dependency was assumed. The data points of the different intermediate floors in the laboratories (with different floor coverings) and of the different field measurements together with the regression line and the regression parameters are shown. According to expectations, the annoyance of the tapping machine is much greater than the annoyance of walking noise. Clearly, the annoyance of the standard tapping machine on the intermediate timber floors in Switzerland ("CH") are rated much higher than the annoyance of the same source on the intermediate concrete floor, even though the subjective annoyance of walking noise on both types of floor are rated with quite similar values i.e, ranging only between 0.5 and 1.73. Also for the intermediate timber beam floors in the lab and in the field ("DE"), the spread of the annoyance of the tapping machine is big even when the annoyance rating of walking on the same floor is similar. This leads to a poor determination coefficient of R^2=0.23. The same analysis considering the annoyance of the Japanese rubber ball is shown in figure 3.

The correlation between the annoyance of the Japanese rubber ball and the annoyance of walking noise shows quite a good linear dependency with a determination coefficient of R^2=0.80. For this source the subjective ratings of the acoustically superior intermediate timber floors in Switzerland and of the intermediate concrete floor are quite similar. Only for the field measurements in Germany ("DE") the annoyance ratings of walking noise shows slightly larger spread. Both outliers, the data points from

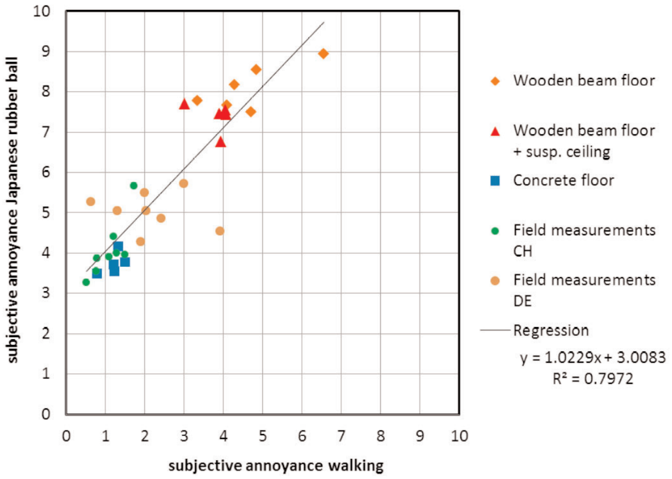

Figure 3: Correlation of the subjectively rated annoyance of the Japanese rubber ball with the annoyance of walking noise

the field measurements ("DE") with the lowest subjective rating and the one with the highest rating were measurements on floors with carpet. The one with the highest subjective rating (3.93/4.5) included high background noise and a rather low walking noise signal. Therefore, for this outlier an increased subjective annoyance rating caused by the raised background noise is assumed. The second outlier with the lowest subjective annoyance rating (0.64/5.3) was an intermediate floor with deep-pile carpet, where the walking noise was reduced by the carpet but the Japanese rubber ball seemed much less affected by the floor covering (the same intermediate floor partly covered by tiles was also investigated, the data point for this floor was (2.01/5.5) in figure 3).

The regression line in figure 3 shows a slope close to 1. This tells us that an increase of annoyance of walking noise by one rating number leads to a similar annoyance increase for the Japanese rubber ball. The overall shift to higher annoyance ratings for the ball can be explained by the stronger excitation (with higher loudness and annoyance) of the rubber ball. For building measurements this stronger excitation is advantageous, as the signal to noise ratio is much greater for the ball than for the other technical sources.

The same analysis was performed for the moving chair noise. An overview of the results for all combinations is shown in table 2. Note that for the regression analysis of the moving chair noise all intermediate floors with carpet as floor covering were excluded.

The results of the correlation between the annoyance of the technical and the "real" sources show that the Japanese rubber ball gives the highest determination coefficient for walking noise. Additionally, the slope of the regression is close to 1. The modified tapping machine gives much higher determination coefficient then the standard tapping machine. Unfortunately, the modified tapping machine is relatively weak in its excitation and gives practical problems at building site measurements because of a low

Table 2. Linear regression coefficients between subjective annoyance of technical source against subjective annoyance of walking noise and chair moving noise

technical source	"real" source	Linear regression coefficients y=ax+b		Determination coefficient
		a	b	R^2
tapping machine	Walking	0.50	6.03	0.23
rubber ball	Walking	1.02	3.01	0.80
modified tapping machine	Walking	0.83	1.45	0.71
tapping machine	Chair	0.71	4.08	0.53
rubber ball	Chair	0.99	0.68	0.72
modified tapping machine	Chair	0.88	-0.72	0.76

signal to noise ratio. For walking noise the Japanese rubber ball is therefore the most appropriate and practical technical source.

Regarding noise from the moving of the chair, the situation is less clear. Here the rubber ball, resulting in $R^2=0.72$ and a slope near 1, is an appropriate source. Nevertheless, the highest determination coefficient is given by the modified tapping machine with $R^2=0.76$. The standardized tapping machine gives a much higher determination coefficient then for walking, but with $R^2=0.53$ it is still lower than for the modified tapping machine and the Japanese rubber ball.

5.2 Single Number Descriptor

In spite of the shortcomings regarding the standard tapping machine and its subjectively rated annoyance due to living noises, it is almost the only technical noise source used in the past in Europe. However, in addition to the rating methods given in ISO 717, the Japanese standard JIS A 1419-2 [18] and the Korean standard KS F 2863 [19] give rating methods for both the standard tapping machine and the Japanese rubber ball.

The most common rating method applied in Europe is the method described in ISO 717. To evaluate if the standard frequency range (100-3150 Hz) single number rating is appropriate to assess walking noise, this single number value ($L'_{\mathrm{nT,w}}$) of ISO 717 is correlated to the subjective annoyance of walking noise. The result is shown in figure 4.

For the weighted standardized impact sound pressure level $L'_{\mathrm{nT,w}}$ the correlation to the subjective annoyance gives a low determination coefficient of $R^2=0.38$. For the field measurements in Switzerland ("CH") and Germany ("DE"), the spread of the single number value can be quite high (more than 10 dB) for the same subjective annoyance rating. Additionally, the Swiss intermediate timber floor constructions have much higher $L'_{\mathrm{nT,w}}$ values compared to the intermediate concrete floor with similar subjective annoyance ratings. This results in a low determination coefficient showing the problem when rating timber constructions using $L'_{nT,w}$ or $L'_{n,w}$. Taking into account the spectrum adaptation term $C_{I,50\text{-}2500}$ (frequencies from 50 Hz), the results from the correlation analysis are shown in figure 5.

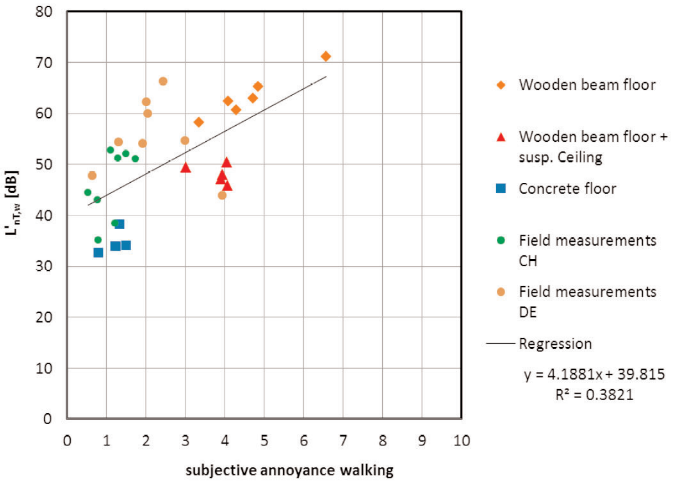

Figure 4: Correlation of the weighted standardized impact sound pressure level $L'_{nT,w}$ with the annoyance of walking noise

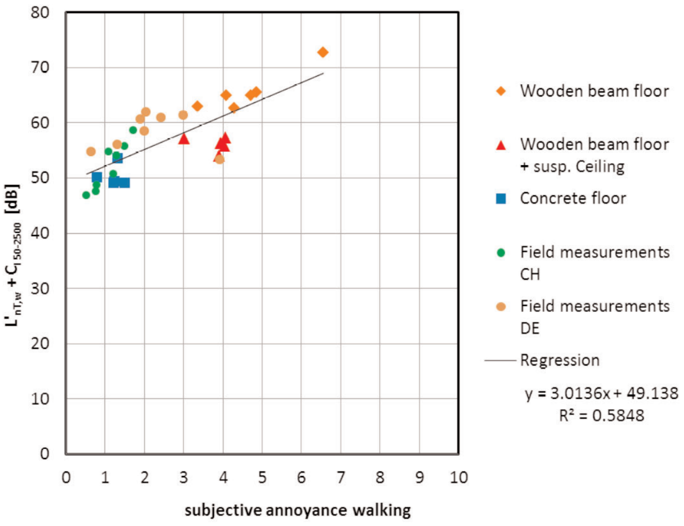

Figure 5: Correlation of the weighted standardized impact sound pressure level $L'_{nT,w} + C_{I,50\text{-}2500}$ with the annoyance of walking noise

Taking the spectrum adaptation term $C_{I,50\text{-}2500}$ into consideration, the determination coefficient increases to $R^2=0.58$. The data points follow much better the linear relationship assumed. It is interesting that the technical descriptor for all the intermediate floors with suspended ceiling in the laboratory lie below the regression curve. For these intermediate floors the main impact noise (highest levels of the A-weighted third octave band spectrum) occurs below 50 Hz and is therefore not included in the spectrum adaptation term.

A similar linear regression analysis was conducted for different single number descriptors, based on the normalized impact sound pressure level in the receiving room. Most of the rating systems are based on the evaluation rules according to ISO 717, but instead use an altered reference curve in terms of shape and frequencies. The different rating curves based on the ISO 717 method are shown in figure 6.

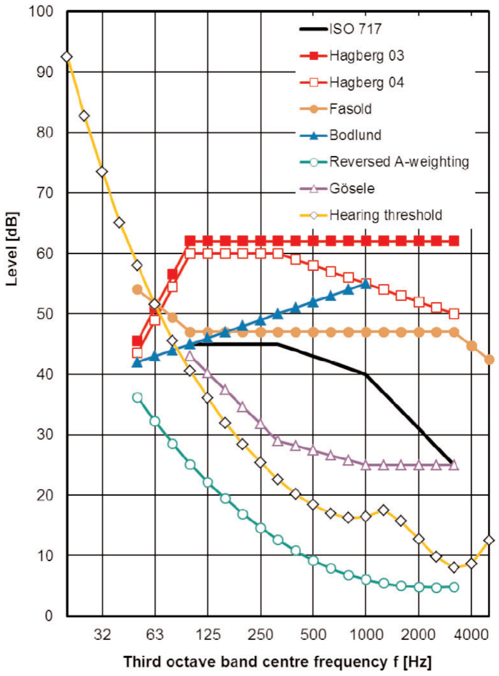

Figure 6: Rating curves used for the different rating methods, based on the evaluation rules according to ISO 717 method

Additional rating methods were taken from JIS A 1419-2. They are somewhat different to the ISO rating method, as they refer to octave band values. The rating curves have high values at low frequencies and lower values at higher frequencies, similar to the shape of the Gösele-curve. Additionally, a proposal of the AkuLite project for a rating method, based on the sum level of the normalized impact sound pressure level and a frequency dependent weighting function was also tried [13]. The results of the determination coefficient for those different rating methods are given in Table 3.

Table 3. Linear regression determination coefficients R^2 between different rating methods of the tapping machine and the subjective annoyance of walking noise

rating method	R^2	rating method	R^2	rating method	R^2
$L'_{\mathrm{nT,w}}$ $(L'_{\mathrm{n,w}})$	0.38 (0.41)	$L'_{\mathrm{nT,Fasold}}$ [16]	0.56	$L'_{\mathrm{nT,hearing\ threshold}}$	0.31
$L'_{\mathrm{nT,w}}+C_{\mathrm{I,100–2500}}$ $(L'_{\mathrm{n,w+}}C_{\mathrm{I,100–2500}})$	0.48 (0.51)	$L'_{\mathrm{n,w}}+$ $C_{\mathrm{I,AkuLite,20\text{-}2500}}$ [13]	0.56	JIS $L_{\mathrm{i,A}}$ [18]	0.35
$L'_{\mathrm{nT,w}}+C_{\mathrm{I,50–2500}}$ $(L'_{\mathrm{n,w}}+C_{\mathrm{I,50–2500}})$	0.58 (0.61)	$L'_{\mathrm{n,w}}+$ $C_{\mathrm{I,AkuLite,20\text{-}2500,hf}}$* [13]	0.56	JIS $L_{\mathrm{i,A,F}}$ [18]	0.29
$L'_{\mathrm{nT,Hagberg03}}$ [14]	0.63	$L'_{\mathrm{n,w}}+$ $C_{\mathrm{I,AkuLite,20\text{-}2500,Sweden}}$** [13]	0.57	JIS $L_{\mathrm{i,A,w}}$ [18]	0.29
$L'_{\mathrm{nT,Hagberg04}}$ [14]	0.62	$L'_{\mathrm{nT,Gösele}}$ [17]	0.36	$L'_{\mathrm{nT,A\ 20\text{-}2500}}$	0.36
$L'_{\mathrm{nT,Bodlund}}$ [15]	0.58	$L'_{\mathrm{nT,reversed\ A\text{-}weighting}}$	0.36	$L'_{\mathrm{nT,A\ 50\text{-}2500}}$	0.36

* AkuLite method with additional high frequency (hf) adaptation

** AkuLite method with restriction to room volume of 31 m^3

The results show that all methods including low frequencies at least down to 50 Hz, Hagberg, Fasold, Bodlund and AkuLite, with the exception of the reversed A-weighting and the hearing threshold, result in relatively high determination coefficients. The best for the given data is the method of Hagberg 03, which has a strong focus on the low frequencies between 50 and 100 Hz with a steep declining reference curve from 100 Hz to 50 Hz. Additionally, the reference curve of Bodlund has a declining reference curve between 50 and 1000 Hz, with a slope not as steep as for the Hagberg 03 reference curve. On the other hand the reversed A-weighting and the hearing threshold curve where the curve is inclining to lower frequencies the determination coefficient is much lower. The Japanese methods with an inclining reference curve towards low frequencies produce also a low determination coefficient.

Additionally, the A-weighted sum level of the tapping machine $L'_{\mathrm{nT,A}}$ for both frequency ranges gives low determination coefficients, which can be explained by the fact that the spectrum of the tapping machine is very different to the spectrum of walking noise.

A similar correlation analysis can be made for the Japanese ball and the modified tapping machine. In this case, less single number rating methods are available. The results are shown in table 4

Table 4. Linear regression determination coefficients R^2 between different rating methods of the Japanese rubber ball and the modified tapping machine against subjective annoyance of walking noise

rating method Japanese Ball	R^2	rating method Japanese Ball	R^2	rating method modified tapping machine	R^2
JIS $L_{\mathrm{i,A}}$ [17]	0.62	$L'_{\mathrm{F,max,nT,A,\ 20\text{-}2500}}$	0.75	$L'_{\mathrm{nT,A\ 20\text{-}2500}}$	0.83
JIS $L_{\mathrm{i,A,Fmax}}$ [17]	0.69	$L'_{\mathrm{F,max,nT,A\ ,50\text{-}2500}}$	0.69	$L'_{\mathrm{nT,A\ 50\text{-}2500}}$	0.76
JIS $L_{\mathrm{i,A,w}}$ [17]	0.62	KS $L_{\mathrm{i,avrg,Fmax\ 63\text{-}500}}$ [18]	0.64	-	-

The results in table 4 show for the Japanese rubber ball and the modified tapping machine that the A-weighted sum level including the very low frequencies from 20 to 2500 Hz gives the highest determination coefficient R^2. All values of R^2 are much higher than for the standard tapping machine, as the spectrum of the rubber ball is much better related to the walking noise.

For the moving of the chair, similar analysis has been conducted. In the following analysis, the intermediate floors with carpet were excluded (on carpet, the chair changes its source behavior as the stick-slip-effect causing the typical moving noise do not occur).

Taking the standardized tapping machine as a technical source to represent the chair, $L'_{nT,w}+C_{I\ 50\text{-}2500}$ gives almost the highest determination coefficient of $R^2=0.72$. Only $L'_{nT,Fasold}$ lies slightly higher with $R^2=0.73$. All other methods give slightly lower R^2. For this source, all methods tend to work equally well. Considering the rubber ball as source for chair noise, the highest determination coefficient was found for $L'_{F,max,nT,A\ 20\text{-}2500}$ with $R^2=0.82$. For the modified tapping machine, $L'_{nT,A\ 20\text{-}2500}$ gave a $R^2=0.82$, $L'_{nT,A\ 50\text{-}2500}$ resulted in a $R^2=0.84$. For the moving of the chair noise and the modified tapping machine as representative noise source, the consideration of the very low frequencies below 50 Hz gives lower determination coefficient than $L'_{nT,A\ 50\text{-}2500}$. This can be explained by the circumstance that the moving of the chair has less very low frequency components, and this is also true for the modified tapping machine.

5.3 Requirement Levels for Single Number Descriptors

In the listening tests the question was asked if the signal is annoying when reading a newspaper, magazine or book. The percentage of test persons perceiving the signal as annoying was correlated to the subjective annoyance rating. This correlation analysis showed very similar linear correlation for both sources alone, the walking noise and the moving of the chair noise. For the walking noise alone the determination coefficient was $R^2=0.94$. The moving of the chair alone gave a determination coefficient R^2 of 0.79. The data of both sources combined is shown in figure 7.

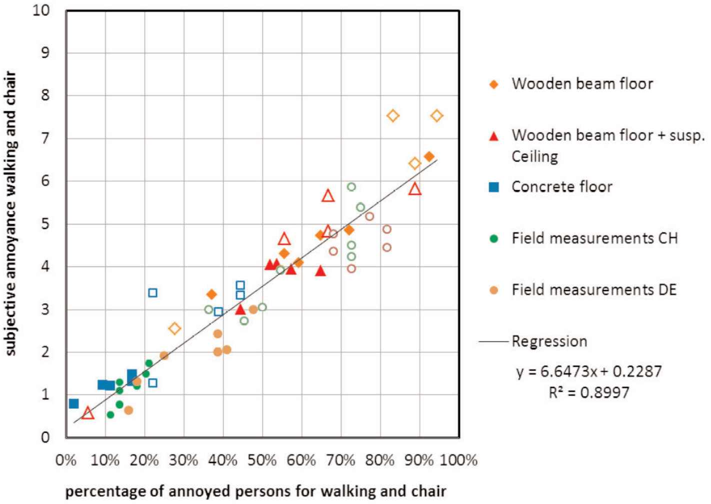

Figure 7: Correlation of the percentage of annoyed persons with the annoyance rating of walking noise (full symbols) and moving of the chair (hollow symbols)

The determination coefficient of the regression is then $R^2=0.90$. The 50% mark of annoyed persons correspond to an annoyance rating of 3.6.

A relationship between a subjective rating scale and a percentage of annoyed or dissatisfied persons has been established in the field of thermal comfort in the 1960s by Fanger [21]. This approach proved successful to formulate requirements based on the predicted percentage of dissatisfied index PPD. A similar approach can be used also to deduce requirements for impact noise.

When recommending requirement levels based on the percentage of annoyed persons, the following question has to be answered: Which kind of noise needs to be addressed by the requirements? The field survey conducted in this project and reported by Liebl [11], can answer this question. The mean judgment of noise annoyance in multi-storey timber buildings in Switzerland with acoustically superior floors was 2.1 on a scale from 0 to 10 for neighbours' walking. This was the highest annoyance judgment for any single noise source addressed (neighbours' music and drums: 1.0; neighbours' rattling of furniture: 1.0; talking in staircases: 1.4; outside traffic: 1.6; water installations: 1.1). Even though the values are quite low, walking noise of neighbours in the flats above are found to be the most prominent source of annoyance. Therefore, the following requirements are focusing on walking noise.

With the high correlation between the subjective annoyance rating and the percentage of annoyed persons, shown in figure 7, it seems reasonable to correlate the single number ratings directly to the percentage of annoyed persons. The correlation and linear regression for the impact sound pressure level $L'_{nT,w} + C_{I,50\text{-}2500}$ is shown in figure 8:

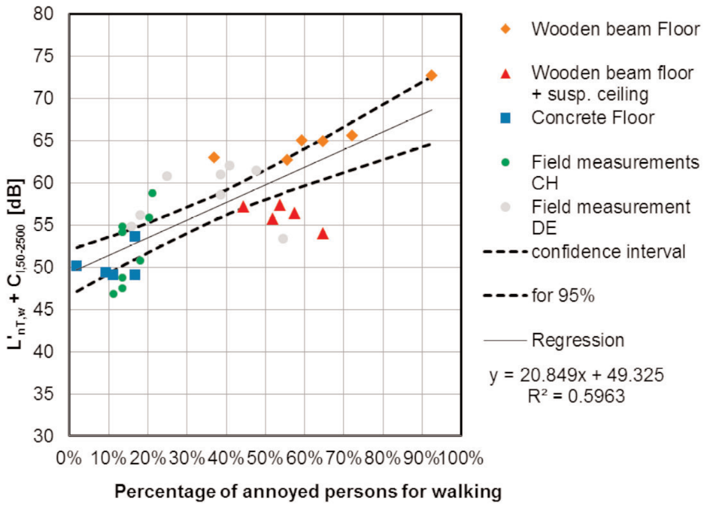

Figure 8: Correlation of the weighted standardized impact sound pressure level $L'_{nT,w} + C_{I,50\text{-}2500}$ with the percentage of annoyed persons for walking noise and linear regression with confidence interval for 95% confidence limit.

The determination coefficient R^2 is slightly higher than for the regression of the annoyance rating in figure 5. The confidence interval for 95% confidence limit shows at low single number values and low percentage of annoyed persons a spread of about 5 dB and at a mid-percentage of 40% a spread below 3 dB. At higher percentage of annoyed persons a bigger spread occurs, due to the lower number of measurement points and the higher deviation of the single measurement point (92.6%/72.7 dB) from the linear regression line.

This analysis can similarly be performed for other single number values. Then, given requirements of standards or recommendations can be related to the percentage of annoyed persons. The most recent recommendations in Germany are given in VDI 4100 [22] for $L'_{nT,w}$. With a linear regression similar to the one in figure 8, the percentage of annoyed persons can be related to the requirements of VDI 4100 [22], shown in Table 5.

Table 5. Requirements of VDI 4100, annoyance rating and percentage of annoyed persons for three levels of acoustic requirements

VDI 4100 (2012)	L´nT,w	Percentage of persons 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%

The recommendation of SST III of VDI 4100 leads to a negative value for the corresponding percentage of annoyed persons, as the value of $L'_{nT,w}$ of 37 dB corresponds to an extrapolated negative value of the annoyance rating. This can be interpreted as an excessive requirement, but also as a safety margin for the relatively low determination coefficient of R^2=0.46 of the linear regression.

An additional analysis of the German DIN 4109 requirements of $L'_{n,w}$ of 53 and 46 dB leads to a percentage of 38% and 14% annoyed persons, when using the correlation between $L'_{n,w}$ and the percentage of annoyed persons.

On the other hand, proposals for requirements can be given, based on the percentage of annoyed persons.

For a minimum requirement a percentage of 40% annoyed persons, and two steps for increased acoustic performance of 20% and 0% annoyed are proposed. Taking the regression formula of figure 8 for $L'_{nT,w}+C_{I,50\text{-}2500}$ and a regression formula from a similar correlation analysis for $L'_{n,w}+ C_{I,50\text{-}2500}$, this leads to the corresponding single number values shown in table 6.

Table 6. Requirements for the different rating methods for the standardized tapping machine representing walking noise

Rating method for the standard tapping machine	Linear regression formula single number value versus percentage of annoyed persons	Determination coefficient R^2	Requirement for percentage of annoyed persons in dB		
			40%	20%	0%
$L'_{nT,w} + C_{I,50\text{-}2500}$	y = 20.8x + 49.3	0.60	58	53	49
$L'_{n,w} + C_{I,50\text{-}2500}$	y = 21.0x + 50.8	0.59	59	55	51

Table 7. requirements given by Hagberg [14] for three stages of acoustic quality

Rating method for the standard tapping machine	Requirement three stages in dB		
	Stage I	Stage II	Stage III
For rooms of V < 31 m^3: requirement for $L'_{n,w} + C_{I,50–2500}$ and $L'_{n,w}$ and for Rooms of V > 31 m^3: requirement for $L'_{nT,w} + C_{I,50–2500}$ and $L'_{nT,w}$	56	52	48

The comparison of the requirements given in Table 6 with the ones of Hagberg in Table 7 shows that the Hagberg requirements are somewhat stricter with values of 1 or 2 dB lower than given in Table 6 for $L'_{nT,w}+C_{I,50\text{-}2500}$. In the database of the AcuWood project, only one Swiss intermediate floor reached stage III of the Hagberg requirement with $L'_{n,w}+C_{I,50–2500}$ = 46.7 dB. Therefore the requirements of Hagberg might be a bit ambitious. There is, however, a potential for optimization of the investigated intermediate floors, for example adding more ballast or a suspended ceilings with low resonance frequency etc., which had not yet been performed.

Additionally, again based on the percentage of annoyed persons, requirements for the Japanese rubber ball and the modified tapping machine are derived similarly to the standard tapping machine and are given in Table 8 and 9 respectively.

Table 8. Requirements for the proposed rating method for the Japanese rubber ball representing walking noise

Rating method for the Japanese rubber ball	Linear regression formula single number versus percentage of annoyed persons	Determination coefficient R^2	Requirement for percentage of annoyed persons in dB		
			40%	20%	0%
$L'_{nT,A,F,max,20\text{-}2500\ Hz}$	y = 24.8x + 46.9	0.74	57	52	47
$L'_{nT,A,F,max,50\text{-}2500\ Hz}$	y = 27.6x + 44.3	0.69	55	50	44

Table 9. Requirements for the proposed rating method for the modified tapping machine representing walking noise

Rating method for the modified tapping machine	Linear regression formula single number versus percentage of annoyed persons	Determination coefficient R^2	Requirement for percentage of annoyed persons in dB		
			40%	20%	0%
$L'_{nT,A,20\text{-}2500\ Hz}$	y = 29.1x + 25.2	0.82	37	31	25
$L'_{nT,A,50\text{-}2500\ Hz}$	y = 29.0x + 23.9	0.75	36	30	24

The choice of three levels of acoustic quality and the given percentage of annoyed persons was related to the proposals of VDI 4100 and Hagberg [14].

5.4 Transferability of the Listening test Data to Real Buildings

Important for the above derived proposals for requirements is the transferability of the laboratory listening test data to the subjective annoyance of living noise in real building situations. The annoyance of living noise in buildings was addressed in the questionnaire surveys in single family houses in Germany and in multi-family houses in Switzerland. Evidence was found that the annoyance ratings in the listening test in the laboratory correspond to the annoyance ratings in real multi-family buildings. The same rating scale was used in the laboratory listening test and the questionnaire field survey. Following from that direct comparison of listening test and questionnaire results were possible for two Swiss multi-family buildings. For both buildings, the annoyance ratings of the listening test and the field survey were similar. The results are discussed in [11].

6. CONCLUSIONS

In the AcuWood project the impact noise of “real” sources of walking noise and chair moving noise and of technical sources, the standardized tapping machine, the modified tapping machine and the Japanese rubber ball have been measured and recorded in different laboratory and field situations. Additionally, these different noise sources were subjectively evaluated by performing laboratory listening tests.

The most appropriate technical source to represent walking noise turned out to be the Japanese rubber ball. In its characteristics and spectrum, it is very similar to real walking noise. Additionally, there are no restrictions regarding floor covering materials, unlike for the other technical sources. The best correlating single number rating for the Japanese rubber ball is $L'_{F,max,nT,A\ 20\text{-}2500}$, with a determination coefficient of R^2=0.75. Based on the percentage of annoyed persons, requirement values for this single number rating are given.

The modified tapping machine represents walking noise very well and has an even higher R^2=0.83 for the single number rating of $L'_{nT,A\ 20\text{-}2500\ Hz}$. Nevertheless, the modified tapping machine is rather unpractical for real building measurements due to low signal to noise ratio.

The standardized tapping machine can also be utilized as impact noise source. $L'_{nT,w}+ C_{I,50\text{-}2500}$ is an acceptable single number descriptor with a determination coefficient of $R^2=0.58$. The best single number descriptor when evaluating the standard tapping machine was $L'_{nT,w\ Hagberg\ 03}$ with $R^2=0.63$. For single number ratings in an extended frequency range according to ISO 717, $L'_{n,w}+ C_{I,50\text{–}2500}$ and $L'_{nT,w}+ C_{I,50\text{-}2500}$, requirements are given, again based on the percentage of annoyed persons.

Regarding the frequency range to be considered for the single number rating, the results showed that frequencies at least down to 50 Hz have to be included. This is the case for $L'_{nT,w}+C_{I,50\text{–}2500}$ and $L'_{nT,w\ Hagberg\ 03}$ evaluating measurements using the standardized tapping machine. For the sum levels of $L'_{F,max,nT,A\ 20\text{-}2500\ Hz}$ and $L'_{nT,A,\ 20\text{-}2500\ Hz}$ evaluating measurements using the Japanese rubber ball and the modified tapping machine respectively, frequencies down to 20 Hz have been found to give slightly better correlation than considering frequencies down to 50 Hz. In this study this finding is caused by intermediate timber floors with suspended ceilings, since they exhibit relevant sound transmission below 50 Hz. Therefore, excluding frequencies below 50 Hz in the single number rating will always carry the risk of excluding relevant sound transmission at very low frequencies.

For the single number descriptors investigated, requirements are deduced from the percentage of annoyed persons. This approach has been proved useful by Fanger [21]. He describes the PPD index for the evaluation of thermal comfort. Acoustical requirements based on the percentage of annoyed persons seem to be more easily understood by builders, clients, lawyers, politicians and other people involved in the building process, even without acoustical knowledge. Evidence was found that the annoyance rating of the listening tests were similar to annoyance ratings in multi-family houses in Switzerland. This evidence still has to be confirmed by comparison of more data sets of multi-family buildings in the future.

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