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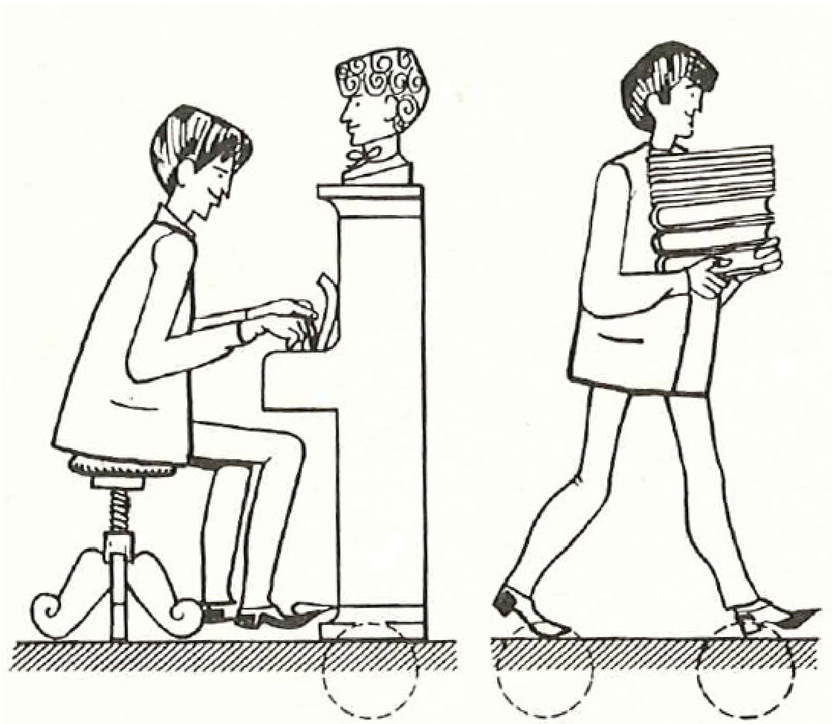

Measurement and evaluation uncertainties of impact sound insulation

An investigation of light weight structures

Master of Science Thesis in the Master Degree Sound and Vibrations

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Examples of sources of impact sound
Furrer W., *Room and Building Acoustics and Noise Abatement*, BUTTERWORTH & CO (1964)

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Abstract

Light weight building technique for multi-storey residential houses become more and more common, approximately 15 – 20 % of all new multi storey apartment buildings in Sweden are built with this technique [1]. However, it is well known among engineers and scientists in the field of acoustics that the methods of measurement and evaluation of impact sound according to ISO 140-7 [7] and ISO 717-2 [3] suffer from shortcomings considering light weight floor structures. These methods do not manage to create an objective single number quantity of the impact sound insulation which sufficiently correlates to the habitant's subjective judgment regarding the sound climate in the building. This is a large disadvantage which might prevent a positive future development of the light weight technique in multi storey residential buildings. This Master thesis aims to extend the knowledge in this field by identifying reasons for measurement and evaluation uncertainties of impact sound insulation measurements in light weight buildings.

The results in this thesis indicate significant uncertainties in current measurement and evaluation methods. According to experiences from engineers, the uncertainties are most crucial in the low frequency range where the largest vagueness of the impact sounds arise. Light weight structures generate highest sound levels in low frequencies where the human ear is most sensitive to level differences. This means in practice, when the impact sound is perceived small changes in noise levels might cause large changes in the subjective experience of the impact sound insulation in a light weight building.

The results emphasize the need of further knowledge, especially at low frequencies to be able to revise the standards (ISO 140-7 and ISO 717-2) successfully which would result in measurement results giving objective single number quantities which correlate well to the subjective perception.

Keywords: Impact sound pressure level, Reverberation time, Distribution, Confidence interval, Reference curve, Low frequencies, Receiving and Source positions.

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1. Introduction

It is well known among engineers and scientists in the field of acoustics that the methods of impact sound measurements and in particular the evaluation of impact sound insulation according to ISO 140-7 [7] and ISO 717-2 [3] respectively suffer from shortcomings considering light weight floor structures. These shortcomings get clear when it comes to create an objective single number quantity of the impact sound insulation, correlating sufficiently to the inhabitant's subjective judgment regarding the sound climate in multi storey light weight buildings. Bodlund [6] claims that there are three different ways to find a solution to the problem:

1. By introducing a new or modified impact sound source which effectively simulates normal impact sources and footsteps (by changing ISO 140-7 [7]).
2. By changing the procedure for evaluation of the single number characterizing the impact sound insulation (by changing ISO 717-2 [3]).
3. By changing 1 and 2.

Many attempts have been made to replace the ISO impact machine or to combine it with a heavier sound source which would produce a sound corresponding to more typical footstep impact on the floor structure [8]. However, if a new standardized impact sound generator would be constructed, consequently the evaluation stated in ISO 717-2 [3] needs to be modified as well. An example of alternative impact sound sources are the heavy rubber wheel or the rubber ball which are used in the Japanese national standard, JIS A 1418 [6]. These sources are soft, heavy and able to generate low frequency sound of another characteristic than the tapping machine to better simulate the sound of a walking person [8]. However, the wheel generates much higher forces on the floor structure, which increase the risk of structural damage as a result of the testing.

Regarding uncertainties in measurements of impact sound insulation, the measurement procedure is performed as stated in ISO 140-7. The results are evaluated according to ISO 717-2. Initially, the frequency range considered in these standards was adapted to measurement of impact sound insulation on concrete structures and concrete elements. Then the methods were acceptable in general since it was not allowed to build light weight (primarily wooden) multi storey buildings at that time. In the early 1990's this changed and it became acceptable to use wood as building material for multi storey residential buildings [8]. Based on this, it is not surprising that the standards ISO 140-7 and ISO 717-2 are not working optimally for light weight floor structures since light weight structures differ from traditional heavy structures from an acoustical point of view.

One weakness with impact sound pressure level measurements on light weight structures is that the measured and evaluated single number impact sound pressure level is not consistent in general with the subjective impression for those who are living in buildings with light weight floor structures. Furthermore, the methods are not adapted to measure as low in frequency as necessary when they are applied to light weight structures. The main problem is the impact sound pressure level in the low frequency domain where high levels are common for light weight structures [8], while for heavy structures the levels are normally low and furthermore decreasing with decreasing frequency, hence not affecting the final result. Figure 1-1 shows typical difference in frequency content from an impact sound pressure level measurement on one heavy and one light floor structure respectively. The measurements presented in Figure 1-1 are made in a laboratory with the same receiving room.

Remarkable is the weighted single number $L'_{n,w} + C_{I,50\text{-}2500}$ which is calculated to 52 dB for both structures even if significant differences exists for the measured levels, especially in the low frequency region.

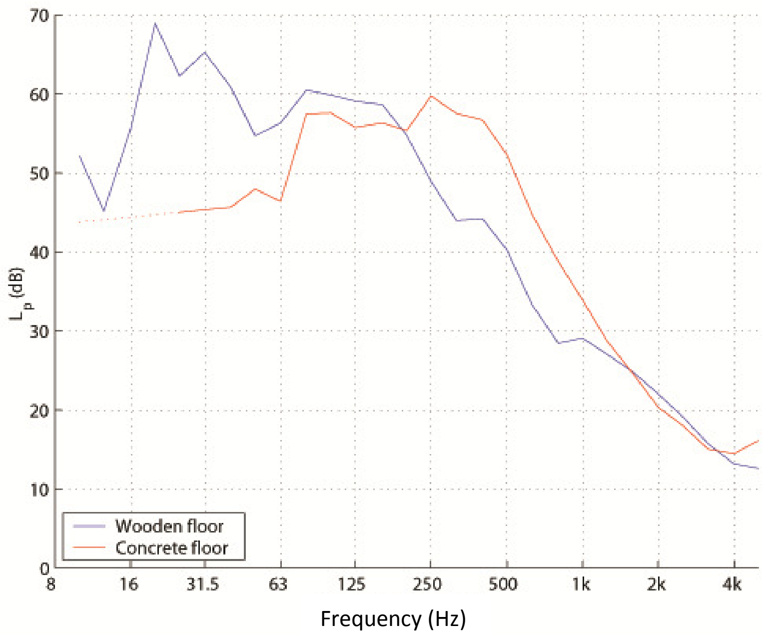

Figure 1-1: Impact sound pressure level measurements performed on a concrete and a wooden floor structure during laboratory conditions [9].

Also, the human ear is more sensitive to level differences in the low frequency region. Once the signal appears, a sound pressure level difference of 3-5 dB is perceived as a doubling of the sound level in the lowest frequencies, compared to 1000 Hz where a 10 dB difference is perceived as a sound level doubling [10], Figure 1-2.

The impact sound pressure level characteristics may not be the only reason why the subjective perception differs from the measured results. Concrete floor structures are homogeneous while wooden floor structures are more complex constructed of joists and beams connected in different manner due to different systems. This may create high uncertainty of the impact sound pressure measurements with respect to the system and where the tapping machine is placed. If it is placed direct over a beam the vibrations can be lead straight to the receiving room compared to when it is placed between beams since no strong path from the tapping machine to the receiving room exists.

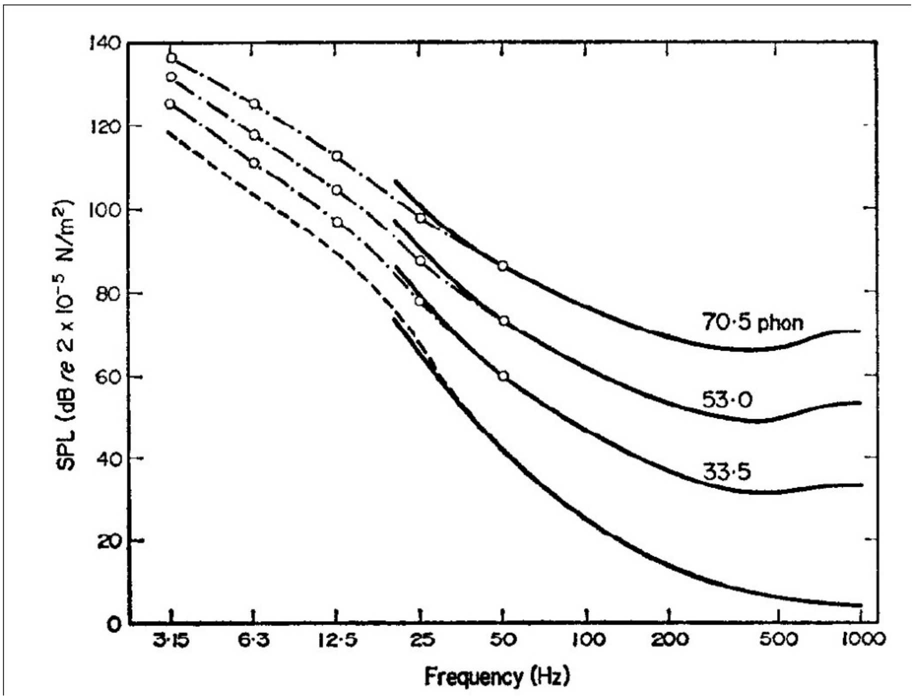

Figure 1-2: Phon curves extended to very low frequencies, describing how the human ears perceive the sound pressure level in different frequencies [27].

Regarding the evaluation method stated in ISO 717-2, a reference curve is used to estimate a weighted single value of the measured impact sound pressure level [3]. Since the result from the existing evaluation method does not sufficiently correlate to the subjective perception, many attempts have been made to define another shape of the evaluation curve designed to take lower frequencies into account, i.e. optimally shaped when still using the tapping machine as sound source. Similar to earlier research of e.g. Hagberg [8] and Bodlund [6], an analysis regarding reference curve shape was included also in this work, based on existing material using a linear regression analysis. The mean weighted values from objective impact sound pressure level measurements are compared with mean values from subjective judgements. The aim with the reference curve investigation is to state whether results from earlier research still hold when objective and subjective data are extended.

1.1. Goal

The main purpose of this investigation is to point out and study uncertainties in the ISO measurement and evaluation method of impact sound insulation (sound pressure level) on light weight structures. Further on, the design of the reference curve will be investigated with the aim to verify a reference curve from earlier investigations used for single numbers adapted to the subjective evaluation of impact sound pressure level. This is made in order to confirm whether the suggested reference curve from Hagberg [8] will alter if the data set is further extended.

Finally, a description of existing measurements based on current ISO 140-7, available at different consultant companies, on impact sound insulation in light weight floor structures and their usefulness for further analyzes in the Akulite research project should be made. Hence, if necessary, a description on existing measurements and their need for supplementary information for the Akulite project should be included.

1.2. Method

Input data has been achieved by contact with various consultants in the acoustical field. The measurements have been assigned a project number to keep them anonymous. For each project there have been measurements on different number of objects. The objects are referred to the appendix number in each measurement report or similar. The measurements of impact sound pressure level has been divided into concrete and light weight (mainly wooden) floor structures for both vertical and horizontal measurements, Table 1-1. All the input data has been treated and analyzed in *Matlab R2009b*.

Measurements according to ISO 140-7 are divided into several parts. There is a need for level measurements to state the impact sound level in the room. However, there is also a need for some corrections of the measured sound level if the room is not fully furnished or sparsely furnished for example, i.e. not corresponding to a normally furnished room. To make reasonable corrections there are thus a need for reverberation time measurements which will be compared to a "normal" reverberation time or equivalent sound absorption area. Furthermore, the background level has to be measured in order to establish that it is not affecting the final results. This investigation has been focused on mainly impact sound pressure level and reverberation time measurements and their influence on the final results.

Table 1-1: Table presenting the measurement data which have been used for the analysis. The projects have gained a number to keep them anonymous. If it has been both horizontal and vertical measurements in a project they have been separated in the table.

Project	Direction	Floor structure	Measurement										
1	Vertical	Light weight	A05	A07	A10	A11	A12						
1	Horizontal	Light weight	A06	A08	A09								
2	Vertical	Light weight	1										
3	Vertical	Light weight	2008 (1)	2008 (2)	2009 (1)	2009 (2)	2007						
4	Vertical	Light weight	A01	A02	A03	A04	A05	A06					
5	Vertical	Light weight	A01	A02	A03	A04	A05	A06	A07	A08	A09		
6	Vertical	Light weight	A10	A11									
6	Horizontal	Light weight	A12										
7	Vertical	Light weight	A15	A16	A17	A18	A19	A20	A21	A22	A23	A24	A25
7	Horizontal	Light weight	A26										
8	Vertical	Concrete	8	9									
9	Vertical	Concrete	A04										
10	Vertical	Light weight	1	2	3	4	5	6	7	8			
11	Vertical	Concrete	1	2									
12	Vertical	Concrete	1										
13	Vertical	Concrete	1	2	3	4							
14	Vertical	Light weight	1										
15	Vertical	Concrete	1										
16	Vertical	Light weight	1										

1.2.1. Uncertainties of measurements

The data have been analyzed with regard to different measurement positions in the receiving room. The distribution of data from impact sound pressure level and reverberation time measurements were investigated with a Weibull distribution plot. The distribution of measured reverberation times in various measurements positions have been more detailed investigated by using quaintile-quantile plots.

Also, different receiving room volumes and their influence on the results have been studied, in order to illustrate how the uncertainties of measurements depend of the receiving room volume.

1.2.2. Impact sound in low frequencies

Some measured impact sound pressure levels down to very low frequencies have been investigated in 1/3 octave bands. The investigation was based on projects with measured impact sound pressure level down to either 6.3 Hz or 25 Hz. The frequency range varies between the investigated measurements depending on the operator's choice at the moment for performing the measurements due to certain needs in the specific case.

1.2.3. Extended measurements

The authors have made own measurements regarding impact sound insulation, performed vertically between two rooms similar in size and volume, the measurement is referred as project 16 in Table 1-1. The aim of these measurements has been to investigate how different positions of the tapping machine in the sending room influence the final weighted impact sound pressure level. The deviation of the impact sound pressure level and reverberation time data from the measurement has been analyzed with a Weibull distribution. The number of tapping machine positions was totally 35, limited by the room boundaries.

1.2.4. Evaluation of reference curve

The correlation analysis to investigate different reference curves has, similar to Hagbergs work [8], been based on a linear regression analyze. Mean values from objective impact sound pressure level measurements have been compared with mean values from subjective judgments using current data from two independent investigations.

1.2.5. Evaluation of performed measurements

The measurement reports of project 1 - 7 in Table 1-1 have been analyzed based on requirements in standard SS-EN ISO 140-7 [7], ISO 717-2 [3] and SS 25267 [2]. The arrangement of the reports has been compared to see if there are deficiencies in the description of measurement procedure.

The work has been limited to only evaluate measurements on light weight (mainly wooden) floor structures for frequencies from 50 to 3150 Hz; since this is the current standard limits (can be extended to 5000 Hz, however not interesting in this project).

The input data evaluation has been limited to focus on the following aspects;

- Are there any differences between measurement reports regarding acoustical results?
- Are the measurement procedures sufficiently clear?
- Are the building structures sufficiently described in the reports?
- Are there any existing risks to use existing measurements in the AkuLite project?

2. Theory

2.1. Building acoustics

A short description and explanation in theory of building acoustics concerning standards, concepts, parameters, procedures and evaluation methods in this thesis follows in this chapter.

2.1.1. Measurement standards

SS-EN ISO 140-7:	Swedish, European and International standard describing how to perform impact sound pressure level measurements in the field.
SS-EN ISO 717-2: second edition:	Swedish, European and International standard describing how to evaluate single number levels from the results of measurements, for example performed according to SS-EN ISO 140-7.
SS 25267:2004, third edition:	Swedish sound classification standard, containing a scheme with four sound classes stating requirement levels, where sound class C corresponds to the Swedish national requirements in the building code, BBR. It also contains additional requirements to the SS EN ISO 140-7 standard.

2.1.2. Acoustic concepts

Impact sound	Sound generated, through mechanical contact to a floor structure, in one room transmitted to another room. Impact sound can have different origins such as walking persons, falling objects or chairs being moved.
Impact sound pressure level:	The sound pressure level in dB which is perceived in a receiving room when a tapping machine is running on the floor in a sending room. Impact sound level is measured between two rooms at different floors where the floor is separating the rooms or between two rooms at the same floor with a separating wall. Consequently, the impact sound insulation can be measured both vertically and horizontally. The Impact sound insulation in the field situation is presented by the normalized or standardized weighted single number parameters, $L'_{n,w}$ and/or $L'_{n,w}+C_{I,50\text{-}2500}$ or $L'_{nT,w}$ and/or $L'_{nT,w}+C_{I,50\text{-}2500}$. The impact sound insulation is also commonly presented as a function of frequency in 1/3 octave bands between 50-3150 Hz.
Schroeder frequency:	The frequency where the modal spacing changes from having less than three modes to having at least three modes within a given mode´s half-power bandwidth [32].

Sound classification: A floor structure can be classified using different sound classes. In Sweden and other Nordic countries four classes exist, A, B, C and D where A is the highest and D is the lowest sound class. Sound class C corresponds to minimum national requirements. In special cases sound class D is used. A structure might be rated with sound class D if it is not possible to achieve the minimum sound class C, e.g. due to the cultural or historical reasons of a building. The limits for impact sound of the sound classes are defined by Table 2-1.

Table 2-1: Impact sound pressure level requirements for classification according to SS 25267 [2].

	Sound class A	Sound class B	Sound class C	Sound class D
Highest level[2)]	48 dB[1)]	52 dB[1)]	56 dB[1)]	60 dB

1) Both $L'_{n,w}$ and $L'_{n,w}+C_{I,50\text{-}2500}$ has to be fulfilled.
2) Receiving room volume is limited to 31 m^3

Tapping machine ISO standard impact sound generator which is used in the measurement procedure according to ISO 140-7. The machine includes five steel-faced hammers, each with a weight of 0.5 kg which strikes the floor structure 10 times per second from a height of 40 mm.

2.1.3. Acoustic parameters

The following description of parameters is due to the measurement standards SS-EN ISO 140-7, SS-EN ISO 717-2 and SS 25267:2004.

A: Equivalent absorption area in the receiving room, given in [m^2].

A_0: Reference equivalent absorption area, set to 10 m^2.

$C_{I,50-2500}$: Spectrum adaptation term to be used to extend the frequency range down to 50 Hz, evaluated according to ISO 717-2 [dB].

L': Equivalent impact sound pressure level in the field for each 1/3 octave band in the frequency range 50-3150 Hz in the receiving room. The index ʻ on L indicates that flank transmission is included (i.e. field situation), given for each 1/3 octave band with one digit [dB].

L_{b}: Averaged measured equivalent sound pressure level for each 1/3 octave band in the frequency range 50-3150 Hz of the background noise in the receiving room, given for each 1/3 octave band with one digit [dB].

L'_{n}: Averaged normalized impact sound pressure level measured in field. L'_n is normalized to the absorption area A_0 = 10 m^2. In Sweden, this parameter is used for rooms with a volume less than 31 m^3, given for each 1/3 octave band with one digit [dB].

L'_{nT}: Standardized impact sound pressure level measured in field. L'_{nT} is standardized to the reverberation time, T = 0.50 s. In Sweden, this parameter is used for rooms with a volume equal to or greater than 31 m^3, given for each 1/3 octave band with one digit [dB].

$L'_{\mathrm{n,w}}$: Weighted and normalized impact sound pressure level, given in one single number value [dB].

$L'_{\mathrm{n,w}} + C_{\mathrm{I,50-2500}}$ Weighted and normalized impact sound pressure level considering the frequency range 50 – 2500 Hz, given in one single number value [dB].

$L'_{\mathrm{nT,w}}$: Weighted and standardized impact sound pressure level, given in one single number value [dB].

$L'_{\mathrm{nT,w}} + C_{\mathrm{I,50-2500}}$ Weighted and standardized impact sound pressure level considering the frequency range 50 – 2500 Hz, given in one single number value [dB].

T: Reverberation time in the receiving room for each 1/3 octave band, given for each 1/3 octave band with two digits [s].

T_0: Reference reverberation, set to 0.50 s for all 1/3 octave bands. The reverberation time corresponds approximately to a furnished room in a “normal dwelling” independent of frequency.

V: Volume of the receiving room (in Sweden limited to 31 m^3) [3].

2.1.4. Measurement procedure

The measurement procedure is described in the international standard SS-EN ISO 140-7. In general, the measurements are performed with a tapping machine in at least four randomly distributed positions in the source room. If the measurement is performed on a light weight floor structure, the tapping machine shall be orientated 45° to the direction of the beams and ribs in the floor structure.

There are two possible approaches to perform the spatial averaging procedure of the impact sound pressure level in receiving rooms, either by fixed microphone positions or by sweeping microphone positions. Either if the measurements are performed with fixed microphone positions or by a sweeping microphone, there shall be at least four sending positions. If the approach with fixed microphone positions is used, the positions shall be at least four. Further on, at least six measurements shall be done. If the measurement is performed with sweeping microphone, the sweep shall be performed with a minimum radius and during a minimum measurement time. At least four measurements shall be done. Further on, some demands regarding distance to boundaries and distances between microphone positions have to be considered for both procedures.

Regarding reverberation time measurements, at least six measurements shall be performed with at least one source position and three microphone positions with two readings in each position.

As a complement to SS-EN ISO 140-7, there are some demands by the Swedish standard SS 25267:2004 in appendix H. This text describes further demands regarding microphone and source positions and also instructions to handle equipment, small rooms and measurement uncertainties.

2.1.5. Evaluation of measurements

The spatial averaged impact sound pressure level is calculated for each 1/3 octave band according to Equation 2-1.

Equation 2-1

$$L = 10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} 10^{L_i/10}\right)$$

where L_i are the sound pressure levels L_1 to L_n at n different positions in the room.

If needed, the averaged impact sound pressure level is adjusted due to the background noise. If the level difference between the impact sound pressure level and background noise is greater than 6 dB but less than 10 dB the correction shall be made according to Equation 2-2. If the level difference is less than 6 dB the correction shall be made according to Equation 2-3. However, if the difference is greater than 10, no correction shall be made.

Equation 2-2

$$L = 10\log_{10}\left(10^{L_{\mathrm{sb},i}/10} - 10^{L_{\mathrm{b},i}/10}\right)$$

Equation 2-3

$$L = L_i - 1{,}3$$

where

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

The properties (i.e. the furnishing) of the receiving room affect the measured impact sound pressure level, hence the level will differ in a room depending on if the room is furnished or not. Therefore, the impact sound pressure level is adjusted to the level of a normally furnished room. This is done either by normalization (i.e. normalize to 10 m^2 absorption area) or by standardization to a normally furnished room (i.e. T = 0.50 s). The most proper way is to standardize to 0.50 s since this makes the level independent of room volume. If normalize to 10 m^2 (i.e. using $L'_{n,w}$) this imply big errors if the receiving room volumes are big. In Sweden $L'_{n,w}$ is used, however there is a limit not to exceed receiving room volumes of 31 m^3 in the evaluation which means that in reality $L'_{nT,w}$ is valid when room volumes exceed 31 m^2. Hence, in Sweden the value is normalized according to Equation 2-4 and 2-5 However, the impact sound pressure level is standardized according to Equation 2-6 if the receiving room volume is equal or greater than 31 m^3.

Equation 2-4

$$L'_{\mathrm{n},i} = L_i + 10\log_{10}\left(\frac{A_i}{A_0}\right)$$

where

Equation 2-5

$$A_i = \frac{0{,}16V}{T_i}$$

and

$$A_0 = 10\ m^2$$

The standardized impact sound pressure level is calculated according to Equation 2-6.

Equation 2-6

$$L'_{\mathrm{nT},i} = L_i - 10\log_{10}\left(\frac{T_i}{T_0}\right)$$

where

$$T_0 = 0{,}50\ s$$

The 1/3 octave band values are then compiled to one single number through a weighting procedure. The weighting procedure to calculate the single number levels $L'_{\mathrm{n,w}}$ and $L'_{\mathrm{nT,w}}$ is performed in the frequency range 100 – 3150 Hz by comparing L'_{n} or L'_{nT} with a reference curve, Figure 2-1, which is defined in ISO 717-2 [3]. ISO 717-2 states that the single number quantity called $L'_{\mathrm{n,w}}$ and $L'_{\mathrm{nT,w}}$ equals the impact sound pressure level at 500 Hz, after the reference curve has been shifted in steps of 1 dB until the sum of the unfavorable deviations from the measured curve is as large as possible but not larger than 32.0 dB. An unfavorable deviation is present in a specific frequency band when the measured level is higher than the value of the reference curve.

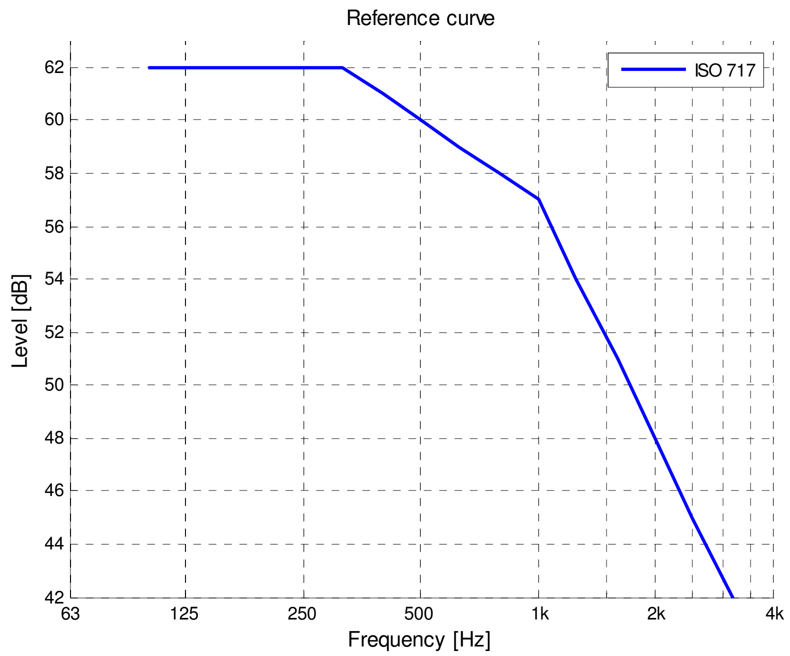

Figure 2-1: Reference curve used for weighting of measured impact sound pressure level, according to ISO 717-2 [3].

To take frequencies lower than 100 Hz into account, the adaptation term $C_{I,50-2500}$, might be added to $L'_{n,w}$ or $L'_{nT,w}$, calculated according to Equation 2-7 and Equation 2-8.

Equation 2-7

$$C_{\mathrm{I,50-2500}} = L'_{\mathrm{n,sum}} - 15 - L'_{\mathrm{n,w}}$$

Equation 2-8

$$C_{\mathrm{I,50-2500}} = L'_{\mathrm{nT,sum}} - 15 - L'_{\mathrm{nT,w}}$$

The sum of the impact sound pressure levels are calculated according to Equation 2-9. Note that only the measured values for the 1/3 octave bands 50 – 2500 Hz are considered in Equation 2-9 and Equation 2-10.

Equation 2-9

$$L'_{\mathrm{n,sum}} = 10\log_{10}\left(\sum_{i=1}^{k} 10^{L_{\mathrm{n},i}/10}\right)$$

Equation 2-10

$$L'_{\mathrm{nT,sum}} = 10\log_{10}\left(\sum_{i=1}^{k} 10^{L_{\mathrm{nT},i}/10}\right)$$

The “low frequency” single number rating is then specified simply by adding the adaptation term to the weighted value i.e. $L'_{n,w}+C_{I,50-2500}$ and $L'_{nT,w}+C_{I,50-2500}$.

According to the description above and guidelines in SS 25267, $L'_{n,w}$ and $L'_{n,w}+C_{I,50\text{-}2500}$ are used even if the real value should be stated as the standardized level ($L'_{nT,w}$) when room volumes exceed 31 m^3.

2.2. Statistics

Two commonly used statistic methods to investigate the measurement uncertainties are standard deviation and confidence interval. These measures can be used in the field of acoustics for instance in evaluation of uncertainties between different microphone positions regarding impact sound pressure level and reverberation time measurements.

2.2.1. Standard deviation

Standard deviation, σ, is a single value describing to what extent the different values in a statistical population deviate from the mean value, which is illustrated in Figure 2-2. A low value on standard deviation indicates that the data tend to be close to the mean value, whereas a high value indicates that the data are widely spread out over a large range from the mean value. The standard deviation is expressed in the same units as the data and is defined as the square root of the sample variance s^2, Equation 2-11. The variance can also be defined as theoretical as σ^2. Since the theoretical variance σ^2 cannot be calculated, the variance is estimated by the sample variance s^2.

Equation 2-11

$$\sigma = \sqrt{s^2}$$

where

Equation 2-12

$$s^2 = \frac{1}{n-1}\sum_{j=1}^{n}\left(x_j - \bar{x}\right)^2$$

and

Equation 2-13

$$\bar{x} = \frac{1}{n}\sum_{j=1}^{n} x_j$$

In the field of acoustics, standard deviation is commonly used to measure the uncertainty of measurements, for instance the uncertainty which different microphone positions in a receiving room gives rise to within each 1/3 octave band. A typical indication regarding uncertainties in a measurement could be if the standard deviation for a certain 1/3 octave band is significantly higher than other 1/3 octave bands, then there is likely some error caused by poor circumstances like loud time-varying background noise.

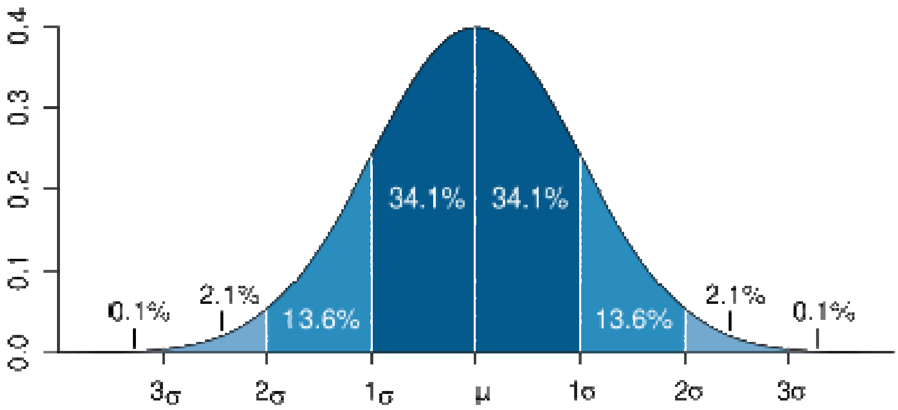

Figure 2-2: A normal distribution standard deviation diagram. Each colored band has a width of one standard deviation. [4].

2.2.2. Confidence interval for an unknown parameter

Confidence intervals are in mathematical statistics a measure of the uncertainty expressed in an interval which is estimated for a given confidence level γ, often 95 %. A confidence level of 95 % means in this work that for each set of measurement series, there is a 95 % probability that the measured mean value lies somewhere within the confidence interval. Examples of other common confidence levels are 90 and 99 %. A confidence level of 90 % ends up with a narrower interval than a 95 % confidence level. In the opposite way, a 99 % confidence level ends up with a wider interval. The confidence interval covers the true parameter value with a certain probability.

A confidence interval can be based on different distributions as; normal distribution, binomial distribution and Poisson distribution. The confidence interval for the expected value of a normal distribution μ, is defined as Equation 2-14. μ is the theoretical mean value of the distribution and can be estimated from the data by using the sample mean value, $\bar{x}$, Equation 2-13.

Equation 2-14

$$\mathrm{CONF}_{\gamma}\{\bar{x} - k \leq \mu \leq \bar{x} + k\}$$

where

Equation 2-15

$$k = \frac{c\sqrt{s^2}}{\sqrt{n}}$$

and

s^2 is the estimated variance, calculated as Equation 2-12.
n is number of observations.
c is the coverage probability from table in Appendix I suit to when σ^2 is unknown and estimated as s^2, this operation is known as Student's t-Distribution[11]. c is chosen in Appendix I from calculated values from Equation 2-16 and Equation 2-17.

Equation 2-16

$$F(c) = \frac{1}{2}(1 + \gamma)$$

where

γ is the confidence level.

Equation 2-17

$$df = (n - 1)$$

where

df is the number of degrees of freedom

The degree of freedom is defined as the number of values in the final calculation of a statistic that are free to vary. A low value of degrees of freedom will give rise to a high value of the coverage probability *c* which results in a wide confidence interval.

2.2.3. Normal distribution

The normal distribution or Gaussian distribution is in statistics and probability theory a distribution which is providing a compatible description of data that are aggregated around the mean. The probability density function is defined as Equation 2-18.

Equation 2-18

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(x-\mu)^2}{2\sigma^2}}$$

where

x is a random variable with mean μ and variance σ^2 in the domain $x \in (-\infty, \infty)$ [5].

A graph over the probability density function is called a Normal curve or a Bell curve and is denoted with a characteristic peak located at the mean which has clustered symmetric data around. A normal distribution has different normal density curves depending on values of mean μ and standard deviation σ, Figure 2-3. The so-called standard normal distribution is given if the normal distribution has a mean of 0 and a variance of 1.

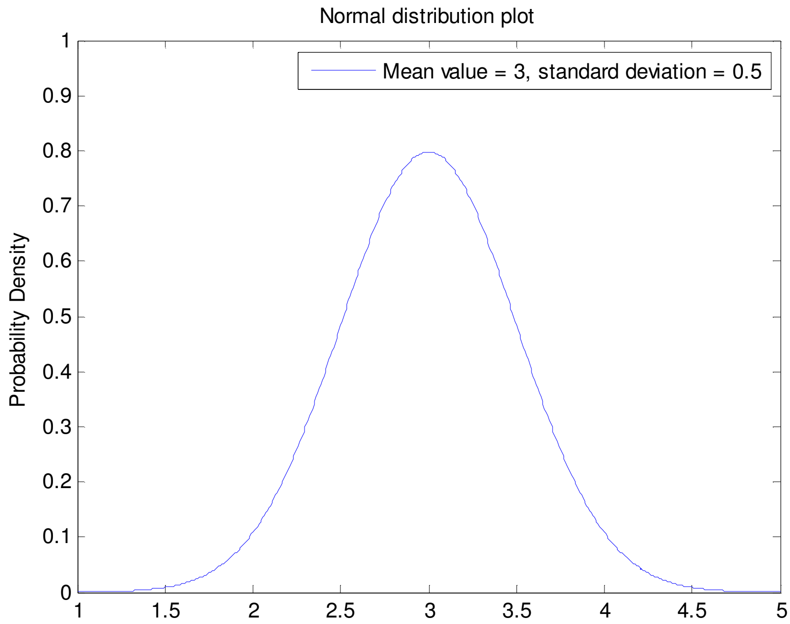

Figure 2-3: An example of a normal distribution plot.

2.2.4. Weibull distribution

A Weibull distribution is a flexible and adjustable distribution, "*The Weibull distribution is one of the most widely used lifetime distributions in reliability engineering. It is a versatile distribution that can take on the characteristics of other types of distributions, based on the value of the shape parameter, β*", [30]. A variable x has a Weibull distribution with parameters α and β is the density function of x is as Equation 2-19 [28].

Equation 2-19

$$f(x)\begin{cases}\frac{\alpha}{\beta^{\alpha}}x^{(\alpha-1)}e^{-\left(\frac{x}{\beta}\right)^{\alpha}}, & x>0\\ 0, & x\leq 0\end{cases}$$

A normal distribution is not a special case of a Weibull distribution, but the shape of the Weibull distribution can still be compared to a normal distribution to establish if the data can be seen as approximately normally distributed [26].

3. Uncertainties of measurements

3.1. Distribution

The spatial distribution of data points within a receiving room from an impact sound pressure level and a reverberation time measurements performed in one light weight and one concrete floor structure have been investigated using a Weibull distribution. The data on the estimated Weibull distribution has been calculated by a direct estimation of the maximum likelihood. The Weibull distribution has appeared to be the best matching distribution after practical comparisons to other distributions, e g normal or Poisson.

When studying the distributions for individual 1/3 octave bands it has turned out that the spatial distribution of the reverberation time at various data points differs from a normal distribution. This can clearly be seen in a quantile-quantile plot, which displays the sample quantiles versus the theoretical quantiles for a normal distribution. If the distribution of *X* is normal, the plot will be close to linear [23]. In the quantile-quantile plots presented in this report, the standard deviation of the measured values is presented on the y-axis and the standard deviation of the normal distribution of the measurements is presented on the x-axis. The quantile-quantile plots show how each measurement data from each measurement point, marked as a "+" sign, are distributed compared to an extrapolated theoretical normal distribution, a straight line. The measurements can be considered to have a normal distribution if the "+" signs are close to the straight line.

Studying measurements from different objects included in this thesis, project 3 (see Table 1-1), was analyzed in particular since this project was a light weight project including most number of positions in the receiving room (12 discrete positions). An object with high number of positions has been of great interest since the reliability of the distribution increases with number of data. Project 15 has been analyzed as a reference object since project 15 has homogenous concrete floor structure including a lot of measurement data. The available data on impact sound pressure level has been picked from sweep measurements in project 15 where each equivalent level of 1 second segments works as a discrete position.

3.1.1. Impact sound pressure level

The shape of the spatial distribution curve regarding impact sound pressure data points from one measurement in a light weight structure divided into the 1/3 octave bands 50 - 400 Hz is illustrated in Figure 3-1. The Weibull distributions are calculated from the measurement positions using maximum likelihood estimation. The calculations rely on the data from the 2007 years measurement in project 3, which consists of impact sound pressure level measurements in 12 discrete positions. The deviation for higher 1/3 octave bands can be seen in Appendix II. The tails of the distributions of impact sound pressure data are not, compared to an ideal normal distribution, equal in shape to each other. It turns out that the left tail is wider than the right tail in all investigated 1/3 octave bands. The distributions are judged to be sufficiently close to the shape of a normal distribution to use the simpler distribution.

If the distribution plots are modified to have equal mean impact sound pressure level, is it possible to see how the width of the distributions changes due to different 1/3 octave bands, Figure 3-1.

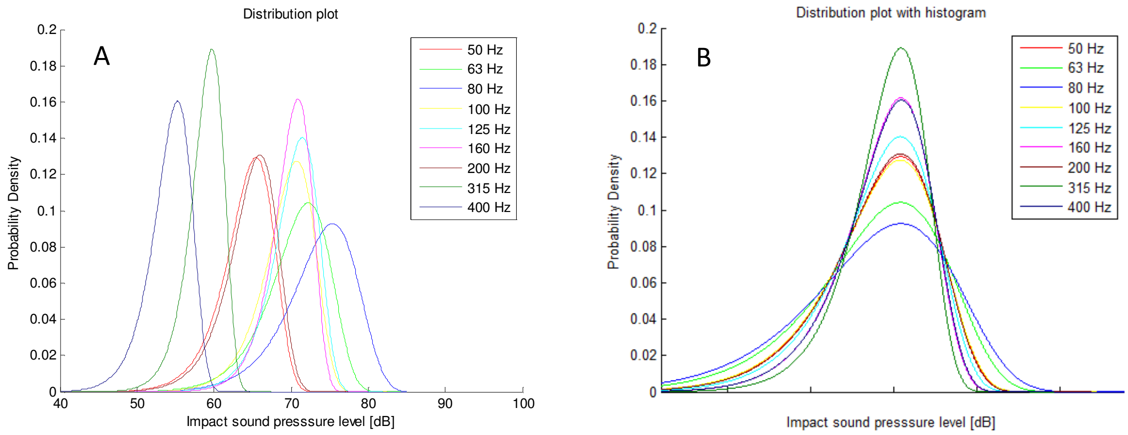

Figure 3-1:

A: Weibull distributions of 12 impact sound pressure level measurements performed on a light weight floor structure presented in 1/3 octave bands 50 - 400 Hz. The result is based on the data from project 3 measurement 2007, where the weighted mean impact sound pressure level was evaluated from these 12 measurements.

B: Weibull distributions of the impact sound pressure level measurements normalized to the highest probability density, project 3 measurement 2007. The distance between 2 ticks is 10 dB

The shape of the distribution curve regarding impact sound pressure levels from a measurement on a concrete structure is illustrated in Figure 3-2 for the 1/3 octave bands between 50 – 400 Hz. The distributions for higher 1/3 octave bands can be seen in Appendix II. The wideness of the distribution varies between different 1/3 octave bands. Furthermore, the left tail is wider than the right one, in nearly all 1/3 octave bands, see Figure 3-2.

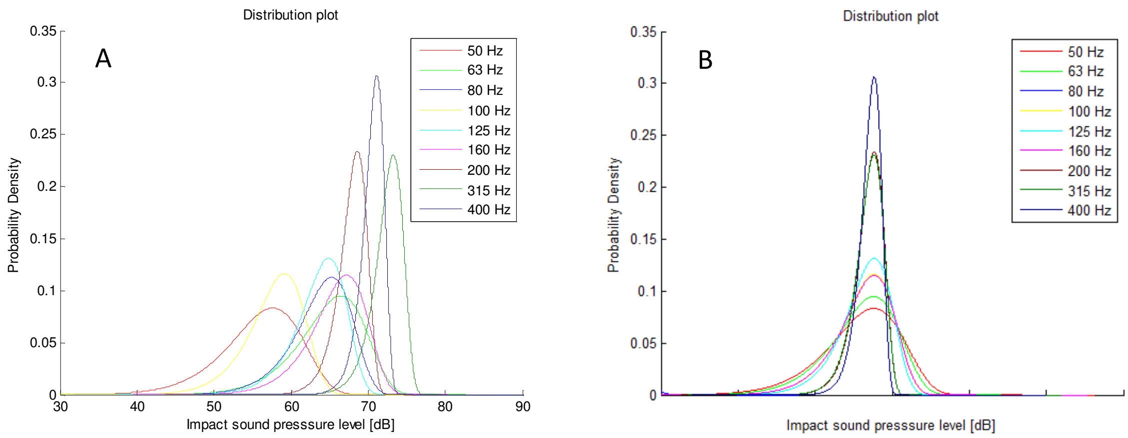

Figure 3-2:

A: Weibull distributions of the time sequences of impact sound pressure level measurements performed on a concrete floor structure presented in 1/3 octave bands 50 - 400 Hz. The result is based on the data from project 15 where a long time measurement of impact sound pressure level have been divided into 1 second time sequences.

B: Weibull distributions of the impact sound pressure level measurements normalized to the highest probability density, project 15. The Distance between 2 ticks is 10 dB

3.1.2. Reverberation time

In this section the reverberation time is analyzed, primarily due to its variation depending on measurement positions, room volumes etc. The shape of the distribution curves, representing typical reverberation time data from measurements in various positions on a light weight structure, changes with frequency. The distributions for the 1/3 octave bands 50 - 400 Hz are illustrated in Figure 3-3 while higher 1/3 octave bands are found in Appendix II. One typical measurement representing 24 reverberation time measurements in discrete positions have been used from the project from year 2007 (project 3). It is rather clear that the distribution for the lowest frequencies is wider and more spread than for the higher frequencies.

Furthermore, the left tail of the distribution is wider than the right tail in nearly all 1/3 octave bands apart from the lowest 1/3 octave bands, see Figure 3-3. The distribution in the two lowest 1/3 octave bands (50 and 63 Hz) shows opposite behavior, with a right tail wider than the left.

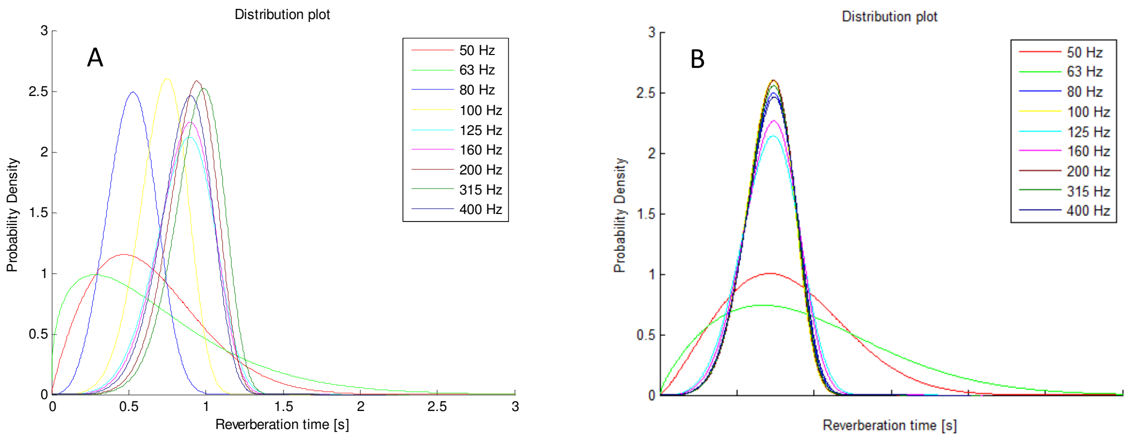

Figure 3-3:

A: Weibull distributions of 24 reverberation time measurements performed in a light weight floor structure presented in 1/3 octave bands 50 - 400 Hz. The result is based on the data from project 3, measurement 2007 where the mean reverberation time was evaluated from these 24 measurements.

B: Weibull distributions of the reverberation times normalized to the highest probability density, project 3 measurement 2007. The distance between 2 ticks is 0.5 s

The skew behavior of the spatial distribution for the two lowest 1/3 octave bands, 50 and 63 Hz was further investigated with quantile-quantile plots, see Figure 3-4 and Figure 3-5. It turns out that the measured reverberation time for these two 1/3 octave bands has two dominant outliers which significantly deviate from the other data and the normal distribution. It is notable that the deviating outliers in the 1/3 octave bands 50 and 63 Hz are not arising from only two measurement points, i.e. the deviating values do not arise from same loudspeaker and measurement positions. The deviations can thus not be judged to be deterministic characteristics for the loudspeaker and microphone positions; instead they seem to be random. This conclusion is reasonable since the measurement was performed using three repetitions for each loudspeaker - receiver combination.

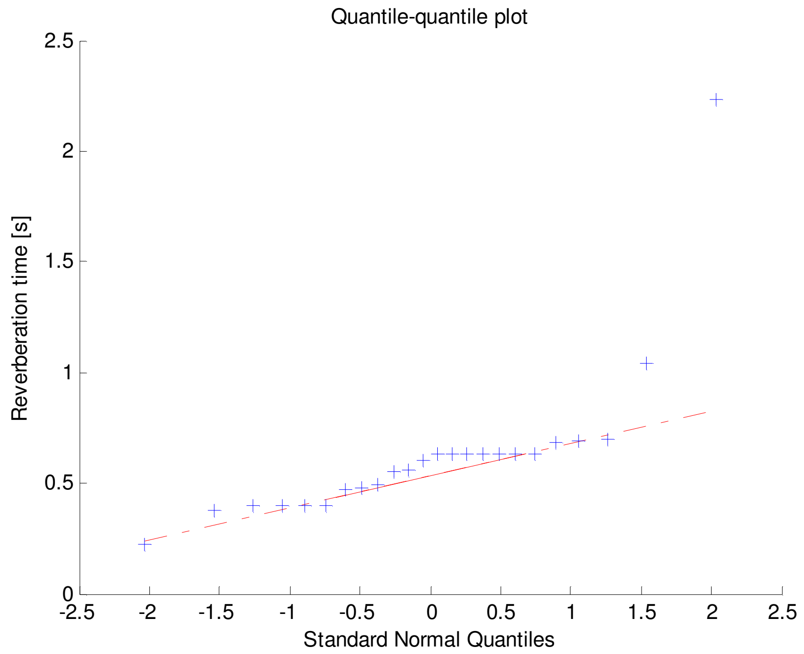

Figure 3-4: Quantile-quantile plot of 24 reverberation time measurements in a light weight structure presented in 1/3 octave band 50 Hz. The figure shows how the measured data deviate from a normal distribution. Each "+"-sign indicates a measurement and the line the estimated normal distribution of the measurements. The result is based on data from project 3, measurement 2007 where the mean reverberation time was evaluated from these 24 measurements.

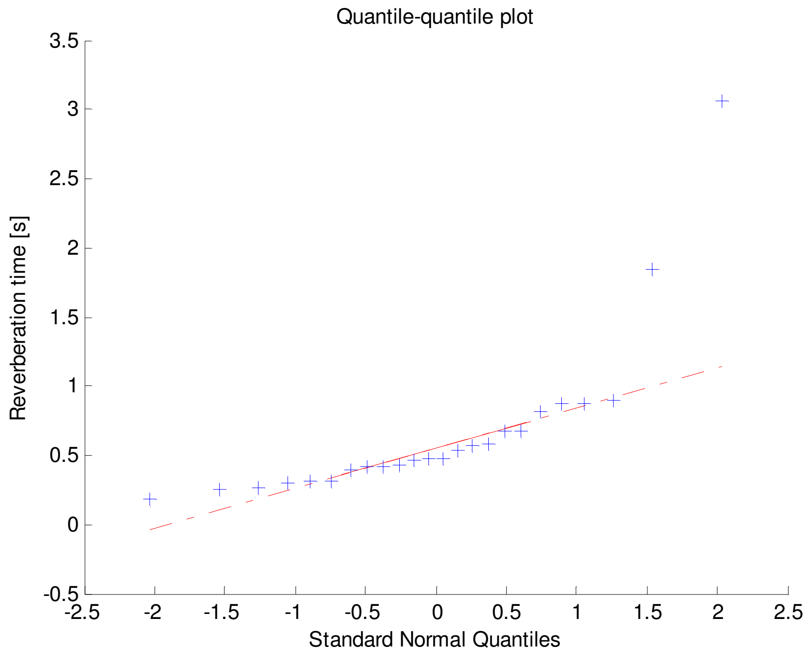

Figure 3-5: Quantile-quantile plot of 24 reverberation time measurements in a light weight structure presented in 1/3 octave band 63 Hz. The figure shows how the measured data deviate from a normal distribution. Each "+"-sign indicates a measurement and the line the estimated normal distribution of the measurements. The result is based on data from project 3, measurement 2007 where the mean reverberation time was evaluated from these 24 measurements.

If the reverberation time measurement data points, containing the outliers in the 1/3 octave bands 50 and 63 Hz were erased, the distribution plots would show a distribution that almost equals a normal distribution, see Figure 3-6.

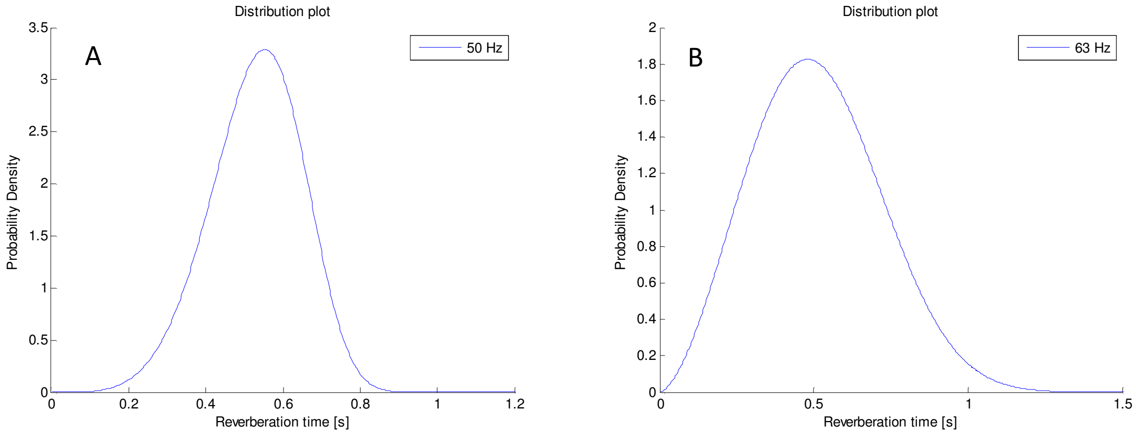

Figure 3-6:

A: Weibull Distribution plot for a 50 Hz reverberation time measurements in a light weight structure presented with the two strong deviating measurements erased, project 3 measurement 2007.

B: Weibull Distribution plot for a 63 Hz reverberation time measurements in a light weight structure presented with the two strong deviating measurements erased, project 3 measurement 2007.

The fact that few outliers can give strange values might cause unpredictable errors, for instance when the instruments are calculating the standardized value (i.e. normalization to the reverberation time 0.5 s). If comparing the results between

1. the "full" reverberation time measurement series and
2. the "reduced" reverberation time measurement series (the two outliers in each of the 1/3-octave bands 50 and 63 Hz excluded)

the standardization of the impact sound pressure level was influenced (see Equation 2-6). Figure 3-7 shows the reduction of the impact sound pressure level when the outliers are excluded. It is clear that the four deviating reverberation time measurement positions in this specific case cause an error that approximately equals 1 dB for the two lowest 1/3 octave bands 50 and 63 Hz.

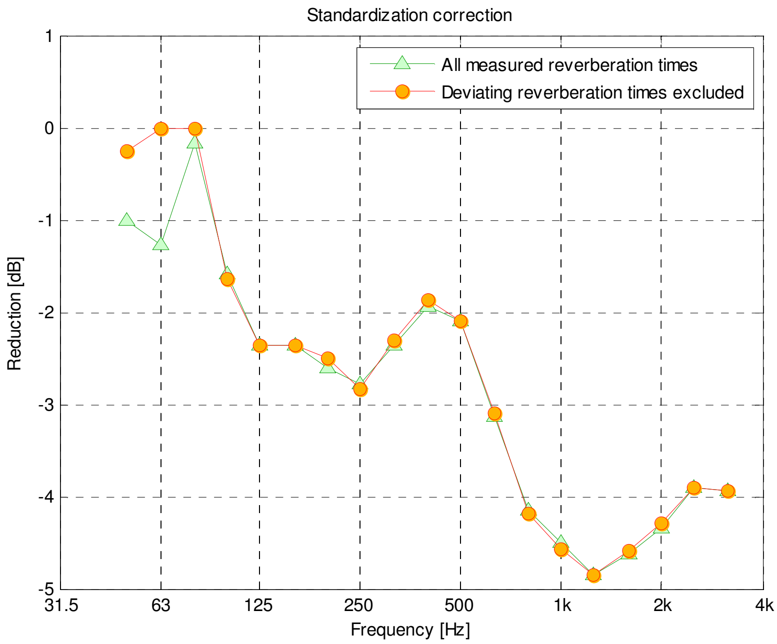

Figure 3-7: Standardization of the impact sound pressure level on a reverberation time measurement in 1/3 octave bands 50 – 3150 Hz with and without the deviating measurements at 50 and 63 Hz, project 3, measurement 2007.

As a comparison similar reverberation time data from measurements on a heavy structure is shown in Figure 3-8. The shape of the distribution curves in the figure are evaluated based on measurement results from 24 discrete reverberation time measurement positions in one room in a building with solid concrete structure, in 1/3 octave bands 50 – 400 Hz. Frequencies above 400 Hz are presented in Appendix II. In general, the distribution of the lowest frequencies is wider and more evenly distributed than the distribution of the higher, however still close to a normal distribution.

Furthermore, the left tail of the distribution is wider than the right in all 1/3 octave bands apart from the lowest 1/3 octave bands, see Figure 3-8.

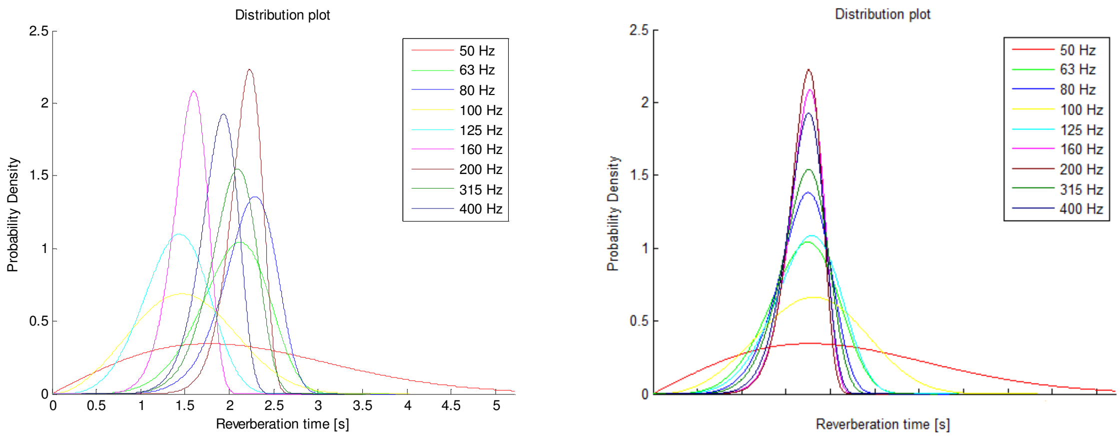

Figure 3-8:

A: Weibull distributions of 24 reverberation time measurements performed in a concrete floor structure presented in the 1/3 octave bands 50 - 400 Hz. The result is based on the data from project 15 where the mean reverberation time was evaluated from these 24 measurements.

B: Weibull distributions normalized to the highest probability density, project 15. The distance between 2 ticks is 10 dB

Hence, measurements from heavy structures appear to exhibit more normal distribution in all frequencies considered in the standard measurement procedure. The two widest and most spread spatial distributions regarding reverberation time data points from measurements in this specific case in a building with concrete structure were found in the 1/3 octave bands 50 and 100 Hz. These 1/3 octaves were further investigated with quantile-quantile plots, see Figure 3-9 and Figure 3-10. No typical outlier is noticed in 1/3 octave band 50 Hz, just a wide spectra of the measured reverberation times. However, the measured reverberation time in the 100 Hz 1/3 octave band has some significant outliers, indicating that similar problems might appear for heavy structures as for light weight structures. However, the final result from measurements in heavy structures is less affected by single errors in the low frequencies since the single number normally is determined by higher frequencies.

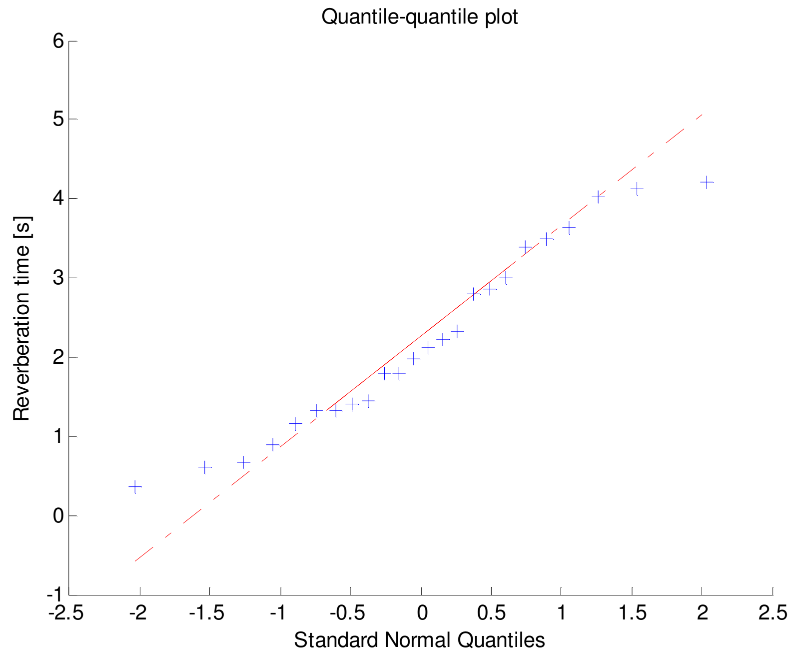

Figure 3-9: Quantile-quantile plot of 24 reverberation time measurements in a concrete structure presented in 1/3 octave band 50 Hz. The figure shows how the measured data deviates from normal distribution. Each "+"-sign indicates a measurement and the line the estimated normal distribution of the measurements. The result is based on the data from project 15 where the mean reverberation time was evaluated from these 24 measurements.

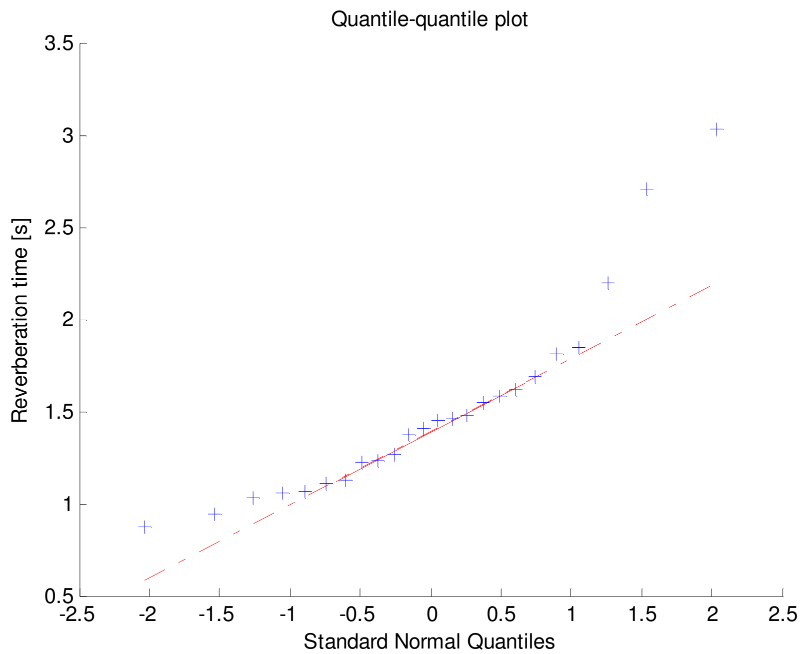

Figure 3-10: Quantile-quantile plot of 24 reverberation time measurements in a light weight structure presented in 1/3 octave band 100 Hz. The figure shows how the measured data deviates from normal distribution. Each "+"-sign indicates a measurement and the line the estimated normal distribution of the measurements. The result is based on the data from project 15 where the mean reverberation time was evaluated from these 24 measurements.

3.2. Effect of receiving room volume

During a measurement, the receiving room volume has to be stated. The receiving room volume is one parameter that might affect the final results, in addition to all other possible details. Therefore, the receiving room volume dependence of the confidence interval for the measured mean impact sound pressure level and mean reverberation time were evaluated for each 1/3 octave band between 50 - 3150 Hz. All investigated impact sound pressure measurements have been performed vertically. Concerning the confidence interval calculations, the spatial distribution of the different positions regarding impact sound pressure level and reverberation time were assumed to have a normal distribution of data for all 1/3 octave bands, even if earlier investigation indicates that the measurements not perfectly fit to a normal distribution. The confidence interval of a measurement explains how much the mean value theoretically can vary between different measurement series. If the confidence interval is narrow, it indicates high accuracy while a wide interval indicates high uncertainty.

A confidence interval has been chosen instead of standard deviation since it reflects more clearly the probability of variation concerning measurement averaged value. As Erwin Kreyszig writes in *"Advanced Engineering Mathematics"* - *"Most important methods of statistical interference are estimation of parameters, determination of confidence intervals and hypothesis testing"* [11]. Standard deviation is more proper when investigating individual measurements to see if any 1/3 octave band or bands deviate from other 1/3 octave bands, which in that case indicates on an uncertain measurement.

3.2.1. Impact sound pressure level

The volume effect of the receiving room was investigated for impact sound pressure measurements performed both on homogenous concrete structures and light weight floor structures. The confidence interval was calculated according to Equation 2-14 which requires that the investigated measurements have the same number of measurement positions. Hence, it was preferable to find many measurements with equal numbers of measurement positions to gain estimation with high accuracy. For light weight structures 22 measurements with five measurement positions in each measurement were found, see Table 3-1. The table also presents the volume of the receiving room, the degrees of freedom *df*, the coverage probability *c* and finally, the confidence level γ for each project included. See Equation 2-14 in theory chapter 2.2.2 where also the mathematical elements are described. Notice that five positions are one more position than required according to ISO 140-7.

Table 3-1: Measurements of impact sound pressure level performed on light weight structures with five measurement positions, used for confidence interval calculations.

Project	Measurement	Volume [m^3]	*df*	c(γ,*df*)	γ
1	A05	56.60	4	2.78	95%
	A10	56.60	4	2.78	95%
	A11	46.30	4	2.78	95%
	A12	46.30	4	2.78	95%
3	2008 (1)	60	4	2.78	95%
	2008 (2)	38,9	4	2.78	95%
	2009 (1)	60	4	2.78	95%
	2009 (2)	38,9	4	2.78	95%
5	A01	169.25	4	2.78	95%
	A02	169.25	4	2.78	95%
	A03	169.25	4	2.78	95%
	A04	169.25	4	2.78	95%
	A05	169.25	4	2.78	95%
	A06	169.25	4	2.78	95%
	A07	68.24	4	2.78	95%
	A08	68.24	4	2.78	95%
	A09	68.24	4	2.78	95%
6	A10	50.00	4	2.78	95%
	A11	50.00	4	2.78	95%
7	A15	34.50	4	2.78	95%
	A18	78.60	4	2.78	95%
	A22	32.10	4	2.78	95%

Concerning the measurements performed on homogenous concrete floor structures, four measurements with four measurement positions were available, see Table 3-2. In the table, also necessary input data for the confidence interval estimations are stated.

Table 3-2: Measurements of impact sound pressure level performed on homogenous concrete floor structures with four measurement positions, used for confidence interval calculations.

Project	Measurement	Volume [m^3]	*df*	c(γ,*df*)	γ
8	8	80.3	3	3.18	95%
	9	107.5	3	3.18	95%
9	A04	32	3	3.18	95%
14	1	90	3	3.18	95%

The confidence interval was calculated for each measurement and 1/3 octave band, indicated as circles in Figure 3-11. Figure 3-11 shows the linear least squares estimation of the volume dependence regarding impact sound pressure level measurements performed on light weight floor structures for the 1/3-octave band 50 Hz. To these 22 calculated confidence intervals of the mean value of the five impact sound pressure level measurement positions, a straight line was fit, marked with squares. Each square of the line indicates a receiving room volume; in this case there were ten different volumes of the receiving rooms for the investigated 22 measurements.

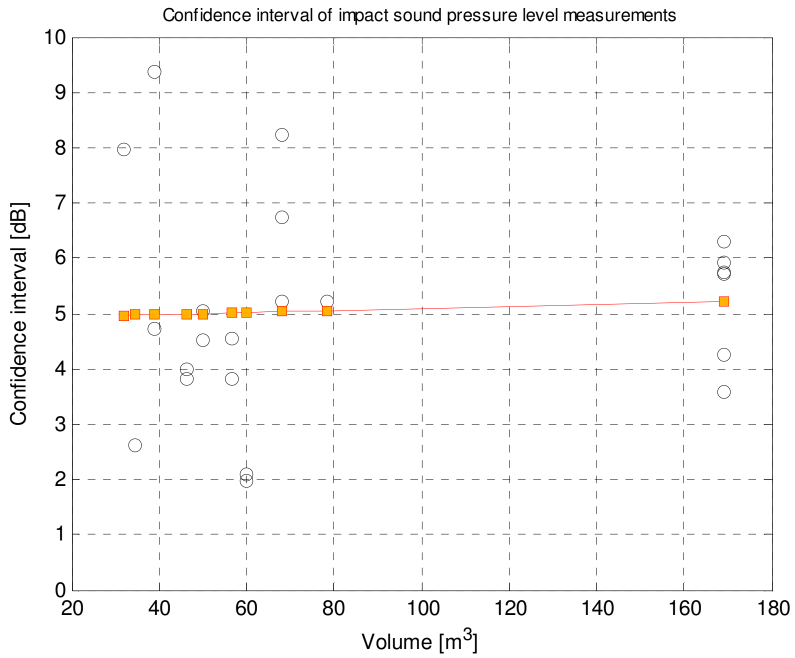

Figure 3-11: Confidence interval of impact sound pressure level measurements as a function of volume for 1/3 octave band 50 Hz. The calculations are based on a 95% confidence level and 22 measurements, each with five measurement positions. The "o"-signs show the calculated confidence interval for each measurement and the square marked line present the linear estimation of the calculated intervals.

This calculation has been performed for each 1/3 octave band 50 - 3150 Hz, all linear estimations can be seen in Appendix IV. Some 1/3 octave bands have been selected for a more detailed analysis since all 1/3 octave bands are not of interest. The six lowest 1/3 octave bands 50 - 160 Hz were selected since discrepancies were mainly found at 1/3 octave bands below 160 Hz. To show the relation between volume and high frequencies, the 1/3 octave bands 250, 500, 1000 and 2000 Hz has also been selected, see Figure 3-12. It has been found irrelevant to show all 1/3 octave bands above 160 Hz since they are of a similar nature.

The confidence intervals for the chosen 1/3 octave bands based on 22 impact sound pressure level measurements in a light weight structures are shown in Figure 3-12. The correlations and equations for all 1/3 octave bands between 50 and 3150 Hz are stated in Appendix III. The differences of the confidence interval for the biggest and smallest room for each 1/3 octave band can be seen in Figure 3-13. The figures indicate that the receiving room volume has less influence on the lower 1/3 octave bands 50 - 160 Hz than on the higher 1/3 octave bands. For the higher 1/3 octave bands, 200 - 3150 Hz, all measurements result in a decreasing confidence interval with an increased volume, i.e. less measurement uncertainty with big receiving room volumes for "high" 1/3 octave bands.

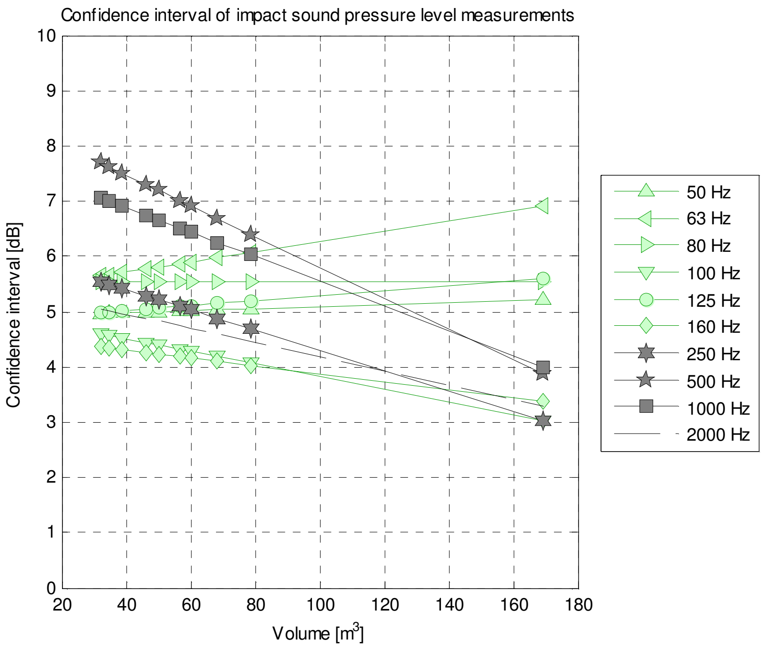

Figure 3-12: Confidence interval of impact sound pressure level measurements performed on light weight structures as a function of volume for selected 1/3 octave bands. The calculations are based on a 95% confidence level and 22 measurements, each with 5 measurement positions.

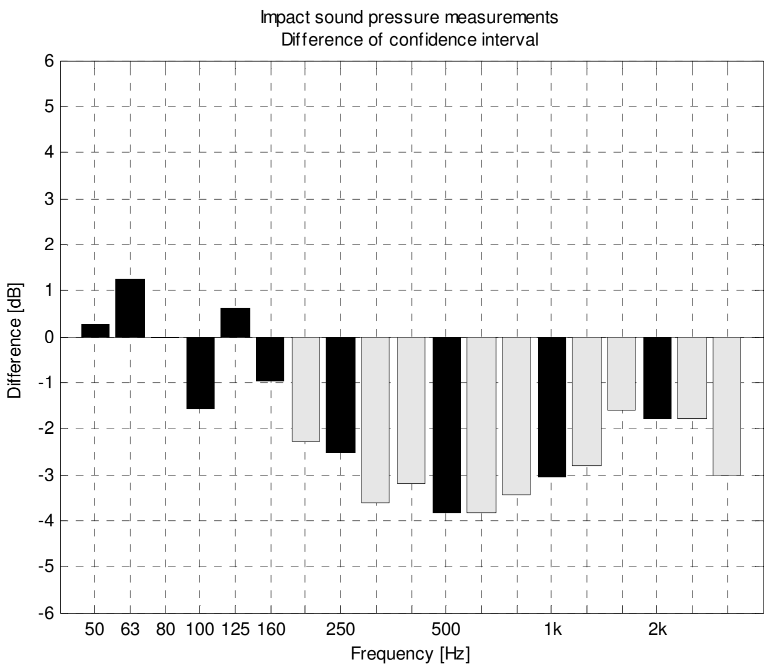

Figure 3-13: Difference between confidence interval over impact sound pressure level in light weight structures of biggest and smallest receiving room for each 1/3 octave band. Black bars presents the difference between the linear estimations of the 1/3 octave bands in Figure 3-12 while the light bars are the remaining 1/3 octave bands. The calculations are based on a 95% confidence level and 18 measurements, each with 5 measurement positions.

The dependence of receiving room volume for each 1/3 octave band for impact sound pressure level measurements performed on homogenous concrete floor structures is presented in Figure 3-14. The figure shows the linear dependency of the (with percentage) confidence interval as a function of receiving room volume for the selected 1/3 octave bands. Figure 3-15 shows the difference between the biggest and smallest receiving room volume of the linear estimation. The result which these two figures present indicates that the biggest volume dependency of impact sound pressure level measurement uncertainty are found at the lowest and highest 1/3 octave bands. In general, the figures indicate that the uncertainty of the low 1/3 octave bands increases with receiving room volume (quite contradictory to what would be expected due to normal diffuse field theory since the Schroeder frequency decreases with increasing room volume. The Schroeder frequency can be used to indicate the lower frequency limit where the sound field in the room can be considered as statistical, i.e. there are a large number of room modes within each 1/3 octave band. At lower frequencies individual room modes can be significant which theoretically would increase the confidence interval.) The uncertainty decreases for higher 1/3 octave bands, which follows the common theory. The correlation and equations of each linear estimation for all 1/3 octave bands between 50 and 3150 Hz are stated in Appendix III.

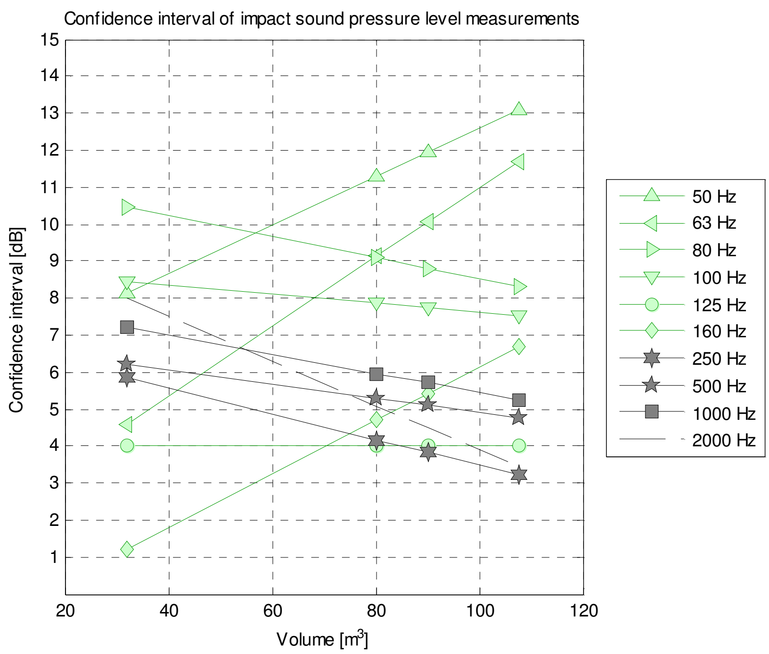

Figure 3-14: Confidence interval of impact sound pressure level measurements performed on homogenous concrete floor structures as a function of volume for selected 1/3 octave bands. The calculations are based on a 95% confidence level and 4 measurements, each with four measurement positions.

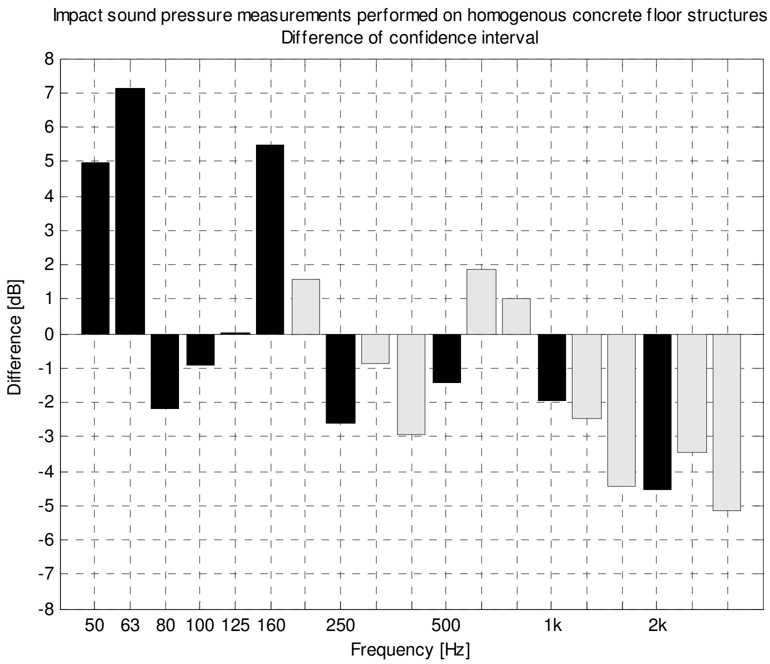

Figure 3-15: Difference between confidence interval over impact sound pressure level in concrete structures in biggest and smallest receiving room for each 1/3 octave band. Black bars presents the difference between the linear estimations of the 1/3 octave bands in Figure 3-14 while the light bars are the remaining 1/3 octave bands. The calculations are based on a 95% confidence level and 10 measurements, each with 4 measurement positions.

3.2.2. Reverberation time

For the reverberation time measurements, the variation of the confidence interval due to receiving room volume was estimated by using ten different measurements (receiving rooms). These measurements were all performed in light weight structure (wooden) buildings. Each measurement has been performed using three microphone positions with two readings in each position, Table 3-3. The measurement equipment has made an average of the two readings in each of the three positions. Hence, this ended up in three measurement data points for each 1/3 octave band. This had consequences for the confidence interval calculations since only the variance for three measurement positions could be calculated (instead of six). It also affected the number of degrees of freedom since only two degrees of freedom could be used instead of five, Equation 2-17. This has only influenced the width of the confidence interval, not the characteristic of the linear regression, shown in Figure 3-16.

Table 3-3: Measurements of reverberation time with three measurement positions with two readings in each position, used for confidence interval calculations.

Project	Measurement	Volume [m^3]	*df*	c(γ,*df*)	γ
1	A10	56.60	2	4.3	95%
	A12	46.30	2	4.3	95%
4	A02	109.00	2	4.3	95%
	A04	109.00	2	4.3	95%
6	A10	50.00	2	4.3	95%
	A11	50.00	2	4.3	95%
7	A15	34.50	2	4.3	95%
	A16	61.00	2	4.3	95%
	A18	78.60	2	4.3	95%
	A22	32.10	2	4.3	95%

The measured mean reverberation time and its dependence on the receiving room volume can be seen in Figure 3-16. The figure includes the same low frequency 1/3 octave bands as for the level measurements (Figure 3-12). The correlations and equations of each estimated line for all 1/3 octave bands within the frequency range 50 - 3150 Hz can be found in Appendix III. The differences of the confidence interval for the biggest and smallest room for each 1/3 octave are shown in Figure 3-17. The uncertainty of the reverberation time measurements increases with receiving room volume for the three lowest 1/3 octave bands 50, 63 and 80 Hz, quite contradictory to what could be expected since an increased volume should result in more diffuse field. However, it could be due to the shape of the room (extended in only two dimensions – still same height) and its effect on certain mode shapes. The higher the frequency the less the volume affect the final results, i.e. the confidence interval of the remaining 1/3 octave bands are relative constant over receiving room volume.

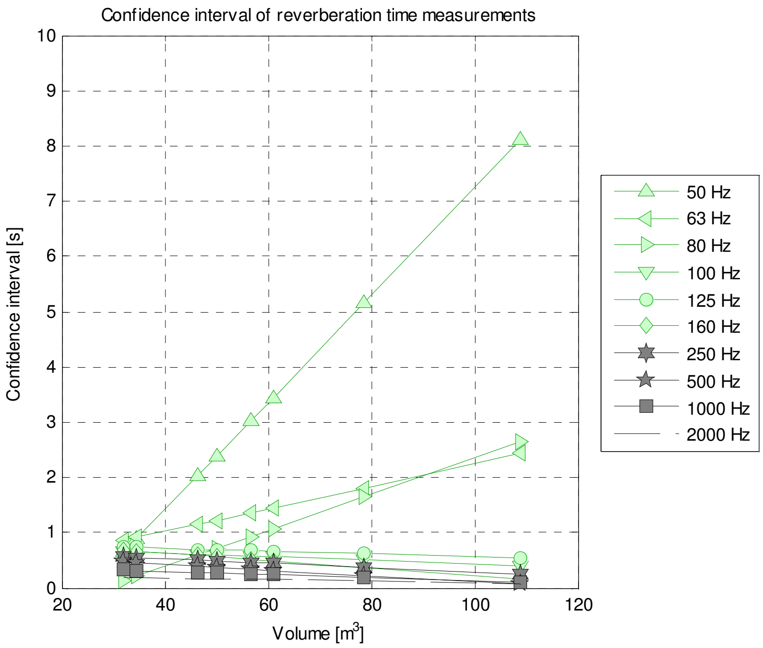

Figure 3-16: Confidence interval of reverberation time measurements performed in light weight structures as a function of volume for selected 1/3 octave bands. The calculations are based on a 95% confidence level and 10 measurements, each with 3 measurement positions with 2 readings in each position.

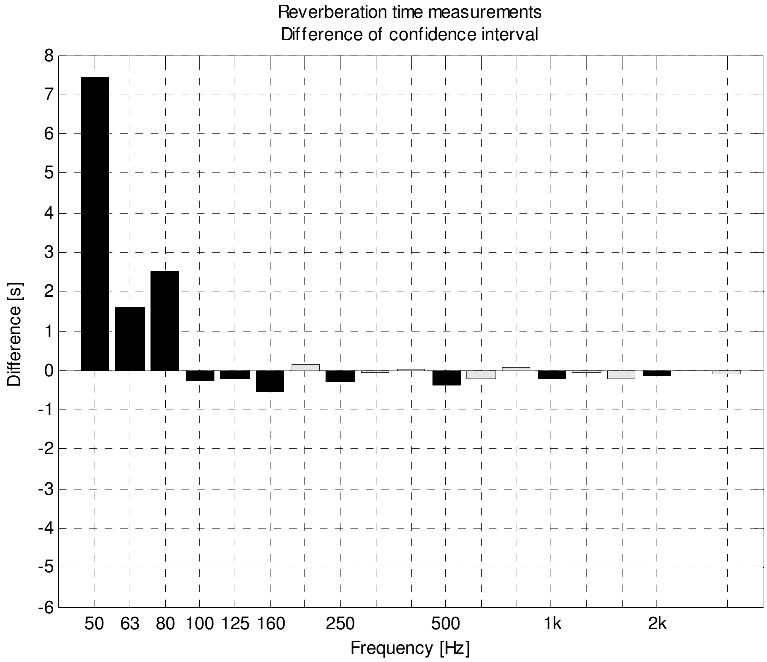

Figure 3-17: Difference between confidence interval over reverberation time in light weight structures in biggest and smallest receiving room for each 1/3 octave band. Black bars presents the difference between the linear estimations of the 1/3 octave bands in Figure 3-16 while the light bars are the remaining 1/3 octave bands. The calculations are based on a 95% confidence level and 10 measurements, each with 3 measurement positions with 2 readings in each position.

4. Impact sound in low frequencies

In this thesis impact sound pressure levels from available measurements in low frequencies have been investigated in 1/3 octave bands. The investigation of project 10, 13, 14 and 15 included 1/3 octave bands 6.3 – 3150 Hz. For project 3, 11 and 12, the 1/3 octave bands 25 – 3150 Hz are included. Notice that project 3, 10 and 14 are performed on light weight structures while project 11, 12, 13 and 15 are performed on concrete floor structures. The highest measured impact sound pressure level in two frequency ranges in each measurement have been investigated in order to make the highest measured level in 1/3 octave bands visible. The two chosen frequency ranges are below 50 Hz and between 50 – 3150 Hz, which can be seen in Figure 4-1 where also the projects has been divided into light weight and concrete floor structures. Figure 4-1 shows that the highest measured impact sound pressure level for the investigated projects often occurs in 1/3 octave bands below 50 Hz, in particular for light weight structures (in 10 of 13 investigated measurements). It is also obvious that the levels are higher in the low frequency region for the light structures. The difference between the maximum impact sound pressure levels varies between different projects. The largest level difference is however found in project 10, measurement 4 where a level difference of 18.4 dB occurs. The measured impact sound pressure levels frequency spectra for each project can be seen in Appendix V.

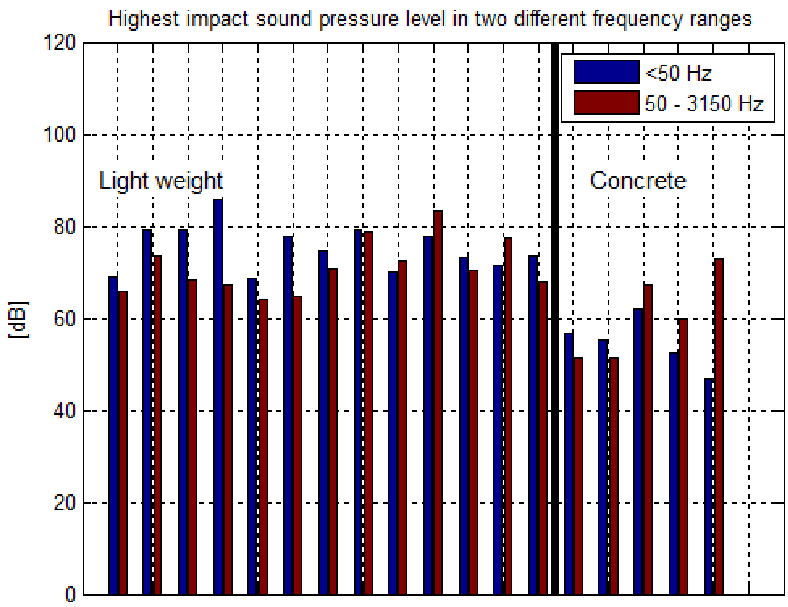

Figure 4-1: Highest impact sound pressure level in frequency ranges, below 50 Hz and in the interval 50 - 3150 Hz for each room in project 3, 10, 11, 12, 13, 14 and 15.

In Figure 4-2, an overview of the occurrence of the highest measured impact sound pressure level in different 1/3 octave band is shown. For light weight structures, most of the highest levels are found in the 1/3 octave bands between 20 – 31.5 Hz. In contrast to the light weight floor structures, the highest levels of impact sound for concrete structures are normally found at higher 1/3 octave band between 50 - 3150 Hz.

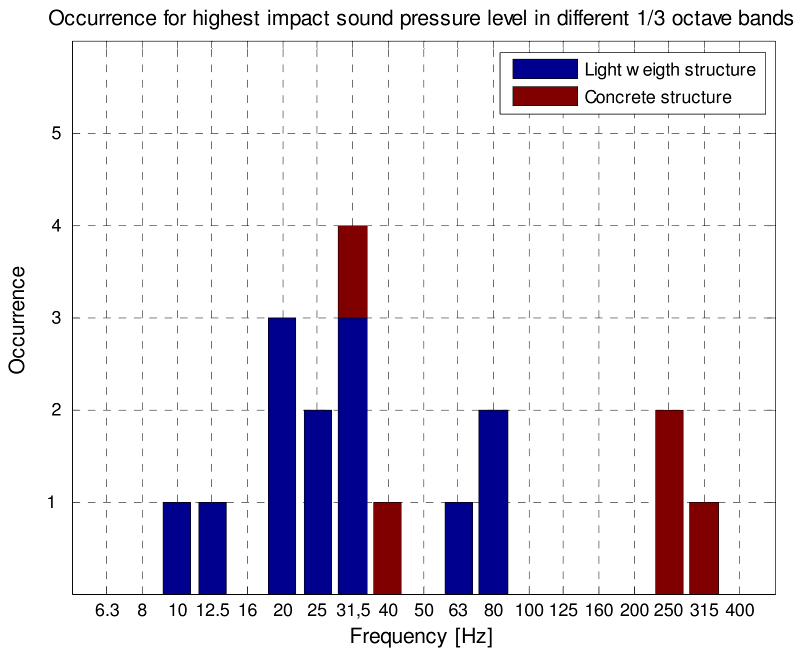

Figure 4-2: Compilation of in which 1/3 octave band the highest measured impact sound pressure level has occurred. The bars illustrate the occurrence for both light weighted structures and concrete structures in project 3, 10, 11, 12, 13, 14 and 15.

5. Extended measurements

In order to confirm statements from current measurements, extended measurements were made in one light weight (wooden) house. The measurements were performed vertically between two rooms. Dimensions and volumes of receiving and sending room can be seen in Table 5-1, sketches of the rooms can be seen in Figure 5-3 and Figure 5-4.

Table 5-1: Dimensions and volume of the receiving and sending room.

Room	Dimensions [m]	Volume [m^3]
Receiving	4.42x3.31x2.50	36.58
Sending	4.42x3.30x2.50	36.47

5.1. Reverberation time measurement

Reverberation time measurements were performed according to measurement standard ISO 140-7. 16 measurement decays were measured with eight set-ups of two microphones with two different source positions, Figure 5-1 and Table 5-2. For each set-up, an average of five readings was performed.

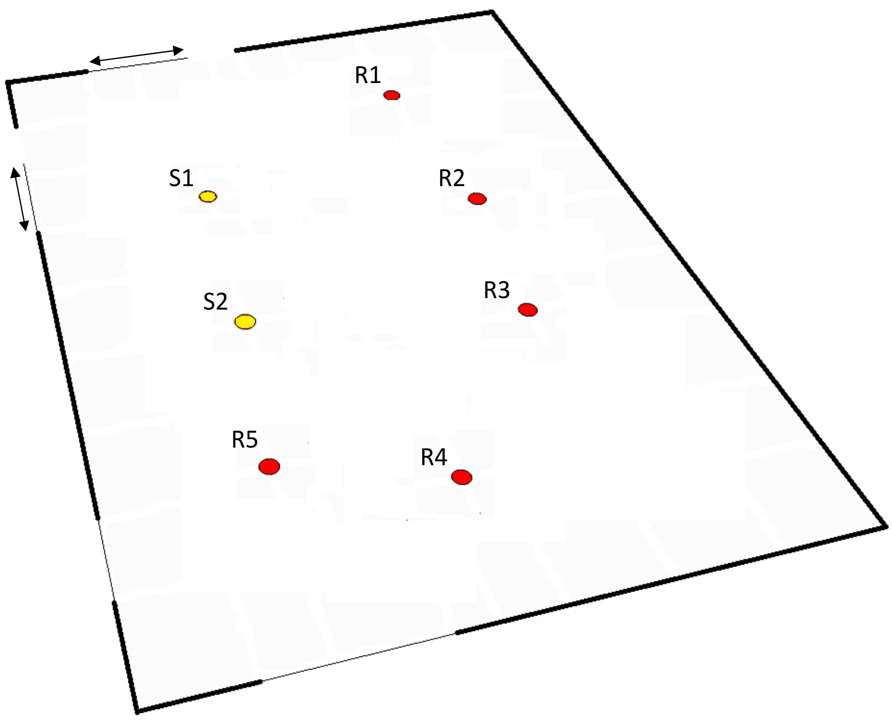

Figure 5-1: Sketch illustrating the source and receiving positions for the reverberation time measurements in the receiving room.

Table 5-2: Measurement procedure for the reverberation time measurements, the positions are shown in Figure 5-1.

Measurement	Source	Receiver
1	S1	R1, R2
2	S1	R2, R3
3	S1	R3, R4
4	S1	R4, R5
5	S2	R4, R5
6	S2	R3, R4
7	S2	R2, R3
8	S2	R1, R2

The Weibull distributions of the reverberation time measurement are shown for 1/3 octave bands 50 - 400 Hz in Figure 5-2. The measured data seems to be reliable since the measurements did not exhibit any outliers causing a distribution deviating significantly to a normal distribution.

A distribution plot with the measured reverberation time normalized to the highest probability density is shown in Figure 5-2. All 1/3 octave bands apart from 1/3 octave band 63 Hz exhibit same pattern as the other investigated measurements in chapter *3.1 Distribution*, a left tail wider than the right tail of the distribution curve.

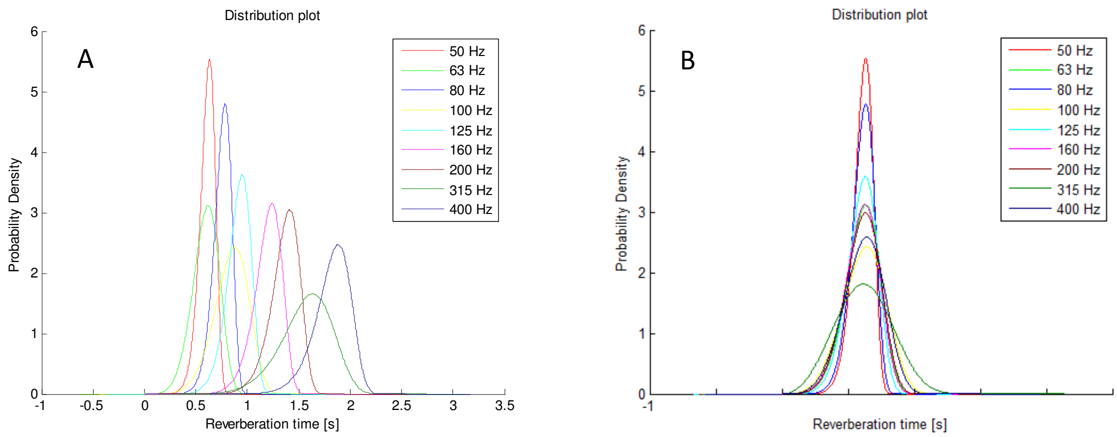

Figure 5-2:

A: Weibull distributions of 16 reverberation time measurements performed in a light weight floor structure presented in the 1/3 octave bands 50 - 400 Hz. The result is based on the data from project 16 where the mean reverberation time was evaluated from these 16 measurements.

B: Weibull distributions of the reverberation time measurements normalized to the highest probability density, project 16.

5.2. Impact sound pressure measurement

35 measurement positions for the tapping machine have been used when performing the impact sound pressure level measurements, in order to investigate different positions and their influence on the spatial average value. The spatial average value in the receiving room was collected by using a rotating boom, continuously sweeping near the middle of the receiving room; Figure 5-3. A sweep

sequence of 30 seconds was used. This approach was chosen in order to compare the influence of different positions of the tapping machine and its positions influence on the receiving room level.

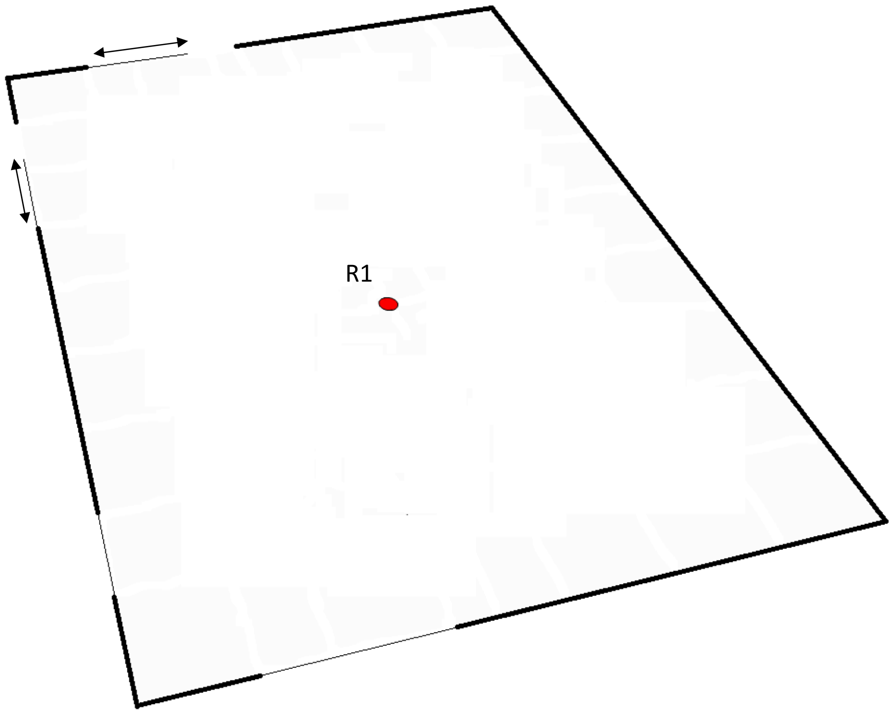

Figure 5-3: Sketch illustrating the receiving position for the impact sound pressure level measurement in the receiving room.

A grid which met demands according to ISO 140-7 regarding distances to boundaries and distances between source positions were set up, marking each tapping machine position on the sending room floor, Figure 5-4. Within the limits set by the boundaries of the room, 35 source positions were used. The tapping machine was running during at least 40 seconds in each position to make sure that all measurements covered a full microphone sweep in the receiving room.

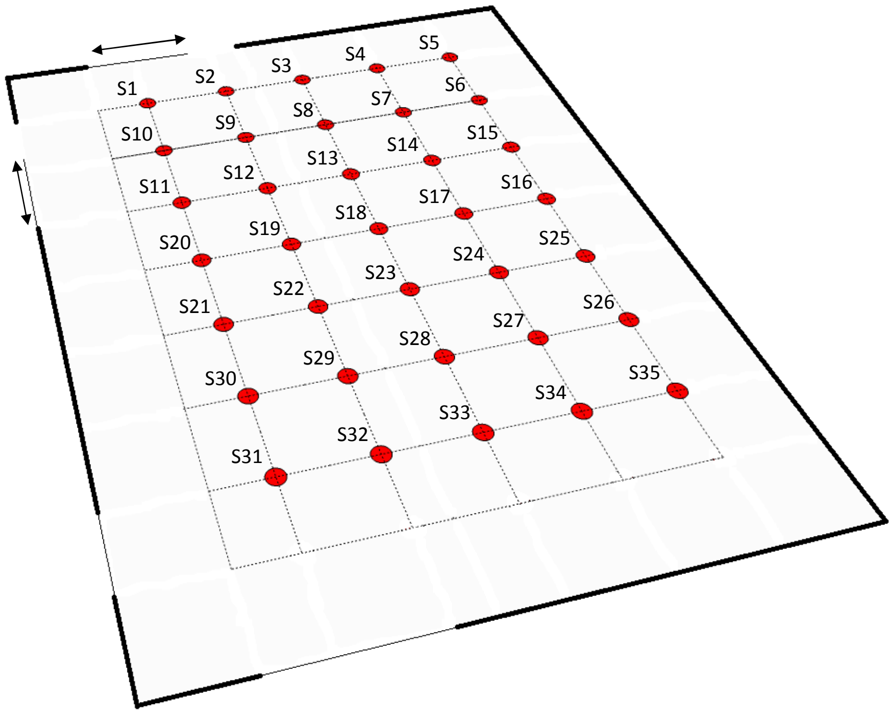

Figure 5-4: Sketch illustrating the source **positions for the impact sound pressure level measurements in the sending room.**

The Weibull distribution of the 35 measurements is shown for 1/3 octave bands 50 - 400 Hz in Figure 5-5. The measured data seem to be reliable since no extreme outliers were observed, causing a distribution which deviate significantly to a normal distribution. A distribution plot with the measured reverberation time normalized to the highest probability density is shown in Figure 5-5. All 1/3 octave bands exhibit same pattern as the other investigated measurements in chapter *3.1 Distribution*, a left tail wider than the right tail of the distribution curve.

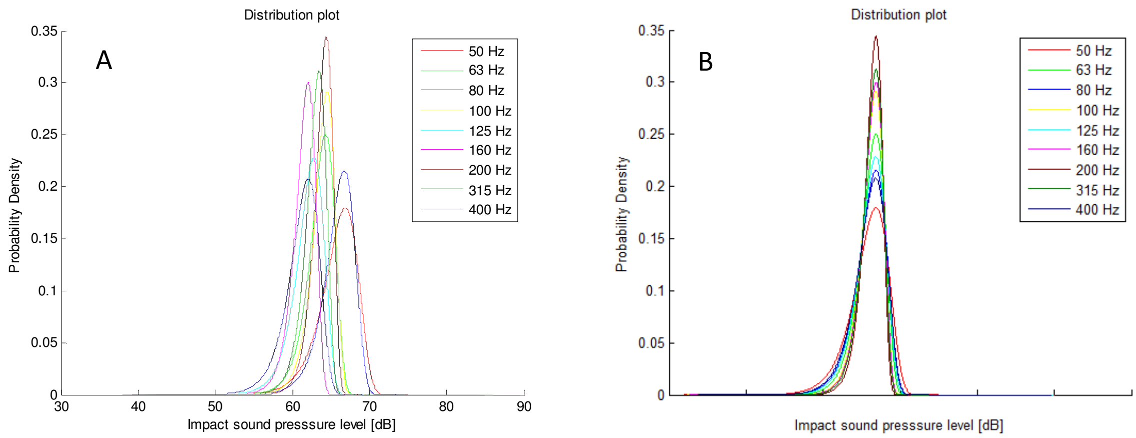

Figure 5-5:

A: Weibull distributions of 35 impact sound pressure level measurements performed in a light weight floor structure presented in the 1/3 octave bands 50 - 400 Hz. The result is based on the data from project 16 where the mean impact sound pressure level was evaluated from these 35 measurements.

B: Weibull distributions of the impact sound pressure level measurements normalized to the highest probability density, project 16.

Measurement standard ISO 140-7 states that a proper measurement shall include at least four randomly placed positions of the tapping machine. By randomly use 4 of the 35 source positions, a single weighted values of $L'_{n,w}$ and $L'_{n,w} + C_{I,50\text{-}2500}$ has been calculated for 100 000 combinations. The standardization of the measurements has been based on mean values of the 16 reverberation time measurements. The highest and lowest calculated single number quantities are stated in Table 5-3.

Table 5-3: Highest and lowest values on single number quantities $L'_{n,w}$ and $L'_{n,w} + C_{I,50\text{-}2500}$ from different source positions in sending room, project 16.

	$L'_{n,w}$ [dB]	$L'_{n,w} + C_{I,50\text{-}2500}$ [dB]
Highest	63	59
Lowest	57	56

The pairs of four source positions of the 35 available that contribute to the minimum value of $L'_{n,w}$ and $L'_{n,w} + C_{I,50\text{-}2500}$ of the 100 000 random source position combinations is illustrated in Figure 5-6 and Figure 5-7. The result show that it is mainly the source positions 1-15, situated deepest in the building which give rise to the minimum level on $L'_{n,w}$, Figure 5-6. Figure 5-7 shows that the minimum level on $L'_{n,w} + C_{I,50\text{-}2500}$ arises just from one combination of source positions (position 4-7). The source positions can be seen in Figure 5-4.

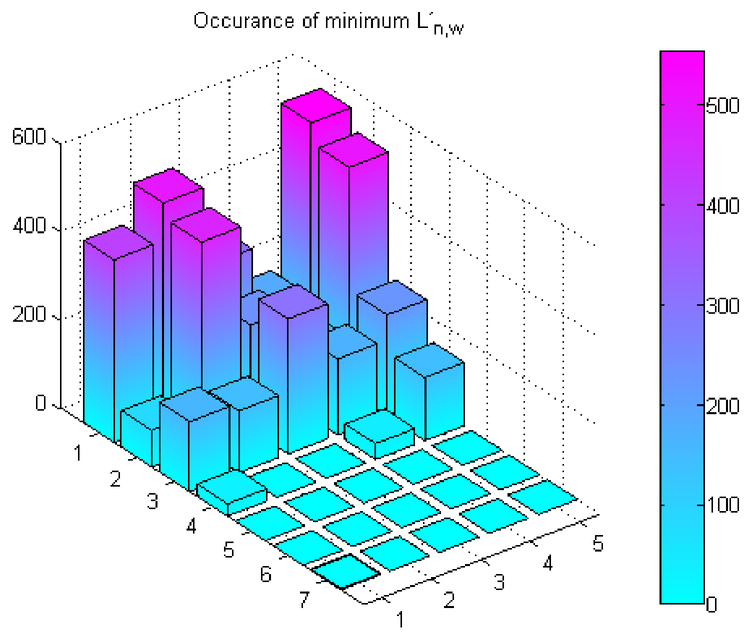

Figure 5-6: Bar plot over how frequently each source position contributes to a minimum value of $L'_{n,w}$.

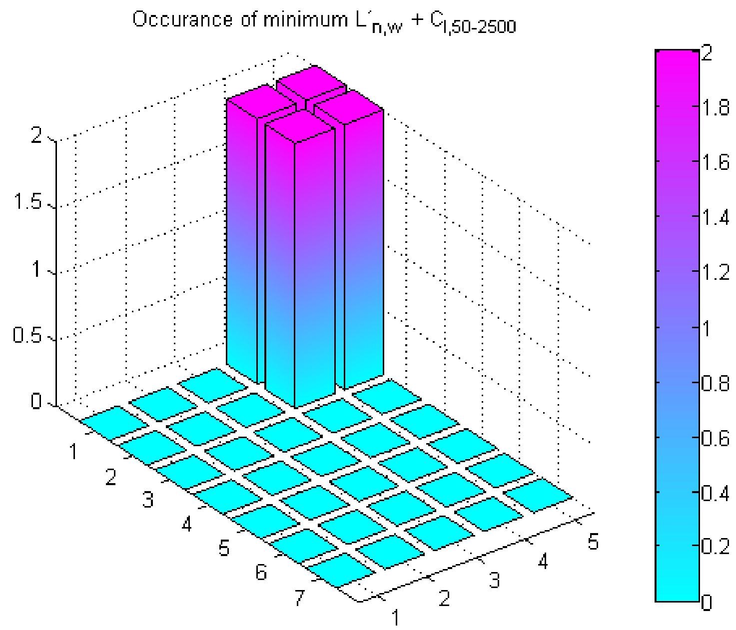

Figure 5-7: Bar plot over how frequently each source position contributes to a minimum value of $L'_{n,w} + C_{I,50\text{-}2500}$.

The source position and its contribution to the highest levels of $L'_{n,w}$ and $L'_{n,w} + C_{I,50\text{-}2500}$ is illustrated in Figure 5-8 and Figure 5-9. The source positions contributing most frequent to the calculated maximum levels on $L'_{n,w}$ are mainly the positions 21 – 35, situated nearest the facade in the building. Source positions 34 and 35 turns out to be very dominant which also was stated subjectively during the measurement and appears to be due to two heat pipes passing vertically between the sending and the receiving room, close to the corner where highest levels were detected. These pipes short circuited the floating floor in the sending room and thus resulted in a clear flanking transmission. The crucial source positions are further confirmed by Figure 5-9. The highest level on $L'_{n,w} + C_{I,50\text{-}2500}$ arises just from one combination of source positions (position 27-28, 34-35). The source positions are illustrated in Figure 5-4.

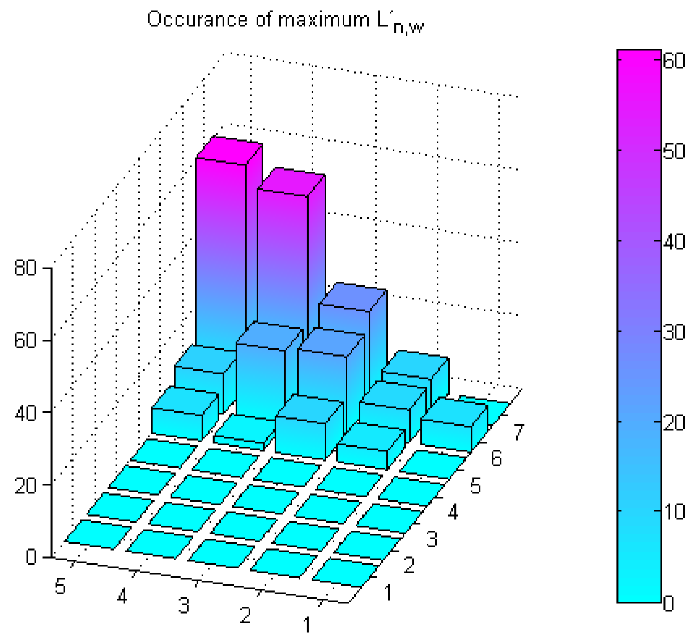

Figure 5-8: Bar plot over how frequently each source position contributes to a maximum value of $L'_{n,w}$.

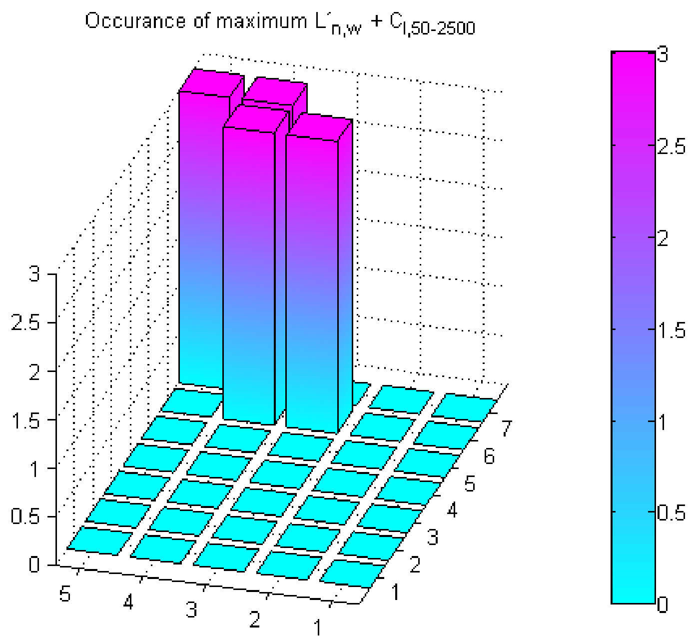

Figure 5-9: Bar plot over how frequently each source position contributes to a maximum value of $L'_{n,w} + C_{I,50\text{-}2500}$.

Carrying out an averaging procedure, based on 100 000 random combinations of four source positions and a sweeping microphone in the receiving room, and then use these different combinations to evaluate $L'_{n,w}$ and $L'_{n,w} + C_{I,50\text{-}2500}$ give a distribution of the single numbers equal to those shown in Figure 5-10. Both distributions have similarities to a normal distribution but, similar to earlier distributions, the left tail is wider than the right tail of the distribution.

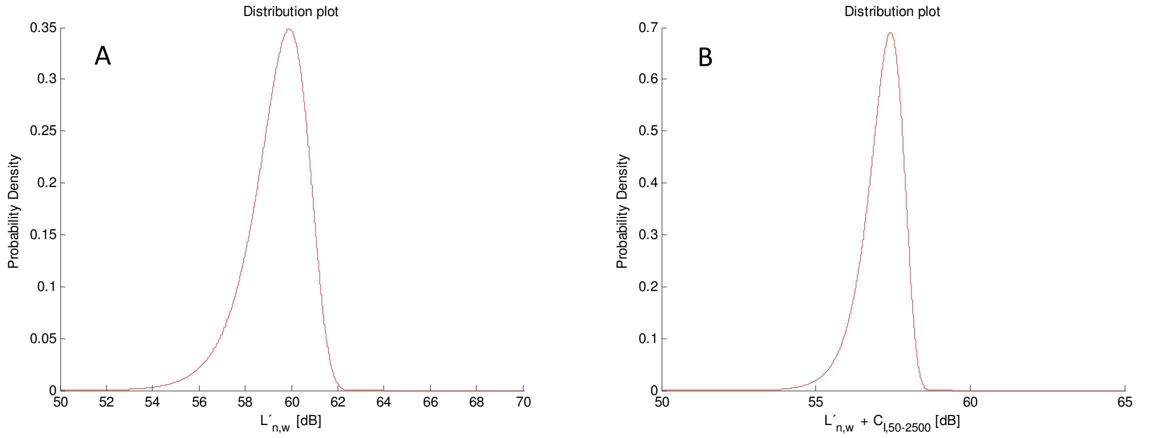

Figure 5-10:

A: Weibull distribution for $L'_{n,w}$ from 100 000 combinations of 4 randomly chosen source positions of 35 available, project 16.

B: Weibull distribution for $L'_{n,w} + C_{I,50\text{-}2500}$ from 100 000 combinations of 4 randomly chosen source positions of 35 available, project 16.

The measurements were performed in the frequency range 10 - 5000 Hz. Similar to earlier measurements, the highest impact sound pressure levels arise in 1/3 octave bands below 50 Hz. The impact sound pressure levels calculated as a spatial mean value for each 1/3 octave band in the frequency range 10 - 5000 Hz based on all the 35 source positions is presented in Figure 5-11.

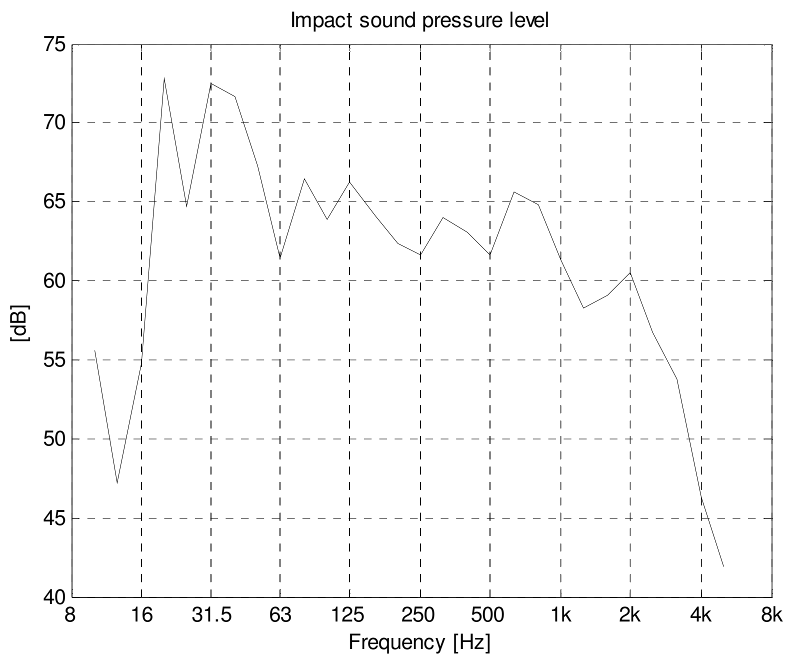

Figure 5-11: The mean impact sound pressure level from the 35 source positions in the receiving room in the frequency range 10 – 5000 Hz.

6. Evaluation of reference curve

The ISO 717-2 reference curve has shortcomings since it has a typical shape adapted to heavy structures. When applied to light weight structures large errors might appear and the final single number does not correlate to the experienced level of real impact sound from those persons living in the housing units [6, 8]. Many attempts have been made during the years to define a reference curve which creates a weighted single value that might be used for any building structure, i.e. involving better adaption to the subjective evaluation of impact sound pressure level for light weighted floor structures. The several proposed reference curves differ from each other, both regarding curve shape and covered frequency range, Figure 6-1. The level in each 1/3 octave band for each weighting curve can be seen in Appendix VI.

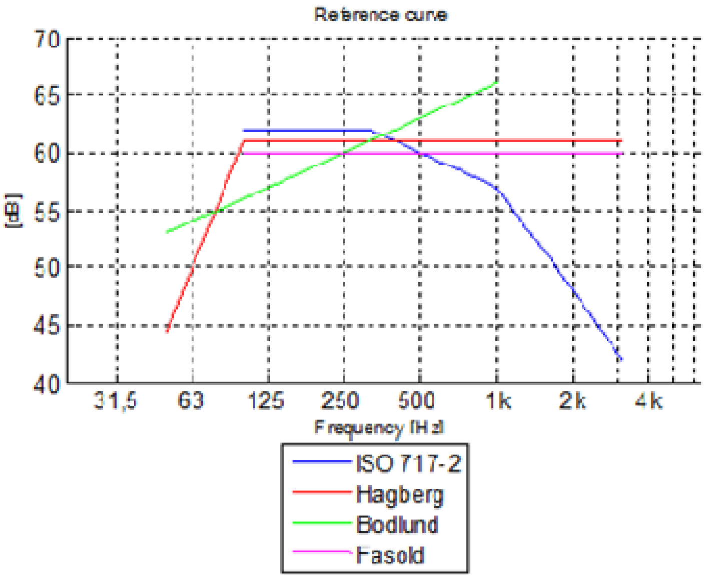

Figure 6-1: Reference curve ISO 717-2 [3] used for single value evaluation of impact sound pressure level together with proposed alternatives; Hagberg [8], Bodlund [6] and Fasold [13].

The reference curves are evaluated based on measurements and interviews with the tenants. From this, a correlation analysis might be done. This approach was performed in the work made by Hagberg [8] and when applying linear regression correlation analysis, the reference curve from ISO 717-2 [3] i.e. $L'_{n,w}$, exhibit a linear regression fit *r* of 74 % between the measured values and the mean subjective results. This might be improved by adding the adaptation term $C_{I,50\text{-}2500}$, see Equation 6-1. However, still further improvement was proved by applying an alternative reference curve which has a shift from a positive slope of 5.5 dB per 1/3 octave band for the 1/3 octave bands between 50 and 100 Hz to a straight line. This curve gives a linear regression *r* of 87 %, Equation 6-2. The proposed curve by Bodlund [6] has a linear regression *r* of 83 %, Equation 6-3.

Equation 6-1

$$L'_{\mathrm{n,w}} + C_{\mathrm{I,50-2500}} = 74.40 - 4.17S\ [r = 84\%, n = 22]$$

Equation 6-2

$$L'_{\mathrm{n,w,Hagberg}} = 79.28 - 4.09S\ [r = 87\%, n = 22]$$

Equation 6-3

$$I_S = 80.27 - 3.98S \; [r = 83\%, n = 22]$$

The linear regression for Hagbergs investigated average objective data versus the average mean score of the subjective data is plotted in Figure 6-2 and Figure 6-3. Figure 6-2 illustrates the regression using $L'_{n,w} + C_{I,50\text{-}2500}$ according to ISO 717-2 [3] and Figure 6-3 illustrates the regression using $L'_{n,w,\mathrm{Hagberg}}$ proposed by Hagberg. The vertical error bars show the maximum and minimum measured values of objective data within each housing unit.

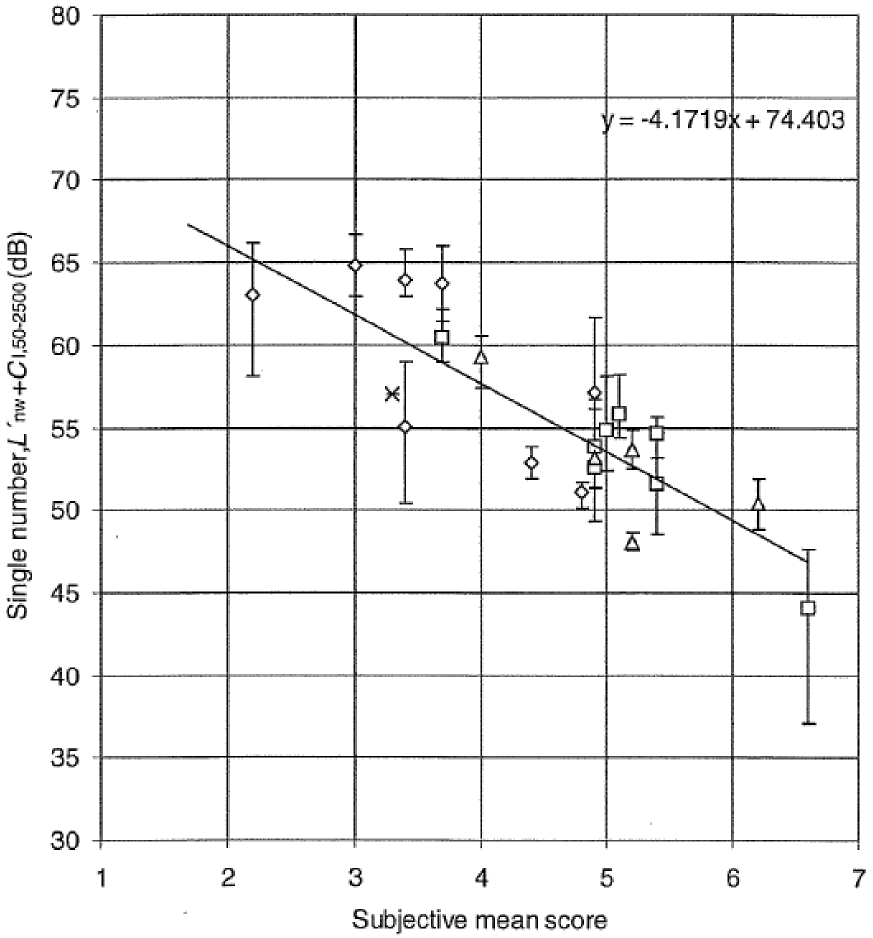

Figure 6-2: Linear regression for whole data sample, $L'_{n,w} + C_{I,50\text{-}2500}$ versus subjective grading; □ = concrete structure, ◊ = wooden floor structures, Δ = hollow concrete structures, × = light weighted steel structures [8].

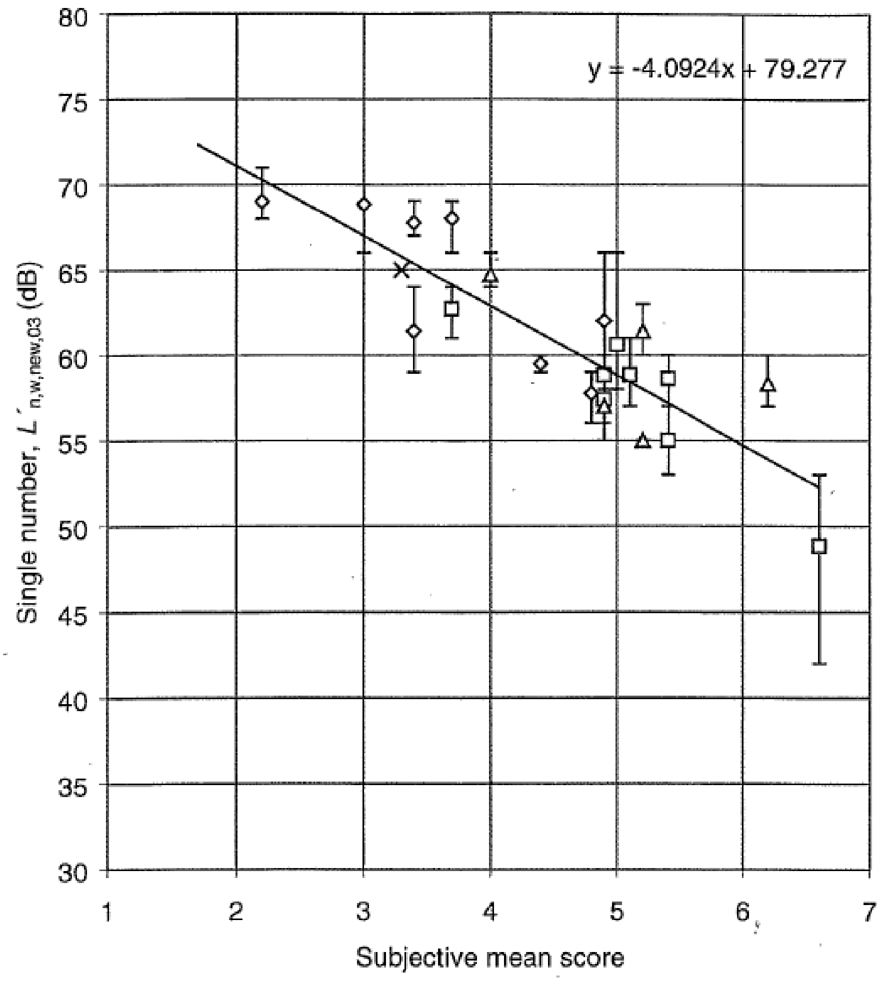

Figure 6-3: Linear regression for whole data sample, $L'_{n,w,Hagberg}$ versus subjective grading; □ = concrete structure, ◊ = wooden floor structures, Δ = hollow concrete structures, × = light weighted steel structures [8].

6.1. Extended investigation in this thesis

In order to further investigate current proposals of reference curve contours from earlier investigations some additional calculations are made in this thesis. Earlier investigation from Hagberg [8] were extended by some current measurements from a National survey [12, 31], involving different structures, amongst those two additional light weight structures. Hence, the investigation of reference curve contours is based on a linear regression analysis; mean values from objective impact sound pressure level measurements were compared with mean values from subjective judgments. A linear regression model could be applied since the responds of interest normally is in the central region of the subjective sample where the relationship can be assumed to be described approximately by a straight line [8], Figure 6-4. Hence, the linear model works insufficiently with extremely high or low subjective values.

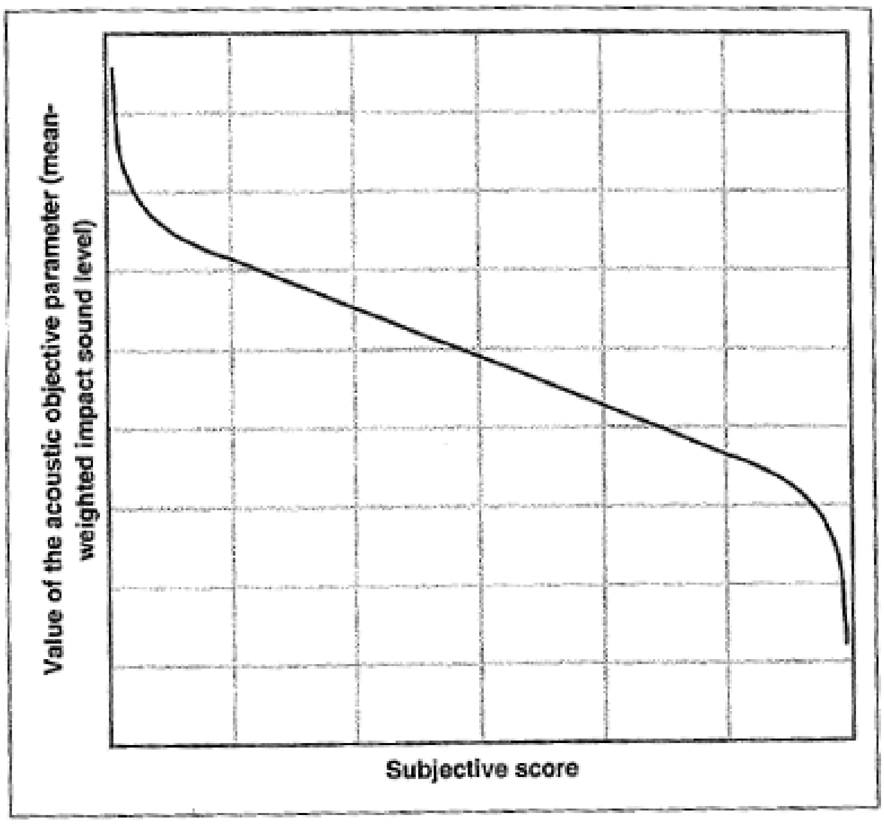

Figure 6-4: Relation between objective result and subjective judgment [8].

A linear regression model assumes that a straight line can be adapted to the data in this thesis, Equation 6-4. The intercept value *I* and regression coefficient *x* are calculated so that the error compared with observed data is as small as possible.

Equation 6-4

$$.< L > = I + xS$$

where

$< L >$ is the mean value of the weighted impact sound pressure level
S is the subjective mean score
x is the regression coefficient that describes the regression line slope
I is the intercepting value of y where the line crosses the y-axis

The lowest subjective score on the rating scale was 1, related to poor impact sound insulation while the highest score was 7, related to excellent sound insulation. The objective data on measured impact sound pressure levels, used in the linear regression model were limited to only vertical measurements.

The most satisfying reference curve has been established by altering different reference curves until the reference curve which created an objective value with the strongest adaptation (i.e. highest correlation) to the subjective value was found.

A written *Matlab* script was used to design different references curves. The script based on a straight line without any slope was shifted in some of the lowest 1/3 octave bands so a positive slope or a positive curvature was achieved. The script created different reference curves by varies the number of arrises in the curvature, the distance between each arris and the angle of each arris. The number of arrises was varied between one and five. In this case, an arris means a point where the curve changes slope. In total, the script tested around 270 000 reference curves.

Further on, the different reference curves have been altered for 26 projects which consisted of 21 projects from Hagbergs licentiate [8] and 5 projects from an investigation performed by WSP [12, 31]. 21 of Hagbergs 22 investigated projects were used since project number 22 was not available. The correlation with the reference curve defined in ISO 717-2 [3] and Hagbergs suggested reference curve [8] was also investigated, with the new number of projects.

Attempts were made with a non linear regression model with a quadratic equation, these attempts showed that the assumption of a straight line describing the subjective scores in the central region is reliable since the non linear regression model which resulted in highest correlation had a flat appearance similar to a straight line.

6.2. Alteration of reference curve

The most sufficient reference curve was established after more than 270 000 different reference curves had been altered. It turned out that the reference curve that showed best fit to the data had strong similarities to the curve Hagberg suggested in 2005 with a positive slope in the low frequencies, Figure 6-5. The altered reference curve differs mainly to Hagbergs with a slope only between the 1/3 octave bands 50 and 63 Hz, i.e. the horizontal part of the altered reference curve is wider than the earlier suggested curve. However, the correlation coefficient decreased and the best fitted curve had a correlation coefficient equal to 79% as Equation 6-5.

Equation 6-5

$$L_{BL1} = 78.36 - 3.58S\ [r = 79\%, n = 26]$$

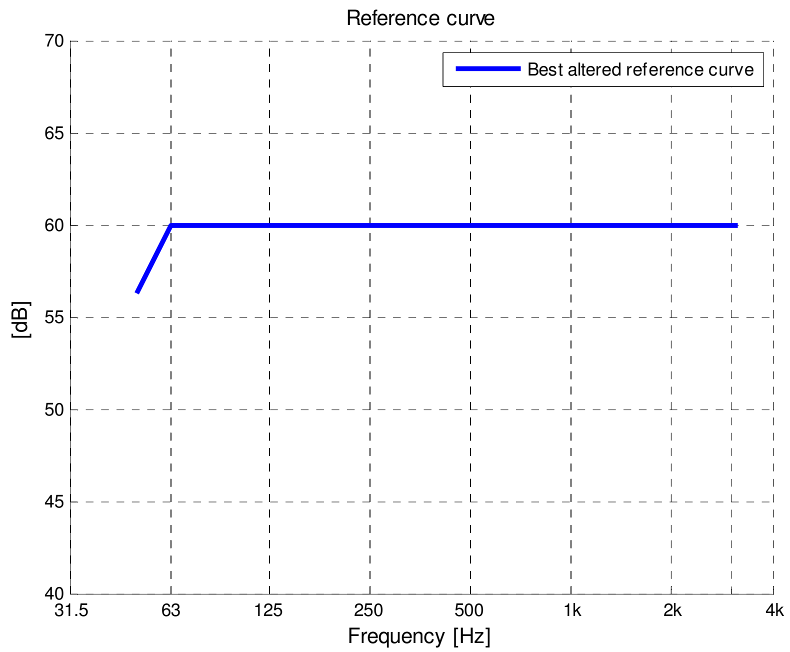

Figure 6-5: The most sufficient reference curve for single value evaluation of impact sound pressure level from the alteration process.

The level in each 1/3 octave band of the most sufficient reference curve after the alteration is stated in Table 6-1.

Table 6-1: Exact level in each third octave band of the most sufficient reference curve after the alteration

1/3 octave band [Hz]	Level [dB]
50	56.3
63	60.0
80	60.0
100	60.0
125	60.0
160	60.0
200	60.0
315	60.0
400	60.0
500	60.0
630	60.0
800	60.0
1000	60.0
1250	60.0
1600	60.0
2000	60.0
2500	60.0
3150	60.0

6.3. Applying four different reference curves

6.3.1. Reference curve according to Fasold

When the reference curve proposed by Fasold [13] was applied on the objective data for calculating a weighted single number, a resulting correlation coefficient for the linear regression modal was calculated to 68%, Equation 6-6. Figure 6-6 illustrates the regression with the weighted single number calculated according to Fasolds proposed reference curve.

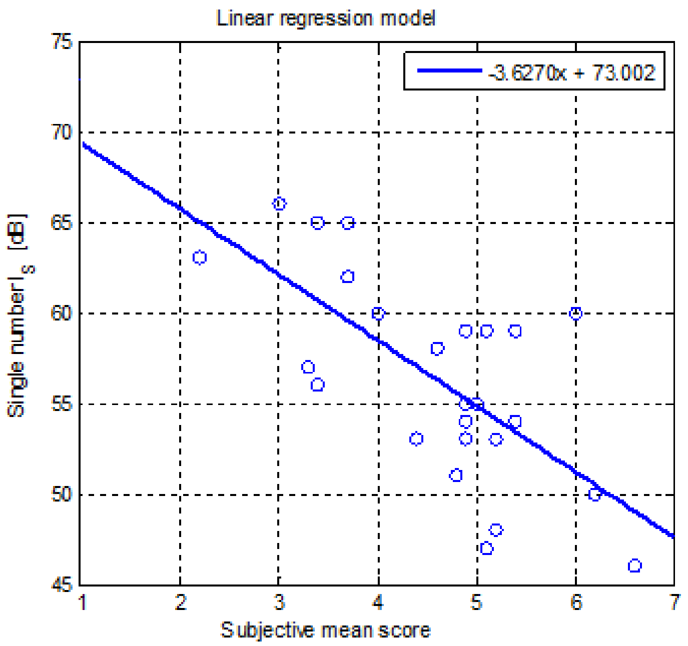

Figure 6-6: Linear regression model based on subjective values from judgments and objective values calculated according to the reference curve proposed by Fasold [13].

Equation 6-6

$$I_S = 73.00 - 3.63S \; [r = 68\%, n = 26]$$

6.3.2. Reference curve according to ISO 717-2

When the reference curve defined by ISO 717-2 [3] was applied on the objective data for calculating $L'_{n,w}$ and further $L'_{n,w} + C_{I,50\text{-}2500}$, a resulting correlation coefficient for the linear regression model was calculated to 71%, Equation 6-7. Figure 6-7 illustrates the regression with $L'_{n,w} + C_{I,50\text{-}2500}$ calculated according reference curve and adaption term defined by ISO 717-2.

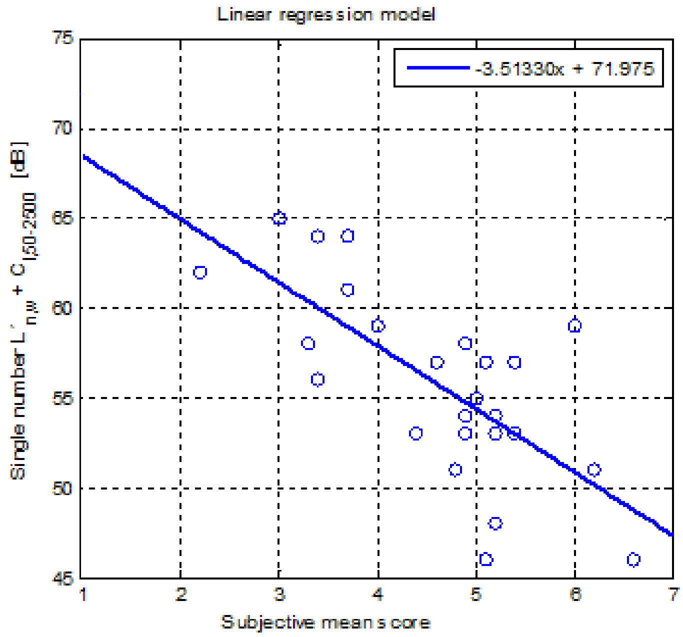

Figure 6-7: Linear regression model based on subjective values from judgments and objective values calculated according to reference curve and C-adaption term defined by ISO 717-2 [3].

Equation 6-7

$$L'_{\mathrm{n,w}} + C_{\mathrm{I,50-2500}} = 71.98 - 3.51S \; [r = 71\%, n = 26]$$

6.3.3. Reference curve according to Hagberg

When the reference curve proposed by Hagberg in 2005 [8] was applied on the objective data for calculating a weighted single number, a resulting correlation coefficient for the linear regression model was calculated to 74%, Equation 6-8. Figure 6-8 illustrates the regression using the weighted single number calculated according the reference curve proposed by Hagberg.

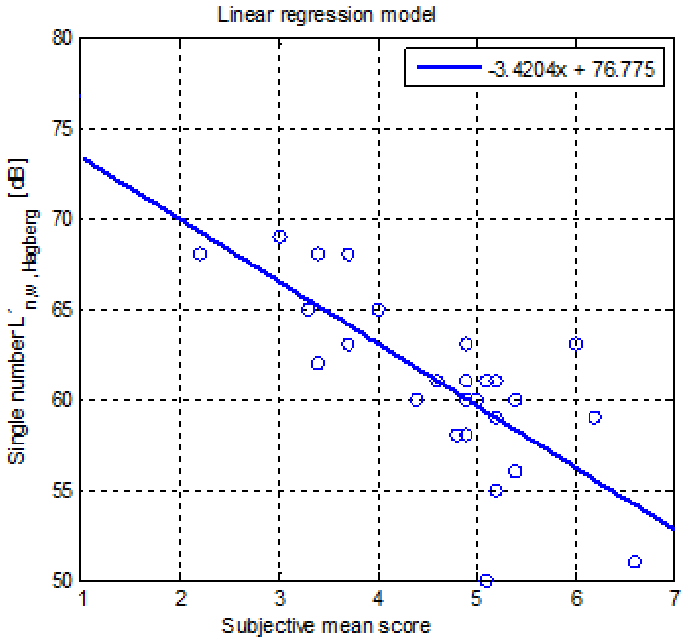

Figure 6-8: Linear regression model with subjective values from judgments and objective values calculated according to the reference curve proposed by Hagberg [8].

Equation 6-8

$$L'_{\mathrm{n,w,Hagberg}} = 76.78 - 3.42S\ [r = 74\%, n = 26]$$

6.3.4. Reference curve according to alteration

When the best altered reference curve was applied on the objective data for calculating a weighted single number, a resulting correlation coefficient for the linear regression model was calculated to 79%, Equation 6-9. Figure 6-9 illustrates the regression using weighted single number from the best altered reference curve.

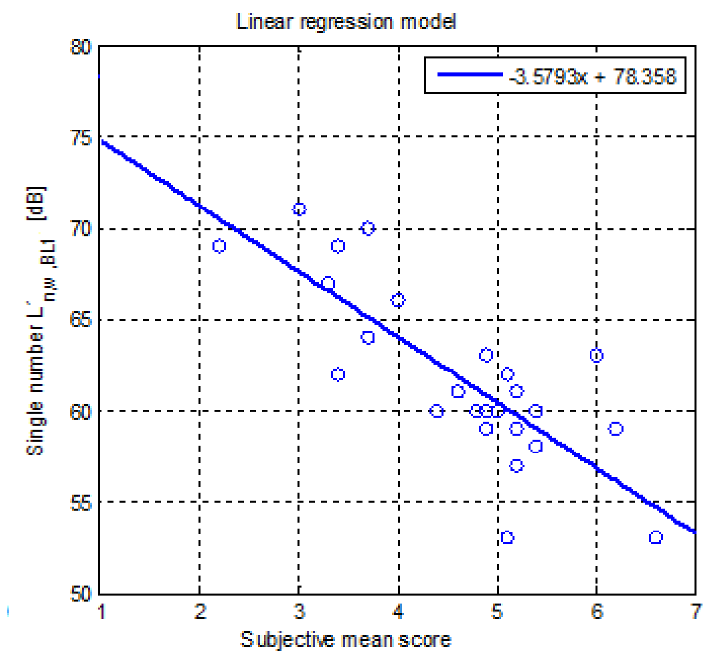

Figure 6-9: Linear regression model with subjective values from judgments and objective values calculated according to the best altered reference curve.

Equation 6-9

$$L'_{\mathrm{n,w,BL1}} = 78.36 - 3.58S\ [r = 79\%, n = 26]$$

When the best altered reference curve was applied on the objective data for calculating a single number, a resulting correlation coefficient for a regression model with two degrees of freedom was calculated to 80%, Equation 6-10 illustrates the regression with two degrees of freedom.

Equation 6-10

$$L'_{\mathrm{n,w,BL2}} = 83.49 - 6.03S + 0.28S^2\ [r = 80\%, n = 26]$$

7. Evaluation of measurement reports

The evaluation of the measurements in project 1 - 7 in Table 1-1 have been performed based on ISO standards SS-EN ISO 140-7 [7], ISO 717-2 [3] and SS 25267 [2]. Notice that project 1 -7 are performed in light weight structures and measured in frequencies from 50 to 3150 Hz, since these are the current standard limits. According to the ISO standards, measurements with less than four sweeping microphone measurements and six discrete microphone positions have been disapproved. Further on, reverberation time measurements with less than six discrete microphone positions have been suggested to be disapproved. Regarding the background noise measurements without measurements or any notification of background noise have also been rejected. Also the reports have been evaluated to judge if the projects are useful for further investigation. When studying the measurement reports the following aspects have been investigated.

- Are there any differences between measurement reports regarding acoustical results?
- Are the measurement procedures sufficiently clear?
- Are the building structures sufficiently described in the reports?
- Are there any existing risks to use existing measurements in the AkuLite project?

Each project has been described in Appendix VII. Disapproved measurements have been described further to mark their failures. When reading the measurement reports from different consultant companies, it is clear that each company have different demands of the reports. This is most obvious how the specificity differs when the floor structure and measurement procedure is described. But since the customers often already are well aware of the floor structure and not interested in the measurement procedure (the customers want to know the result of the measurements which they are paying for) makes a detailed description superfluous. A well written report is still to recommend if the object should be of interest for studies of measurement uncertainties or comparisons of acoustic properties for different examples of similar constructions in the field.

8. Summary of evaluated results

8.1. Distribution with regard to spatial averaging procedure

Almost all data from impact sound pressure level and reverberation time measurements in any light weight and / or concrete structures have similarities to a normal distribution. However, reverberation time data in low frequencies emanating from measurements in a light weight structure might differ from a normal distribution curve and then create unexpected and, if not carefully investigated, unknown errors. Hence, there is an obvious risk for outliers that might create a skew distribution curve with a right “tail”, i.e. there is a potential risk to obtain outliers representing long measured reverberation times that appears to be correct but actually differ a lot from the mean value. These outliers can affect the weighted single number quantities.

In general, the distributions of all impact sound pressure level and reverberation time data, apart from reverberation time data in the lowest frequencies is almost normally distributed, apart from some skew appearance of the distributions always with a left tail wider than the right tail. The skew appearance indicates that the lowest measured level deviates stronger from the mean value than the highest measured. Why this pattern arises is not fully clarified, but perhaps it could be a result from the fact that the main part of the measurements are made in the central parts of the room with slightly lower levels than along the boundaries.

8.1. Effect of receiving room volume

In this study it has been shown that the volume of the receiving room influence the measurement results in both light weight and concrete structures. For the impact sound pressure level, the result varies from each 1/3 octave band. When studying 1/3 octave bands above approximately 160 Hz, all 1/3 octave bands exhibit similar behavior with regard to confidence interval. The confidence interval of the mean impact sound pressure level becomes narrower when the volume of the receiving room is increased. This behavior is normal and expected. However below 160 Hz the confidence interval seems to be rather independent of the receiving room volume for light weight structures.

Concerning the reverberation, the confidence interval for the three lowest 1/3 octave bands 50, 63 and 80 Hz deviates significantly from the other 1/3 octave bands. For these three 1/3 octave bands the confidence interval of the mean reverberation time is increasing with increasing receiving room volume. This is contradictory to all other 1/3 octave bands which exhibit relative constant confidence interval of the mean reverberation time as the receiving room volume increases. Hence, there exists a source of measurement uncertainty of the lowest 1/3 octave bands that might give rise to an unwanted reduction of the impact sound pressure level when the evaluation procedure is fully carried out, i.e. when the standardization to 0.5 s is performed. Adding the unknown effects of even lower frequency bands and their impact on subjective response, confirms that there is a lot of uncertainties regarding the reverberation time measurements reliability for the low 1/3 octave bands, not taken into account in current standards.

8.2. Impact sound in low frequencies

The investigation of impact sound measurements indicates that the highest sound pressure levels for light weight structures mainly occurs in 1/3 octave bands below 50 Hz. However, depending on floor structure the highest measured impact sound pressure levels can also arise in other frequency regions, i.e. for measurements performed on concrete floor structures the highest levels often occur above 50 Hz. In general, the characteristics of the impact sound pressure levels depending on floor structure is typically as shown in Figure 1-1, representing measurements performed during lab conditions. In the field additional affects are added (joints, floor span length, building system in general etc) which might emphasize the effects or at least make them less unpredictable.

8.3. Extended measurements

The evaluation of $L'_{n,w}$ and $L'_{n,w} + C_{I,50\text{-}2500}$ levels show that the locations of the tapping machine at the measurement site has the possibility to strongly affects the measurement result; positions nearest the façade and nearest a subjectively noticed flanking transmission gave highest levels, positions furthest away from the flanking transmission gave lowest values. In this case the results were affected by strong sound propagation (flanking transmission) through heat water pipes. Hence this is an important effect to take into account during measurements in light weight structures. The result of this investigation shows that even if measurements are performed according to ISO 140-7, the four random chosen positions of the tapping machine can influence significantly on the weighted single number values $L'_{n,w}$ and $L'_{n,w} + C_{I,50\text{-}2500}$.

The distributions of both the measured impact sound pressure level and reverberation time are similar to the distributions of earlier investigated measurements with a left tail wider than the right of the distribution. This indicates that the lowest measured level deviates stronger from the mean value than he highest measured.

The mean impact sound pressure level based on the 35 source positions becomes equal to a typical frequency spectrum in a light weight structure, Figure 1-1. The highest levels are found below 50 Hz, levels which are not considered in the evaluation of the single weighted values $L'_{n,w}$ and $L'_{n,w} + C_{I,50\text{-}2500}$.

8.1. Evaluation of reference curve

The investigation in this thesis regarding different reference curves confirms former investigations, for example Hagberg from 2005. Both the curve from Hagberg and the curve finally suggested by the authors have a sharp positive slope in the low frequency region which emphasizes the importance of the lowest frequencies in light weight structures. This sharp slope makes the reference curve evaluation sensitive to minor errors at low frequencies. Hence, uncertainties in the low frequency region (which are described in this thesis) might affect the final result strongly.

8.2. Evaluation of measurement reports

In general, it is not recommended to use the measurements included in this thesis for more detailed investigations within AkuLite. 16 of 41 evaluated measurements are fully based on requirements in ISO 140-7 [7]. The other 25 evaluated measurements could reach the demands ISO 140-7 states if complementary measurements are made for some projects.

Some projects should be rejected even if the measurements have been performed in a proper way. With regard to further investigations of impact sound insulation in frequencies below 50 Hz (i.e. within AkuLite) only project 3, 10, 11 and 12 are useful as far as we are concerned.

9. Discussion

9.1. Distribution

The distribution of the measured impact sound pressure level and reverberation time from different measurement positions may be seen as approximately compatible to a normal distribution when a confidence interval investigation is made. The data distribution's compatibility is confirmed by associate professor A. Särkkä [24] who assumes that the data could be seen as approximately normally distributed when a confidence interval investigation is made. According to the central limit theorem which says that a summation of a large amount of randomly distributed values will have an asymptotic distribution of the summation for which the distribution of the sum will move towards a normal distribution. The data in this study can be seen as approximately normally distributed although the data for the lowest 1/3 octave bands show a skewed distribution since the skew behavior is not so significant [24]. Further on, the difference in confidence interval based on data with a slightly skew distribution compared to data which is normally distributed (i.e. not skew) is small. A fact which is confirmed by a reliable statistic experimental investigation where the sensitivity of different distributions in experiments was investigated [25], i.e. confidence intervals based on this data may not be misleading due to skewness.

The distributions of both impact sound pressure level and reverberation time data have been shown to have a skew behavior for most investigated 1/3 octave bands. The skew distribution with a left tail wider than the right tail indicates that the lowest measured value is deviating more from the mean value than the highest measured value. Why this pattern appears is hard to determine without further investigations. However as earlier stated, it can be explained by the measurement positions which often are rather centralized in the room where normally lower levels arise. Perhaps this distribution could be more similar to a normal distribution if using more positions by increasing the number of measurement points along edges and in corners.

This investigation is only a brief overview of risks regarding measurement uncertainties. The investigation regarding distribution in this thesis is based only on one measurement, which of course is vague. Hence, a pattern according to this investigation does not immediately mean that other measurements would show the same pattern and behavior. Further on, the number of measurement data points in each investigated measurement should be numerous in order be able to study the distribution; if necessary to adapt the central limit theorem. According to A. Särkkä [24] a rule of thumb says that between 25 and 30 values is needed to be able to apply the central limit theorem in practice.

9.2. Effect of receiving room volume

The reliability of the linear estimations can be discussed when studying the correlations between calculated confidence intervals and receiving room volumes, in Appendix III. It is obvious that more measurements have to be included in the sample in order to draw any final conclusions. Especially important are measurements taken at receiving rooms with volumes in the range 80 m^3 - 169 m^3 since the lack of measurements in this volume range. It is important with both impact sound pressure level and reverberation time measurements made in this room volume range.

It is well known among engineers and scientist in the field of acoustics that the reverberation time measurements below 50 Hz suffers from shortcomings. P. Thorsson claims that sufficient problems exists with low frequency reverberation time measurements, he is even doubtful if it exists such a thing as reverberation time for these low frequencies [26]. The uncertainties for the reverberation time measurements in the low frequency region are also confirmed by this thesis which indicates on especially high uncertainty of reverberation time measurements in large rooms. The vagueness with a weak or non existing reverberant field for the lowest frequencies may be explained by the mass law since the receiving room requires heavy surrounding elements to reflect the low frequency sound and thereby create a reverberant field. Further on, it is often hard to assume a diffuse sound field for the lowest frequencies; something which is a condition used in the measurement standards. Based on this arguments, huge difficulties exists to state what is really measured, is it reverberation time in "ordinary manner" as stated in ISO 140-7, or is it rather the loss factor of the entire building system. However, authors claim that a possible measurement and evaluation solution should not be limited to the frequencies included in ISO 717-2 since it has been shown in this thesis that levels in even lower 1/3 octave bands are of great interest, if the reverberation time is such a major problem in the low frequencies, a new evaluation method has to be developed that avoids this problem with another evaluation approach.

Concerning the standardization of the impact sound pressure level to 0.5 s, it is very doubtful if this approach at all can be used in the lowest 1/3 octave bands since:

1 Statistical building acoustic theory is not applicable.
2 Other uncertainties described in earlier chapters exist.
3 Since the standardization to 0.5 s is a way to correct for abnormal furnishing, will a normal furnishing affect the reverberation time at such low frequencies?

9.3. Impact sound in low frequencies

It has been shown that the highest impact sound pressure level occurs for frequencies below 50 Hz in light weight structures. Hence, it seems strange why the lowest 1/3 octave bands (below 50 Hz) are not included in the final single number quantity $L'_{n,w}$ or $L'_{n,w} + C_{I,50\text{-}2500}$, calculated according to ISO 717-2. Especially since $L'_{n,w}$ and $L'_{n,w}+C_{I,50\text{-}2500}$ are such important parameters which sets the final sound class according to classification in SS 25267:2004, third edition [2]. The human ears are also most sensitive for level differences in the low frequency region where the highest levels normally arise. A difference of 3-5 dB in the low frequencies is by human ears perceived as a doubling of the sound level while 10 dB in 1000Hz is perceived as a sound level doubling. The main reason to not include the lowest frequencies is measurement problem and uncertainties. Research has to be done in order to take care of the lowest frequency range in the evaluation of impact sound insulation.

The highest impact sound pressure level below 50 Hz in the investigation is more than 15 dB higher than the highest sound pressure level in the "normal" frequency range above 50 Hz, Figure 4-1. Based on this, the authors suggest that a possible step to a sufficient solution could be that the impact sound pressure in 1/3 octave bands below 50 Hz should be treated to ensure that the highest levels is included in the evaluation. It is probably necessary to use a completely different approach for the lowest frequencies since it has been shown in this thesis that reverberation times measured for low 1/3 octave bands are unreliable. It is not even clear if reverberation time measurements are applicable, and certainly not the standardization procedure.

9.4. Extended measurements

It has been shown in project 16 that the impact sound pressure level in the receiving room is highly affected by the tapping machine position (note that it is not applicable to other light weight projects). Significant uncertainties arise during the choice of at least four random tapping machine positions according to ISO standard 140-7.

The choice of tapping machine position may have a large impact on the final sound class since the span between the lowest and highest $L'_{n,w}$ was 6 dB respectively 3 dB for $L'_{n,w} + C_{I,50\text{-}2500}$. In case the measured levels are lower than in reality these uncertainties can be painful for the habitants.

The project where the investigation from this thesis was taken is a project which was rejected due to too poor impact sound insulation, mainly caused by the strong flanking transmission through the heating pipes between sending and receiving room. However it is interesting to see that the result of the grid method with many tapping machine positions correlates to the subjective impression of the flanking transmission path. The grid method could actually be used as a tool for investigate some kinds of flanking transmission.

For further investigation it is of interest to investigate the distribution of impact sound levels in 1/3 octave bands below 50 Hz.

9.1. Evaluation of reference curve

The positive slope in the low frequencies of the proposed reference curves by the authors and by Hagberg [8] based on the tapping machine as the impact source clearly shows the importance of the low frequencies regarding annoyance. It indicates that the low frequencies are not taken into account enough. If lower frequencies were taken into account in the unfavorable summation, probably a more harmonic and flat shape of the reference curve, without clearly determining 1/3 octave bands had been altered to the most sufficient since levels in the lowest frequencies often are high and thereby strongly involved in the summation. Hence, clearly determining 1/3 octave bands would probably not be consistent since the need of a sharp slope in the reference curve would be erased. In general, the slope emphasizes the need of a more detailed study regarding the low frequency phenomena, not only in light weight structures but also for structures of concrete and hollow concrete since alteration of the most sufficient reference curve has been based on all three structure types. Further on, the sharp slope also denotes on a large uncertainty where such a curve gives the low frequencies with highest uncertainty largest possibility to influence the weighed single number, Figure 9-1.

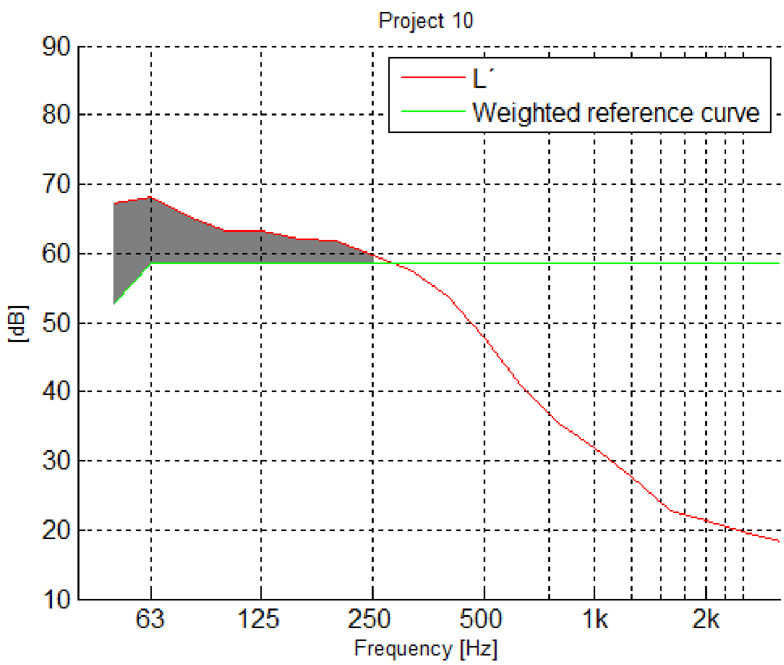

Figure 9-1: Impact sound pressure level and authors altered reference curve for one room in project 10, which is a light weight construction.

The calculated correlations in this thesis are not as high as the correlations in Hagbergs thesis [8] perhaps due to the extended database which includes some heavy concrete projects, Figure 9-2.

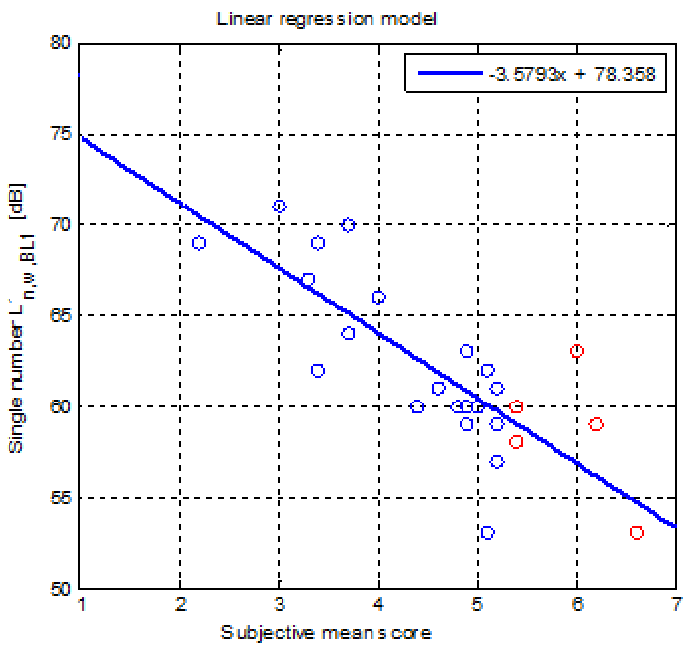

Figure 9-2: Linear regression model with subjective values from judgments and objective values calculated according to the best altered reference curve. The blue rings corresponds to data from Hagberg, red rings corresponds to data from WSP.

In Figure 9-3 all included types of constructions are shown by different colors; 1. green, floor structures with hollow concrete; 2. red, floor structures with homogeneous concrete; 3. blue, light weight floor structures. Hollow concrete may be seen as a third type of floor structure, somewhere in between heavy concrete structure and a light weight structure.

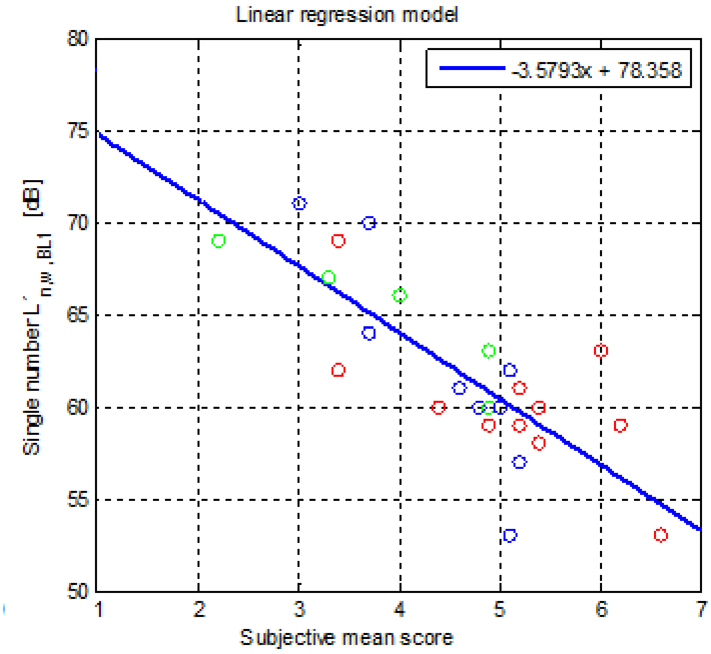

Figure 9-3: Linear regression model with subjective values from judgments and objective values calculated according to the best altered reference curve. The blue rings correspond to light weighted floor structure, red rings correspond to homogenous concrete floor structures and green rings correspond to hollow concrete floor structures.

The equation of the regression line makes it possible to estimate the objective value from a "wanted" subjective value. The regression line equations could be used as an indication of the sound climate in a room based on the subjective grade. To increase the reliability, more projects need to be included to establish a reasonable reference curve. It is also likely that some improvements of the questionnaires and the interview technique are needed. Anyway, the equation is and will always be limited to just be an indicator of the sound climate. A total reliability is not possible to achieve with the regression equation since the model is based on average values, hence there is a range of values for which each average is based on, both regarding subjective and objective values which of course creates uncertainties.

For further studies, an even more developed Matlab-like program should be created so engineers in the field of acoustic easily could alter different reference curves until the most sufficient curve is found. Such a program would save much time, create better results and enable more frequently alterations as soon as the database of projects with both objective and subjective values had been extended with new data. An alteration program could be developed so several hundred thousand different reference curves, with different shapes could be altered at the same time. But of course it requires that the tapping machine is retained.

Future studies would also include living habits, type of accommodation etc. which means that old data successively should be replaced with new data in order to keep the knowledge up to date

9.2. Evaluation of measurement reports

It is often a need of more detailed information in the reports available at the consultants. There is often a lack of detailed information regarding the performance of the measurements in order to use them directly in research. They were performed in order to state whether a construction meet current requirement or not. However, it would be helpful to have better basis for future development from daily work at consultants and it would also be a natural development process within their own organizations, i.e. raise the quality and knowledge amongst their employees.

Furthermore, more detailed information would create a possibility to study the measurements more in detail, give better abilities to repeat them afterwards and hopefully create a base for better understanding of the measurement result. Better description of source and receiver position is primary needed. Also, a more detailed description on the construction; floor structure, walls and junction design and age of the building is preferable. For further studies, it would be valuable and helpful if a database or register over reliable measurements, measured and evaluated:

1 According to current standards (ISO 140-7 and ISO 717-2)
2 In an extended frequency range below 50 Hz.

The problem from the consultant's point of view is that it takes time and thus increases the costs. A discussion on the balance between documentation and its price is necessary.

10. Conclusions

It is rather difficult to find current measurement reports comprising sufficient information with high quality. The data is often insufficient due to missing measurements or due to too few measurement points according to ISO 140-7 [7], left without comments. The report is often short; a clearer explanation of the measurements and the building is required.

An investigation of the confidence interval on reverberation time measurements in light weight structures indicates an increasing uncertainty as the receiving room volume increases, in 1/3 octave bands below 100 Hz. The uncertainty in 1/3 octave bands above 100 Hz is low and almost constant over increasing room volume. If the reverberation time measurements are not carefully analyzed them might give rise to large and unwanted errors due to high reduction of low frequency impact sound pressure level. The errors is especially unpleasant since the low frequencies in light weight buildings often has high levels and therefore affects the experienced sound insulation

The tapping machine position influence the uncertainty during impact sound insulation measurements on light weight structures. The single number quantities describing the sound climate in the receiving room differ a lot depending on where the tapping machine is placed. This is something which the performer has to be aware of to avoid misleading results. Actually, this could be very obvious when measurements are affected by flanking elements which was the case in our own measurements.

The current reference curve to state weighted single number value in ISO 717-2 do not consider the lowest 1/3 octave bands. However both authors and Hagberg [8] have proved that a flat reference curve with a sharp positive slope in the lowest frequencies (the curve extended down to 50 Hz) creates the best correlation between objective and subjective values which clearly emphasize the importance of the low frequencies. If the ISO standard is renewed it is important not only to take the shape of the reference curve into account but also the frequency range since the highest impact sound pressure levels are found below 50 Hz. Further, one has to discuss among other things:

1. The tapping machine approach in impact sound measurements in light weight structures.
2. If more measurement points near corners and edges should be included in the averaging to generate result which better correlates to the mean value.
3. In which 1/3 octave bands reverberation times measurements should be made.
4. How uncertainties due to room volume should be treated.
5. The reverberation time measurements and their effect of the final results for light weight structures.

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12. Appendix I – Elements of confidence interval calculations

Table 12-1: table showing the c-value for different confidence level, γ, and degrees of freedom, *df*[11]

Table A9 ***t*-Distribution**

Values of z for given values of the distribution function $F(z)$ (see (8) in Sec. 25.3).
Example: For 9 degrees of freedom, $z = 1.83$ when $F(z) = 0.95$.

$F(z)$	Number of Degrees of Freedom									
	1	2	3	4	5	6	7	8	9	10
0.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.6	0.32	0.29	0.28	0.27	0.27	0.26	0.26	0.26	0.26	0.26
0.7	0.73	0.62	0.58	0.57	0.56	0.55	0.55	0.55	0.54	0.54
0.8	1.38	1.06	0.98	0.94	0.92	0.91	0.90	0.89	0.88	0.88
0.9	3.08	1.89	1.64	1.53	1.48	1.44	1.41	1.40	1.38	1.37
0.95	6.31	2.92	2.35	2.13	2.02	1.94	1.89	1.86	1.83	1.81
0.975	12.7	4.30	3.18	2.78	2.57	2.45	2.36	2.31	2.26	2.23
0.99	31.8	6.96	4.54	3.75	3.36	3.14	3.00	2.90	2.82	2.76
0.995	63.7	9.92	5.84	4.60	4.03	3.71	3.50	3.36	3.25	3.17
0.999	318.3	22.3	10.2	7.17	5.89	5.21	4.79	4.50	4.30	4.14

$F(z)$	Number of Degrees of Freedom									
	11	12	13	14	15	16	17	18	19	20
0.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.6	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
0.7	0.54	0.54	0.54	0.54	0.54	0.54	0.53	0.53	0.53	0.53
0.8	0.88	0.87	0.87	0.87	0.87	0.86	0.86	0.86	0.86	0.86
0.9	1.36	1.36	1.35	1.35	1.34	1.34	1.33	1.33	1.33	1.33
0.95	1.80	1.78	1.77	1.76	1.75	1.75	1.74	1.73	1.73	1.72
0.975	2.20	2.18	2.16	2.14	2.13	2.12	2.11	2.10	2.09	2.09
0.99	2.72	2.68	2.65	2.62	2.60	2.58	2.57	2.55	2.54	2.53
0.995	3.11	3.05	3.01	2.98	2.95	2.92	2.90	2.88	2.86	2.85
0.999	4.02	3.93	3.85	3.79	3.73	3.69	3.65	3.61	3.58	3.55

$F(z)$	Number of Degrees of Freedom									
	22	24	26	28	30	40	50	100	200	∞
0.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.6	0.26	0.26	0.26	0.26	0.26	0.26	0.25	0.25	0.25	0.25
0.7	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.52
0.8	0.86	0.86	0.86	0.85	0.85	0.85	0.85	0.85	0.84	0.84
0.9	1.32	1.32	1.31	1.31	1.31	1.30	1.30	1.29	1.29	1.28
0.95	1.72	1.71	1.71	1.70	1.70	1.68	1.68	1.66	1.65	1.65
0.975	2.07	2.06	2.06	2.05	2.04	2.02	2.01	1.98	1.97	1.96
0.99	2.51	2.49	2.48	2.47	2.46	2.42	2.40	2.36	2.35	2.33
0.995	2.82	2.80	2.78	2.76	2.75	2.70	2.68	2.63	2.60	2.58
0.999	3.50	3.47	3.43	3.41	3.39	3.31	3.26	3.17	3.13	3.09

13. Appendix II – Additional distribution plots

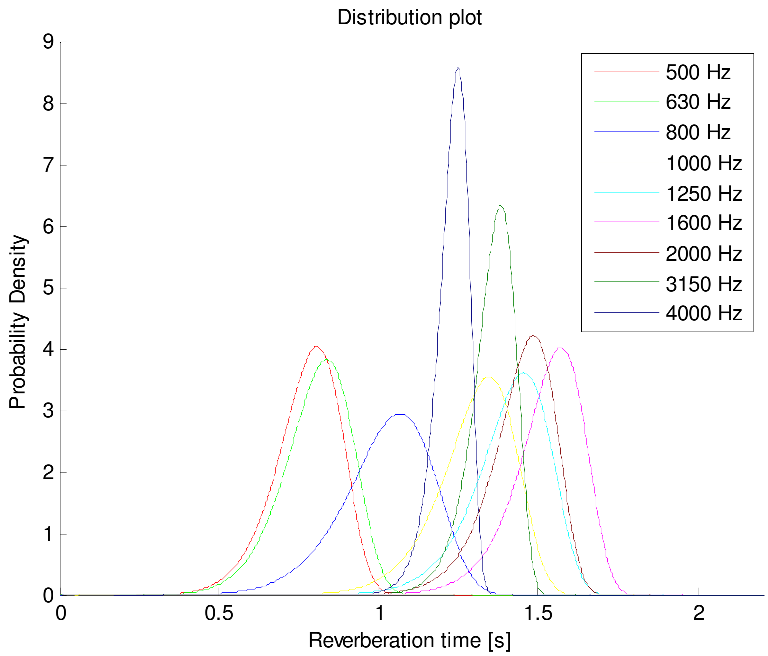


Figure 13-1: Weibull distributions of 24 reverberation time measurements performed in a light weight floor structure presented in the 1/3 octave bands 500 - 4000 Hz. The result is based on the data from project 3, measurement 2007 where the mean reverberation time was evaluated from these 24 measurements.

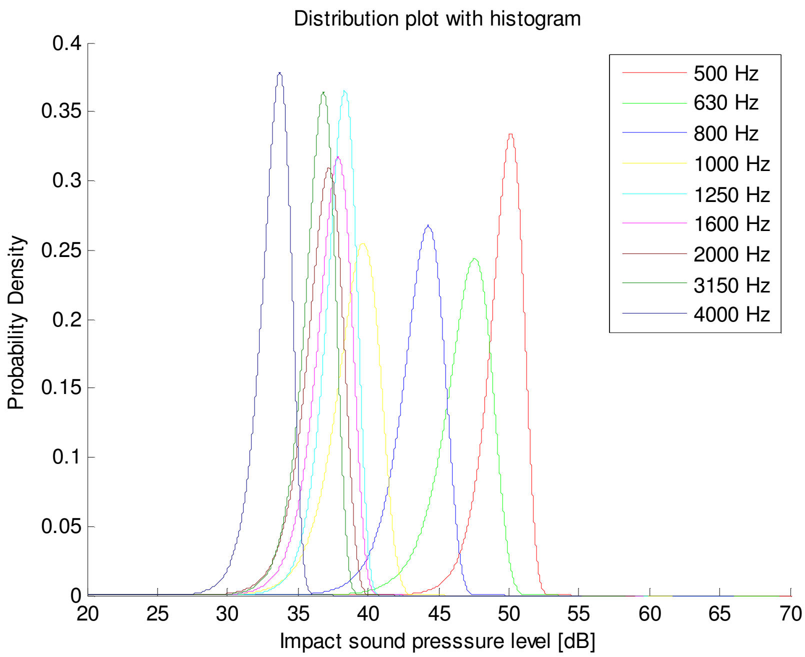


Figure 13-2: Weibull distributions of 12 impact sound pressure level measurements performed in a light weight floor structure presented in the 1/3 octave bands 500 - 4000 Hz. The result is based on the data from project 3, measurement 2007 where the mean impact sound pressure level was evaluated from these 12 measurements.

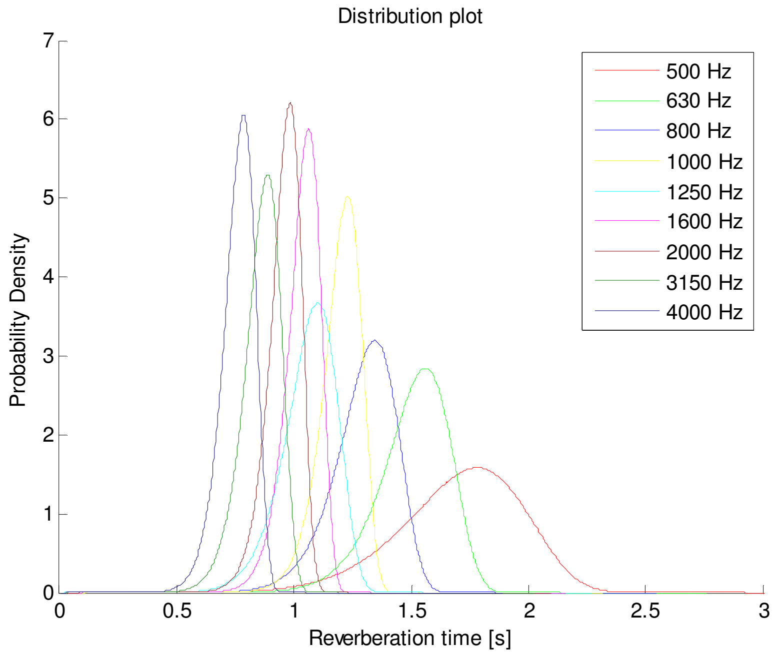


Figure 13-3: Weibull distributions of 24 reverberation time measurements performed in a concrete floor structure presented in the 1/3 octave bands 500 - 4000 Hz. The result is based on the data from project 15 where the mean reverberation time was evaluated from these 24 measurements.

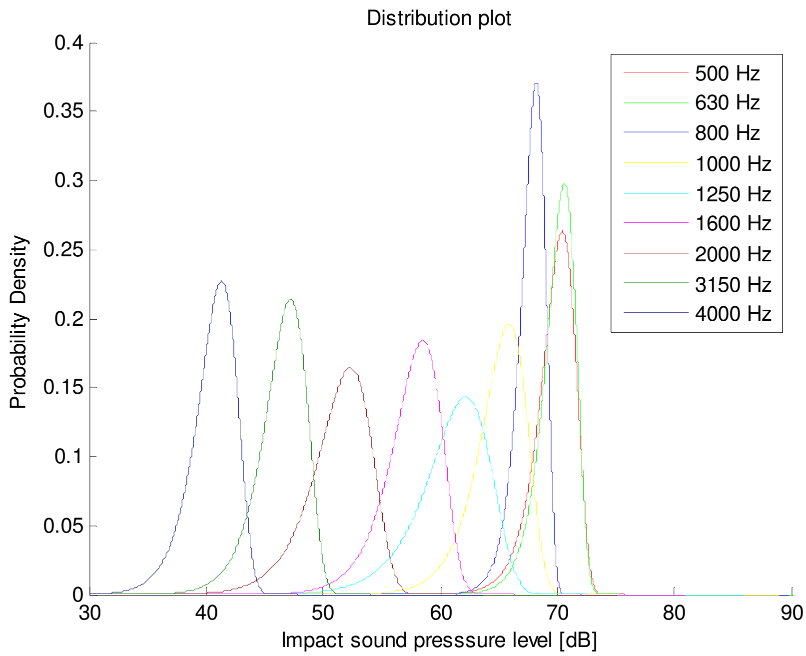


Figure 13-4: Weibull distributions of the time sequences of impact sound pressure level measurements performed on a concrete floor structure presented in the 1/3 octave bands 500 - 4000 Hz. The result is based on the data from project 15 where a long time measurement of impact sound pressure level have been divided into 1 second time sequences.

14. Appendix III – Equations of linear estimations

Table 14-1: The equations for the estimated linear dependence and its correlations between confidence intervals and receiving room volumes, for all 1/3 octave bands of the impact sound pressure level measurements performed on homogenous concrete floor structures.

Frequency [Hz]	$CONF_{\gamma}\{\bar{L}_{con} - k \leq \bar{L}_{con} \leq \bar{L}_{con} + k\} =$ [dB]	Correlation
50	0.0657V + 6.03	0,56
63	0.0945V + 1.55	0,87
80	-0.0288V + 11.4	0,37
100	-0.0124V + 8.85	0,11
125	0.0002V + 4	0,00
160	0.0724V + -1.1	0,66
200	0.0209V + 3.69	0,37
250	-0.0347V + 6.95	0,75
315	-0.0114V + 3.72	0,22
400	-0.0389V + 6.7	0,64
500	-0.019V + 6.81	0,45
630	0.0246V + 3.15	0,33
800	0.0135V + 3.78	0,25
1000	-0.026V + 8.05	0,48
1250	-0.0326V + 7.68	0,55
1600	-0.0589V + 9.31	0,95
2000	-0.0603V + 9.92	0,85
2500	-0.0457V + 10.22	0,60
3150	-0.0684V + 11.69	0,89

Table 14-2: The equations for the estimated linear dependence and its correlations between confidence intervals and receiving room volumes, for all 1/3 octave bands of the impact sound pressure level measurements performed on light weight floor structures.

Frequency [Hz]	$CONF_{\gamma}\{\bar{L}-k \leq \bar{L} \leq \bar{L}+k\} =$ [dB]	Correlation
50	0.0018V + 4.91	0,05
63	0.0093V + 5.35	0,23
80	-0.0001V + 5.55	0,00
100	-0.0116V + 4.98	0,32
125	0.0046V + 4.83	0,16
160	-0.0072V + 4.6	0,31
200	-0.0165V + 5.43	0,35
250	-0.0183V + 6.13	0,47
315	-0.0264V + 6.95	0,47
400	-0.0232V + 7.54	0,34
500	-0.0279V + 8.59	0,37
630	-0.028V + 8.1	0,43
800	-0.0251V + 8.3	0,42
1000	-0.0223V + 7.78	0,37
1250	-0.0206V + 6.87	0,37
1600	-0.0118V + 5.95	0,20
2000	-0.0129V + 5.47	0,25
2500	-0.0131V + 4.85	0,26
3150	-0.022V + 6.05	0,37

Table 14-3: The equations for the estimated linear dependence and its correlations between confidence intervals and receiving room volumes, for all 1/3 octave bands of the reverberation time measurements.

Frequency [Hz]	$CONF_{\gamma}\{\overline{T}-k\leq\overline{T}\leq\overline{T}+k\}=$ [s]	Correlation
50	0.0969V + -2.46	0,47
63	0.0205V + 0.2	0,50
80	0.0326V + -0.92	0,66
100	-0.0035V + 0.78	0,23
125	-0.0025V + 0.82	0,17
160	-0.0069V + 0.91	0,57
200	0.0018V + 0.3	0,26
250	-0.004V + 0.69	0,45
315	-0.0007V + 0.44	0,09
400	0.0002V + 0.45	0,03
500	-0.0052V + 0.64	0,65
630	-0.0026V + 0.48	0,47
800	0.0011V + 0.25	0,20
1000	-0.0028V + 0.42	0,54
1250	-0.0009V + 0.29	0,32
1600	-0.0026V + 0.33	0,50
2000	-0.0016V + 0.25	0,54
2500	-0.0002V + 0.16	0,07
3150	-0.0011V + 0.17	0,39

Table 14-4: The equations for the estimated linear dependence and its correlations between standardization of the impact sound pressure level measurements to 0.5 s and receiving room volumes, for all 1/3 octave bands. The standardization is based on the mean reverberation time.

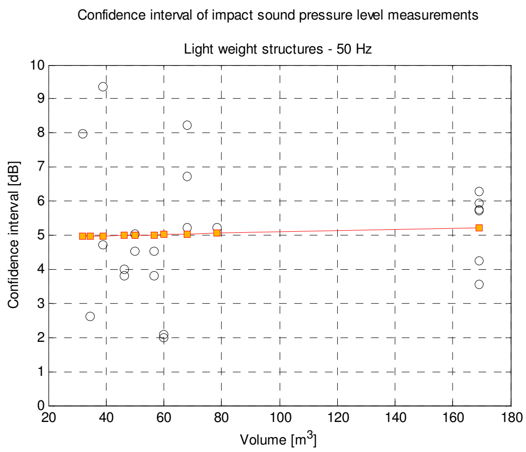
Frequency [Hz]	$CONF_\gamma\{\overline{S}-k \leq \overline{S} \leq \overline{S}+k\} =$ [dB]	Correlation
50	0.004V + -3.54	0,06
63	-0.0089V + -2.33	0,30
80	-0.0066V + -2.26	0,14
100	0.0051V + -2.48	0,13
125	0.0128V + -3.3	0,29
160	0.0212V + -4.11	0,37
200	0.0087V + -3.4	0,17
250	0.0127V + -4.04	0,25
315	0.0234V + -5.15	0,45
400	0.0259V + -5.65	0,55
500	0.0248V + -5.47	0,57
630	0.0241V + -5.36	0,61
800	0.0247V + -5.41	0,50
1000	0.0296V + -5.77	0,54
1250	0.0286V + -5.7	0,49
1600	0.031V + -5.73	0,52
2000	0.0309V + -5.33	0,52
2500	0.0311V + -4.95	0,52
3150	0.033V + -5.2	0,52

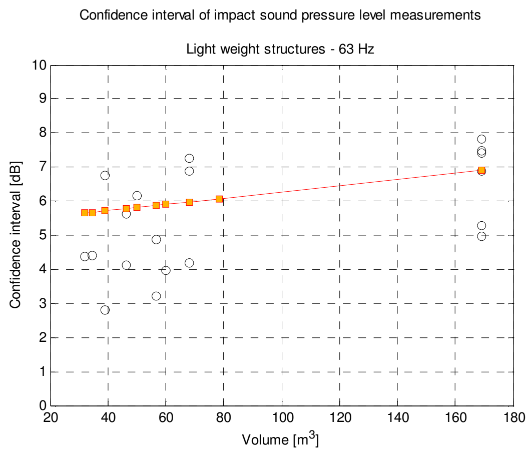
Table 14-5: The equations for the estimated linear dependence and its correlations between standardization of the impact sound pressure level measurements to 0.5 s and receiving room volumes, for all 1/3 octave bands. The standardization is based on the upper limit of the confidence interval of the mean reverberation time.

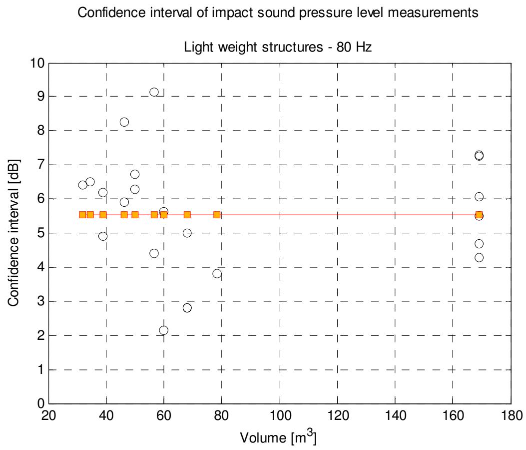
Frequency [Hz]	$CONF_{\gamma}\{\overline{S}_{T+konf} - k \leq \overline{S}_{T+konf} \leq \overline{S}_{T+konf} + k\} =$ [dB]	Correlation
50	-0.0039V + -5.72	0,03
63	-0.0261V + -3.39	0,46
80	-0.0313V + -2.24	0,44
100	0.0082V + -3.8	0,17
125	0.017V + -4.77	0,32
160	0.0275V + -5.43	0,50
200	0.0061V + -4.02	0,12
250	0.0144V + -4.92	0,27
315	0.0221V + -5.69	0,42
400	0.0213V + -6.13	0,53
500	0.031V + -6.34	0,65
630	0.0244V + -5.9	0,61
800	0.0202V + -5.62	0,40
1000	0.0302V + -6.2	0,57
1250	0.0277V + -6.05	0,51
1600	0.0344V + -6.19	0,55
2000	0.0318V + -5.66	0,54
2500	0.0282V + -5.07	0,48
3150	0.0338V + -5.45	0,53

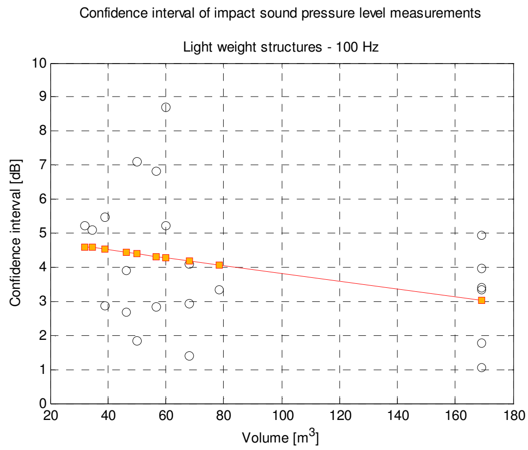
15. Appendix IV – Additional linear estimations

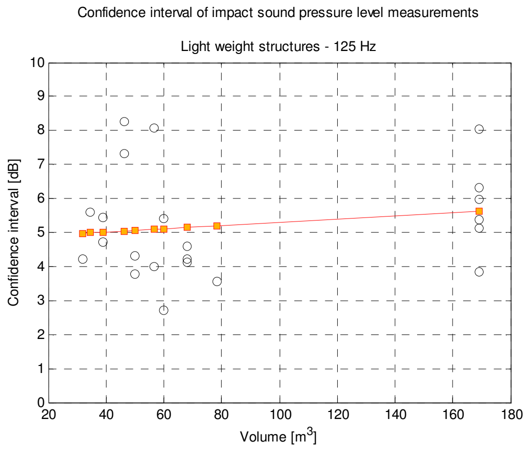
Following figures show the linear estimations of the receiving room volume dependence of the confidence interval for measured impact sound pressure level in light weight structures. The estimations consider the 1/3 octave bands 50-3150 Hz.

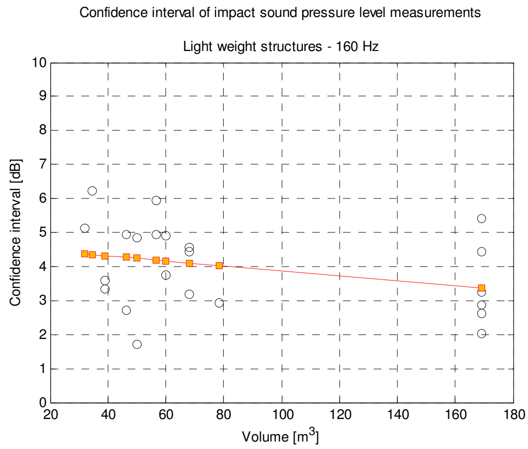


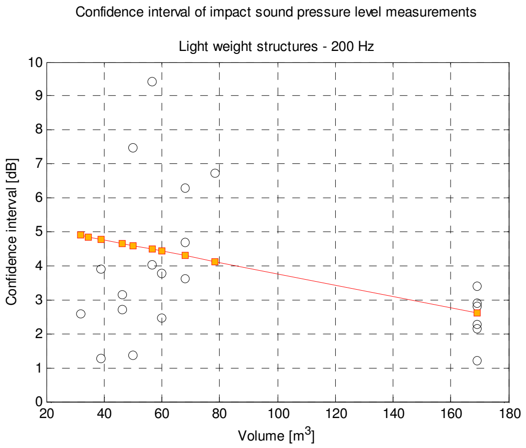


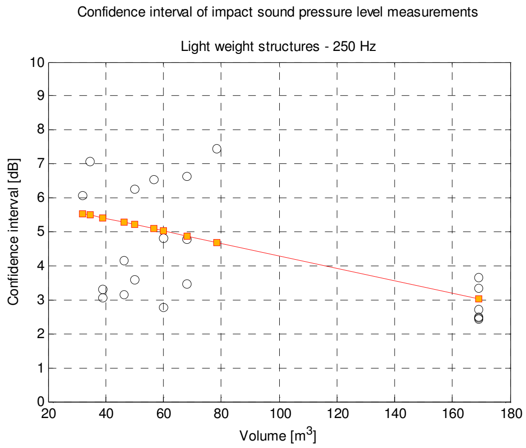


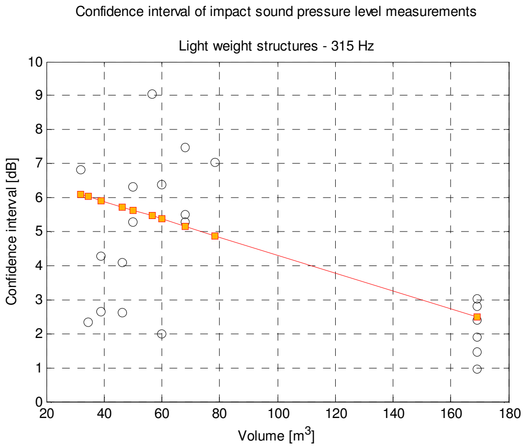


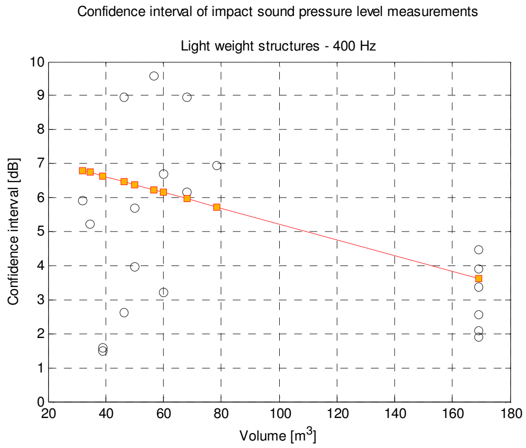


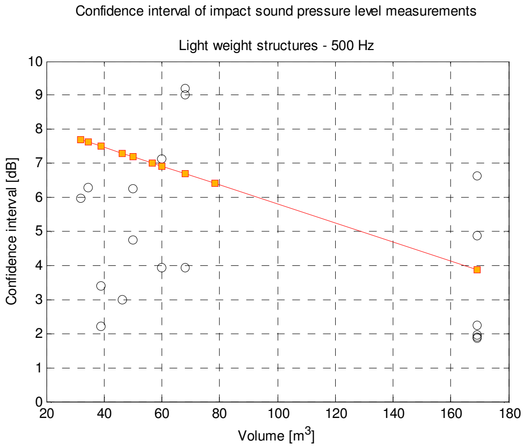


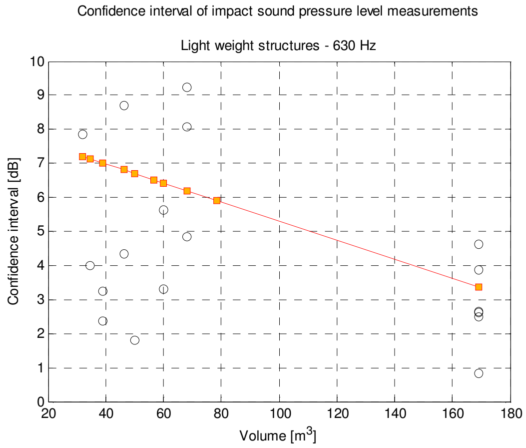

Confidence interval of impact sound pressure level measurements
Light weight structures - 200 Hz
Confidence interval [dB]
Volume [m3]

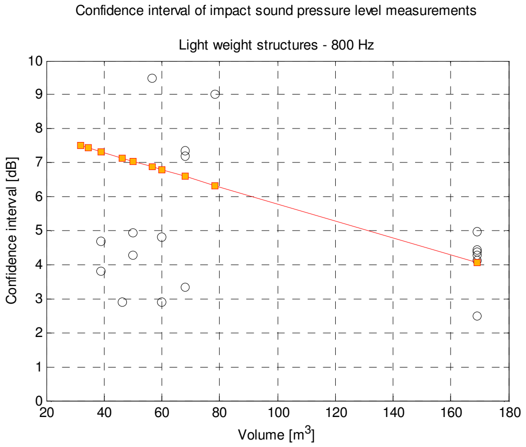

Confidence interval of impact sound pressure level measurements
Light weight structures - 250 Hz
Confidence interval [dB]
Volume [m3]

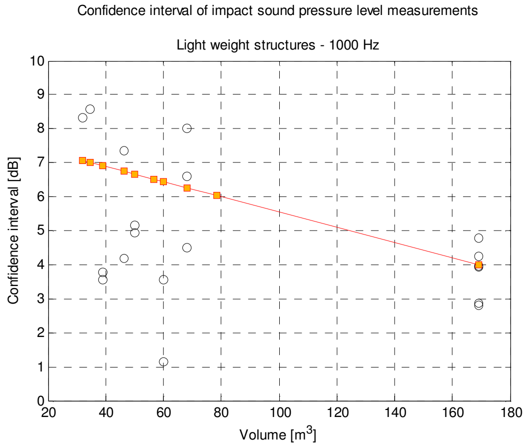

Confidence interval of impact sound pressure level measurements
Light weight structures - 315 Hz
Confidence interval [dB]
Volume [m3]

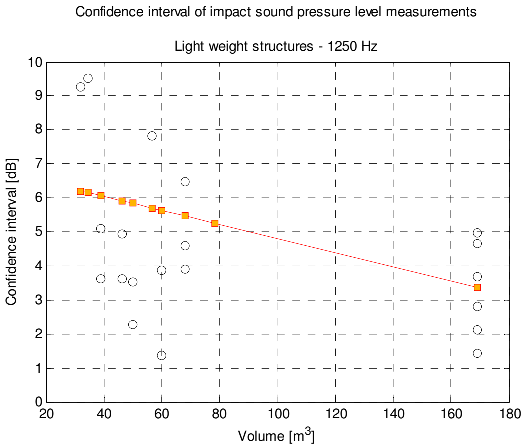

Confidence interval of impact sound pressure level measurements
Light weight structures - 400 Hz
Confidence interval [dB]
Volume [m3]

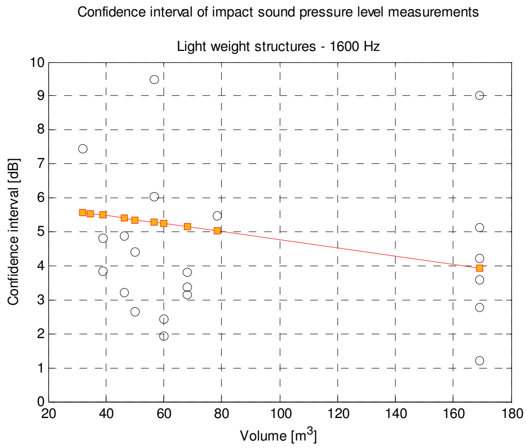

Confidence interval of impact sound pressure level measurements
Light weight structures - 500 Hz
Confidence interval [dB]
Volume [m3]

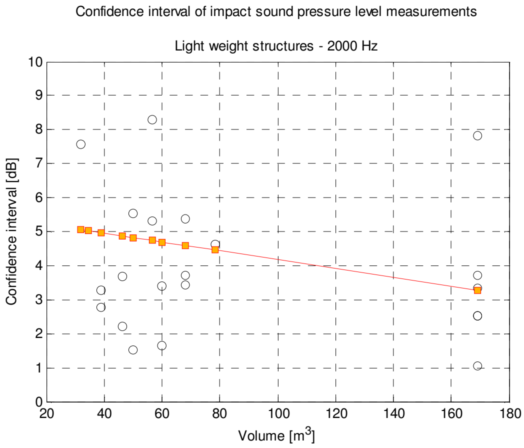

Confidence interval of impact sound pressure level measurements
Light weight structures - 630 Hz
Confidence interval [dB]
Volume [m3]

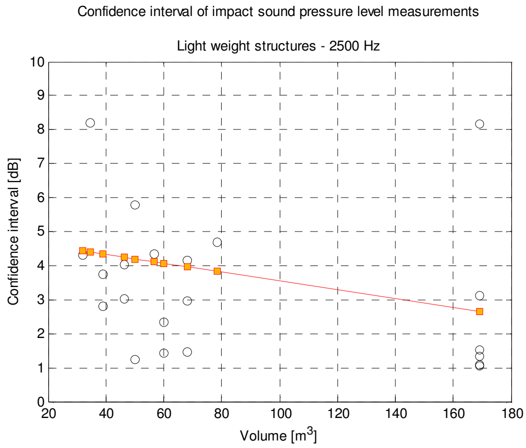

Confidence interval of impact sound pressure level measurements
Light weight structures - 800 Hz
Confidence interval [dB]
Volume [m3]

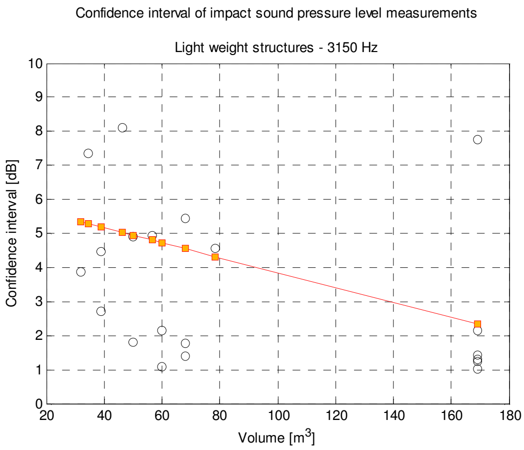

Confidence interval of impact sound pressure level measurements
Light weight structures - 1000 Hz
Confidence interval [dB]
Volume [m3]


Confidence interval of impact sound pressure level measurements
Light weight structures - 1250 Hz
Confidence interval [dB]
Volume [m3]

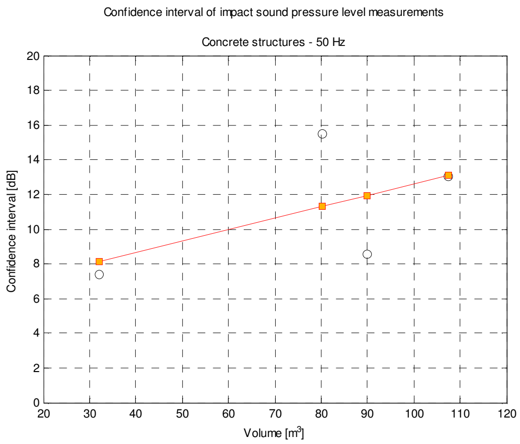

Confidence interval of impact sound pressure level measurements
Light weight structures - 1600 Hz
Confidence interval [dB]
Volume [m3]

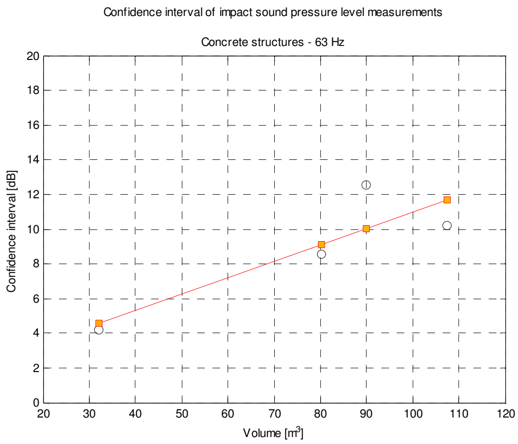

Confidence interval of impact sound pressure level measurements
Light weight structures - 2000 Hz
Confidence interval [dB]
Volume [m3]

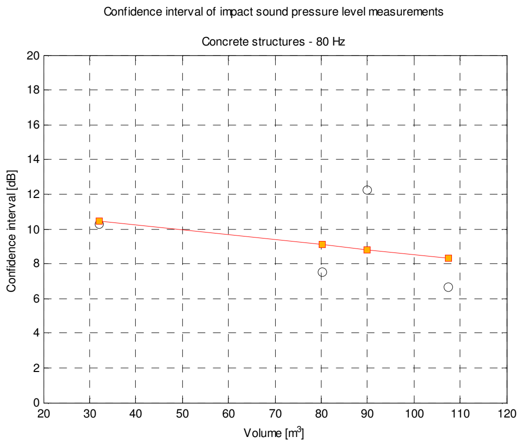

Confidence interval of impact sound pressure level measurements
Light weight structures - 2500 Hz
Confidence interval [dB]
Volume [m3]

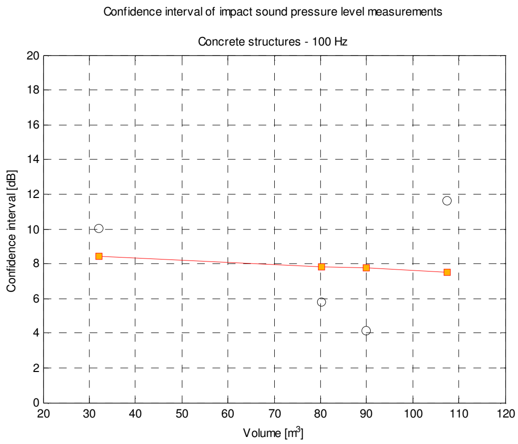

Confidence interval of impact sound pressure level measurements
Light weight structures - 3150 Hz
Confidence interval [dB]
Volume [m3]

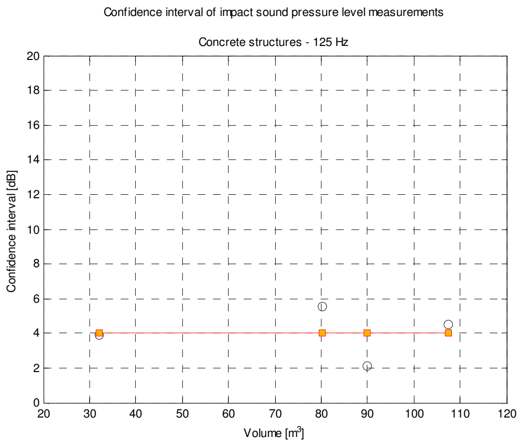
Following figures show the linear estimations of the receiving room volume dependence of the confidence interval for measured impact sound pressure level in concrete structures. The estimations consider the 1/3 octave bands 50-3150 Hz.

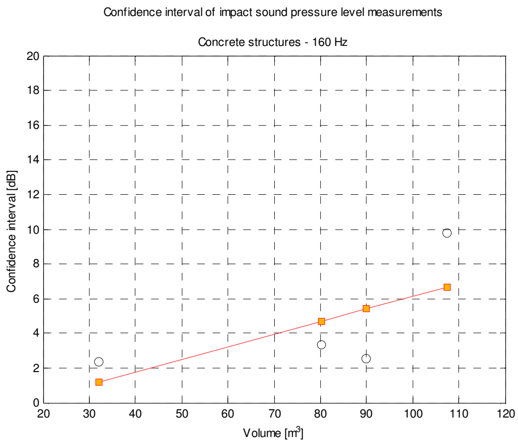


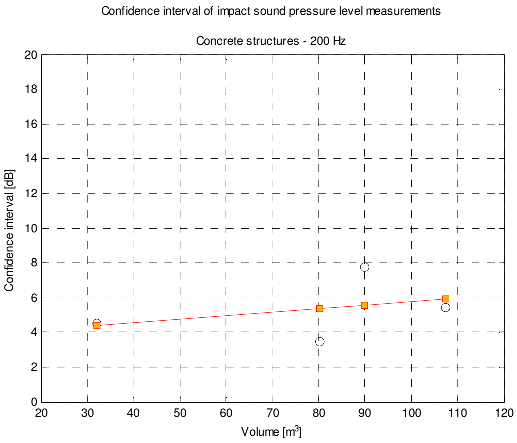


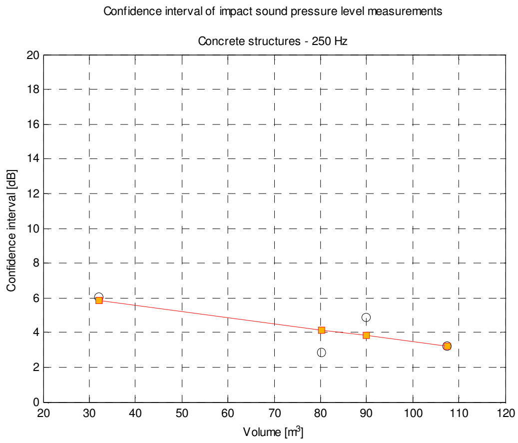


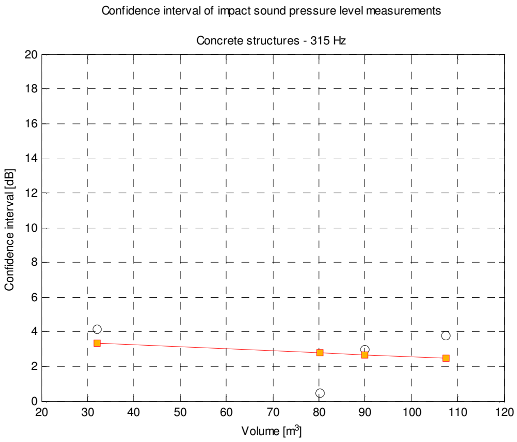


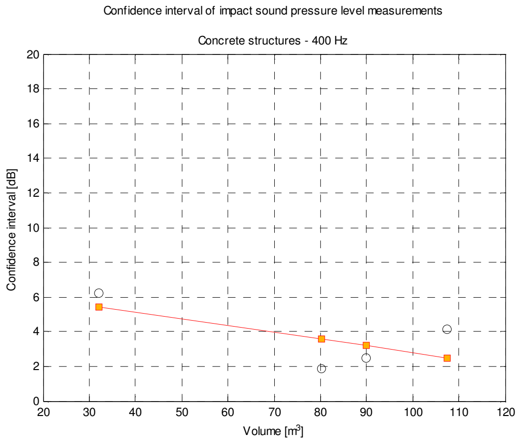


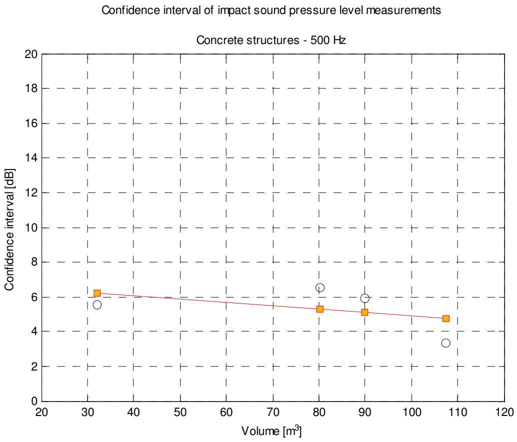


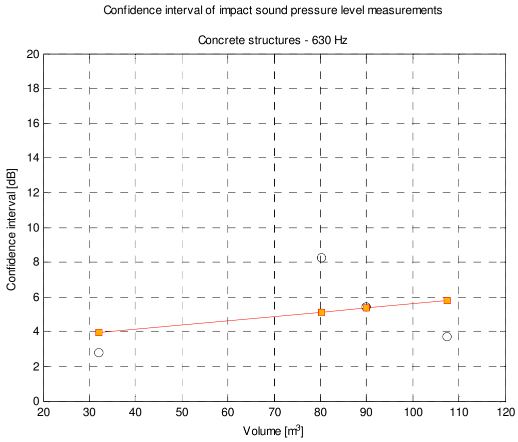

Confidence interval of impact sound pressure level measurements
Concrete structures - 200 Hz
Confidence interval [dB]
Volume [m^3]

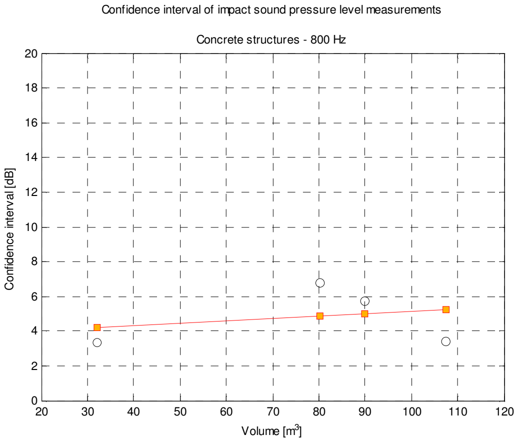

Confidence interval of impact sound pressure level measurements
Concrete structures - 250 Hz
Confidence interval [dB]
Volume [m^3]

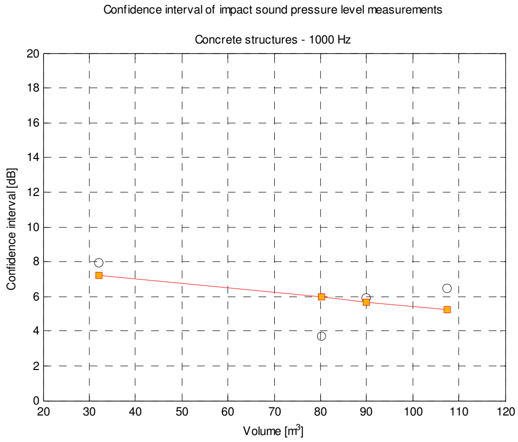

Confidence interval of impact sound pressure level measurements
Concrete structures - 315 Hz
Confidence interval [dB]
Volume [m^3]

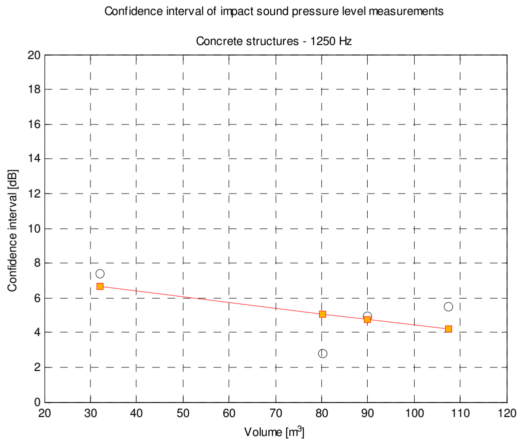

Confidence interval of impact sound pressure level measurements
Concrete structures - 400 Hz
Confidence interval [dB]
Volume [m^3]

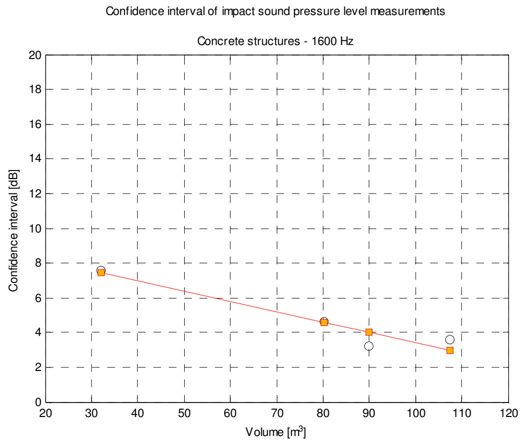

Confidence interval of impact sound pressure level measurements
Concrete structures - 500 Hz
Confidence interval [dB]
Volume [m^3]

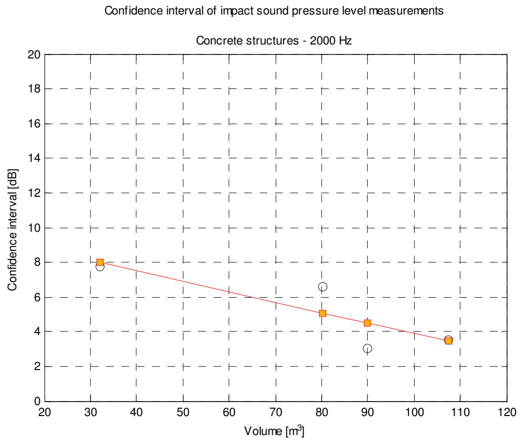

Confidence interval of impact sound pressure level measurements
Concrete structures - 630 Hz
Confidence interval [dB]
Volume [m^3]

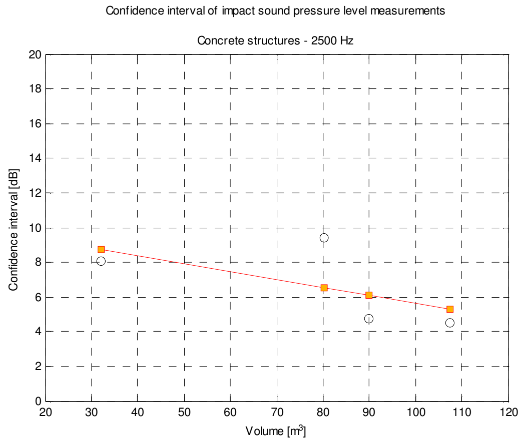

Confidence interval of impact sound pressure level measurements
Concrete structures - 800 Hz
Confidence interval [dB]
Volume [m^3]

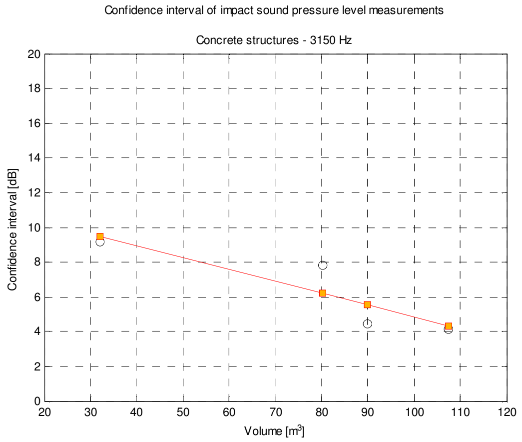

Confidence interval of impact sound pressure level measurements
Concrete structures - 1000 Hz
Confidence interval [dB]
Volume [m^3]


Confidence interval of impact sound pressure level measurements
Concrete structures - 1250 Hz
Confidence interval [dB]
Volume [m^3]

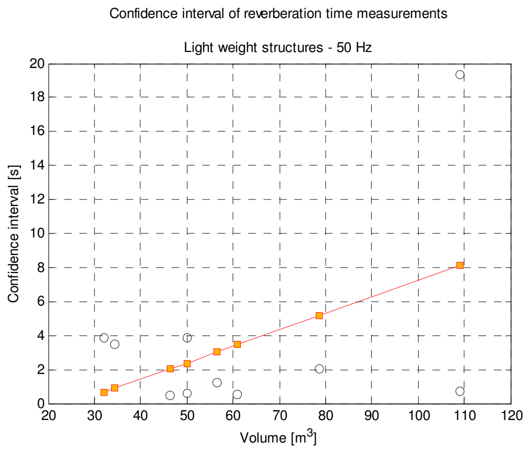

Confidence interval of impact sound pressure level measurements
Concrete structures - 1600 Hz
Confidence interval [dB]
Volume [m^3]

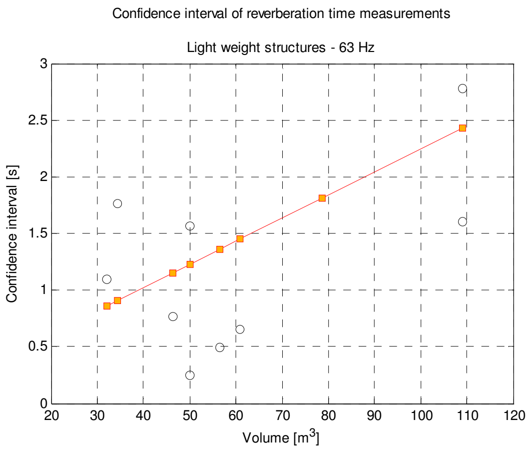

Confidence interval of impact sound pressure level measurements
Concrete structures - 2000 Hz
Confidence interval [dB]
Volume [m^3]

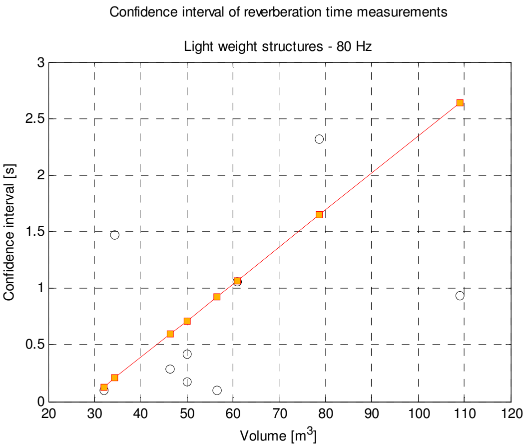

Confidence interval of impact sound pressure level measurements
Concrete structures - 2500 Hz
Confidence interval [dB]
Volume [m^3]

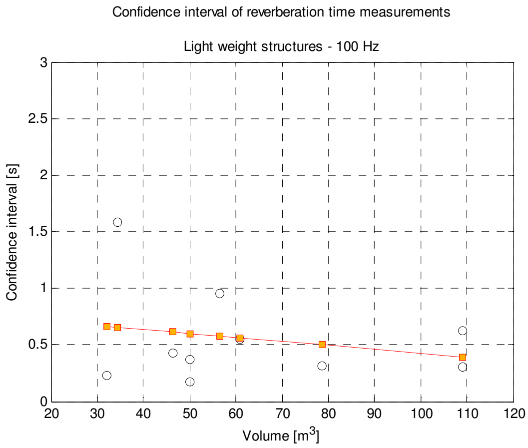

Confidence interval of impact sound pressure level measurements
Concrete structures - 3150 Hz
Confidence interval [dB]
Volume [m^3]

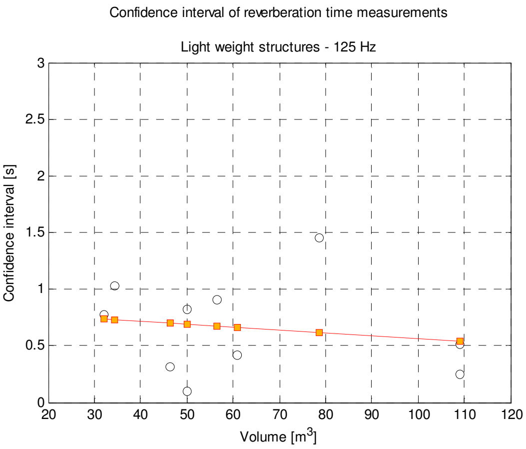
Following figures show the linear estimations of the receiving room volume dependence of the confidence interval for measured reverberation time in light weight structures. The estimations consider the 1/3 octave bands 50-3150 Hz. Notice that the y-axis at the 50 Hz estimation is set to 0-20 s while it is set to 0-3 s for the other 1/3 octave bands.

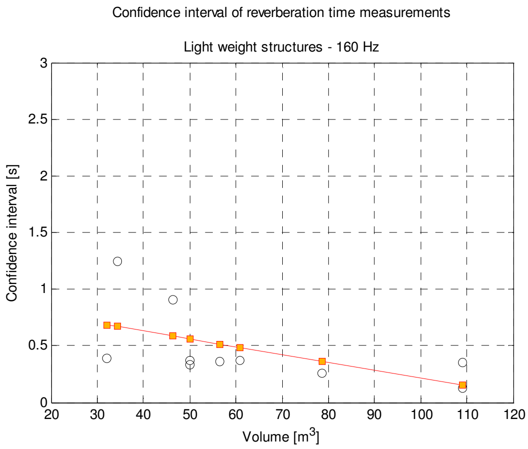


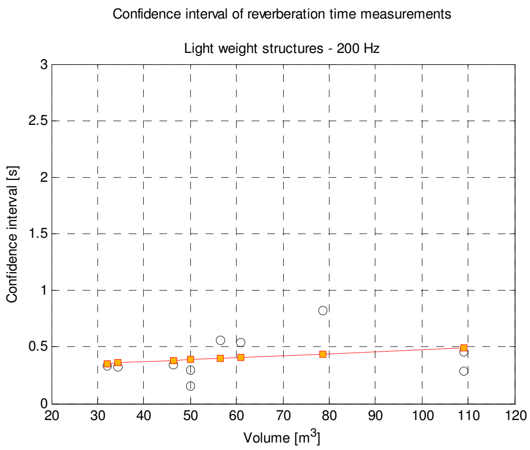


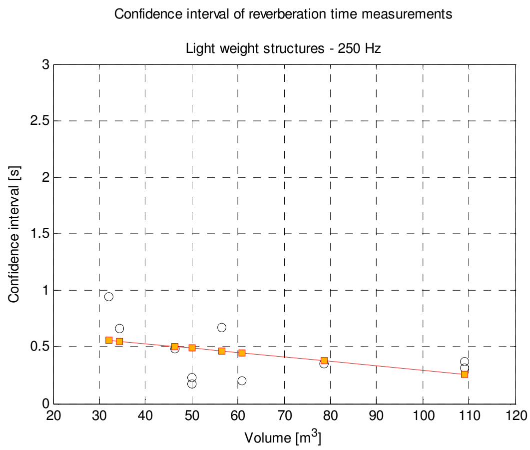


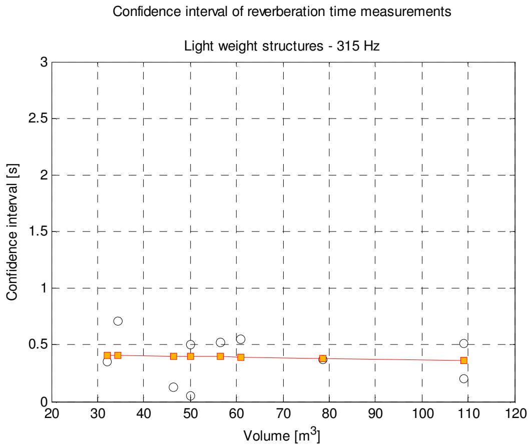


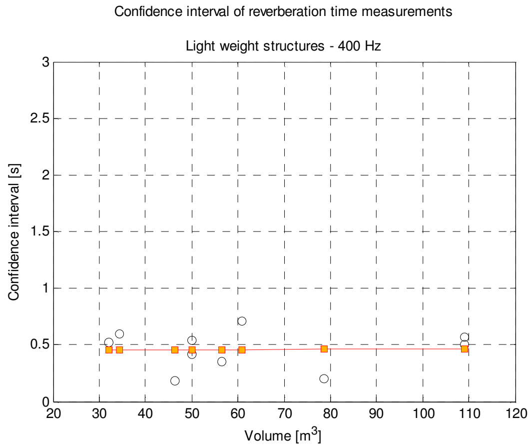


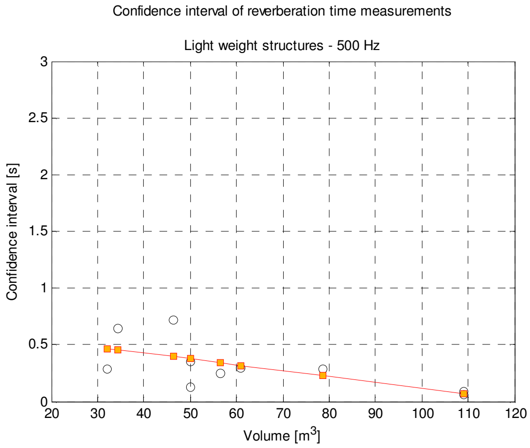


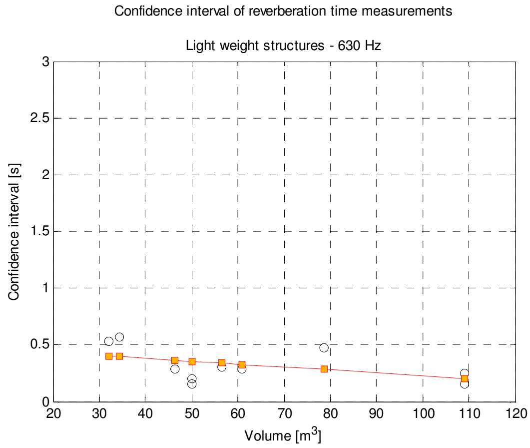

Confidence interval of reverberation time measurements
Light weight structures - 200 Hz
Confidence interval [s]
Volume [m3]

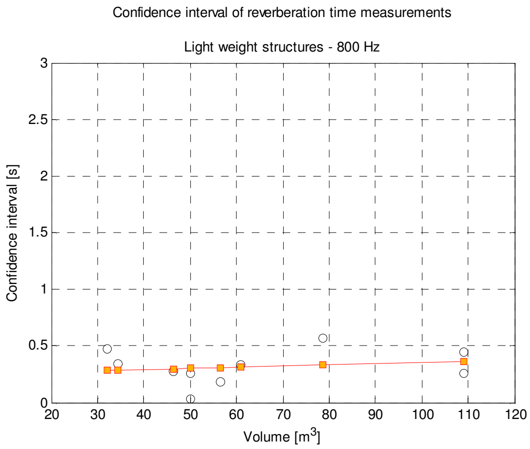

Confidence interval of reverberation time measurements
Light weight structures - 250 Hz
Confidence interval [s]
Volume [m3]

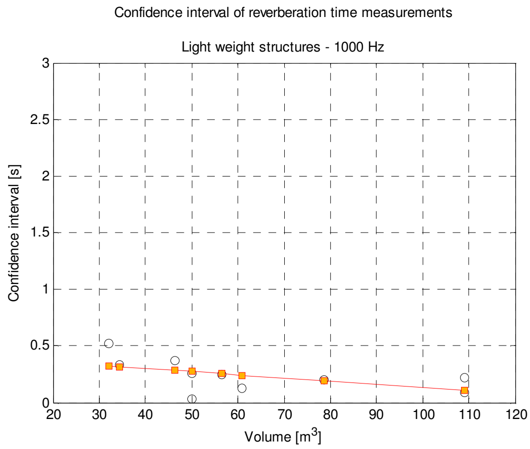

Confidence interval of reverberation time measurements
Light weight structures - 315 Hz
Confidence interval [s]
Volume [m3]

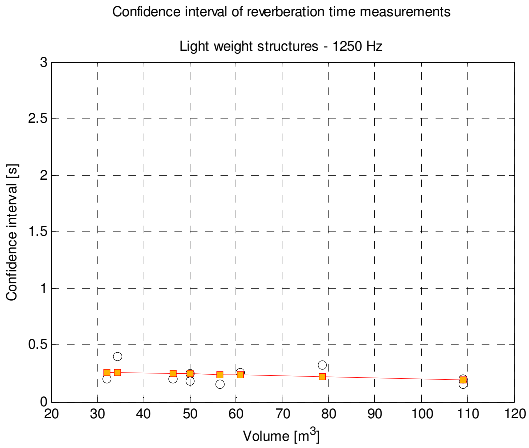

Confidence interval of reverberation time measurements
Light weight structures - 400 Hz
Confidence interval [s]
Volume [m3]

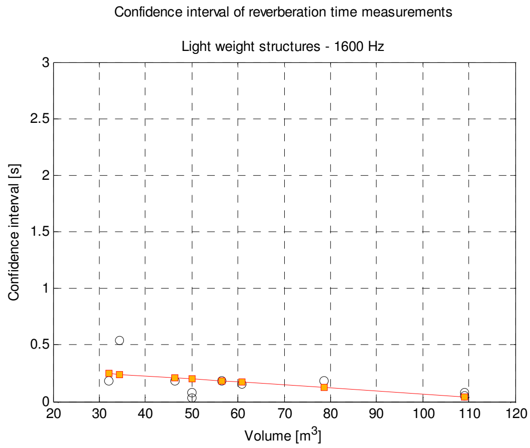

Confidence interval of reverberation time measurements
Light weight structures - 500 Hz
Confidence interval [s]
Volume [m3]

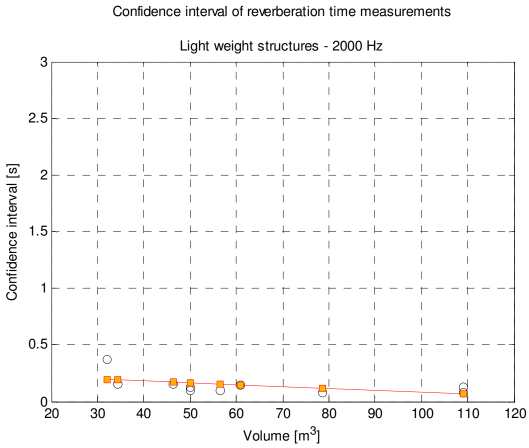

Confidence interval of reverberation time measurements
Light weight structures - 630 Hz
Confidence interval [s]
Volume [m3]

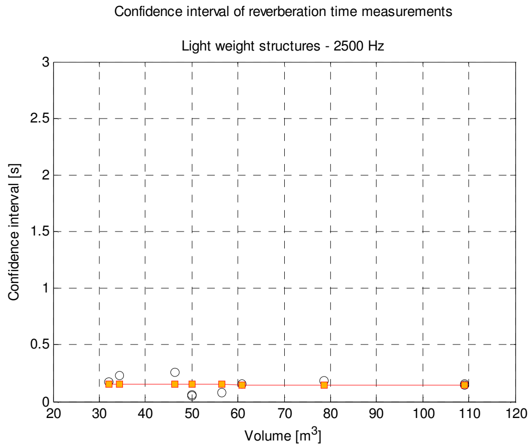

Confidence interval of reverberation time measurements
Light weight structures - 800 Hz
Confidence interval [s]
Volume [m3]

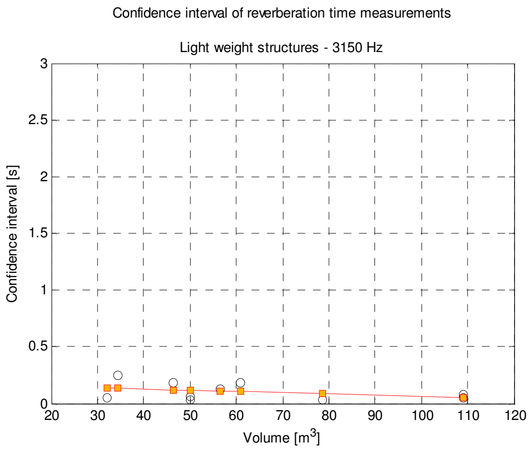

Confidence interval of reverberation time measurements
Light weight structures - 1000 Hz
Confidence interval [s]
Volume [m3]


Confidence interval of reverberation time measurements
Light weight structures - 1250 Hz
Confidence interval [s]
Volume [m3]


Confidence interval of reverberation time measurements
Light weight structures - 1600 Hz
Confidence interval [s]
Volume [m3]


Confidence interval of reverberation time measurements
Light weight structures - 2000 Hz
Confidence interval [s]
Volume [m3]


Confidence interval of reverberation time measurements
Light weight structures - 2500 Hz
Confidence interval [s]
Volume [m3]


Confidence interval of reverberation time measurements
Light weight structures - 3150 Hz
Confidence interval [s]
Volume [m3]

16. Appendix V –Low frequency impact sound

The frequency spectra's of the impact sound pressure level for project 3, 10 and 14 which were performed on light weight floor structures can be seen in Figure 16-1, Figure 16-2 and Figure 16-3. Notice that peaks occurs in the lower frequency region.

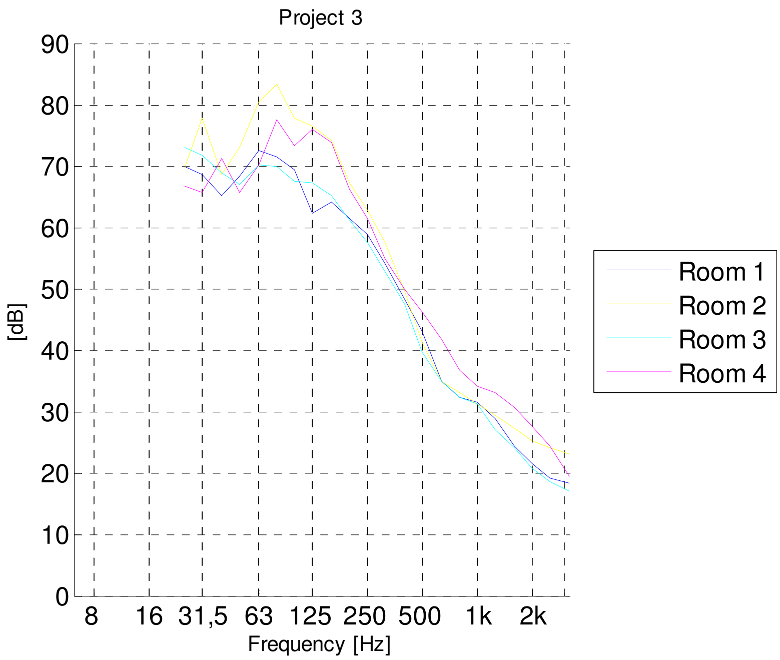


Figure 16-1: Impact sound pressure level in project 3 presented in 1/3 octave bands.

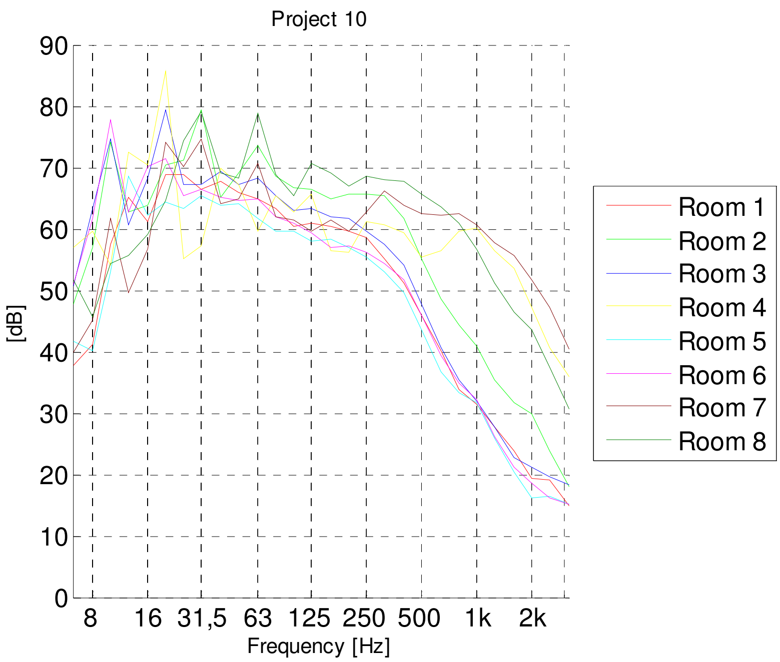


Figure 16-2: Impact sound pressure level in project 10 presented in 1/3 octave bands.

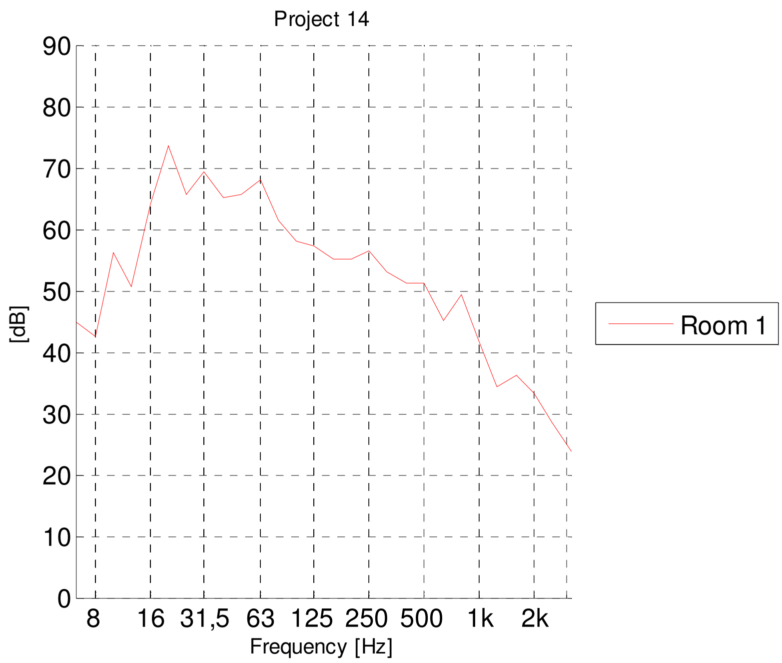


Figure 16-3: Impact sound pressure level in project 14 presented in 1/3 octave bands.

The frequency spectra's of the impact sound pressure level for project 11, 12, 13 and 15 which were performed on concrete floor structures can be seen in Figure 16-4, Figure 16-5, Figure 16-6 and Figure 16-7. Compared to the spectra's of the light weight structures project 11 and 12 show a less frequency depended spectra and project 13 and 15 peaks around 250-500 Hz.

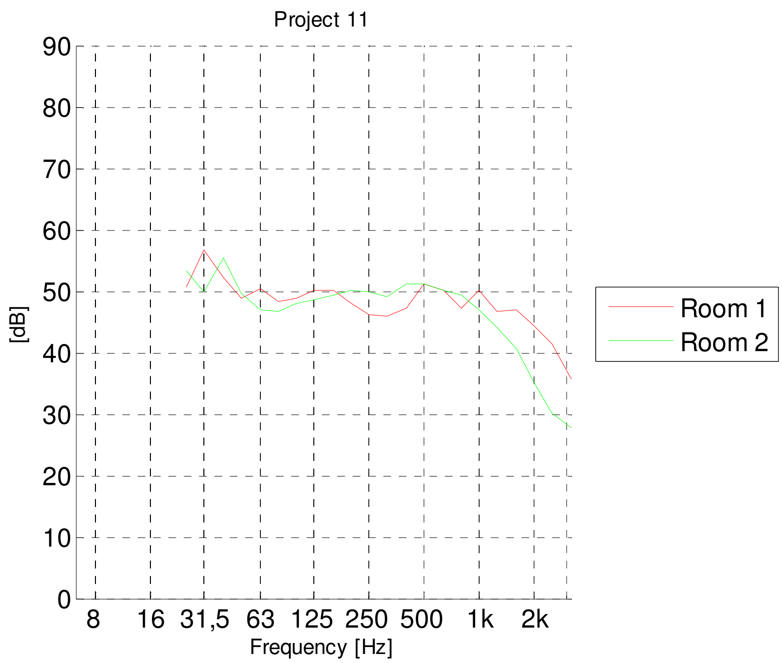


Figure 16-4: Impact sound pressure level in project 11 presented in 1/3 octave bands.

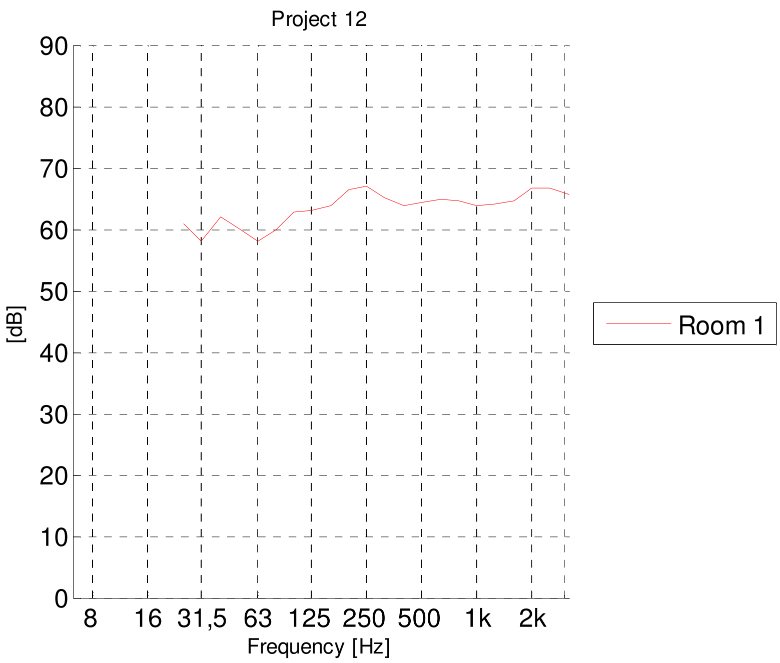


Figure 16-5: Impact sound pressure level in project 12 presented in 1/3 octave bands.

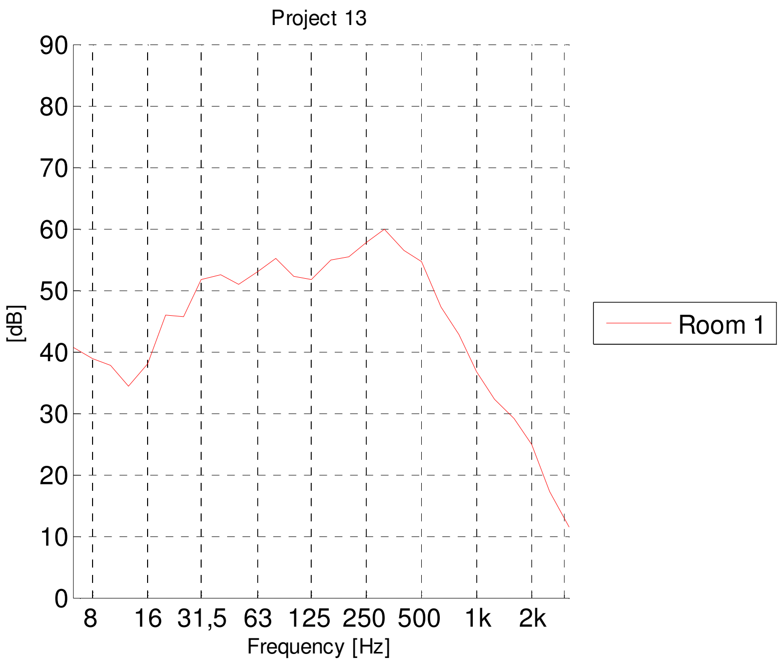


Figure 16-6: Impact sound pressure level in project 13 presented in 1/3 octave bands.

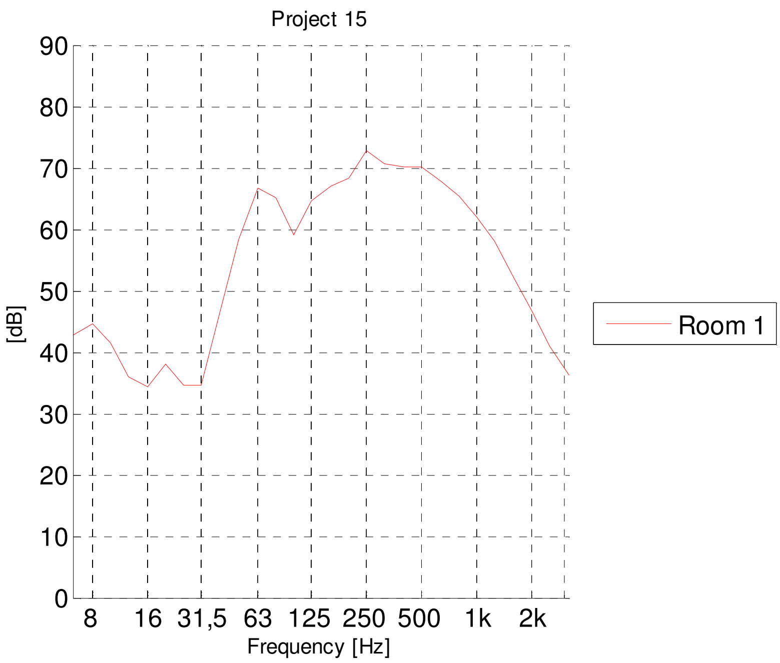


Figure 16-7: Impact sound pressure level in project 15 presented in 1/3 octave bands.

18. Appendix VI – Reference curve coordinates

Table 18-1: Coordinate level in each 1/3 octave band of the reference curve defined in ISO 717-2 [3].

1/3 octave band [Hz]	Level [dB]
100	62
125	62
160	62
200	62
315	62
400	62
500	61
630	59
800	58
1000	57
1250	54
1600	51
2000	48
2500	45
3150	42

Table 18-2: Coordinate level in each 1/3 octave band of the reference suggested by Hagberg [8].

1/3 octave band [Hz]	Level [dB]
50	45.5
63	51
80	56.6
100	62
125	62
160	62
200	62
315	62
400	62
500	62
630	62
800	62
1000	62
1250	62
1600	62
2000	62
2500	62
3150	62

Table 18-3: Coordinate level in each 1/3 octave band of the reference suggested by Bodlund [6].

1/3 octave band [Hz]	Level [dB]
100	53
125	54
160	55
200	56
315	57
400	58
500	59
630	60
800	61
1000	62
1250	63
1600	64
2000	65
2500	66
3150	67

Table 18-4: Coordinate level in each 1/3 octave band of the reference suggested by Fasold [13].

1/3 octave band [Hz]	Level [dB]
100	60
125	60
160	60
200	60
315	60
400	60
500	60
630	60
800	60
1000	60
1250	60
1600	60
2000	60
2500	60
3150	60

19. Appendix VII - Evaluation of measurement reports

Table 19-3 was used as a basis for the evaluation of the measurements. The data presented in this table is due to the information which have been found in belong reports. The table tells the size of the receiving room and also the quantity of background noise, impact sound pressure level and reverberation time measurements. The table also gives the information how the background noise and reverberation time measurements have been chosen to be handled. Measurements with the equal background noise measurement number have the same background noise applied to the evaluation of impact sound pressure level. Measurements with an individual background noise measurement indicate that it is the only measurement in the project where the background noise measurement has been applied to the evaluation impact sound pressure level. The reverberation time measurements have been selected to receive the same treatment.

Measurements which been considered approved for further analyses are presented in Table 19-1 while the disapproved measurements are presented in Table 19-2.

Table 19-1: Measurements approved for further analysis.

Project	Direction	Floor structure	Measurement			
1	Vertical	Light weight	A05	A10	A11	A12
1	Horizontal	Light weight	A06	A08	A09	
2	Vertical	Light weight	1			
3	Vertical	Light weight	2009 (1)	2009 (2)		
6	Vertical	Light weight	A10	A11		
7	Vertical	Light weight	A15	A16	A18	A22

Table 19-2: Measurements disapproved for further analysis.

Project	Direction	Floor structure	Measurement								
1	Vertical	Light weight	A07								
4	Vertical	Light weight	A01	A02	A03	A04	A05	A06			
5	Vertical	Light weight	A01	A02	A03	A04	A05	A06	A07	A08	A09
6	Horizontal	Light weight	A12								
7	Vertical	Light weight	A17	A19	A20	A21	A23	A24	A25		
7	Horizontal	Light weight	A26								

Table 19-3: Properties of the measurements in Table 19-1and Table 19-2.

Project	Measurement	Receiving room volume [m^3]	Quantity Background noise	Quantity Impact sound pressure level	Quantity Reverberation time	Background noise measurement	Reverberation time measurement
1	A05	56.6	1	5	6	1	1
	A06	56.6	1	5	6	2	1
	A07	56.6	0	5	6	Unknown	1
	A08	56.6	1	5	6	3	1
	A09	56.6	1	5	6	4	1
	A10	56.6	1	5	6	5	1
	A11	46.3	1	5	6	6	2
	A12	46.3	1	5	6	7	2
2	1	73.3	Checked	6	15	1	1
3	2009(1)	60.0	Checked	5	6	Checked	1, 2008(1)
	2009(2)	38.9	Checked	5	6	Checked	2, 2008(2)
4	A01	109.0	1	4	6	1	1
	A02	109.0	1	4	6	1	1
	A03	31.0	1	1	6	1	2
	A04	109.0	1	4	6	1	3
	A05	31.0	1	1	6	1	4
	A06	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
5	A01	169.25	1	5	10	1	1
	A02	169.25	1	5	10	1	1
	A03	169.25	1	5	10	1	1
	A04	169.25	1	5	10	1	1
	A05	169.25	1	5	10	1	1
	A06	169.25	1	5	10	1	1
	A07	68.24	1	5	10	1	2
	A08	68.24	1	5	10	1	2
	A09	68.24	1	5	10	1	2
6	A10	50.0	1	5	6	1	1
	A11	50.0	1	5	6	2	2
	A12	50.0	0	3	6	Unknown	3
7	A15	34.5	1	5	6	1	1
	A16	61.0	1	4	6	2	2
	A17	32.1	1	1	6	3	3
	A18	78.6	1	5	6	4	4
	A19	32.1	1	2	6	5	5
	A20	34.5	0	5	6	Unknown	6
	A21	78.6	0	5	6	Unknown	7
	A22	32.1	1	5	6	6	8
	A23	78.6	0	5	6	Unknown	9
	A24	38.0	0	5	6	Unknown	10
	A25	78.6	0	5	6	Unknown	9
	A26	38.0	0	4	6	Unknown	10

19.1. Project 1

This project was performed by ÅF 2009-09-01, report 545827 [14]. Project 1 consists of horizontal and vertical measurements in two different types of receiving rooms. Measurement A05 – A10 are performed in living rooms with a volume of 56.6 m^3 while the measurements A11 – A12 are performed in kitchen rooms with a volume of 46.3 m^3. The same reverberation time has been used for room A05-A10 due to the living rooms identical design. This is also the case for kitchen rooms A11 - A12 where the same reverberation time has been used for both rooms; see Table 19-3 [14]. Regarding the background measurements one measurement for each measurement was performed.

The report states that the standard SS-EN ISO 140-7 has been followed for the measurements. The evaluation is made according to SS-EN ISO 717-2 [14]. Further on, the floor structure is fairly well described but it could have been done in more detail. A negative note is that neither time of day when the measurements were performed or floor structure area is specified in the report.

19.1.1. Measurement A07

This measurement is advised to be rejected as long as no complementary measurements are made. It fails since no background noise level measurement is performed and a note of why the measurement is not made is missing, Table 19-3.

19.2. Project 2

This project was performed by Akustikverkstan 2006-01-25, Report 06-02. Project 2 consists of one vertical measurement between two living rooms [19]. Properties of the measurement can be seen in Table 19-3.

The report states that the standard SS-EN ISO 140-7 has been followed for the measurements. The evaluation is made according to SS-EN ISO 717-2 [19]. The time of day when the measurements were performed is mentioned and also that the microphones used during the measurement were calibrated immediately before and after the measurements. A lack in the report is that neither separating floor area nor separating floor structure is specified in the report.

19.3. Project 3

This project was performed by Akustikverkstan 2009-06-04, Report 07-11R3 [20]. Project 3 deviates from the other projects which been investigated for further analysis. In this project there are total five measurements performed on two different floor structures at two different times, 2008 and 2009. Notice that the reverberation times were measured during the 2008 years measurements since the properties of the receiving room not was changed between the measurements times. Project 3 consists then of two vertical measurement between two living rooms and two bed rooms [20]. The reverberation time was measured in each room and the background noise level was checked during the measurements, Table 19-3.

The report states that the standard SS-EN ISO 140-7 has been followed for the measurements. The evaluation is made according to SS-EN ISO 717-2 [20]. Further on, the time of day when the measurements were performed is described and also that the microphones used during the measurement were calibrated immediately before and after the measurements. A lack in the report is that neither floor structure area nor separating floor structure is specified in the report.

19.4. Project 4

Project 4 was performed by WSP 2008-01-22, report 10080075.91 and consists of vertical measurements [15]. Initially all measurements are performed in a building which was not finished which leads to unreal conditions and makes these measurements inappropriate for further analysis.

19.5. Project 5

This project was performed by WSP 2007-01-17, report 10080075.01 [16]. The purpose of project 5 was to investigate the sound class for different floor structures. All investigated structures were performed vertically in the same receiving room and had the same rough floor structure but with different top floors constructions in the sending room. Unfortunately this makes these measurements inappropriate for further analysis.

19.6. Project 6

This project was performed by ÅF 2009-11-16, report 549305 [17]. The purpose of project 6 was to investigate and control the impact sound pressure levels in a multi story building. The reverberation time was measured in each receiving room and also the background noise was measured independently for measurement A11 and A12. Unfortunately the background noise measurement is missing for measurement A12. The measurement properties are mentioned in Table 19-3.

The report states that the standard SS-EN ISO 140-7 has been followed for the measurements. The evaluation is made according to SS-EN ISO 717-2 [17]. In general project 6 has a well described floor structure. Lacks of the report are that neither separating floor area nor time of day when the measurements were performed is mentioned.

19.6.1. Measurement A12

This measurement is advised to be rejected as long as no complementary measurements are made. It fails since too few measurements on impact sound pressure level were made, only three instead of four. Also the background noise measurement is missing.

19.7. Project 7

This project was performed by ÅF 2009-06-29, report 545373 A [18]. The purpose of project 7 was to ensure that the new multi story building achieves the demands on impact sound pressure level. The first three floors have a floor structure in concrete, while the remaining floor structures are built by a wooden construction. The reverberation time in receiving rooms in measurement A23 and A25 is assumed equal, as well as the receiving rooms A24 and A26. All other rooms have individual measured reverberation times. How the background noise measurements have been chosen to be handled for the rooms can be seen in Table 19-3.

The report states that the standard SS-EN ISO 140-7 has been followed for the measurements. The evaluation is made according to SS-EN ISO 717-2 and SS 25267 [18]. In general project 7 has a vaguely described floor structure. Further on, no separating floor area or time of day for the measurements is specified in the report.

19.7.1. Measurement A17

This measurement is advised to be rejected as long as no complementary measurements are made. It fails since too few measurements on impact sound pressure level were made, only one instead of four.

19.7.2. Measurement A19

This measurement is advised to be rejected as long as no complementary measurements are made. It fails since too few measurements on impact sound pressure level were made, only two instead of four.

19.7.3. Measurement A20

This measurement is advised to be rejected as long as no complementary measurement is made. It fails since no measurement on background noise was made and a note of why the measurement is not made is missing.

19.7.4. Measurement A21

This measurement is advised to be rejected as long as no complementary measurement is made. It fails since no measurement on background noise was made and a note of why the measurement is not made is missing.

19.7.5. Measurement A23

This measurement is advised to be rejected as long as no complementary measurement is made. It fails since no measurement on background noise was made and a note of why the measurement is not made is missing.

19.7.6. Measurement A24

This measurement is advised to be rejected as long as no complementary measurement is made. It fails since no measurement on background noise was made and a note of why the measurement is not made is missing.

19.7.7. Measurement A25

This measurement is advised to be rejected as long as no complementary measurement is made. It fails since no measurement on background noise was made and a note of why the measurement is not made is missing.

19.7.8. Measurement A26

This measurement is advised to be rejected as long as no complementary measurement is made. It fails since no measurement on background noise was made and a note of why the measurement is not made is missing.

20. Appendix VIII – Contribute to ICA 2010.

The results from this thesis were presented at the 20^{th} international congress on acoustics by the following paper written by Klas Hagberg and Ponthus Thorsson.

Proceedings of 20th International Congress on Acoustics, ICA 2010
23-27 August 2010, Sydney, Australia

Uncertainties in standard impact sound measurement and evaluation procedure applied to light weight structures

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PACS: 43.10.LN, 43.15.+S, 43.20.YE, 43.40.QI, 43.50.BA

ABSTRACT

A three year research programme has recently started in Sweden, aiming at improving the mutual connection between the perceived sound, vibration and springiness and their corresponding measured values in lightweight structures. The main goal is to describe new objective measures of assessing the acoustic quality, with the expected result that the experienced sound, vibration and springiness are not dependent of structural bearing system in the building any more. The consequence of new methods will be that various structural systems within one certain sound class in a classification scheme will provide fairly equal evaluation with regard to subjective response. The research programme, *AkuLite,* is divided into seven work packages (WP). Initial results from one work package (WP 4), related to current subjective and objective field data are presented in this paper. The aim of topical part of the study is to investigate the liability of measurements results and evaluation procedure when those are carried out in accordance to ISO 140 and ISO 717. It involves an initial inventory and analysis from objective measurements, according to ISO 140, performed on light weight structures on the field by various consultants in Sweden. The study considers principal problems with current standards, affecting each operator performing field measurements in light weight structures and thereby impacting the final result quality. Typically, the measured sound pressure level and the reverberation time differ a lot in low frequencies, compared to heavy structures. The measurement result (distribution) between various measurement positions is rather random in the low frequency region, i.e. there is no typical pattern for light weight structures in general. The complexity of different light weight structural bearing systems and their sensitivity in the low frequency range requires a more rigid description of the measurement and evaluation procedure. The lack of objective sound and vibration data below 50 Hz is also a problem since subjective disturbance often emanates from this frequency range.

INTRODUCTION

Considering light weight floor structures it is a well known fact that the measurement methods and the evaluation methods for impact sound insulation according to ISO 140-7 [1] and ISO 717-2 [2] suffers from shortcomings [3, 5]. The measurement results do not exhibit single number quantities which correlate to the subjective evaluation sufficiently for any arbitrary structural bearing system. Additionally, it is not clear whether the measurements itself are distinct enough, in particular in the low frequency third octaves (< 100 Hz) and their influence on the measurement results.

In Sweden a new research programme recently started. It is abbreviated *AkuLite*, and involves a three year research programme and interest a broad spectrum of universities and industrial partners. The research programme focuses on sound, vibration and springiness in light weight structures and aims to state new measures for evaluating sound insulation (impact sound insulation in particular). To reach the goal the work is divided into seven Work Packages where each research partner is responsible for one Work Package. The seven Work Packages are as follows:

- WP 1 – Subjective experience of sound, vibrations and Springiness – Method development involving laboratory and field studies
- WP 2 – Physical models for structure borne noise sources – Method development
- WP 3 – Calculation methods for components, systems and entire buildings – Method development and simulation
- WP 4 – Current subjective and objective data – Inventory and analysis (present study)
- WP 5 – New measurements focusing on low frequencies and coupling between sound and vibrations – Method development, data collection and analysis
- WP 6 – Correlating data from subjective and objective evaluations – Compiling analysis
- WP 7 – Requirements for sound insulation, vibration and springiness and their entire effect – Results

In this paper some initial results from an investigation within WP 4 is presented, focused on the liability of impact sound insulation measurements and belonging evaluation procedure carried out on light weight structures in multi storey residential buildings. The investigation is based on current data available at consultants in Sweden. The measurements and evaluation of single numbers of impact sound insulation are performed as stated in ISO 140-7 [1] and ISO 717-2 [2] respectively.

These standardized measurement and evaluation methods were developed during a period when the dominating structural materials were heavy (i.e. concrete, bricks etc.) and multi storey houses with light weight structures were not even in building contractors mind, and wooden structures were not even allowed due to fire resistance regulations. In the early 1990's this changed and it became permitted to use wood as structural bearing material for multi storey residential buildings in Sweden and this became the starting point of a new development of light weight structural bearing systems for multi storey family houses. The interest of using light weight structural systems is increasing all over Europe.

Present work is made in order to understand if current measurement procedures performed by professional consultants fulfil the need of accuracy when applied to light weight structures. Some doubts are raised and need for further investigations are proposed prior to use these standardized measurements for further studies in *AkuLite*. Applying current ISO measurements on light weight structures involve new problems and as new building structures develop, it has become obvious that it is far more complex than it appears to be for the measurement performers. There are certain problems appearing in the low frequency region and it involves: (i) liability of reverberation time measurements in low frequencies, (ii) averaging procedure regarding reverberation time in the low frequency region with respect to room volumes, (iii) averaging procedure regarding level measurements with respect to room volumes, (iiii) normalization or standardization procedure, (iiiii) optimized reference curve shape. Adding, lack of information of the constructions complete build up (due to complexity of light weight structures) and scarce available data below 50 Hz, increase the difficulties.

BACKGROUND

Light-weight structures differ significantly from traditional heavy structures from an acoustical point of view. The frequency content of sound originating from a structural impact on a light weight structure distinguish a lot from structural impact on a heavy concrete slab, as shown in Figure 1. In this figure two measured impact sound level curves are presented, one emanating from a light structure and one from a heavy structure. The light weight structure is a wooden floor construction using both a floating floor and a resiliently mounted ceiling. This particular floor construction was earlier measured in the field and was then proved to fulfil the impact sound requirements of the Swedish building code (BBR) [9]. The heavyweight floor is a homogeneous concrete slab with 160 mm thickness. The top surface (floor covering) of both floors was 16 mm parquet on 3 mm resilient underlayer. These two particular measurement results can be directly compared without correction to equal reverberation times or absorption area since both emanates from laboratory measurements using the same receiving room. Moreover, the two floors have the same evaluated impact sound level according to ISO 717-2 if the $C_{I,50\text{-}2500}$ term is included.i.e.

$$L_{n,w} + C_{I,50\text{-}2500} = 52 \text{ dB},$$

which would fulfil the minimum requirement in the Swedish national building code [9] if they represented field values. The characteristics of these impact sound pressure level spectra are quite different since the concrete floor structures result in higher frequency sound (high levels above 200 Hz) while the wooden floor structures result in lower frequency sound (high levels below 50 Hz).

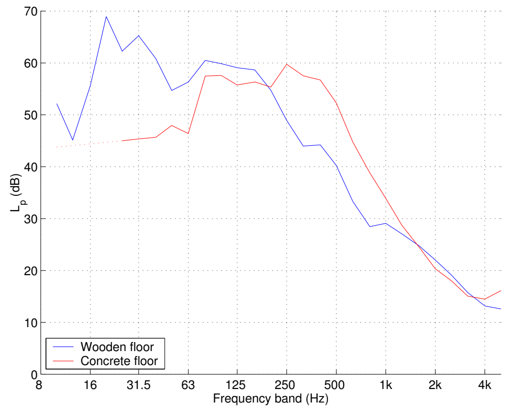

Figure 1: Impact sound pressure level measurements from laboratory tests performed on solid concrete (160 mm), red line, on wooden floor structure, blue line.

Measured sound pressure levels from a field project is shown in Figure 2, where spectra due to tapping machine excitation is presented for 8 rooms in the same building in the frequency range, 8 Hz - 2.5 kHz. From the impact sound curves in Figure 2 it is evident that the highest sound pressure levels are found at frequencies below 100 Hz, and for many rooms the highest sound pressure levels are found below 50 Hz. This is important since the single number value, $L_{n,w}$ + $C_{I,50\text{-}2500}$, is an energetic sum of all included third octave bands, i.e. the frequency bands with highest sound pressure levels influence the single number value the most.

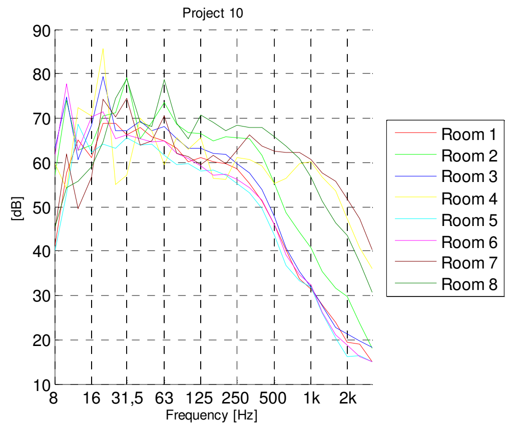

Figure 2: Typical levels from different rooms in one project in a building with light weight structure. The highest levels appear in general below 50 Hz.

One certain problem that appears at high levels of low frequency sound is that the human ear is more sensitive to level differences in the low frequency domain. Once the signal appear a sound pressure level difference in 3-5 dB is perceived as a doubling of the sound level for the lowest frequencies, compared to 1000 Hz where a 10 dB difference is perceived as a sound level doubling [4, 7]. One very common misunderstanding is that human hearing only is active for frequencies higher than 20 Hz. As has been shown in some papers [4], human ears may work all way down to 1 Hz. Figure 3 shows isophon curves down to 3.15 Hz. Studying the isophon curves from ISO 226 [7] it is important to note the 20 Hz value is an extrapolation of values at higher frequencies. However, from Figure 3 it is evident that the actual isophon curves at frequencies lower than 25 Hz do not have as steep slope as indicated by the ISO 226 curves. It is also obvious when studying the measured impact sound levels in Figure 1 and Figure 2 and compare those levels to the levels in Figure 3, that it is most likely that the signal exceed the hearing threshold, even with the impact sound machine as a sound source. What happens then when humans are walking or children are jumping?

Where does the misunderstanding that human hearing stops at 20 Hz come from? In studies of low frequency hearing it is often mentioned that the subjective impression of the sound stimulus changes significantly somewhere between 15 and 20 Hz. One of the main differences is that the concept of pitch is lost at lower frequencies, i.e. a sinusoidal stimulus at 10 Hz is not heard as a tone but as an amplitude-modulated rumble.

However, the impact sound pressure level spectra using the tapping machine may not be the only reason why the subjective perception differs from the measured results. Concrete floor structures are homogeneous while wooden floor structures are more complex, constructed out of joists and beams. The structural system differences also lead to different structural losses which probably can affect the subjective impression. Furthermore, the complexity of common light weight structures makes the practical construction more difficult and thus building errors happen more likely, if the process is not fully controlled. This may result in high uncertainties of the impact sound pressure measurements with respect to where the tapping machine is placed. If it is placed direct over a beam the vibrations can be lead straight to the receiving room compared to when it is placed between beams since there is no strong path from the tapping machine to the receiving room.

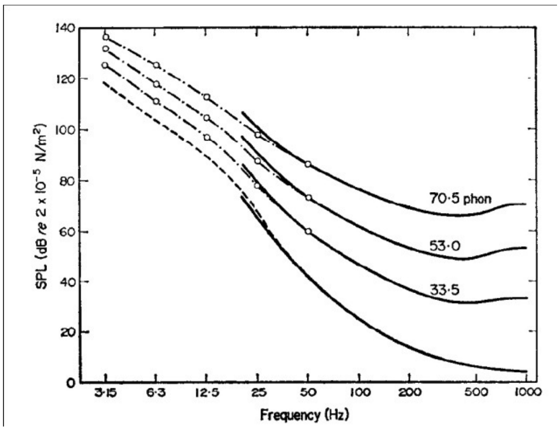

Figure 3: The phon curves extended to very low frequencies (from [4]), describing how the human ear perceives the sound pressure level of different frequencies.

One of the main shortcomings of the ISO measurement methods is the impact source itself. It has been argued in numerous papers that the ISO tapping machine does not resemble the most common sources of structure borne sounds, i.e., human walking, dropped objects, rattling doors etc [10,11]. The shortcomings are related both to the source admittance and that the tapping machine give mainly force excitation in the normal direction, while footsteps include multidirectional excitation [10]. Many attempts have been made to replace the ISO impact machine or to combine it with a heavier sound source which would produce a sound corresponding to more typical footstep impacts on the floor structure. However, in spite of all shortcomings, there are advantages to retain current impact source since it is simple and easy to use for consultants and engineers and it is also established since many decades [3]. One should note that this is not a new argument. The tapping machine was originally designed in the 1930's and its shortcomings became known not long afterwards. For instance there are papers containing severe criticism towards the tapping machine in the 1960's and a similar argumentation was presented in 1965 [10]. In the AkuLite project the choice of source for impact sound measurements will be thoroughly discussed.

Regarding the evaluation method [2], the reference curve is used to estimate weighted single value of the measured impact sound pressure level. As earlier mentioned, applying the method on light weight structures, the result does not correlate to the subjective perception. Therefore, many attempts have been made to define an optimum shape of the reference curve (but still retain the tapping machine). Historically the current reference curve have been criticized many times and alternative shapes have been proposed, at least as early as 1968 [8], where a flat contour was suggested to improve the correlation between objective and subjective results.

The lack of correlation between measured values and subjective judgements, are due to the different characteristics between the impact sound pressure level generated on concrete and light weight floor structures. Similar to earlier research of e.g. Hagberg [3] and Bodlund [5], a further extended brief analysis is included in this investigation in order to confirm whether previous results are emphasized or not, i.e. if the reference curve shape has to take low frequencies into consideration as much as expected.

METHOD

This work is based on studies on several measurements performed according to current ISO standards [1, 2] by consultants in Sweden. The measurements are studied in detail in order to draw conclusions on each parameter included in the measurements, (i.e. reverberation time, level measurements, receiving room volume calculations, normalization etc) and their effect on the final result. Finally, a brief analysis regarding reference curve evaluation is included, by adding five new objects from a Swedish investigation [6] to a previous investigation in [3].

As earlier mentioned, the final results from measurements in buildings erected with light weight structures are normally assumed to be highly affected by the low frequency region, since it does not fulfil the common assumptions in building acoustics theory, i.e. a diffuse and statistical sound field. This implies certain difficulties when measuring and evaluating reverberation time and sound pressure levels at low frequencies. Furthermore, error limits for various measurement aspects (such as receiving room shape and volume) are not established in this frequency region. The results from this investigation points out important parameters in the measurement procedure that might cause errors that affect the final measurement results, in particular when studying light weight structures. The parameters that have been studied regarding error bounds are:

- Reverberation time
- Sound pressure level
- Receiving room volume

Reverberation time measurements

Observant acousticians who have made impact sound measurements in a field situation have probably noticed the large discrepancies of individual reverberation times at low frequencies. To put it in other words: reverberation times can vary a lot in the low frequency region. As previously mentioned there are specific low frequency problems when evaluating the reverberation times, problems which mainly are consequences of not having a sufficiently high modal density in the receiving room. The question arises if the evaluated reverberation times are normally distributed and if it is possible to find error bounds to reverberation time discrepancies. Furthermore, there are huge difficulties to state what is really measured; is it reverberation time in "ordinary manner" as stated in ISO 140-7, or rather the loss factor of the entire building system?

Figure 4 shows the distribution plot from one project where 24 measurement decays are used. The 1/3 octaves between 50 Hz and 400 Hz are presented, the distributions at higher frequencies were very similar. From figure 4 it is obvious that the reverberation times in the lowest 1/3 octave bands differ significantly from a normal distribution. Compared to the distributions at the higher frequency bands in Figure 4 the lowest frequencies show wider distribution, i.e. the error bounds are larger.

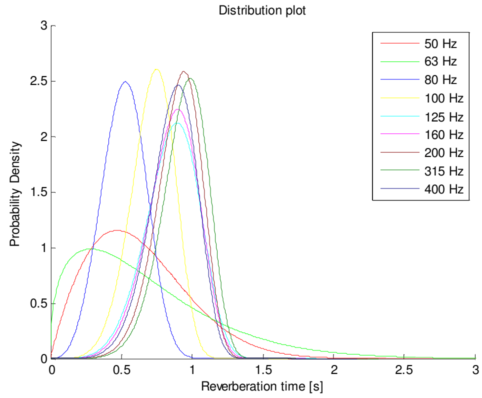

Figure 4: Distribution plot from one project where 24 measurement decays are used. The 1/3 octaves between 50 Hz and 400 Hz are represented.

The reason for the different distribution shape can be searched by studying the data points, for instance using a quantile-quantile plot. Such plots for the 50 and 63 Hz third octave bands are shown in Figure 5 and 6 respectively. In the figures the reverberation time data points are fitted to a normal distribution. If the data would be normally distributed all data points would lie on the straight red line. The solid center section of the red line gives the ± 1 □ confidence interval and the dashed line gives the ± 2 □ confidence interval. It is clear from Figure 5 and Figure 6 that there are some outliers that cause the strong deviation from a normal distribution in the lowest frequency region. The data points would follow a normal distribution much better if these outliers are removed. It is interesting to note that even though the numbers of outliers are equal in both the 50 and 63 Hz band, the outliers are not from the same combination between loudspeaker and microphone position. A simple pragmatic approach to simply omit the individual measurements that introduce the outliers is thus not practically feasible, since only individual third octave bands would be necessary to omit. To rely on a manual choice of which frequency bands that would be omitted, or in other words, which frequency bands that would be included in the evaluation creates a risk of "choosing" the measurement result. A better procedure would be to evaluate the full distribution using e.g. a quantile-quantile plot to identify individual data points that would increase the error bounds and evaluate the expectation value from the modified distribution. However, this procedure assumes that the outliers are results from measurement errors. In practice there are rooms where the reverberation time varies significantly from position to position, e.g., when strong flutter echoes are present. To omit some measurements in such a room would be erroneous. Reverberation times measured in buildings with heavyweight structures, also included for reference in this investigation, show similar patterns in the low frequency region.

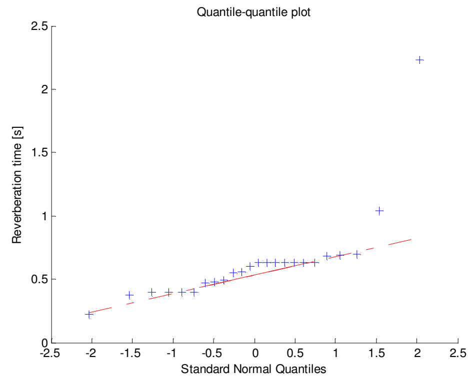

Figure 5: quantile-quantile plot for the 1/3 octave 50 Hz from one project where 24 measurement decays are used. Two typical outliers with long reverberation time are identified

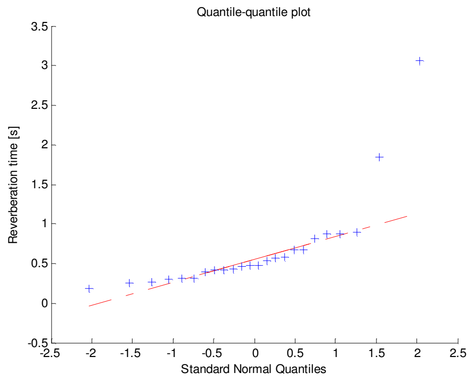

Figure 6: quantile-quantile plot for the 1/3 octave 63 Hz from one project where 24 measurement decays are used. Two typical outliers with long reverberation tmie are identified

At higher frequencies the distribution of the reverberation time measurement results between different positions in the receiving room becomes more normally distributed. This typical example for a light weight structures and uncertainties in the reverberation time measurements can thus be an important error source, due to the effect of normalization to 10 m^2 absorption area or standardization to 0.5 s reverberation time, especially since high sound pressure levels in the lowest frequencies determine the single number value, $L_{n,w}$ + $C_{I,50\text{-}2500}$, and also the degree of disturbance. Furthermore, it is likely to suspect that this skew and wide distribution will retain if the measurements are performed at even lower frequencies.

The size of the term which couples the measured impact sound pressure level to the standardized impact sound level

$$10\log\left(\frac{T}{T_0}\right)$$

can differ with as much as 10 dB in the 50 Hz band evaluated from the minimum and maximum values in Figure 5. This shows that the reverberation time values can affect the standardized impact sound levels, and thus the single number value, significantly.

If the measurement performer is not observant, large errors might appear and the quality of measurement result becomes unacceptable. This could happen even if the results appear to be fine according to the instruments.

Level measurements

One part of impact sound measurements in a building site is to determine the level produced by the tapping machine in the receiving room. In the field situation this is normally made by taking a number of discrete positions well away from the room's boundaries and then averaging these values to one single number. Best fitted distributions of 10 individual equivalent sound pressure level measurements in a receiving room is shown in Figure 7 for the third octave bands between 50 and 400 Hz. Two aspects are visible in the figure: first that the distribution width is comparable for all frequency bands, and second that the distributions are slightly skewed compared to a normal distribution with a longer tail towards lower levels. In other words, it is more likely to receive lower levels than what would be expected from the mean value. The reason for this behaviour is not known, but it might be explained by the allowed location of the microphone positions, away from the boundaries, thus avoiding the higher levels along the room's boundaries. For most frequency bands the skewness is so small that it can be judged not to influence the final results significantly.

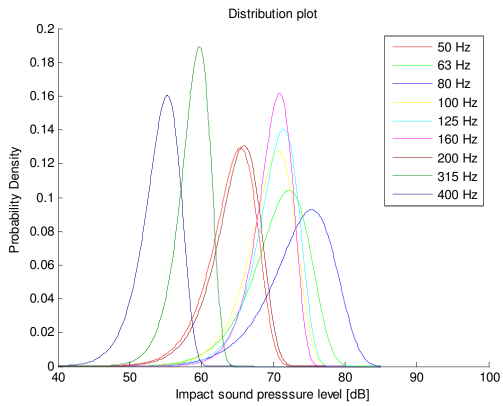

Figure 7: Distribution plot from one project where 10 measurement levels are recorded. The 1/3 octaves between 50 Hz and 400 Hz are represented.

The widths of the distributions are larger than 10 dB for most frequency bands in the figure. The same argument as was used for the reverberation time, i.e., that any eventual error in an individual frequency band can affect the final $L_{n,w}$ + $C_{I,50\text{-}2500}$ value can be used for the sound pressure level measurements as well. However, the risks do not seem to increase at lower frequencies in opposition to the reverberation time.

The effect of receiving room volumes

Reverberation time

Another parameter affecting the final result is the receiving room volume. According to statistical acoustics, discrepancies and thus also confidence intervals, should decrease when the room volume increases since the modal density increases with the volume. Of course, this assumes a room approximately homogeneous in terms of absorption and diffusion.

The 95 % confidence interval for reverberation times measured in different room volumes is shown in Figure 7 for selected third octave bands. The confidence intervals for the reverberation time increase for low frequencies as the room volumes increase, quite contrary to the first expectation. This holds for the 50, 63 and 80 Hz frequency bands, while the confidence interval appears to be more stable above these 1/3 octaves. The symbols on the curves are markings of which volumes that are included in this investigation. The straight line is the least squares fitted first order polynomial for each third octave band. The assumption that the modal density is the main factor for measurement precision at lower frequencies, as shown in figure 7, seems to be incorrect. Why the confidence interval increases at low frequencies with room volume is still unknown.

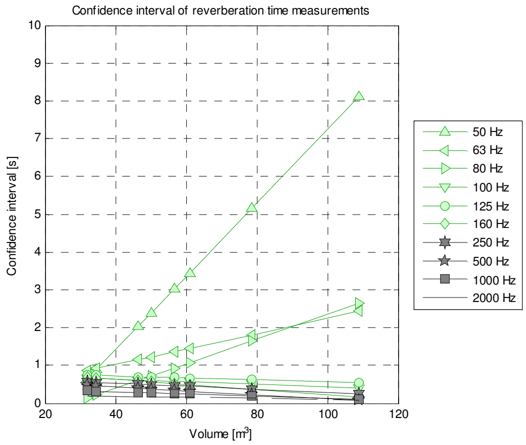

Figure 7: Confidence interval for reverberation time in different frequencies depending on room volumes of the receiving room

Sound pressure level

A similar plot of the relationship between the room volume and the 95 % confidence interval for the measured sound pressure level from the tapping machine is shown in Figure 8. Again it seems like the lower frequencies behave differently compared to higher frequencies, although the differences are not so pronounced as for the reverberation time. The most striking feature of Figure 8 is the decrease in confidence interval at higher frequencies. The behaviour for the third octave bands not shown in the figure was similar.

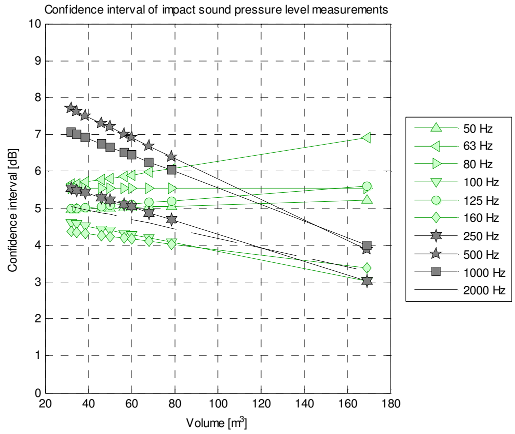

Figure 8: Confidence interval (95 %) for the sound pressure level in different frequency bands depending on room volumes in the receiving room

EVALUATION OF SINGLE NUMBERS

In this paper a number of plots have been shown and mainly general risks for errors or even complete failure are presented. But are the low frequencies annoying in buildings and do the levels normally exceed the hearing threshold and actually create disturbance? At the end, do we need to further investigate and raise the knowledge within this topic? The answer is yes mainly due to the following

1. It is obvious that the statistical methods which constitute basis for measurements and evaluation of single numbers in current standards have shortcomings. This is emphasized when frequency bands outside the "statistical range" determine the single number value. It seems that the reverberation time measurements create certain difficulties.

2. The performers of measurements at consultants working in the field, on site, learn the standard procedure but naturally, they are not aware of all potential shortcomings regarding complex structures and low frequency measurements.

3. The subjective annoyance might appear due to noise levels in frequencies below the frequency range considered in the standards *and* in these 1/3 octaves even more severe, still unknown, evaluation problems might appear.

It is likely that these low frequencies contribute highly to the annoyance. Earlier studies [3, 5] emphazises the need for more focus on the lowest frequencies. This can be further supported by Figure 9 where equivalent level spectra for one of the authors walking and jumping on a floor which was measured to $L_{n,w} + C_{I,50\text{-}2500} = 53$ dB. It is clear that for this floor the highest sound pressure levels are found in the region below 20 Hz. Recordings of footsteps of the same person on the same floor construction in a laboratory are clearly audible, which also can be understood by comparing the spectra in Figure 9 with the extended isophon curves in Figure 3. The exceeding of the hearing threshold is not large measured in dB, but the common experience from studies of low frequency hearing is that small level differences can give large differences in subjective impression.

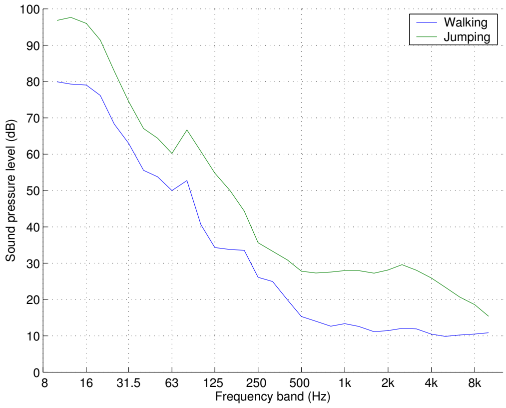

Figure 9: Measured sound pressure level for walking and jumping on a lightweight floor.

In the studies [3,5] field measurements were used and they were compared to interview surveys with inhabitants. Naturally, the results regarding objective measurements according to ISO 140 raises doubts regarding their reliability in low frequencies. Nevertheless, in current study further five objects from a Swedish survey [6] were added to the study [3] in order to extend the number of test objects in the correlation analysis. The results further emphasize the need for more severe studies regarding the low frequency phenomena appearing in light weight structures and how to evaluate the annoyance correctly. Similar to prior studies, present investigation used an optimization procedure to find the reference curve that fitted the subjective data best. Starting with a straight line, this line was tilted in both directions in several steps. The curve was then broken in two segments, each having its own slope. The reference curve was made more and more elaborate by introducing more segments, each with its own slope (uncorrelated to the slopes of the other segments). Up to five segments were used, implying that more than 270,000 curve shapes were tested. The best fitted evaluation curve using linear regression after the extension according to current study is shown in figure 10. It is interesting to note that the reference curve is flat for all third octave bands but the 50 Hz band. Regarding the frequency range where the ISO reference curve is defined, i.e., 100-3150 Hz, the curve agrees with the suggestion by Fasold cited in [8].

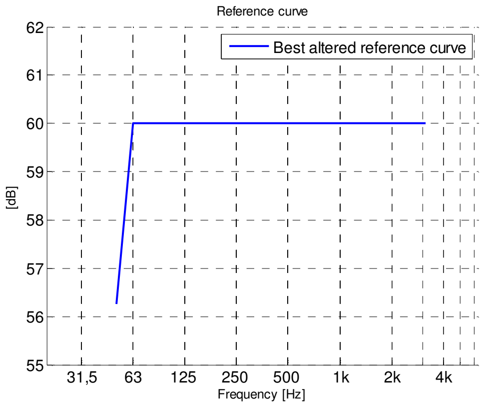

Figure 10: Best fitted evaluation curve after extending the investigation [3] with yet another five building objects from a national survey made by the National Board of Housing Building and Planning [6].

The very steep curve at low frequencies is in accordance with the findings in earlier studies [3] and indicates a need for more scientific and deep studies focused on modern light weight structures and suitable requirements for these structures. The steep curve for low frequencies is itself a warning of “strange behaviour” since it is at the boundary of the evaluation range. Lower frequency bands are probably needed to accurately predict annoyance to a reasonable degree. The optimized curve shape together with the sound pressure level spectrum for walking, shown in Figure 9, emphasizes that high frequencies probably do not affect the final single number evaluation.

CONCLUSIONS

Some major conclusions, or rather proposals for further investigations within WP 4 of the project *AkuLite*, might be drawn from this study

1. The reverberation time measurement with regard to averaging procedure is not satisfactory
2. The reverberation time measurements and their effect of the final results for light weight structures needs to be clarified and quantified
3. Room volume effects with regard to reverberation time measurements at low frequencies and effects on the final results have to be clarified.
4. When point 1, 2 and 3 above is more clarified, establish a measurement programme in general but applicable to light weight structures in particular which is more precise in the low frequency region and hence, useful to use as objective input to the future development of new evaluation methods.

DISCUSSION

The results from present study indicate some important aspects. First of all there is a need for a more extensive overview of the measurement methods and the evaluation principles to promote a successful future development of light weight structures in multi storey residential buildings. So far heavy structures are not included in the work presented in this paper, but instead only highlighting uncertainties that could become severe when applied to light weight structures. Nevertheless, it is likely to believe that current statistical methods are acceptable for heavy structures since the single numbers are determined by mid- and high frequencies. However, as the building technique develops towards more complex and light structures current methods and their applicability decrease, since their rating solely is determined by low frequencies. Hence, the lower the annoying frequencies the more difficult just to extend to lower frequency bands frequencies, but retaining the main method.

Accordingly, as long as the building structures are heavy, i.e. homogeneous concrete, the low frequencies could be neglected. However, if the development of new building technique will stay positive the frequencies which really cause annoyance have to be included in the measurements and the evaluation. But to include these, more knowledge is needed and revised standards (both ISO 140-7 and ISO 717-2) are required rather quick.

Present standards might cause high uncertainties due to:

- Reverberation time is not consistent below 100 Hz, see figure 3, 4 and 5, deviations can affect the final result with several dB:s

- The volume of the receiving room can highly affect the final results in the low frequencies, see figure 7

- For light weight structures, low frequencies (sometimes very low) determine the degree of annoyance, i.e. unknown small errors in the measurement and evaluation procedure might cause incorrect evaluation, either better than expected or worse than expected, at present difficult to quantify.

This work will continue during autumn 2010, with the aim at trying to further investigate and also quantify the errors emanating from measurements according to ISO 140-7, for various structural bearing systems due to the parameters discussed in this paper.

There are several additional issues that has to be discussed further in the continuation of the work within WP 4 in the project *AkuLite*

- If using normalized impact sound pressure, is it proper to use 10 m^2 as reference equivalent sound absorption area at low frequencies?

- If using standardized impact sound pressure, is it proper to use the reverberation time 0.5 s as reference reverberation time at low frequencies?

- Is it proper at all to use reverberation time measurements at low frequencies or is it better to state some sort of structural loss factor for different structural bearing systems?

- Trying to quantify at which frequencies and for which structural bearing systems the problems might arise.

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