

AN EVALUATION OF VARIOUS SOUND INSULATION PROGRAMS AND THEIR USE IN THE DESIGN OF SILENT ROOMS

MASTER'S THESIS IN THE MASTER'S PROGRAMME IN SOUND AND VIBRATIONS

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Cover: Transmission loss of a single panel in a diffuse field.

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Abstract

In both building and room acoustics, the ability to predict how sound insulation will affect the sound level and quality in rooms is a crucial technique that is needed, that saves both time and money. As a result, over the past couple decades many sound insulation programs such as Insul, Bastian, ENC, Reduct and Winflag have been designed to increase both the efficiency and accuracy of these predictions. Most, if not all of these top quality programs on the market are based on very specific international standards (ISO), and/or other local national standards as well as the theoretical pioneering works of authors such as Cremer, Maidanik and others. Consequently, different sound insulation programs on the market have different functions and are based on different theoretical approaches and assumptions. As a result, one should be aware of the theoretical definitions, assumptions, as well as the limitations of the different programs if one desires to reproduce accurate results while using.

Part I of this document outlines some of the fundamental definitions, assumptions and theories that are used by some of these programs. While part II describes a process of how these programs can be used while trying to design a silent room.

The results from this investigation show, that even though all of the programs are based on well established theories the accuracy and the reliability of each program varies. The programs are ranked according to their performance. From this, the combination of Bastian and Insul together seemed to be the most reliable when trying to model the sound insulation between two adjacent rooms. Two case studies are presented. The first validates the accuracy of using both Bastian and Insul in combination with each other, while trying to predict the sound insulation between two adjacent classrooms. While the second, shows the importance of understanding the theoretical basis of these programs as the predictions made within Bastian are manipulated in order to meet the standards required when converting an ordinary classroom into a music room. The results show that it is possible to use these programs when trying to design a silent room.

Keywords: Sound insulation, Silent room, Sound insulation programs, Bastian, Winflag, Insul, ENC, Reduct.

Acknowledgments

The completion of this thesis represents the end of a seven year journey which began in 1999 when I left my country (Trinidad and Tobago) to pursue my desire to study acoustics. This journey took me around the world firstly to America then to Sweden. During which time I have missed some special events within my family such as my father's 50th birthday as well as my Grandparents 50th wedding anniversary celebrations. I have also made many new friend and received a new prospective of life and for this I thank my Lord and Savior Jesus Christ for his guidance.

I will like to thank my father (Patrick Cambridge) who always believed in me, never gave up and gave me all of the support that I needed. My grandparents (Cuthbert and Mary James) who helped to set the foundation of my life. The Pascal family (i.e my uncle Junior, auntie Monica, my cousins Afiya and Akilah) who I lived with during my teenage years. The Alexander family (i.e uncle Dexter and Auntie Debbie) for all their support and making me feel at home while I was in America. Also, to all my other family members who made the old African proverb true which says that "it takes a village to raise a child".

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1 INTRODUCTION

1.1 Background

The requirements for sound insulation have changed significantly from the 25 cm brick requirement that was introduced in the German system in 1938 [5] and from those recommended after the extensive survey conducted during 1952-1953 in England [6]. The measurement standards as well as the grading systems used have also changed even though the number of terms (including the corrections terms used) as well as the grading curves used still vary from country to country [31]. The suitability of these terms currently being used were evaluated by Rasmussen and Rindel [31] by analyzing how suitable, well defined, as well as how reproducible they are. From this investigation the authors indicated that some of the current methods used in ISO 717 were inappropriate and gave suggestions on how to improve the situation. These suggestions were aimed at bring a consensus about the terms and standards that are currently in use. A small example of the differences that are present between a few European countries with regards to their standards and requirements can be seen in Table. 1.1

Country	Quality	Classes	Sufficient	Good	Standard
Germany	R'_w	I/II/III	I:53-54	II:56-63	VDI 4100
Netherlands	$D_{nT,w} + C$	5/4/3/2/1	3:52	2:57	NEN 1070
Sweden	$R'_w + C_{50-3150}$	D/C/B/A	C:53	B:57	SS 25267 (3rd edition)

Table 1.1. Requirement for airborne sound insulations in different European countries (modified form from[31])

From this table it can be seen that a room classified as being good could have as much as 7 dB difference if one compares the Swedish and Netherlands standard with the upper limit of the German Standard, therefore showing in a small way the differences that occur in the requirements among these European countries. However, even though a consensus does not exist in Europe about the requirements, terms used, as well as the frequency range to which they are applied, one does exist for the need for improvement. This comes from the fact that even though vast improvements have been made, up until the 1990's the number of people annoyed by their neighbor's still remained high (i.e. around 15%-20%) [15]. This can also be seen from the continuous introduction of new terms such as the C_{tr} weighting that was introduced in the United Kingdom in 2003 (This weighting is intended to optimize sound insulation against traffic and other noise sources with a significant low frequency content e.g. Disco music [31]).

According to Gerretsen [15] changes in the building trends such as the move from the use of heavy building materials to lighter prefabricated ones, as well as changes

in the complexity of noise sources may account for the high percentage of people who are still annoyed by their neighbor's noise. Consequently, as a result of the ever changing dynamics (i.e. in building techniques, materials etc.) of the building industry, one cannot afford to use sound insulation techniques that are based on a trail and error basis. The need for proper calculation models for the prediction of sound insulation during the design phase has become apparent in order to save both time and money. Furthermore, the need for easy to use software programs that accurately reflect these calculation models is also crucial in order to carry out these complex calculations efficiently.

1.2 Aim

The aim of this thesis is to investigate the theoretical definitions, assumptions as well as the limitations of some of the commonly used sound insulation program on the market. Furthermore, the accuracy of these programs is to be evaluated by comparing the values obtained from their predictions to measured values. The final aim of this investigation is to use these programs during the design of a room required for music. Such a design should provide enough sound insulation so that persons in the neighboring room will not be disturbed.

1.3 Method and Limitations

The investigation into the theoretical basis of these programs was done by first looking at the help files as well as any other sources of information that were given by the developer. In most cases, these theories that were outlined within these sources were then compiled to emulate the respective programs. These assumed theories were then verified by comparing their results to those obtained directly from the programs. The major limitation encountered while using this approach came from the fact that some of the programs did not have a detailed help file. This lack of specific information limited this investigation in cases where two or more possible theories had to be used for a specific calculation parameter. As a result, some assumptions had to be made.

1.4 Basic Theory-Airborne Sound insulation

In order to understand the basic theory behind airborne sound insulation one can think of it as a means of preventing energy from moving within a system. According to the first law of thermodynamics energy cannot be created or destroyed but it is converted from one form to another. As a result of this law when the energy in a sound wave is incident on a surface this energy must be either absorbed, reflected or transmitted through the surface. When the sound waves are absorbed by

the surface what actually happens is that the sound energy is converted to another form of energy (e.g. heat). Consequently, the sound insulation or sound reduction/transmission loss of a panel/room partition is simply a measure of how well it is able to prevent acoustical energy from going through it.

The transmission loss is simply the ratio of the total sound power (W_{tot}) transmitted into the receiving room to the sound power incident on a panel/room partition (W_1). According to the EN12354-1 standard [9] this ratio can be represented by the following equation.

$$\tau' = W_{tot}/W_1 \quad (1.1)$$

From this the sound reduction index can be found from the following;

$$R = -10\log_{10}\tau' \quad (1.2)$$

According to Cremer and Heckl [8] once the volume (V) of the room as well as the area (S) of the test panel/room panel is known, the sound reduction can be found by measuring the sound pressure level in both the receiving room (L_E) and sending room (L_S) as well as the reverberation time (T). The sound reduction can then be calculated from the following;

$$R = L_S - L_E + 10\log\left(\frac{T * S}{0.163 * V}\right) \quad (1.3)$$

Both the transmission loss and the sound reduction are frequency dependent. For a single leaf panel it has been observed that in a diffuse field the transmission loss varies according to figure 1.1 below.

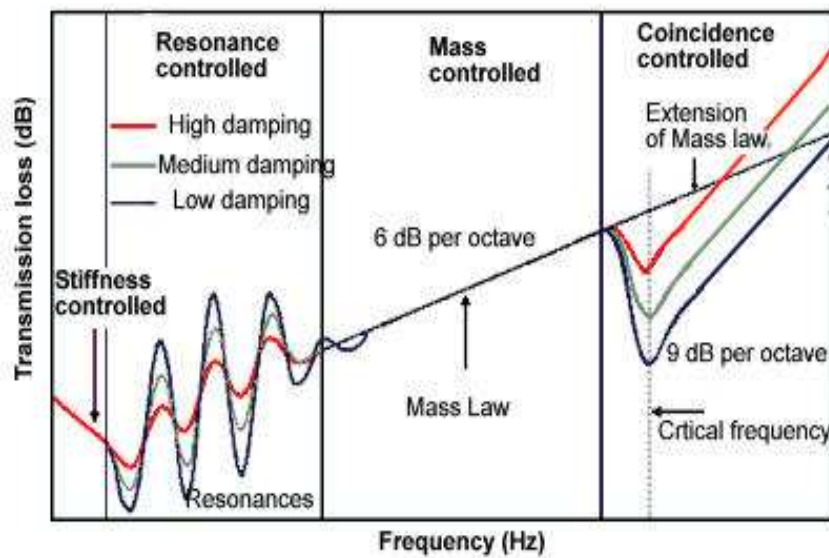


Figure 1.1. Showing the characteristics of the transmission loss of a single leaf panel

From figure 1.1 it can be seen that different regions exist that are controlled by either the stiffness, resonance, mass or coincidence. Many attempts have been made in the past to accurately model these different regions. One such example of how the stiffness, resonance and mass controlled region can be modeled was presented by Fahy [12]. In this model Fahy stated that for frequencies well below the first resonance frequency the sound reduction can be found from the following;

$$R = 20\log_{10}s - 20\log_{10}f - 20\log_{10}(4\pi\rho_0c) \quad (1.4)$$

Where s represents the stiffness of the homogeneous panel. From this it can be seen that the sound reduction index is dependent on the stiffness only within this region. Using this model the sound reduction index decreases at 6 dB per octave as indicated in figure 1.1.

At the resonance frequency Fahy [12] proposed the following relationship provided that the fluid is the same on both sides of the panel.

$$R = \begin{cases} 0 & \eta \ll \rho_0c/\omega m \\ 20\log_{10}f_0 + 20\log_{10}m + 20\log_{10}\eta - 20\log_{10}(\rho_0c/\pi) & \eta \gg \rho_0c/\omega m \end{cases}$$

Where η represents the loss factor. For the mass controlled region the sound reduction increases at a rate of 6 dB per octave as indicated in figure 1.1. This region can be modelled by the following;

$$R = 20\log_{10}(mf) - 42 \quad (1.5)$$

Finally, within the coincidence controlled region the following model proposed by Cremer and Heckl [8] (page 557) may be used for frequencies greater than the critical frequency (f_c). In this region the sound reduction increases at a rate of 9 dB per octave.

$$R = 10\log\left(\frac{\omega^2 m^2}{4\rho^2 c^2}\right) + 10\log\left(\frac{2\eta f}{\pi f_c}\right) \quad (1.6)$$

Between the mass controlled region and the coincidence controlled one a transition occurs. This transition usually occur from approximately 0.5 to twice the critical frequency according to Kleiner [24]. In this region the transmission loss becomes constant. This coincidence plateau can be approximated by the following;

$$R = 20\log(mf) + 10\log(\eta) - 41 \quad (1.7)$$

The above only gives one example of how the transmission loss for a single leaf homogeneous panel in a diffused field can be modeled. Other models also exist for double panels, double walls with studs, rooms or any wall system with various air-gaps with or without absorbers inside. In these cases, and for more complex models for a single panel and other systems, careful consideration must be given to following;

- How to model the damping into the system
- How to account for other types of waves like shear waves that may be present
- How to model what happens around the critical frequency
- How to account for the differences that occur between thin and thick walls
- How to account for different angles of incidence

These are just a few parameters that affect the accuracy of the transmission loss model that one can create. A few of these models and their parameters will be investigated within this paper by evaluating some of the programs that use them. Also, once one is able to create an accurate model of the transmission loss, then and only then, can one systematically improve the sound insulation based on these facts as shown in section during the design of silent rooms portion of this thesis.

Part I

Analysis of various sound insulation software

2 Bastian

2.1 Bastian-Introduction

Bastian uses a graphical window-user interface and event-controlled programming in its calculation of sound insulation between rooms. It is based primarily on the European Standard series EN 12354 but also utilizes other parameters and definitions from other Standards such as ISO 140 and ISO 717. The theories utilized by Bastian are based on works from Craik, Fischer, Maidanik, Timmel, Sonntag, Cremer, Donato, Heckl and some others. It contains a large database with approximately 1500 constructions as well as 40 sound sources. The construction data stored within the program is primarily based on measurements using the appropriate standard. However, some of the data for both heavy single leaf elements and floors for both the sound reduction index and impact noise level are based on calculations according to the user manual [17].

In Bastian calculations of the airborne sound insulation, impact noise transmission and outdoor transmission can be performed. These calculations can be performed either as either a detailed or simplified model. A summary of the standards which these calculations and models are based on can be seen in Table 2.1.

Feature	Standard(s)	Comment
Detailed Model (DM)	DIN EN12354-1,2 and 3	Data entry must be in $\frac{1}{3}$ octave bands but calculation results can be in octave bands
Simple Model (SM)	DIN EN12354-1,2 and 3	Restricted field of applications that is deduced from the DM but uses single number rating for the elements according to ISO 717-1,2
Airborne Sound Insulation	DIN EN12354-1	R'_w , $D_{nT,w}$ and $D_{n,w}$ can be calculated with adaption terms C , $C_{100-5000}$, $C_{50-5000}$, or $C_{50-3150}$
Impact sound transmission	DIN EN12354-2	$L'_{n,w}$ and $L'_{nT,w}$ can be calculated with spectrum adaption terms, C_I or $C_{I,50-2500}$
Outdoor sound transmission	DIN EN12354-3	$R'_{450,w}$, $R'_{tr,s,w}$, $D_{2m,nT,w}$, $D_{2m,n,w}$ can be calculated with adaption terms C_{tr} , $C_{tr,100-5000}$, $C_{tr,50-5000}$ or $C_{tr,50-3150}$

Table 2.1. Summary of some of the general calculation options available within Bastian

In order to use Bastian effectively it is imperative that one understands the calculation models utilized by the program as well as some of the assumptions used. As a result the calculation models used for the both the sound insulation between rooms

and for the construction data, that are based on calculations will be discussed within the following sections. For the models used for some of the different construction data (especially for monolithic walls) some differences do occur between the standards and the models used within Bastian. Some of these differences are a result of different theoretical approaches as well as different correction terms that are used. These difference will also be discussed.

2.2 Airborne sound insulation of monolithic walls

As mentioned above some of the construction data stored within Bastian for the sound reduction of monolithic walls are based on calculations. These calculations are based on the model presented within the EN12354-1 standard. However, some difference do occur between the model presented within this standard and the one used by Bastian, which may account for some of the differences seen in figure 2.1.

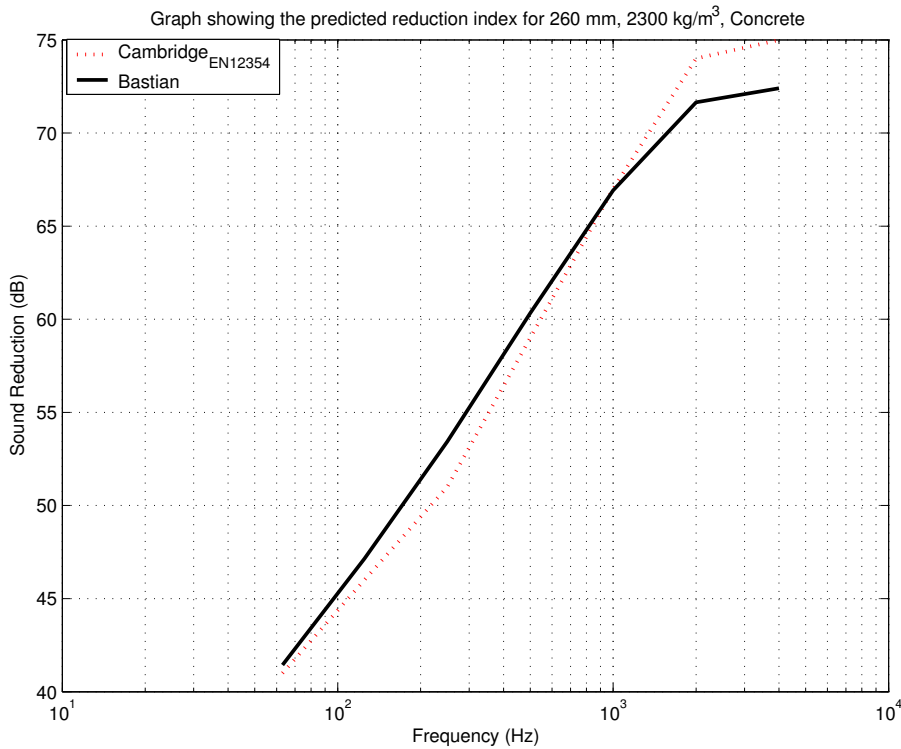


Figure 2.1. Predicted reduction index for 260 mm, 2300 kg/m³ concrete

In Figure 2.1 the Cambridge_{EN12354} values were obtained by creating a Matlab program that implemented the different variables, conditions and assumptions as outlined within this standard. A copy of the code used can be seen within appendix A.1. It was necessary to use this approach in order to obtain a greater sense of exactly how the values that were given as an example within the standard were obtained. When compared to the values given in the EN12354 standard, the gen-

eral trend shows that the calculated values exactly match the values stated within the standard except for frequencies below 200 Hz (see figure 2.2). This discrepancy may be accounted for, from the fact that even though the standard gave all of the necessary material properties such as the density, the longitudinal speed of sound with the material as well as the internal loss factor, they simply neglected to state its dimensions. Since the dimensions have a greater effect on the sound reduction in this model presented by Josse and Lamure [22] (see section 2.2.1) below the critical frequency, this may account for some of the observed differences. As a result, the wall dimensions (i.e. $4m * 3m$) that are utilized in Bastian were used in this model.

The Bastian values used in figure 2.1 are the values that are stored within the program. However, similar to the calculated EN12354 case (i.e. $\text{Cambridge}_{EN12354}$), a Matlab code was also develop to get a sense of how these values were obtained (see Appendix A.2). A comparison between these calculated values and those stored within the program can be seen in Figure 2.3.

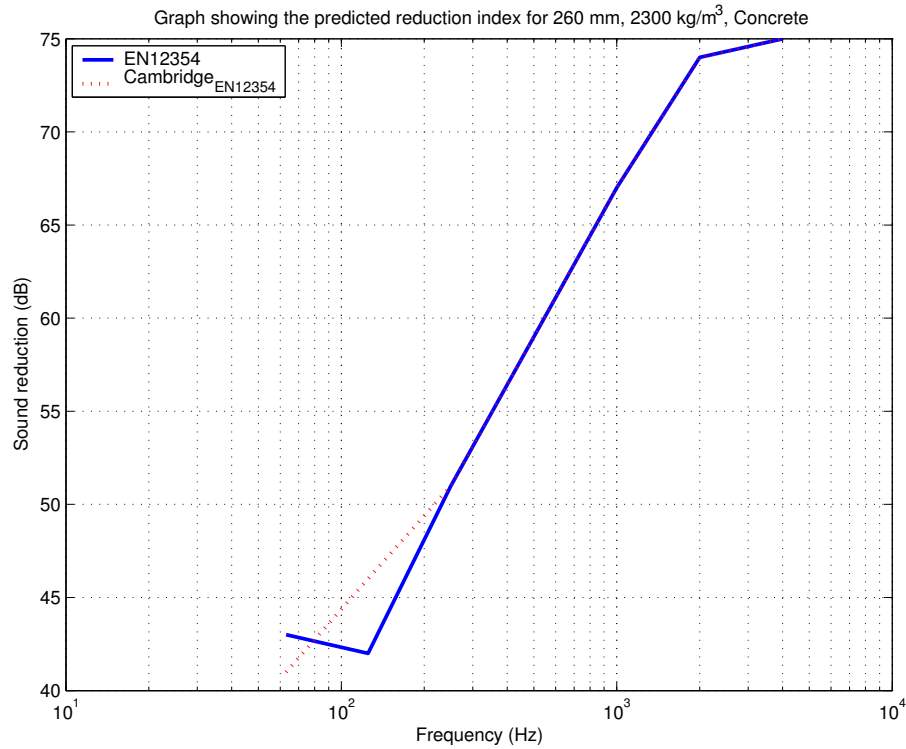


Figure 2.2. Predicted reduction index for 260mm, 2300 kg/m³ concrete while using the EN12354 calculation model

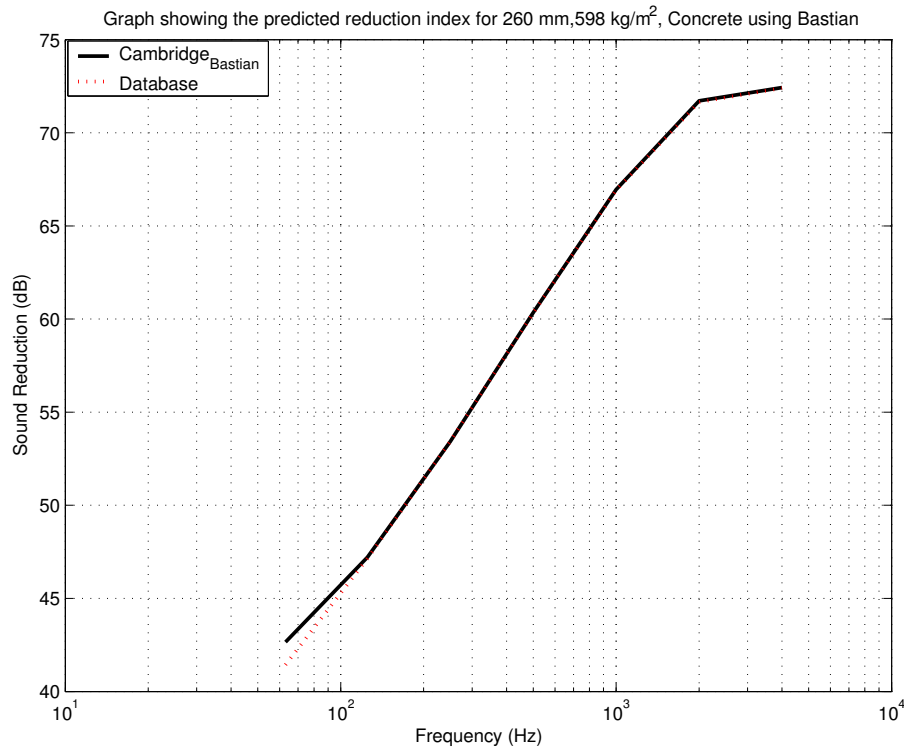


Figure 2.3. Predicted reduction index for 260mm, 2300 kg/m³ concrete while using the Bastian calculation model

Even though Figure 2.1 shows that the obtained values are quite similar as the maximum deviation seems to be around 3 dB. These deviations may be due to differences in the calculation model used by Bastian and the one given in the EN12354 standard. Some of these differences that occur between these two models will therefore be discussed within the following sections.

2.2.1 Monolithic wall calculation model

Both Bastian's and EN12354-1 calculation models are designed for calculating the sound reduction of monolithic elements and both require the following input data;

- Thickness (h)
- Density (ρ)
- Surface mass render (m''_{render})
- Longitudinal wave speed (c_L)
- Internal loss factor (η_{int})
- Perimeter length (a,b)

Using these input data the radiation factor for forced and free waves, the total loss factor and consequently the sound reduction can be calculated. The differences that occur in the calculation of these parameters will be discussed in the following sections, while the differences in calculating the sound reduction itself will be discussed here.

The formulas used for calculating the transmission loss within the EN12354 standard were derived from Josse and Lamure's work [22]. The following are used;

$$R = -10 \lg \tau \quad (2.1)$$

$$\tau = \begin{cases} \left(\frac{2\rho_o c_o}{2\pi f m'} \right)^2 \frac{\pi f_c \sigma^2}{2f \eta_{tot}} & \text{if } f > f_c \\ \left(\frac{2\rho_o c_o}{2\pi f m'} \right)^2 \frac{\pi \sigma^2}{2\eta_{tot}} & \text{if } f \approx f_c \\ \left(\frac{2\rho_o c_o}{2\pi f m'} \right)^2 \left(2\sigma_f + \frac{(l_1 + l_2)^2}{l_1^2 + l_2^2} \sqrt{\frac{f_c}{f}} \frac{\sigma^2}{\eta_{tot}} \right) & \text{if } f < f_c \end{cases}$$

Where

τ is the transmission factor

m' is the mass per unit area

f is the frequency in Hertz

f_c is the critical frequency

η_{tot} is the total loss factor for the laboratory situation

σ is the radiation factor for free bending waves

σ_f is the radiation factor for forced transmission

$l_1 l_2$ are the lengths of the borders of the rectangular element in meters

From this it can be seen that the transmission loss is not dependent on the length near to and greater than the critical frequency. Also, according to Kernén [23] when compared to Ljunggren's model for thin plates [28] the sound reduction will decrease with an increase in the plate area for frequencies below the coincidence frequency in Ljunggren's [28] model while the opposite occurs in Josse and Lamure's model [22].

For frequencies approximately close to and greater than the critical frequency, Bastian utilizes the same formulas as the standard for the transmission factor. However,

for the frequencies lower than the critical frequency two distinct differences occur. Firstly, the radiation factor for forced transmission is not included in the Bastian code as discussed in section 2.2.2 and secondly it depends on whether the plate is strongly damped (R_b), has a medium loss factor (R_η) or has a very small loss factor (R_{min}). Consequently, the sound reduction for the low frequencies within Bastian are calculated by comparing the relative inequalities in the following manner.

if $R_\eta > R_b$ then $R_{low} = R_b$
else
if $R_\eta < R_{min}$ then $R_{low} = R_{min}$ else $R_{low} = R_\eta$
 Where

$$R_b = 20\log_{10}\left(\frac{\pi f m'}{\rho_o c_o}\right) - 3dB$$

$$R_\eta = R_b - 10\log_{10}\left(1 + \frac{2.25\sigma_{T,corr}^2 \pi f c}{\eta_{tot,lab} f}\right)$$

$$R_{min} = 10\log_{10}\frac{\pi f m'}{\rho_o c_o} + 10\log_{10}\frac{\pi S \sqrt{f f_c}}{U c_o}$$

The above inequality indicates that the area of the panel is only considered if its loss factor is small.

Even though it was not stated in the Bastian 2.0 [17] user manual, one can assume that R_b in the above inequalities was derived from Ljunggren's work on thin walls [28]. Since he stated that the transmission loss due to forced transmission below the critical frequency can be found by using the following.

$$\tau = 20\log\left(\frac{\omega m}{2\rho c}\right) - 3 - 10\log s_d \quad (2.2)$$

Where s_d is the radiation factor with respect to the forced plate field excited by diffuse sound. Ljunggren [28] mentions that this radiation factor can be calculated from the graph that he proposed within this paper, or from Sato's [33] or Swell's [34] works. Since Bastian's calculation model does not include the radiation factor for forced waves it can therefore be understood why the s_d term was not included within the model. The EN12354-1 model on the other hand applies the radiation factor for forced transmission directly into its model by utilizing Swell's [34] correction.

It is difficult to access where the R_η term comes from since the source was not given in the user manual. The R_{min} values on the other hand are based on Sonntag's works [37].

2.2.2 Radiation factor for forced waves

After carefully investigating the Bastian Model and comparing it to the EN12354-1 model it can be seen that the radiation factor for forced waves are not included within

the model for calculating the sound reduction of monolithic walls as mentioned in 2.2.1. This simply means that the monolithic wall values stored with the program do not account for this factor. Instead the radiation factor for forced waves is included as a optional correction term when one investigates the transmission between rooms. The correction used is based on Sonntag [37] works and can be added to calculation values R and L_n . This correction takes into account forced excitation of bending waves as allowed by EN 12354-1 [9] and EN 12354-2 [10] as oppose to the excitation due only to the airborne sound only. The only difference that occurs is that the radiation factor for forced waves are calculated according to Sewell's [34] work in the EN12354 standards (see section 3.2) while Sonntag's correction [37] is utilized within Bastian. According to the user manual, this correction can be applied to heavy single leaf elements, double leaf lightweight elements or to all types of flanking elements, with all paths being affected except for the direct path (i.e. Dd see figure 2.5).

This point concerning the radiation force factor is an important fact to recognize especially if one has to use other sound insulating software such as Insul to calculate the sound reduction index of a particular building element to input into Bastian. Careful attention must be placed on such input values to ensure that the correction factor for forced waves isn't taken into account twice (i.e. within the Building element software such as Insul which applies this correction factor based on Swell's works and Bastian). Errors will obviously occur in the predicted values if this is done.

2.2.3 Radiation factor for free waves

Both Bastian and the EN12354-1 [9] standard uses variations of Maidinik's [29] equations in their calculation of the radiation factor for free waves. In Bastian the following are used.

$$\begin{aligned}
 f < \frac{f_c}{10^{\frac{1}{20}}} & \quad \sigma_1 = \frac{\lambda_c^2}{S} \left(2g_1 + \frac{U}{\lambda_c} g_2 \right) \leq 1 \\
 \frac{f_c}{10^{\frac{1}{20}}} < f < f_c \cdot 10^{\frac{1}{20}} & \quad \sigma_2 = \sqrt{\frac{a}{\lambda_c}} + \sqrt{\frac{b}{\lambda_c}} \\
 f > f_c \cdot 10^{\frac{1}{20}} & \quad \sigma_3 = \frac{1}{\sqrt{1 - \frac{f_c}{f}}} \leq \sigma_2
 \end{aligned}$$

Where

$$g_1 = \begin{cases} \frac{4}{\pi^4} \left(1 - \frac{2f}{f_c} \right) \frac{1}{\sqrt{\alpha} \sqrt{1-\alpha}} & f < \frac{f_c}{2} \\ 0 & \frac{f_c}{2} < f < f_c \end{cases}$$

$$g_2 = \frac{1}{4\pi^2} \frac{(1 - \frac{f}{f_c}) \ln \frac{(1+\alpha)}{(1-\alpha)} + 2\alpha}{(1 - \alpha)^{\frac{3}{2}}}$$

$$\alpha = \sqrt{\frac{f}{f_c}}$$

In the EN12354-1 standard however the σ_2 and σ_3 terms are different while all other terms including the auxiliary terms g_1 and g_2 are the same. The σ_2 and σ_3 terms are found from the following relationships;

$$\sigma_2 = 4l_1l_2 \frac{f^2}{c_o}$$

$$\sigma_3 = \sqrt{\frac{2\pi f (l_1 + l_2)}{16c_o}}$$

This may account for the differences seen in figure 2.4 for the radiation factor of free waves. From this, it can be seen that both the Bastian without Timmel's correction [38] and EN12354-1 model approaches one. They have the same shape even though the Bastian's values are higher for the low frequencies. Both predictions however, are quite similar. Timmel's correction is also shown on this graph since this correction is taken into account directly within the Bastian model.

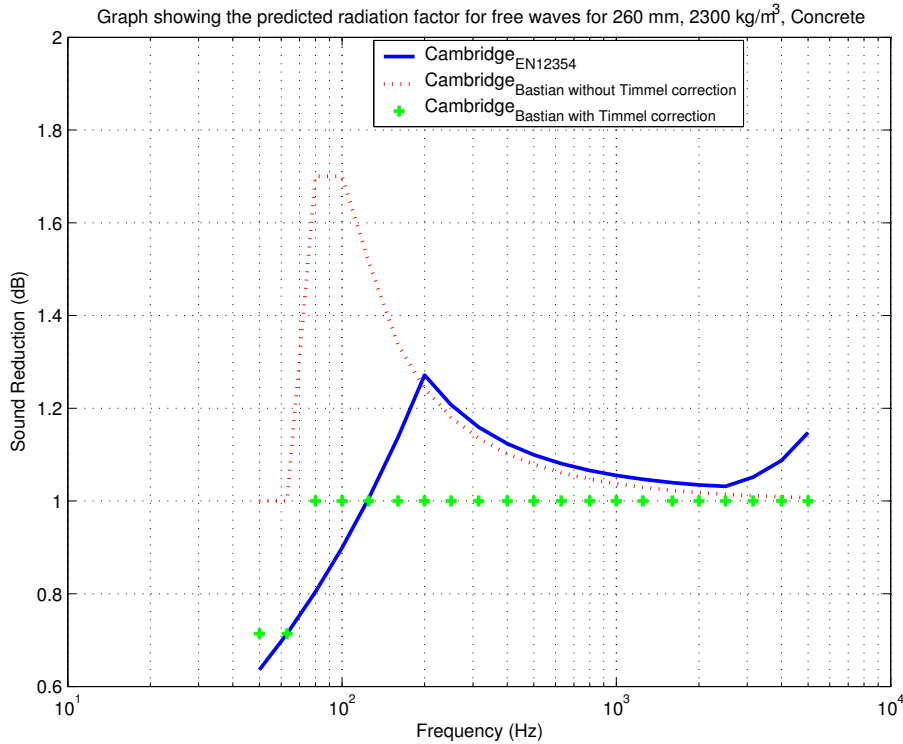


Figure 2.4. Radiation factor for free waves

Maidanik's [29] formula was formulated by considering the results obtained from the simple situation for single mode radiation resistance of a finite simply supported

and baffled panel. These results were then expanded for the case where the panel's vibrational field is reverberant (i.e. where most or all the modes on the panel contribute to the the amplitude of the field). The results for the single mode case were formulated by considering that the radiation (R_{rad}) can be found from the following;

$$R_{rad} = \left(\frac{16}{\pi}\right) \rho_o c_o k_o^2 \int \int_{-\infty}^{\infty} dx_1 dx_2 \Psi(x_1, x_2) \Phi(x_1, x_2) \quad (2.3)$$

From this Maidanik stated that for free waves on an infinite panel R_{rad} can be found from the following;

$$R_{rad}(\omega)/A_p = \begin{cases} 0 & k_p > k_a \\ \rho_a c_a (1 - k_p^2/k_a^2)^{-\frac{1}{2}}, & k_p < k_a \end{cases}$$

This relationship basically shows that for an infinite plate no sound radiation will occur below the critical frequency. However, if discontinuities are present some radiation will occur. With this fundamental base, Maidanik calculated the radiation resistance for the two dimensional case for above, below and approximately close to the critical frequency as well as for the cases where different modes are present. Using these results the above equation were then formulated for the reverberant field case, since according to Maidanik

In most practical cases the panel vibrational field is a multimodal vibration where most or all of the modes of the panel contribute to the amplitude of the field. Thus it is desirable to extend the formalism to cover all these cases. We shall assume that there are enough variations at the boundaries and the panel so that the motion is complex enough to be considered reverberant... (Maidanik [29] page 817)

Therefore based on the above quote it can be assumed that this formula would be valid for the typical building situations. According to Kropp [26] when this formulation is used the following assumptions are made :

- Point excitation
- Only the modes with resonance frequencies in the frequency range of the excitation signal are considered
- The amplitudes of all the modes are considered to be the same
- The phase relation of the modes are random
- The plate is simply supported and mounted in and infinite baffle
- Valid as long as the plate is larger than a quarter of the wavelength of the surrounding medium

The point made concerning the plate size will be discussed in section 2.2.4 as a correction is needed if the wavelength is larger than a quarter of the surrounding medium. Despite all of these assumptions made, the Maidanik's formulas that were used are still considered to be valid for typical building elements

2.2.4 Thick Walls

Both Bastian and the EN12354 model make provisions to deal with thick wall elements. They both apply Ljunggren's thick wall formulation even though they both seem to apply it in different ways. According to Ljunggren [27] the word thick refers to:

A thickness larger than that associated with the common thin-plate theory: That is, a thickness larger than a sixth of the bending wavelength...This limit can also be expressed by means of Helmholtz number $k_B\sigma$ as $k_B\sigma \approx 1$, where k_B is the wave number of the bending wave and σ the plate thickness. (Ljunggren [27] page 2338)

In Bastian, Ljunggren's work is taken into account by having it as a correction in relation to Heckl/Donato's [18] work with the plateau associated with this work (i.e. Ljunggren) taken into account by using the formula;

$$R_{Ljunggren} = \left(20 \log_{10} \frac{\rho c_L}{4 \rho_0 c_0} + 10 \lg \frac{\eta_{tot,lab}}{0.02} \right) dB \quad (2.4)$$

In the EN12354-1 [9] model on the other hand an effective critical frequency is used that affects all frequencies for thick walls. This is also based on Ljunggren's work [27]. This effective critical frequency is implemented through the use of the following formulas

$$f_{c,eff} = \begin{cases} f_c \left(4,05 \frac{tf}{c_L} + \sqrt{1 + \left(4,05 \frac{tf}{c_L} \right)^2} \right) & f < f_p \\ 2f_c \left(\frac{f}{f_p} \right)^3 & f \geq f_p \end{cases}$$

Where

f_p is $\frac{c_L}{5,5t}$

t is the thickness of the element in meters

c_L is the longitudinal velocity of the material in m/s

Despite these differences, in the approach Ljunggren's plateau can still be seen in both results in figure 2.1. Ljunggren's plateau simply shows/indicates that in thick walls at high frequencies the reduction index becomes constant. According to Ljunggren, this occurs because;

the TL in the high frequency region seems more to be decreasing frequencies of the thickness resonances than a general increase in the TL. This can be seen as a consequence of the fact, that if the influence of the thickness resonances is expected, the TL is almost independent of frequency in this range and the TL is invariant in $(f\delta)$ [Ljunggren [27] page 2342]

Thus explaining the reason for the plateau. This effect can clearly be seen in chapter 6 in figure 6.1 which shows the results obtained by Winflag when 180mm concrete is modeled both as a thick and thin plate.

2.2.5 Summary: Monolithic walls

The above discussion showed some of the differences that exist between the calculation model used by Bastian and that used by the EN12354 standard. The point of this discussion was to simply show that even though Bastian uses a different approach in the calculation of some of the parameters mentioned above, these differences do not result in a large deviation from the results obtained from the standard. Thus verifying the model used by Bastian as one that meets the requirements of the standard. The above discussion also gives insight into the reasons why certain terms such as the radiation factor for force vibration is not included into the model used by Bastian. From this the user of the program can gain an understanding of exactly what correction terms should be used while performing calculations.

A summary of some of the comparisons made between the two models can be seen in table 2.2. It should be noted that the structural reverberation time, the loss factor due to radiation as well as a description of the laboratory situation was not discussed above. They will however be discussed within the following sections. These three parameters directly affect the calculation of the total loss factor (i.e. η_{tot}), hence the reason why it is being mentioned here.

Quantity	Bastian	EN12354-1
Calculation Model	For homologous building materials not suitable for elements with medium or large perforations.	For single leaf elements made of Clay bricks, CaSi, concrete, gypsum, autoclave concrete and other light weight concrete. If holes are present they must be less than 15% of the gross volume.
Radiation factor for forced waves	Not directly calculated. However Sonntag's [37] correction can be applied to account for this (i.e. sigma forced).	According to Sewell [34]
Radiation factor for free waves	Calculated according to Maidanik [29] however Timmel's [38] correction is applied	Calculated according to Maidanik [29]
Thick wall	A correlation between Ljunggren's [27] thick wall formula and Heckl/Donato's [18] formula.	Ljunggren's [27] thick wall.
Structural Reverberation time	Same as standard	Based on Annex C of the EN12354-1
Loss factor due to radiation	Formula used is similar to the standard but is frequency dependent and varies by a factor of 2 for frequencies below the critical frequency compared to EN12354. Timmel's [38] correction is also used.	One formula for all frequencies is used.
Laboratory situation (loss factor lab)	A heavy frame of 400 mm concrete around the test area is considered	A heavy frame of 600 mm concrete around the test area is considered

Table 2.2. Comparison of the calculation model for monolithic walls as used by Bastian and EN 12354-1 standard.

2.3 General calculation model

The calculation model used within Bastian allows it to calculate the sound insulation that will occur for the actual field situation. This is done by considering the transmission that will occur between the junctions of adjacent rooms due to the coupling at these junctions as well as the elements present. For the airborne sound insulation between rooms the transmission paths considered by Bastian are the same as those considered by the EN12354-1 standard. The total sound transmission loss can be found from the following, while figure 2.5 gives an illustration of the transmission

paths considered.

$$R' = -10lg \left(\tau_d + \sum \tau_{d,i} + \sum \tau_{e,i} + \sum \tau_{f,i} + \sum \tau_{s,i} \right) \quad (2.5)$$

Where

τ_d is the transmission factor via the separating element

$\tau_{d,i}$ is the transmission factor via inserted elements(i.e. doors, windows etc.)

$\tau_{e,i}$ is the transmission factor via the transmitting elements

$\tau_{f,i}$ is the transmission factor via the flanking elements

$\tau_{s,i}$ is the transmission factor via transmitting systems

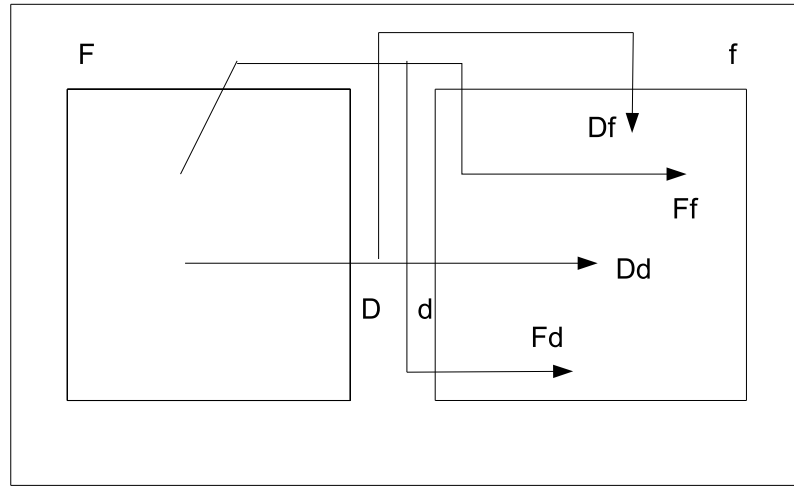


Figure 2.5. Showing the Transmission paths considered in Bastian

Similar, summations are also done for the calculation of the impact sound level and for the air borne sound insulations against outdoor sound according to the standards outlined in Table 2.1. According to the EN12354-1 [9] standard when this approach is used the main assumptions are;

the transmission paths described can be considered to be independent and the sound and vibrational fields behave statistically. With these restrictions this approach is quite general, in principle allowing for various types of structural elements, i.e. monolithic elements, cavity walls, lightweight double leaf walls and different positioning of the two rooms. However, the available possibilities to describe the transmission by each path imposes restrictions in this respect. The model presented is therefore restricted to adjacent rooms, while the type of element is mainly restricted by the available information on the vibration index to monolithic and lightweight double elements. [EN12354-1 [9] page 12]

The above summation/principle forms the primary basis of how the calculations performed by Bastian are complied. This, combined with the calculation of the structural reverberation time, the velocity reduction index and the velocity level difference for the different types of junctions, provide the core means for the calculations performed by the program. In the following sections it will be shown as an example exactly how these parameters are used in the calculation of the airborne sound insulation between two adjacent rooms. The procedure for impact sound insulation as well as for the sound insulation against outdoor noise follows that of their respective standard, and is quite similar to the procedure for the airborne sound insulation between adjacent rooms. However, regardless of the calculation parameter selected in Bastian the following must be specified;

- The room dimensions
- The construction of elements in the rooms
- The type of junctions present
- The coupling between the junctions
- The type of excitation (i.e either airborne sound or impact sound)
- The direction of transmission

2.4 Airborne sound insulation between rooms

The calculation model used for the airborne sound insulation between adjacent rooms is based on the model presented within the EN12354-1 [9] standard. The total sound reduction can be found from the summation given by equation 2.5 while the sound reduction for both the direct path (R_{Dd}) and for the flanking paths (R_{ij}) can be calculation from equations and below.

$$R_{Rd} = R_{s,situ} + \Delta R_{D,situ} + \Delta R_{d,situ} \quad (2.6)$$

$$R_{ij} = \frac{R_{i,situ}}{2} + \Delta R_{i,situ} + \frac{R_{j,situ}}{2} + \Delta R_{j,situ} + \overline{D_{v,ij,situ}} + 10 \log \frac{S_s}{\sqrt{S_i S_j}} \quad (2.7)$$

Equation 2.6 simply indicates that the actual field sound reduction for the direct path can be found from the summation of the field sound reduction of the separating element ($R_{s,situ}$) and the sound reduction improvement that occurs from having additional layers on either the sending ($\Delta R_{D,situ}$) or receiving ($\Delta R_{d,situ}$) side of the separating element. The sound reduction improvement for additional layers such as floating floors, wall linings etc. is based on the model presented in Annex D of the EN12354-1 [9] standard. For the flanking path moving from the sending to the receiving room (R_{ij}), the actual field sound reduction can be found from the

summation of the actual field sound reduction of the flanking elements ($R_{i,situ}$ and $R_{j,situ}$), the addition improvement layers on these elements ($\Delta R_{i,situ}$ and $\Delta R_{j,situ}$), the vibration reduction index for the junction ($\overline{D_{v,ij,situ}}$) and from a ratio between the areas of the separating element and the flanking elements as seen in equation 2.7.

In order to calculate the actual field sound reduction in equations 2.6 and 2.7 the structural reverberation time has to be calculated in order to convert the laboratory calculations. This conversion from the laboratory to the in situ (i.e. field) values is done by using the following equation according to the EN12354-1 [9] standard.

$$R_{situ} = R - 10 \log_{10} \frac{T_{s,situ}}{T_{s,lab}} \quad (2.8)$$

According to Bastian's help file [17] the in situ structural reverberation time ($T_{s,situ}$) can be calculated according to EN12354-1 [9], Craik [7] (A method that uses SEA) or Fischer et al [13] (A method that accounts for the loss factor when measuring and calculating the sound reduction of heavy walls). Regardless of the method used, the structural reverberation time calculation is based on equation 2.11. The difference between the different methods occurs when calculating η_{tot} . When the calculations are done according to either Craik and Fischer, η_{tot} is calculated according to equations 2.9 or 2.10 respectively. If ($T_{s,situ}$) is calculated according to the EN12354 standard then η_{tot} is calculated in the same manner as for $T_{s,lab}$.

$$\eta_{tot,situ} = 0.015 + \frac{1}{\sqrt{f}} \quad (2.9)$$

$$\eta_{tot,situ} = 10^{0.1[-12.4-3.3\log(f/100)]} \quad (2.10)$$

The structural reverberation time in the laboratory ($T_{s,lab}$) is based on the EN12354-1 standard. According to the help file the laboratory situation is simulated by a concrete frame 400 mm thick, while the energy transmission at the perimeter of the test element is represented by a rigid T-junction. When the model presented within the standard is used, the structural reverberation time is calculated from the following;

$$T_s = \frac{2.2}{f\eta_{tot}} \quad (2.11)$$

Where η_{tot} is the total loss factor (i.e. the sum of all the internal losses, losses due to radiation as well as losses that occur at the perimeter of the element). The internal loss factor for the structure has to be inputted into Bastian (this is included within the construction data stored within Bastian and is required if the user chooses to input a new construction). The losses due to radiation is frequency dependent and utilizes Timmels correction [38] according to the following (the deviation of $\sigma_{T,corr}$ was discussed in section 2.2.3);

$$\eta_{rad} = \begin{cases} \left(\frac{2\rho_o c_o \sigma_{T,corr}}{\pi f \dot{m}} \right) & f < \frac{f_c}{10^{\frac{1}{20}}} \\ \left(\frac{\rho_o c_o \sigma_{T,corr}}{\pi f \dot{m}} \right) & \frac{f_c}{10^{\frac{1}{20}}} < f < f_c \cdot 10^{\frac{1}{20}} \\ \left(\frac{2\rho_o c_o \sigma_{T,corr}}{\pi f \dot{m}} \right) & f > f_c \cdot 10^{\frac{1}{20}} \end{cases}$$

This relationship used by Bastian is very similar to the one used within the EN12354 standard. The only two differences that occur are that the standard does not utilize Timmel's correction and the relationship used by Bastian's for the frequency range ($f < \frac{f_c}{10^{\frac{1}{20}}}$) is twice that of the standard.

For the losses that occur at the perimeter Bastian uses the following;

$$\eta_{peri,lab} = \frac{c_o}{\pi^2 S \sqrt{f \cdot f_{c,element}}} \cdot U \cdot \alpha_k \quad (2.12)$$

Where

$f_{c,element}$ is the critical frequency of the panel being tested

U is the perimeter of the element

α_k is the absorption coefficient

Within the calculation model used by Bastian it is assumed that double energy is transferred due to the coupling of the plates in the sending and the receiving rooms. Therefore allowing the absorption coefficient in equation 2.12 to be calculated according to;

$$\alpha_k = 2 \sqrt{\frac{f_{c,frame}}{f_{ref}}} \cdot 10^{-K_{ij}/10} \quad (2.13)$$

Where

$f_{c,frame}$ is 46 Hz (i.e. the critical frequency of the 400mm concrete frame)

f_{ref} is 1000 Hz (i.e. the reference frequency)

K_{ij} is the vibration reduction index

The Vibration reduction index (i.e. K_{ij}) for junctions gives a measure of the attenuation of sound that occurs due to vibrations at the junctions. Within Bastian this calculation for various types of junctions are based on generalized data from measurements of the velocity level difference that can be found within the EN12354-1 standard. According to Gerretsen [16] in most cases the vibration level difference

is frequency independent, and could be based on one number. Gerretsen indicates that this is true for the cases when almost only homogeneous building materials are used. However, for the cases when lightweight or double leaf constructions are used a small frequency dependence can be seen. As a result one has to be careful when selecting the junction type that one uses when making predictions within Bastian. Careful attention should be paid not only on type of junction (i.e. rigid cross, rigid T junction etc.) but also on the construction of the panels at these junction.

As mentioned above a rigid T junction (see figure 2.6) is considered in the calculation of $T_{s,lab}$. According to the EN12354-1 standard the vibration reduction index for this type of junction can be found by using equations 2.14 and 2.15, while the quantity M can be found by using equation 2.16

$$K_{13} = 5.7 + 14.1M + 5.7M^2 \quad (2.14)$$

$$K_{12} = 5.7 + 5.7M^2 \quad (2.15)$$

$$M = \log_{10} \frac{\dot{m}_{\perp i}}{\dot{m}_i} \quad (2.16)$$

Where

m_i is the mass per area of the element i in the transmission path ij in kg/m^2

$m_{\perp i}$ is the mass per area of the other perpendicular element making up this junction in kg/m^2

Bastian also utilizes the formulas mentioned above for a rigid T-junction as well as the other formulas stated within the EN12354-1 standard for other types of junctions. However, as mentioned within the standard these formulas are designed for junctions where the elements at either side of the junction in the same plane have the same mass. For the case of the rigid T-junction this means that m_1 and m_3 in figure 2.6 has to be equal. Practically, this means that the mass per area of the walls in the sending room and in the receiving room, in the same plane has to be equal in order for the equations utilized to be valid in their true sense. Obviously, in reality this may not be the case in many situations. As a result, in order to compensate for the difference in the mass per area that may occur Bastian uses the mean value in order to calculate M as shown in equation 2.17.

$$M = \log_{10} \frac{\dot{m}_{\perp i}}{0.5(\dot{m}_i + \dot{m}_j)} \quad (2.17)$$

Where m_i and m_j in the denominator represents the mass per area of the walls in the sending and receiving rooms respectively. The approximation used in equation

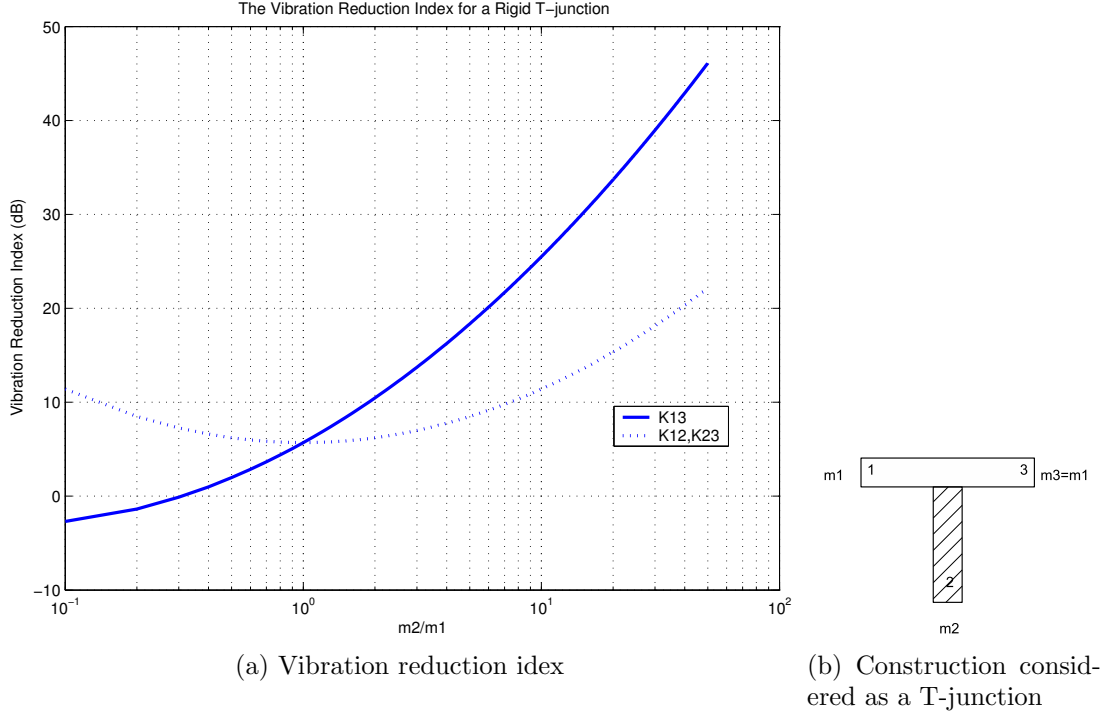


Figure 2.6. Showing the construction of a rigid T junction as well as how the vibration reduction index varies according to the mass ratio m_2/m_1

2.17 is not mentioned within the standard. Consequently great care must be paid when using Bastian if a large difference exist between the mass per area of the wall in the sending and receiving rooms in the same plane, as an invalid value may result for the vibration reduction index. This may occur as information on the effect of having these different masses is not available.

Once the vibration reduction index is found then the absorption coefficient (α_k) and consequently the losses that occur at the perimeter ($\eta_{peri,lab}$) can be found according to the equations given above. The total losses and consequently the structural reverberation time can be found according to equation 2.11. While, $T_{s,situ}$ when calculated according to the standard, is calculated in the same manner as $T_{s,lab}$ above but the parameters (i.e. the junction type, mass per unit area etc.) may be different.

For doors, windows, small elements and systems the in situ values are taken as being equal to the laboratory values as $T_{s,situ}$ is taken as being equal $T_{s,lab}$ in equation 2.8. This agrees with the standard when it states that the correction term in equation 2.8 (i.e. $10 \log_{10} \frac{T_{s,situ}}{T_{s,lab}}$) can be taken as 0 for the following elements;

- lightweight, double leaf elements, such as timber framed or metal framed studs
- elements with an internal loss factor greater than 0.03
- elements which are much lighter than the surrounding structural elements (by

a factor of at least three)

- elements which are not firmly connected to the surrounding structural elements

As a result, for doors and windows since $T_{s,situ}$ is taken as being equal to $T_{s,lab}$ its transmission loss ($\tau_{d,i}$) can be found from the following;

$$\tau_{d,i} = \frac{S_{d,i}}{S_s} 10^{-R_{d,i}/10} \quad (2.18)$$

Where $S_{d,i}$ and S_s represents the area of the inserted element and the area of the separating wall respectively.

$T_{s,situ}$ may also not be calculated when calculating the equivalent absorption length (i.e. $a_{i,situ}$ or $a_{j,situ}$) if the element fulfills the criteria mentioned above. In such cases the equivalent absorption length is taken as being equivalent to the area of the element. This length is used in the calculation of the junction velocity level difference ($\overline{D_{v,ij,situ}}$) as follows;

$$\overline{D_{v,ij,situ}} = K_{ij} - 10 \log_{10} \frac{l_{ij}}{\sqrt{a_{i,situ} a_{j,situ}}} \quad (2.19)$$

Where

$$a_{i,situ} = \frac{2.2\pi^2 S_i}{c_o T_{s,i,situ}} \sqrt{\frac{f_{ref}}{f}}$$

$$a_{j,situ} = \frac{2.2\pi^2 S_j}{c_o T_{s,j,situ}} \sqrt{\frac{f_{ref}}{f}}$$

l_{ij} is the coupling length of the common junction between elements i and j in meters

f_{ref} is the reference frequency (taken as 1000 Hz in this case)

c_o the speed of sound in air

S_i and S_j is the area of the element in the sending and receiving room respectively in meters

In Bastian the coupling length l_{ij} is taken into account when the coupling between the junctions is defined. The following three options are available;

- Maximum coupling
- Minimum coupling
- User defined coupling

From this the coupling length is obtained. On the other hand S_i and S_j are calculated directly from the room dimensions that are inputted into Bastian. However when windows, doors or other elements are considered these areas (i.e. S_i and S_j) must be adjusted in order to compensate for the presence of these additional elements. This is done by subtracting the area of these additional elements from the area of the walls. Bastian provides provisions for making this subtraction to correct the construction data. If this is not done the resulting sound reduction will be incorrect.

Once all of the above parameters are found then the the total sound reduction for the room can be found from the summation given in equation 2.5 above. A summary of exactly how all of these parameters are connected in order to do this summation is given in figure 2.7. In this figure the parameters that are enclosed within a rectangle are those that are inputted or selected by the user for the specific situation and must be entered for any calculation performed by Bastian. Those parameters enclosed within a circle on the other hand are parameters that are calculated using these input parameters. For example, in order to calculate η_{peri} one must calculate the α_k and K_{ij} first as in equation 2.13. However in order to calculate K_{ij} the \dot{m} from the construction selected must be used to find M as in equation 2.16. The junction type must also be selected so that the right equation for K_{ij} is used. A proper understanding of this figure can help the users easily understand how to design/adjust a room to meet a specific requirement while using Bastian as demonstrated in section 9.2.

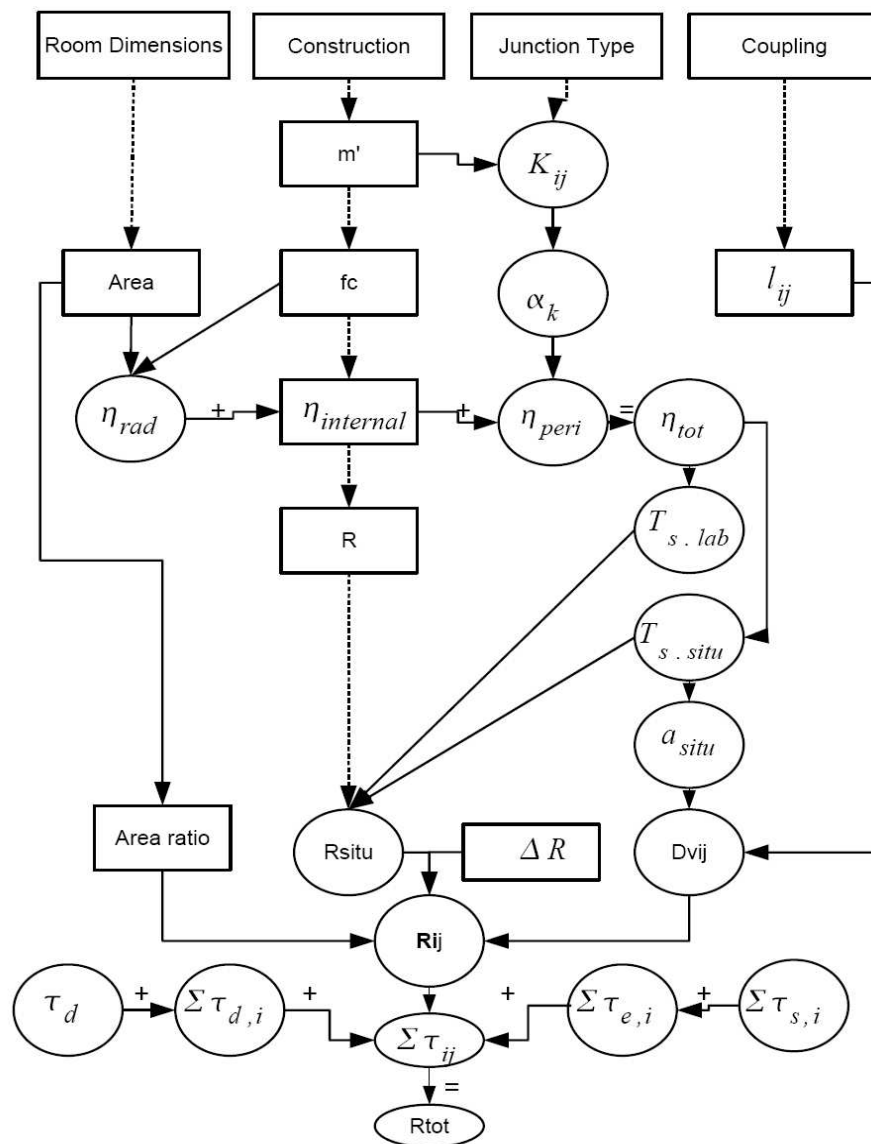


Figure 2.7. Showing how the various parameters contribute to the total sound reduction in the room.

2.5 Summary and Conclusions: Bastian

To summarize all of the information given above, Bastian's primary theoretical basis is based on the quotation given in section 2.3 as well as its consideration of the vibration reduction index for the various junctions and the structural reverberation time. These factors enables Bastian to carry out its calculations for the actual in situ situation. Bastian is not designed to calculate the sound reduction index specifically for building elements as the other programs that will be discussed. Instead, it is primarily designed to calculate the transmission when all of the walls, junctions, ceilings and floors between two rooms are considered. The majority of construction

data stored within the program is based on measurements carried out according to the appropriate standards or from literature. The construction data for heavy single leaf elements and floors for both the sound reduction index and the impact noise level are calculated according to [17]. The calculations of the impact noise level seem to exactly match those within the standard while some differences were found between the standard and the monolithic wall calculation model. Hence the reason for the discussion within section 2.2.

While investigating the theoretical models used by Bastian it was discovered that the user should be aware of the following;

- Should be familiar with assumptions made for the different formulas used such as the those for the radiation factor of free waves as given in section 2.2.3 and for the summation given in section 2.3.
- Should be aware that the area of the panel is only considered when the loss factor is small when calculating the sound reduction of monolithic walls for frequencies below the critical frequency. For panels with medium or large loss factors as well as for the models used within the standard the area is considered for this range (see section 2.2.1)
- Should not compensate for the radiation factor for forced transmission twice when using Bastian in-conjunction with other building element software (see section 2.2.2).
- Should be aware that Bastian does not apply the radiation factor for forced transmission on the direct path. This can therefore be added to the separating element if modeled by a build element software (see section 2.2.2).
- Should consider the type of walls present and not just the connections at junction when selecting the junction type as the vibration reduction index for junctions is frequency dependent for some types of walls.
- Should be cautious about using Bastian if the mass per area of the walls connected to the junctions in the same plane differ by a large amount.
- Should be cautious about using Bastian in situations where the effect of including windows, doors, systems etc. do not meet the requirements that allow for the omission of the calculation of the structural reverberation time.
- Should always make the correction to the area of the walls when including walls, doors etc. in the model.
- Should be aware of how the different calculation parameters are related to each other as shown in figure 2.7.
- Should be aware of the fact that it does not seem as though Bastian adjusts the mass ratio M as in equation 2.16 after a wall lining is added to the separating wall. This seems strange since this ratio directly affects the calculation of the vibration reduction index.

Once the user is aware of the above, then he/she can produce accurate models and be aware of the assumptions and the possible sources of error that may occur due to approximations made within the program. From this investigation into the theoretical basis of the program it was verified that the theories used are primarily based on those used by the standards as the developers claim. Verification of the accuracy of these predictions when compared with measurements will be investigated in section 8.

3 Insul

3.1 Insul-Introduction

Insul is a sound insulation program designed for predicting the sound reduction index of building elements such as walls, floors, ceilings and windows. For the calculations of the sound reduction index of a wall; timber studs, staggered timber studs, staggered+resilient rail/bar, steel studs, staggered steel, steel +resilient rail, point connections, double timber studs, double steel studs, rubber isolation clip timber studs as well as rubber isolation steel studs are the available options. For ceilings the following types can be calculated; solid joist, suspended light steel grid, resilient clip or channel, rubber isolation clip and separate joists. For windows on the other hand, the materials available for double glazing are, glass, laminated glass and plexiglass. For both the wall and ceiling calculations rockwool(60 kg/m^3), glass fiber(10 kg/m^3), glass fiber (22 kg/m^3) or nothing can be added as the material present within the cavity.

Insul bases its calculations on models generated by applying the mass law theory, taking the critical frequency into consideration as well as other model approaches that were suggested by B.H Sharp, Cremer and others. It has a limited number of materials built into the program (i.e. approximately 20 to 30). However, the sound reduction index of new materials can be added by directly inputting their values or by calculating them by entering the material's density, critical frequency, surface area as well as the internal dampening of the panel. This feature makes Insul extremely useful and flexible especially if used in combination with other software such as Bastian as done in section 8.1.

In Insul the transmission loss of single or multiple panels can be calculated even if it is composed of two different materials or of two different thickness. Sewell's correction [34] can be added to the calculations as well as an edge dampening correction which is the factor that models energy loss from the edge of the panels.

Insul's help file does not contain a detailed explanation of its theoretical basis, assumptions or equations used. The information given is not specific as it only says that it is based on the mass law theory. As a result, an investigating into the theoretical basis of the program can be difficult and cannot be done without making some assumptions. However, after discovering that K.O Ballagh was the person responsible for the creation of Insul and that he presented the paper: Accuracy of Prediction Methods for Sound Transmission Loss [1] at 33rd International Congress and Exposition on Noise Control Engineering, it was assumed that he used some of the theories discussed within his paper within the program. Using this paper as a guide and investigating the various sources used, a plausible discussion about its theoretical basis is possible. As a result, comparisons will therefore be made between the results obtained while using these assumed theories and the ones obtained from

Insul to validate these suspicions in the following sections.

3.2 Single Panels

From Ballagh's [1] discussion, the manufacture's website [30] as well as from the help file one can assume that Insul uses the modified mass law formula from equation 3.1 to find the sound reduction for thin homogeneous materials below the critical frequency while 3.2 is used for frequencies greater than or equal to the critical frequency.

$$R = 20\log(mf) - 48 \quad (3.1)$$

$$R = 20\log(mf) + 10\log\left(\frac{2\eta f}{\pi f_c}\right) - 44 \quad (3.2)$$

These equations were devised from Cremer's works. Even though they predict the sound reduction index to a satisfactory degree of accuracy, it does not take into account the transmission due to forced transmission. In order to account for this factor, the option to include Swell's correction has to be implemented within the program. When Sewell [34] did this investigation he concluded that his findings were reasonable for frequencies below the critical frequency and is valid once the partition exceeds 10 kg/m^2 . He also concluded that the resonance transmission is often more important when the internal forced transmission is low since it was observed that;

This resonance transmission is 3 dB higher for a partition in a baffle when the internal loss coefficient is small and 6 dB higher when the internal loss coefficient is fairly large. [Sewell [34], page 29]

If the above statement is properly understood then one can discern when the use of Sewell's correction may not be needed while using Insul.

In Ballagh's discussion he indicates that Sewell's corrections should be used for typical test construction areas between $10\text{-}12 \text{ m}^2$ and for frequencies less than 200 Hz. This correction can be implemented by using equation 3.3.

$$\Delta R = -\log_{10}[\ln(kA^{\frac{1}{2}})] + 20\log_{10}\left[1 - \left(\frac{\omega}{\omega_c}\right)^2\right] \quad (3.3)$$

Where k represents the wave number.

Using the above theories, the sound reduction index of 26 mm, 2300 kg/m^3 concrete was calculated using the Matlab code in appendix A.3 and the results are shown

in figure 3.1. This figure shows the calculated results with and without Swell's correction as well as the results produced directly from the program. From this it can be seen that the results produced by the assumed theories matches well with those produced by the program up to approximately 1000 Hz. The reason for the discrepancies above this frequency is simply due to the fact that the correction required for thick walls was not taken into account as the exact method used within Insul was not clearly known. The correction used is a combination of Ljunngren's [27] and Rindel's thick wall formulations according to the developers [30]. Such a correction would reduce the obtained sound reduction index by some degree and will probably match the results obtained from within the Insul model. Furthermore, figure 3.1 does indicate that the expected reduction in the sound reduction index that occurs within thick walls especially at high frequencies is taken into account as the manufactures claim, as a deviation from the ordinary mass law can be seen.

Based on Ballagh's discussion, the manufactures website [30] as well as the results shown in figure 3.1 it would seem as though the theories and formulas mentioned above form the theoretical bases for the single panels within Insul.

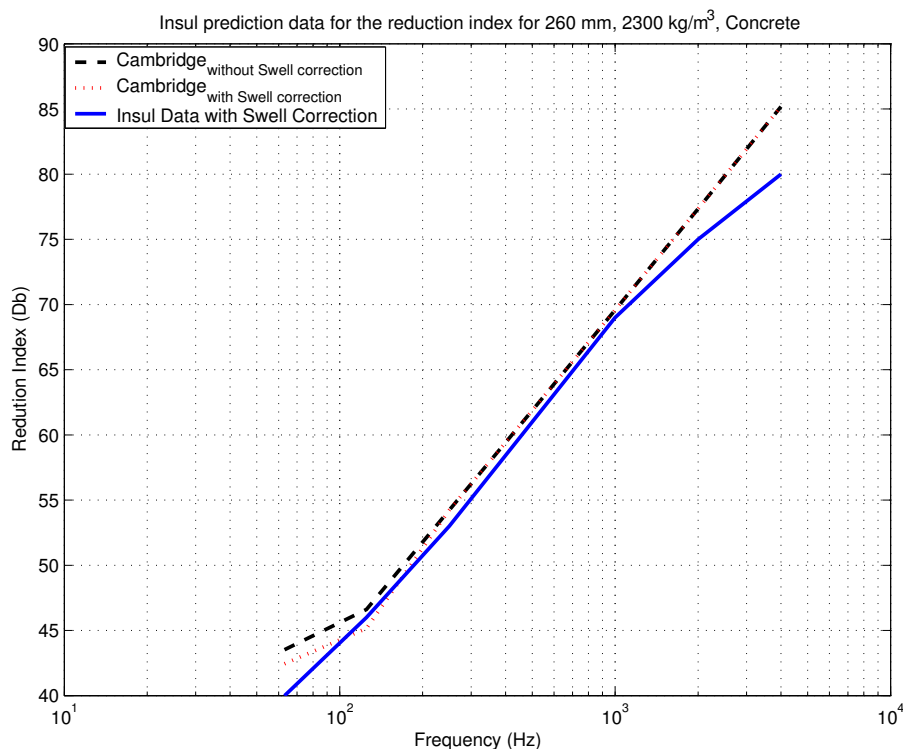


Figure 3.1. Comparing the results obtained while using Insul and those obtained while using the suspected theory

3.3 Double Panels

For double wall panels it is assumed that Insul implements the following relationship that were discussed by Sharp [35].

$$R = \begin{cases} 20\log(f(m_1 + m_2)) - 47 & f < f_0 \\ R_1 + R_2 + 20\log(fd) - 29 & f \geq f_0 \leq f_l \\ R_1 + R_2 + 6 & f \geq f_l \end{cases}$$

Where

m_1, m_2 is the surface mass of each panel

d is the air space between both panels

f_0 is the fundamental mass spring resonance frequency of the of the panel masses and the cavity air stiffness (i.e. $f_0 = \frac{113}{\sqrt{m_e d}}$ where $m_e = \frac{2m_1 m_2}{m_1 + m_2}$)

f_l is equal to $\frac{55}{d}$

R_1, R_2 are the individual transmission loss calculated from 3.2

According to Sharp [35] this relation provides an accurate means of determining the transmission loss for double panels. For this relationship to be valid it is assumed that both panels are mechanically isolated from each other (i.e the only path for airborne transmission is via the airborne path). However, in reality some sort of mechanical connection is often needed so that the construction can withstand lateral loading. According to sharp;

These connections usually take the form of wooden or metal studs in building structures. Their effect is to provide an additional transmission path in parallel to the airborne path previously considered, with the result that the acoustic radiation from the structure is increased and the transmission loss correspondingly reduced. [Sharp, page 59]

These mechanical connections (i.e. studs) are usually connected to the panels in either a line/s or as points. In line connections the two panels are connected along a line or series of lines while in a point connection the connections occur along a small cross-sectional area or a point. According to Sharp [35] both point and line connections can be taken into account in the calculations for the transmission loss by using equations 3.4 and 3.5 respectively. Or alternatively using the practical approximations given by equations 3.6 and 3.7, which were also developed by Sharp.

$$\Delta R = 20\log(ef_c) + K - 45, dB \quad (3.4)$$

$$\Delta R = 10\log(bf_c) + K - 18, dB \quad (3.5)$$

$$\Delta R = 20\log(e f_c) + 20\log \left[\frac{m_1}{(m_1 + m_2)} \right] - 45dB \quad (3.6)$$

$$\Delta R = 20\log(bf_c) + 20\log \left[\frac{m_1}{(m_1 + m_2)} \right] - 18dB \quad (3.7)$$

Where

e is the spacing of the point connections (assumed to be regular) in meters

b is the spacing of the line connections (studs) in meters.

f_c is the highest critical frequency of the two panels.

$$K = 20\log \left[\frac{m_1(Z_1 + Z_2)}{Z_1(m_1 + m_2)} \right]$$

Z is impedance of the panel. For point connections $Z = \left(\frac{4}{\pi}\right) c^2 \left(\frac{m}{f_c}\right)$. For line connections $Z = 2(1 + j)mc \left(\frac{f}{f_c}\right)^{\frac{1}{2}}$

Equations 3.4 and 3.5 were deviated by Sharp [35] by comparing the radiated acoustical power of a wall with studs (W_B) to one without them (W_P). In this deviation the panel impedances were used to calculate the velocity of the panels which were then used to calculate the ratio of the radiated acoustical power with studs to those without them (see [35] for the exact deviation). The reduction in the transmission loss (TL_B) due to the sound bridges were then calculated using the following.

$$TL_B = 10\log \left[1 + \frac{W_B}{W_P} \right] \quad (3.8)$$

According to Ballagh's the resulting corrections shown in 3.6 and 3.7 are valid below the critical frequency of both panels. Starting with the assumptions that the studs are completely stiff, the velocity on both sides of the studs are the same and their mass is negligible compared to the mass of the panels Rindel [32] also developed a correction for the effect of having studs. In this deviation, Rindel used a similar approach to Sharp [35]. The correction developed however is valid over the critical frequencies and also takes into account the boundary conditions, resonances, elastic connections as well as the coupling factor. All of these factors as well as the contribution due to the both connections present (i.e. point and line connections) can be expressed by the following;

$$\Delta R_m = -10\log \left[\frac{8c^2}{S\pi^3 f_{cp}^2} N_p \gamma_p \kappa_p + \frac{2c}{S\pi f_{cl}} \left(L_l \gamma_l \kappa_l + \frac{1}{2} L_r \gamma_r \kappa_r \right) \right] \quad (3.9)$$

The exact meaning of each term can be found within [32]. If line connections are the only parameter considered the correction factor is simply;

$$\Delta R_{m,l} \cong 10 \log \left[\frac{S}{L_t} \frac{\pi f_{cl}}{2c} \right] \quad (3.10)$$

$$f_{cl} = \left[\frac{m_1 \sqrt{f_{c2}} + m_2 \sqrt{f_{c1}}}{m_1 + m_2} \right]^2 \quad (3.11)$$

Based on information given by the developers [30] and from Ballagh's paper, it is assumed that Insul implements a combination of both Sharp and Rindel's theories when considering the effect of studs. Also, based on the fact that Insul can predict the transmission loss for the variety of studs and connections mentioned above in the introduction of this section, it is believed that the effect of the boundary conditions, resonances, elastic connections as well as coupling factor are take definitely take into account for these different types. The resulting differences that can occur while using different types of studs and consequently different boundary conditions, resonances, elasticities can be seen in figure 3.2. By making these specific consideration Insul holds a distinct advantage over Reduct and ENC as it is believed that average values or values obtained when only considering the type of connection (point or line) are utilized.

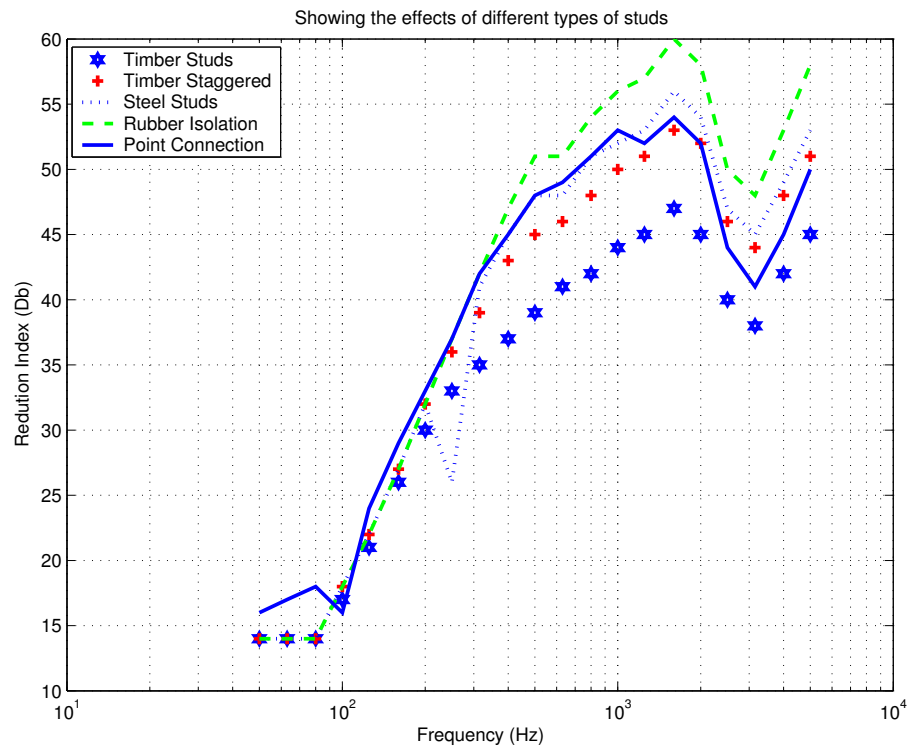


Figure 3.2. Showing the effects of having different types of studs on a Gypsum double wall

For the cases where acoustic absorbent materials are used between the two panels it is believed that Fahy's [12] solution (i.e equation 3.12) is utilized to take this into account based on Ballagh's discussion.

$$R = R_1 + R_2 + 8.6\alpha d + 2 - \log_{10} \left(\frac{\beta}{k} \right) \quad (3.12)$$

Where

α and β are the real and imaginary parts of the propagation coefficient of the absorptive blanket

k is the wave number

According to Kernen [23] this propagation coefficient (i.e. $\gamma = \alpha + i\beta$) can be found according to Delany and Bazley by the following;

$$\gamma = \frac{\omega}{c_0} 0.189 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.595} + \frac{i\omega}{c_0} \left[1 + 0.0978 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.700} \right] \quad (3.13)$$

Where

σ is the flow resistivity.

According to Fahy [12] the 8.6α in equation 3.12 corresponds to;

the attenuation of the waves traveling through the absorptive material. The physical interpretation of eq.. is that the incident acoustic wave is progressively attenuated by passage through the first leaf, the absorbent and the second leaf, and provided that $\alpha d \geq 1$, there is effectively no acoustic coupling between the two leaves. [Fahy, page 175]

In other words no connections (i.e. studs etc.) are assumed to be present. In Ballagh's [1] paper however, he indicates that equation 3.12 is valid for $f \geq f_l$ (i.e $\frac{55}{d}$) as opposed to the $\alpha d \geq 1$ criteria outlined by Fahy. Therefore it can be assumed that this criteria was used with the program.

Using these above theories the sound reduction of a gypsum double wall with steel studs and rockwool between the panels was calculated and compared to results obtained while using Insul. The results of which can be see in figure 3.3.

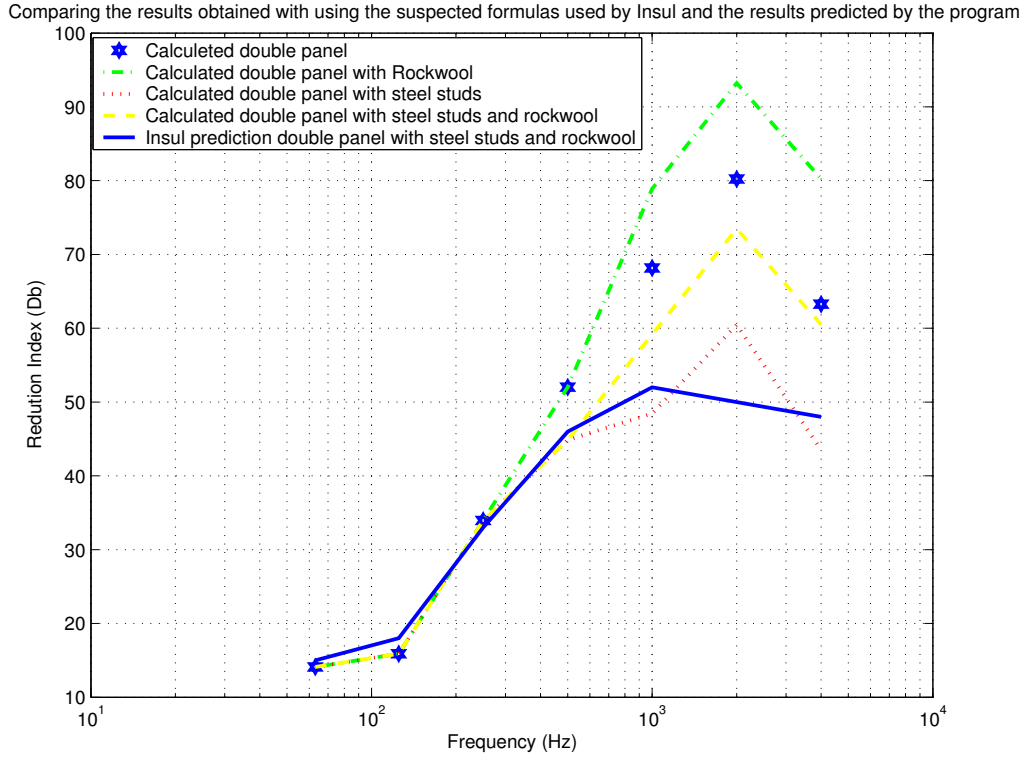


Figure 3.3. Comparing the results obtained with using the suspected formulas used by Insul and the results predicted by the program

From the results obtained different aspects of the assumed theories used by Insul and may be validated for the following frequency ranges.

$$f \leq f_0$$

Since the results obtained using the assumed theories matches that which were predicted by Insul for frequencies below the first mass spring resonance, f_0 (i.e. 107 Hz in this case) one can assume that the same method/theories were used within the program for this region.

$$f_0 \leq f \leq f_l$$

For the region greater than f_0 but less than f_l (i.e. the frequency where the wavelength is not as large as the cavity, otherwise known as the knee or limiting frequency $f_l = 786$ Hz in this case) the suspected theory has also been validated. As the reduction in the transmission loss due to the studs can be seen as the calculations made in this region based on Sharp's theories exactly matches those predicted by the Insul program.

$$f \geq f_l$$

For this region it may seem as though the theories used within the program are completely different from those obtained while using the assumed theories as the

results do not match. Also, since the results obtained while using the assumed theories for the double wall with studs better matches the results obtained when the absorption material is also considered in-conjunction with the studs. It may seem as though the suspected theories used for the calculations for the absorptive material within the panel may not have been utilized within the program. However, this may not be the case, as a number of factors that were not known or considered during the calculations may account for these large discrepancies.

The first factor that may cause the differences seen within this region is the fact that the flow resistivity of the rockwool stored within Insul is not given and cannot be accessed. As a result, the values used for the calculations were the ones that were found at from literature [4]. Since the effect of the absorptive material only occurs within this region this could explain the differences obtained.

The second factor that may account for the differences seen within this region comes from the fact that the boundary conditions as well as the resonances were not accounted for as outlined by Rindel. Instead the formulation for a line connection of studs as outlined by equation 3.10 was used. If the resonances were accounted for, the sound reduction would be decreased and should come close to the results obtained using from using Insul.

Finally, an error may have also occurred from the fact that there is no real designation in the frequency range where Sharp theories as opposed to Rindel's theories ought to be used. This could affect the obtained results. For the calculations done using the assumed theories Sharp's theories were used from $0.5 f_l$ to f_l while Rindel's were applied for frequencies greater than this range. Also, it cannot be known for sure based on the information given by the developers exactly how these two theories are implemented. However, at least from the results shown in 3.3 one can assume that it was done in some way.

3.4 Summary: Insul

Insul is a sound insulation program designed to calculate both the airborne and impact sound insulation of building elements. The theories used within Insul for the calculation of the airborne sound reduction of single panels were analyzed. With the exception of knowing exactly how Insul uses a combination of Ljunggren's and Rindell's thick walls formulas all of the assumed formulas for single panels were verified. The theories used within Insul for double panels below f_l were also analyzed and verified. Above this frequency the assumed theories could not be completely verified as discrepancies occurred. Possible explanations for these discrepancies were discussed and reasons were given why it is believed that the program is based on these theories.

From this analyzing into Insul's theoretical basis users can appreciate and be aware of the following aspects of the program;

- Should appreciate when to add Sewell's correction to their calculations.
- Should be aware that the forced vibrations is only taken into account while using Sewell's correction for frequencies below the 200 Hz
- Should appreciate the variety of options available to deal with various types of studs.
- Should be aware that the boundary conditions, coupling etc. used in the formulas to take into the account the effect of studs may be different from those utilized by programs such as Bastian when exporting values to them.
- Should always verify that the default values used by the program matches the particular situation that is being investigated. In the event that this information is not accessible (such as the values for the flow resistivity) then the frequency range where this parameter directly affects the results should be looked if strange results are obtained.

These are just some of the things users of Insul should appreciate and be aware of. This in combination with the discussion into the theoretical basis as well as the information given by the developers should give the user enough information to create accurate models while using this program. The accuracy of these models produced when compared to measurements will be discussed within section 7.

4 Reduct

4.1 Reduct-Introduction

Reduct is another sound insulation program used to calculate the sound reduction index of various building elements. It is primarily based on Kaj Bodlund's report [3] that was done in 1980 and is used within Ingemansson acoustical consultants in Sweden. Despite the fact that this report was done so long ago, the theories outlined within it are quite similar to those used by Sharp and Rindel as discussed in section 3.3. Consequently, from reviewing the formulas that are outlined within this report it is believed that the theoretical basis of the program are similar to those used within Insul except for some minor differences, and corrections that were added on by the original developer. No information is available about the these additional corrections.

4.2 Reduct-Theoretical Basis

From Kaj Bodlund's [3] report it is believed that Reduct uses the same mass law formula for frequencies below the critical frequency as given by equation 3.1. The mass law can be taken into account up until approximately 0.5 times the critical frequency. Above this frequency Bodlund mentions that the coincidence effect needs to be taken into account. According to Kleiner [24] this coincidence effect can be taken into account between the range of 0.5 to 2 times the critical frequency. It is believed that Insul uses this range for the coincidence effect. According to Bodlund [3] this is can be done through the use of the following equation;

$$R \approx R_{masslaw} + 10\log(\eta) - 8 \quad (4.1)$$

Where $R_{masslaw}$ is found according to 3.1.

Above this frequency range the coincidence controlled region is modeled by the following.

$$R = 20\log\left(\frac{\pi m f}{\rho c}\right) + 10\log\left(\frac{2\eta f}{\pi f_c}\right) \quad (4.2)$$

Using these assumed theories a Matlab code was developed to compare the results obtained from these theories and those generated by Reduct for 180 mm, 2400 kg/m³ concrete. These results are shown in figure 4.1. From this figure it can be seen that the assumed theories matches well to the predictions generated from Reduct. It should be noted, that the coincidence effect was taken from 0.6 to 2 times the

critical frequency (i.e. 87 Hz) since it was believed that this effect started above 50 Hz in this case. From this figure it can be seen that a discrepancy exist between the both predictions around the critical frequency. It is believed that this difference is due to an additional "smoothening" of the graph that the programmer added and not due to a difference in theories.

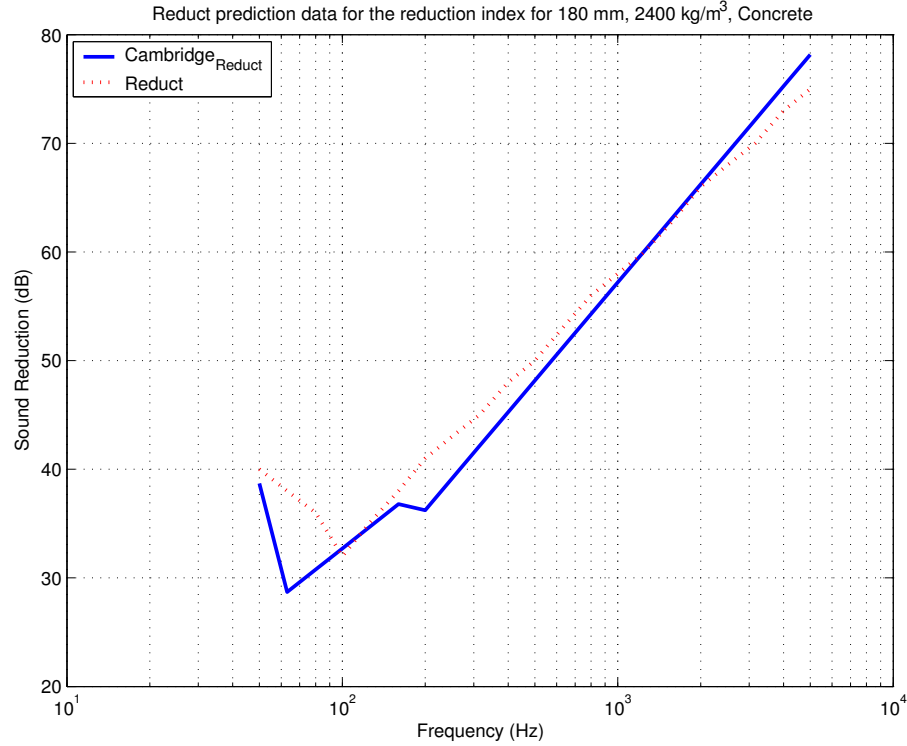


Figure 4.1. Comparison between the assumed theory and prediction generated from Reduct for 180mm, 2400 kg/m³ concrete

The results shown in figure 4.1 are the results for the sound reduction for a laboratory situation. However, in Reduct the developer of the program added an additional correction to convert these laboratory values to in situ (i.e. field) values. This correction is made by simply subtracting 5 dB from each value. Based on the discussion given within 2.4 it would seem as though such an approximation will provide inaccurate results. As this implies that the correction generated from the ratio of the T_{situ} and T_{lab} in equation 2.8 will always be equal to 5. This obviously will not always be the case as the structural reverberation time is affected by other parameters such as the junction type, mass etc. As a result, the accuracy of this 5 dB correction that is used within Reduct was tested by comparing it to the correction that one will obtain if both T_{situ} and T_{lab} were calculated. The calculations for the structural reverberation times were done by using Bastian, for a 180 mm, 2400 kg/m³ concrete while connected to a rigid T junction. The difference between the 5 dB and the correction obtained through the use of the structural reverberation times is shown in Table 4.1. The standard deviation is also shown within this table and is also represented graphically as error bars in figure 4.2. From these results one

can see that the 5 dB correction utilized by Reduct is an overestimation as above 500 Hz the difference between both corrections ranges from between 1 and 2.28 dB. However, this correction may be justified if one only looks at the weighted sound reduction index. This can occur because a heavier weighting is placed on this index for the lower frequencies and because of the fact that the weighted sound reduction index varies in 1 integer increments. Since the difference between both corrections is small for the lower frequencies then the overall difference between both could be only be 1 or 2 dB. Therefore justifying the use of the 5 dB correction as a rough estimate for this case. However, it must be stressed that this is truly a rough estimate as it may not be justified for other junction types.

Frequency	Tsitu	Tlab	Correction	Difference	STD
50	0.208	0.569	4.3705	0.62951	0.44513
63	0.183	0.503	4.3912	0.60883	0.43051
80	0.163	0.446	4.3715	0.62853	0.44444
100	0.147	0.412	4.4758	0.5242	0.37067
125	0.13	0.358	4.3994	0.6006	0.42469
160	0.115	0.313	4.3485	0.65154	0.4607
200	0.102	0.273	4.2756	0.72438	0.51221
250	0.09	0.237	4.2051	0.79494	0.56211
315	0.079	0.205	4.1413	0.85873	0.60722
400	0.07	0.177	4.0288	0.97125	0.68678
500	0.061	0.152	3.9651	1.0349	0.73176
630	0.054	0.13	3.8155	1.1845	0.83757
800	0.047	0.111	3.7323	1.2677	0.89643
1000	0.041	0.095	3.6494	1.3506	0.95502
1250	0.036	0.08	3.4679	1.5321	1.0834
1600	0.031	0.068	3.4115	1.5885	1.1233
2000	0.027	0.057	3.2451	1.7549	1.2409
2500	0.023	0.048	3.1951	1.8049	1.2762
3150	0.02	0.04	3.0103	1.9897	1.4069
4000	0.017	0.033	2.8807	2.1193	1.4986
5000	0.015	0.028	2.7107	2.2893	1.6188

Table 4.1. Showing the difference in the correction required to convert the laboratory predictions to field predictions when using the 5 dB correction as compared to the use of the T_{lab} and T_{situ}

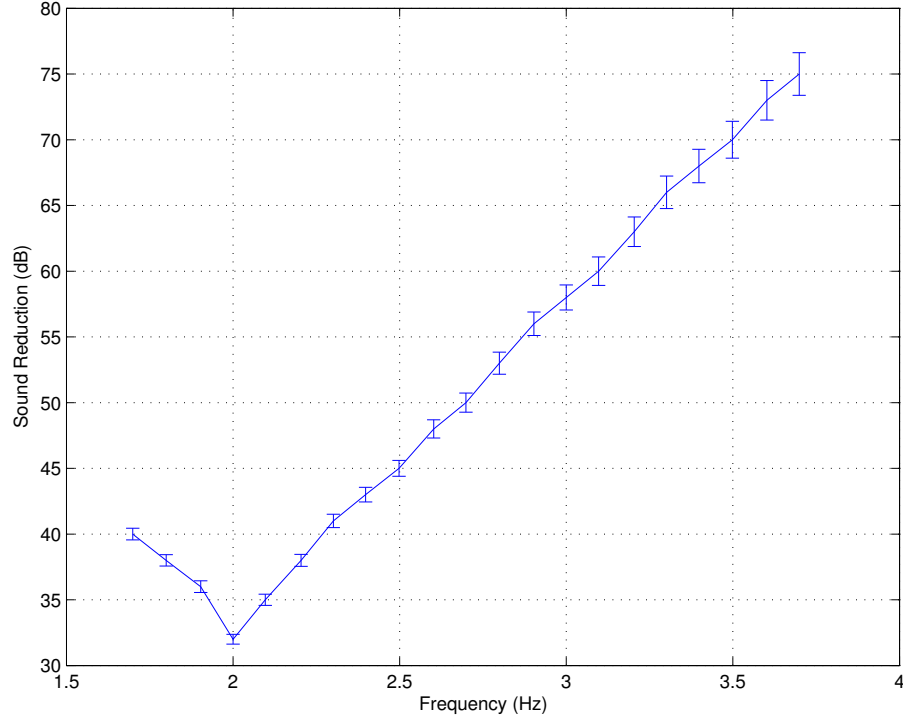


Figure 4.2. Showing the standard deviation between using the 5 dB correction in Reduct to the correction derived from calculating T_{lab} and T_{situ}

For double walls it is believed that Reduct uses similar theories as Insul. However, one clear difference between both approaches comes about when considering the effect that studs have on the prediction. It is believed that the following which were stated in Bodlund's report are utilized by Reduct;

$$\Delta R_M = 20 \log \left[\frac{m_1 f_{c2}^{\frac{1}{2}} + m_2 f_{c1}^{\frac{1}{2}}}{m_1 + m_2} \right] + 10 \log b - 23.4 \quad (4.3)$$

$$\Delta R_M = 20 \log \left[\frac{m_1 f_{c2}^{\frac{1}{2}} + m_2 f_{c1}^{\frac{1}{2}}}{m_1 + m_2} \right] + 20 \log e - 44.8 \quad (4.4)$$

These equations that were derived by Bodlund are quite similar for the ones formulated by Rindel for both point and line connections. They, however do not account for resonances, different boundary conditions or elasticities. This difference will directly affect the predictions made by Reduct near to and greater than the critical frequency. Taking these factors into account should reduce the predicted transmission loss around this region.

4.3 Summary Reduct

Reduct is sound insulation program used to calculate the sound reduction index of various building elements. It is primarily based on Kaj Bodlund's report [3] that was done in 1980 and is used within Ingemansson acoustical consultants in Sweden. It extremely similar to Insul, so users of Reduct should also be aware of the same things that users of Insul should be aware of as outlined in section 3.4. Reduct attempts to add a correction factor to correct the laboratory values for single monolithic structures to in-situ values by simply subtracting 5 dB from each value. This correction was not outlined within Bodlund's report [3] but was a simple addition added on by the creator of the program. It was discovered that this correction was a rough estimate as it did not take into account the junction type, boundary conditions etc. that may be present as discussed above. The accuracy of the models created by Reduct when compared to measurements will be discussed within section 7.

5 ENC

5.1 ENC-Introduction

ENC is an acoustical program that is essentially a supplement to the book Engineering Noise Control [2]. The program covers every area outlined within this book ranging from calculations concerning some of the fundamentals of acoustics (such as the addition of decibels) to more complicated calculations involving the power radiated from machines. However, for the purposes of this report only the module relating to sound insulation will be discussed. Within this module calculations can be carried out for single, double and composite panels as well as for enclosures, indoor and outdoor barriers. Since this program supplements all of the theories, formulas and necessary assumptions that are outlined within [2] this will be used in conjunction with the help file to analysis the program. Furthermore, since [2] gives a full discussion about all the assumptions, equations etc. the proceeding discussion only outline the necessary theories/information that are essential to understanding the program.

5.2 ENC-Single Panels

Within the ENC program the transmission loss for both isotropic and orthotropic panels can be calculated. Isotropic panels are uniform with one critical frequency while orthotropic panels have varying stiffness with more than one critical frequency depending on the direction of the incident acoustical wave.

For the isotropic panels either Sharp's model or the model proposed by Davy J.L can be used. The essential difference between these two models relates to the way in which both treats the limiting angle. This angle greatly affects the results obtained for the transmission coefficient. In Sharp's model a constant limiting angle $\approx 85^\circ$ is used while a frequency dependent angle according to equation 5.1 is utilized within Davy's Model.

$$\theta_L = \cos^{-1} \sqrt{\frac{\lambda}{2\pi\sqrt{A}}} \quad (5.1)$$

As a result the sound reduction according to Sharp's model below the critical frequency can be calculated according to equation 3.1 while equation 4.2 can be used above the critical frequency. On the other hand the transmission loss while using Davy's model can be found while using the following relations.

$$TL = \begin{cases} 20\log_{10} \left[\frac{\pi f m}{\rho c} \right] + 20\log_{10} \left[1 - \left(\frac{f}{f_c} \right)^2 \right] - 10\log_{10} \left[\log_e \left(\frac{1+a^2}{1+a^2 \cos^2 \theta_L} \right) \right] & f < 0.95f_c \\ 20\log_{10} \left[\frac{\pi f m}{\rho c} \right] + 10\log_{10} \left[\frac{2\eta \Delta_b}{\pi} \right] & 0.95f_c < f < 1.2f_c \\ 20\log_{10} \left[\frac{\pi f m}{\rho c} \right] + 10\log_{10} \left[\left(\frac{2\eta}{\pi} \right) \left(\frac{f}{f_c} - 1 \right) \right] & f \geq 1.2f_c \end{cases}$$

Where $a = \left(\frac{\pi f m}{\rho c} \right) \left[1 - \left(\frac{f}{f_c} \right)^2 \right]$ and Δ_b is the ratio of the filter bandwidth to the filter center frequency used for measurements. Therefore $\Delta_b = 0.236$ for one third octave bands and 0.707 for octave bands.

A comparison between these two models can be seen in figure 5.1. From this figure the differences between the way both models predict the sound reduction at the low frequencies and around the critical frequency can be seen. According to [2]:

the Davy method generally is more accurate at low frequencies while the Sharp method gives better results around the critical frequency of the panel.[ENC page 355]

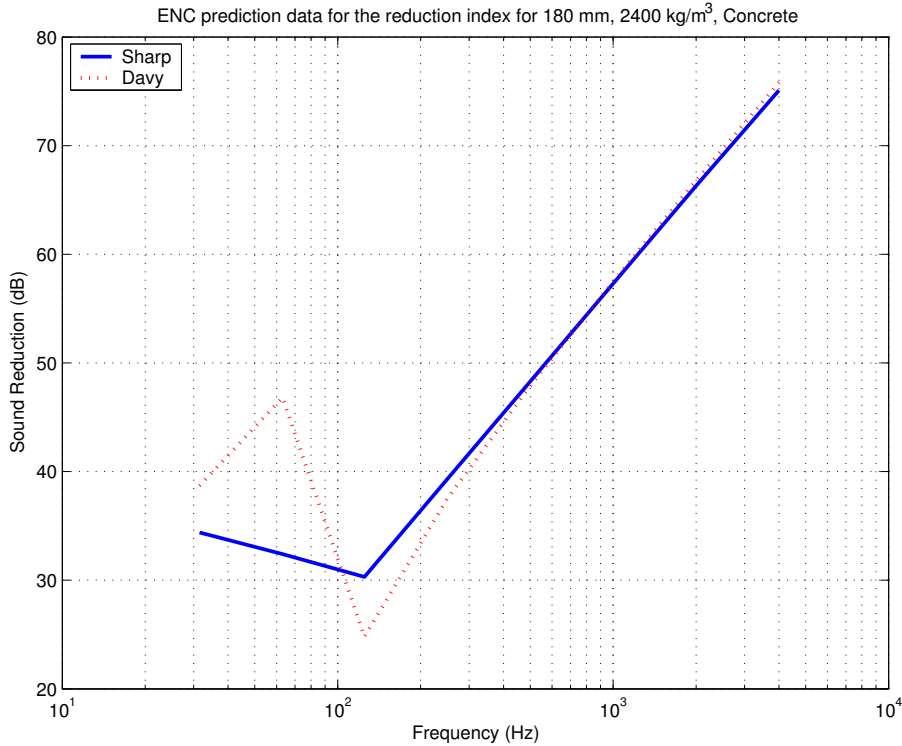


Figure 5.1. Comparison between the predictions generated by ENC while using Sharp and Davy's model for 180 mm concrete, 2400 kg/m³

If this quotation is taken to heart, then one can use both models in comparison with each other in order to obtain an accurate sense of the prediction. This can simply be done by using Davy's model for the low frequencies and Sharp's model for around the critical frequency. For the higher frequencies both models give similar predictions as seen in figure 5.1.

5.3 ENC-Double Panel

Similar to the case for single panels, predictions within ENC can be modeled according to either Sharp or Davy's works. When modeled according to Sharp's theories the equations for transmission loss for the double panels are the same as those mentioned in section 3.3. However, when considering the effect of having stud, the transmission loss is calculated according to equations 5.2, 5.3 or 5.4 for line-line, point-point and line-point connections respectively.

$$TL_{l-l} = 10\log_{10}m_1 + 10\log_{10}(f_{c2}b) + 20\log_{10}f + 20\log_{10}\left(1 + \frac{m_2f_{c1}^{1/2}}{m_1f_{c2}^{1/2}}\right) - 72 \quad (5.2)$$

$$TL_{p-p} = 10\log_{10}m_1 + 10\log_{10}(f_{c2}e) + 20\log_{10}f + 20\log_{10}\left(1 + \frac{m_2f_{c1}}{m_1f_{c2}}\right) - 99 \quad (5.3)$$

$$TL_{l-p} = 10\log_{10}m_1 + 10\log_{10}(f_{c2}e) + 20\log_{10}f + 10\log_{10}[1 + 2X + X^2] - 93 \quad (5.4)$$

Where $X = \frac{77.7m_2}{m_1e\sqrt{f_{c1}f_{c2}}}$

As mentioned within section 3.3 Sharp's equations are only valid below the critical frequency. According to Bies and Hansen [2] equation 5.2 gives a very good comparisons between predictions and measurements, 5.3 seem to compare fairly with measurements while 5.4 over estimates the transmission loss. With this in mind one can have an idea of the accuracy of the predictions if any of these options are utilized.

As discussed within section 3.3 Sharp made the assumption that the studs are completely stiff when devising his formulas. According to Bies and Hansen [2] this gives a good approximation if wooden studs are used but not if metal studs are utilized. As a result of this ENC provides the option of using Davy's model which takes into account the compliance of the studs. This improves upon Sharp's theories as done by Rindel and Bodlund as used within Insul and Reduct respectively. A comparison between Sharp's and Davy's model can be seen in figure 5.2.

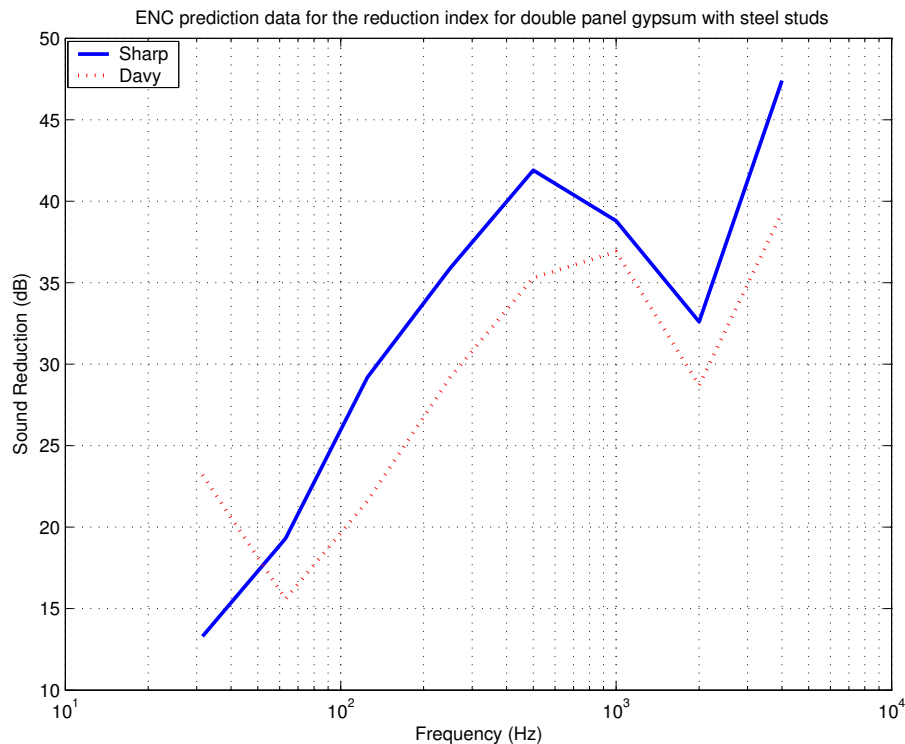


Figure 5.2. ENC prediction of a gypsum double wall with steel studs according to Sharp and Davy's model

From this figure the effect of taking into account the compliance can clearly be seen as there is a greater reduction in the transmission loss when the Davy's model is utilized.

5.4 Summary:ENC

ENC is essentially a supplement to the book Engineering Noise Control [2]. As a result all the formulas, assumptions etc. used within this program can be found within this book. With regards to the module which deals with the sound insulation, this program provides a lot of useful models and options that can be used to create an accurate model. Once a proper understanding is obtained about the different models that can be created, then a sound judgment can be made about the accuracy of each model within different frequency ranges (As mentioned in section 5.2 when comparing Sharp and Davy's model for single panels). From using and evaluating the theoretical basis of ENC users should appreciate and be cautious of the following.

- Should appreciate the number the different models that can be created within the program
- Should appreciate the fact that the entire program is based on the book Engineering Noise Control [2] so all equations, assumptions etc. used within the

program are readily available. This is not the case of any other program that was evaluated during this thesis

- Should appreciate the range of calculations that could be done by the program
- Should be careful when using the default values as some of these seem to be completely wrong
- Should be extremely careful to update all input values continuously as this is not done automatically as in the other programs since the user has to select "run" each time.

The accuracy of the models produced by ENC when compared to measurements will be discussed within section 7.

6 Winflag

6.1 Winflag-Introduction

Winflag is a program designed to calculate the sound reduction index, impedance and absorption coefficient for various materials. Its help file has a very detailed description of the properties, theoretical basis (including some of the formulas, transfer matrices etc.) as well as the sources of the information used. Consequently the proceeding discussion will be based on a combination of information outlined in this source and from the mentioned references.

As opposed to Bastian and Insul which used general formulas in their calculation of the reduction index, the method employed by the Winflag program is one which uses different transfer matrices to represent different layers in order to carry out the necessary calculations. The complexity of these transfer matrices are more advanced than the equations used within either Bastian or Insul. According to the help file;

This program is modeling the acoustic properties of a combination of such layered materials using the transfer matrix method. Basically, each layer in the combination, assumed to be infinite extent, is represented by a matrix giving the relationship between a set of physical variables on the input and the output side of the layer. These matrices may then be combined to give the relationship between the relevant physical variable for the whole combination. Characteristic data as the absorption coefficient, input impedance and the transmission loss (sound reduction index) may then be calculated assuming wave incidence. [Winflag help file]

From this quote two things can be gathered about the two major parameters that are required for the calculation of the absorption coefficient, input impedance or transmission loss. These two parameters are the material layers and the angle of wave incidence.

Firstly, the different material layers that are available within the program are as follows;

- Air
- Porous/Delany-Bazley
- Porous/Mechel
- Porous/Attenborough

- Porous/Allard-Johnson
- Slotted plate
- Perforated plate
- Micro-perforated plate
- Limp mass
- Thin plate(panel)
- Thick plate(elastic)
- Sandwich
- Hard wall
- Add layer from file

The disadvantage of having so many types of material layers and consequently so many transfer matrices is that it may confuse the average user, because of the many options that one has, even though it is simple to use once the help file is carefully read. Conversely, its advantage is that once these options (e.g like the different models available for the porous materials) are properly understood then the program could effectively be applied to a wide variety of situations.

In order to use any of the above layers, the appropriate parameters must be entered. Tables 6.1 and 6.2 show the required parameters that are needed for the porous and plate elements respectfully. These tables can greatly help clarify some of the differences between the different models, based on the input requirements. However, it must be stressed that great attention must be placed on the definition of these parameters as an improper understanding of which will lead to errors. For example, even though the input requirements for both the thick and thin plates are the same, the results shown in figure 6.1 for concrete 180 mm thick enough to be simulated as a thick plate demonstrates the importances of understanding the definition of each layer. The layers are not interchangeable, and should not be selected primarily based on the availability of the required input values. The differences shown in figure 6.1 can clearly be seen as the decrease in the reduction index as described in section 2.2.4 cannot be seen with the thin plate layer, thus emphasizing the point that proper understanding of the layers is required.

The second parameter required for the calculation of the absorption coefficient, input impedance or transmission loss is the angle of incidence. This feature can be useful if investigating a situation where knowing the effect of having different angle of incidence is crucial. For the transmission lose diffuse incidence is required for the calculations of the weighted sound reduction index. The effect of having different angles of incidence can be seen in figure 6.2

Porous Elements				
Property	Delany-Bazley	Mechel	Attenborough	Allard-Johnson
Thickness	X	X	X	X
Resistivity	X	X	X	X
Porosity	N/A	X	X	X
Tortuosity	N/A	N/A	X	X
Viscous length	N/A	N/A	N/A	X
Thermal length	N/A	N/A	N/A	X

Table 6.1. Properties required for the specific porous elements available in Winflag

Plate Elements						
Property	Slotted	Perforated	Micro-perforated	Limp Mass	Thin	Thick
Thickness	X	X	X	X	X	X
Density	X	X	X	X	X	X
Resistance	X	X	X	X	N/A	N/A
Slot width	X	X	N/A	N/A	N/A	N/A
Center to Center Distance	X	X	N/A	N/A	N/A	N/A
Resistance Correction	X	X	N/A	N/A	N/A	N/A
Diameter of hole	N/A	N/A	X	N/A	N/A	N/A
Area/hole	N/A	N/A	X	N/A	N/A	N/A
Young's Modulus	N/A	N/A	N/A	N/A	X	X
Poissons ratio	N/A	N/A	N/A	N/A	X	X
Loss factor	N/A	N/A	N/A	N/A	X	X

Table 6.2. Properties required for the specific plate elements available in Winflag

Where

N/A -Not applicable

X -require parameter

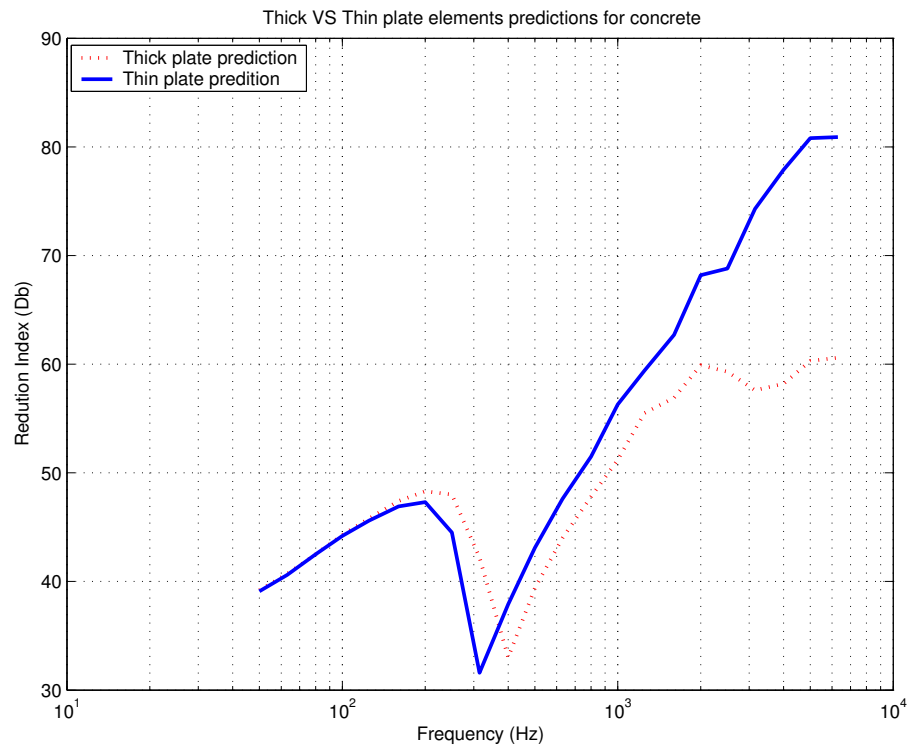


Figure 6.1. Comparision showing the results for 180mm concrete while using the thick and thin plate layer

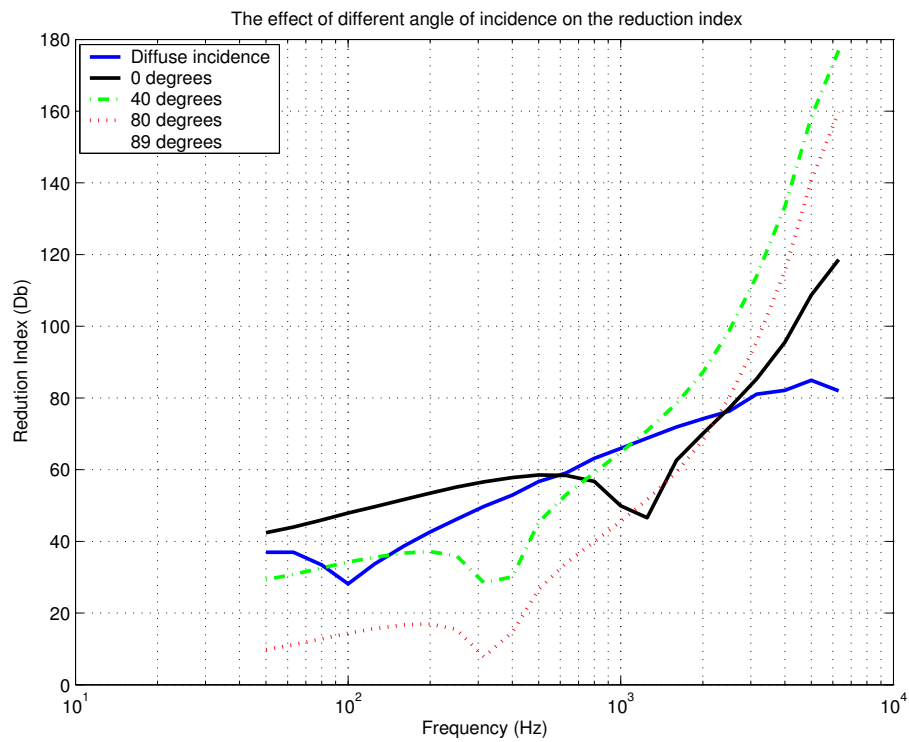


Figure 6.2. The effect of different angle of incidence on the reduction index

An example of how Winflag uses the matrices to find the transmission coefficient for thick wall can be seen below. More details describing all the other layers can be found within the file and will not be discussed here.

6.2 Deviation of matrices used for thick walls

As mentioned within the help file, Ljunggren's theories for thick wall are used within the program. In order to include these results into the program the approach used by Folds and Loggins [14] is used. In this approach the velocities and stress for both longitudinal and transverse waves within a multi-layered material is analysed for the incident and reflected wave. This was done assuming that a plane elastic wave hits a multi-layered material as shown moving in the z direction. Applying the usual boundary conditions of having continuity of the normal and tangential displacements and normal and shear stresses at the interfaces the following potential functions (i.e. the solution to the traditional wave equation) for longitudinal(ϕ_l) and transverse (ψ_l) waves were used;

$$\phi_l = [A_l e^{i\alpha_l z} + B_l e^{-i\alpha_l z}] e^{i(\sigma x - \omega t)} \quad (6.1)$$

$$\psi_l = [C_l e^{i\beta_l z} + D_l e^{-i\beta_l z}] e^{i(\sigma x - \omega t)} \quad (6.2)$$

From this both the velocities(v_x, v_z) and stress(Z_z, Z_x) in both the longitudinal and transverse directions were found based on the following relationships;

$$v_x^{(l)} = \frac{\partial \phi_l}{\partial x} - \frac{\partial \psi_l}{\partial z} \quad (6.3)$$

$$v_z^{(l)} = \frac{\partial \phi_l}{\partial z} + \frac{\partial \psi_l}{\partial x} \quad (6.4)$$

$$Z_z^{(l)} = \frac{i \left[\lambda \left(\frac{\partial v_x^{(l)}}{\partial x} + \frac{\partial v_z^{(l)}}{\partial z} \right) + 2\mu \frac{\partial v_z^{(l)}}{\partial z} \right]}{\omega} \quad (6.5)$$

$$Z_x^{(l)} = \frac{i\mu \left[\frac{\partial v_x^{(l)}}{\partial z} + \frac{\partial v_z^{(l)}}{\partial x} \right]}{\omega} \quad (6.6)$$

Furthermore, using the fact that the velocities and stress at the uppermost layer (i.e. at the surface) is infinitesimal the following general solution was as found;

$$\begin{bmatrix} v_x^{(n)} \\ v_z^{(n)} \\ Z_z^{(n)} \\ Z_x^{(n)} \end{bmatrix} = \begin{bmatrix} a_{11}^{(n)} & a_{12}^{(n)} & a_{13}^{(n)} & a_{14}^{(n)} \\ a_{21}^{(n)} & a_{22}^{(n)} & a_{23}^{(n)} & a_{24}^{(n)} \\ a_{31}^{(n)} & a_{32}^{(n)} & a_{33}^{(n)} & a_{34}^{(n)} \\ a_{41}^{(n)} & a_{42}^{(n)} & a_{43}^{(n)} & a_{44}^{(n)} \end{bmatrix} \begin{bmatrix} v_x^{(n-1)} \\ v_z^{(n-1)} \\ Z_z^{(n-1)} \\ Z_x^{(n-1)} \end{bmatrix}$$

The vlaues of all of the above $a_{ij}^{(n)}$ values are found in the appendix in [14]. However, as mentioned in Winflag's help file under the assumption that the same fluid layers or equivalent fluid layers exist on both sides of the plate only a_{31}, a_{32}, a_{41} and a_{42} are needed to calculate the wall impedance which can then be used to calculate the transmission loss. These parameters can be calculated by the following;

$$a_{31}^{(n)} = -H_n G_n (1 - G_n) (\cos P_n - \cos Q_n) \quad (6.7)$$

$$a_{32}^{(n)} = -iH_n \left[\frac{[(1 - G_n)^2 \sin P_n]}{E_n} + F_n G_n^2 \sin Q_n \right] \quad (6.8)$$

$$a_{41}^{(n)} = -iH_n \left[E_n G_n^2 \sin P_n + \frac{(1 - G_n)^2 \sin Q_n}{F_n} \right] \quad (6.9)$$

$$a_{42}^{(n)} = a_{31}^{(n)} \quad (6.10)$$

The exact meaning of each variable above can be found within [14]. Using these variables both the normal and shear stresses can be found and used to find the wall impedance that occurs due to these two factors. Hence the reason why only the four variables mentioned above are needed. From this, the benefits of using this method for thick walls can immediately be seen since the impedance due to sheer stresses can directly be found. This impedance due to the shear stress is the difference between the thick and thin wall layers used within the program, as the thin wall layer's matrix is found by using the following.

$$Z_W = j\omega m \left[1 - \frac{(f)^2}{(f_c)^2} * (1 + j\eta) \sin^4 \psi \right] \quad (6.11)$$

6.3 Summary: Winflag

Even though the method employed by Winflag is more complicated than the ones utilized by, Bastain, Insul or Reduct, once the theoretical basis of each layer available within the program has been clearly understood, it can prove to be a very flexible and powerful program that can be used for circumstances even outside of building

acoustics. The only disadvantage that this program has as compared to the others is that it does not factor in the effect of having studs. However, this short coming may be overcome by the fact that calculations can be done for structures such as perforated plates and for some other types of structures which cannot be simulated by the other programs. From looking at the various features and the theoretical basis of this program users should appreciate/be cautious of the following;

- Should appreciate the many different types of layers that are available in order to make accurate models.
- Should be cautious about using different types of layers if he/she is not familiar with the theories used. Selection of a particular layer should not be based only on the availability of the required data.
- Should appreciate having the option of being able changing the angle of incidence as most programs do not have this feature.
- Should be cautious about the way one creates a particular model as different options are available. For example a double wall could be modeled as two thin walls with a porous layer in between or simply as a sandwich construction.
- Should appreciate the fact that all data used to create models can be viewed and edited by the user. Therefore giving the user full control over each parameter.
- Should appreciate the fact that this program is able to calculate the impedance as well as the absorption coefficient.

All of these features adds to Winflag's flexibility and dynamic character that enables it to be used for a wide variety of situations. An analysis of how the predictions generated from this program compares to measurements will be done in section 7

7 Program Comparisons

7.1 Program Comparisons-Introduction

Within the previous chapters the theoretical basis of the various programs has been evaluated. From this it was discovered, that for single panels all of the building element programs with the exception of Winflag was based on variations of the mass law. For double walls all of the programs showed some dependence on Sharp's theories when considering the effect that studs have on their predictions. All of the assumed theories were verified by comparing the results generated from these programs with those obtained while using these assumed theories. However, in order to verify the accuracy of these predictions, they need to be compared with measured data. Consequently such comparisons will be made within the following chapter in order to verify the accuracy of these predictions and to establish the reliability of each program.

7.2 Single Panels

The accuracy of the predictions generated by the various programs for single panels will be verified by comparing their results to the measurements obtained for a 180 mm concrete panel. These measurement values were taken from Bastian's database. A comparison between these measurements and the predictions can be seen in figure 7.1.

From the results shown within figure 7.1 the accuracy of each program can be analyzed for the following frequency ranges.

$f \leq f_c$

Below the critical frequency (i.e. ≈ 88 Hz) all of the programs produce similar results which are close to the measured values. This result does not come as a surprise since it was discovered that ENC, Insul and Reduct all use the same mass law theory within this frequency range. Even though Winflag utilizes a different approach the results obtained are similar.

$f \approx f_c$ (i.e. 63-180Hz)

From the results shown within 7.1 it can be seen that Insul's predictions best compares with the measurements. Insul's prediction, shows only a small dip at approximately 80 Hz which best compares with the measurements, as no decrease in the sound reduction can be seen from the measured values. ENC, Reduct and Winflag on the other hand, all simulate the critical frequency dip in a similar manner at approximately 100 Hz. The critical frequency dip simulated by Reduct is more

comparable to the results obtained from the measurements when compared ENC and Winflag's predictions. As a result, based on these results one can conclude that Insul's prediction is the most accurate, followed by Reduct's, then by Winflag and ENC's predictions for this frequency range.

$f \geq f_c$

For this frequency range both Insul's and Winflag's predictions are very close to the measured values. Above 1000 Hz both predictions slightly overestimated the sound reduction, however Insul's prediction comes closer to the measured values. ENC's prediction approaches the measured values at the higher frequencies, even though large differences can be seen between 200 and 1000 Hz. The prediction made by Reduct on the other hand seems to follow the trend predicted by Insul and those observed from the measurements as this predictions seem to run parallel to these results. The difference being about 6 dB. From these observations one may conclude that Insul's prediction is the most accurate, followed by Winflag, ENC and then Reduct for this frequency range.

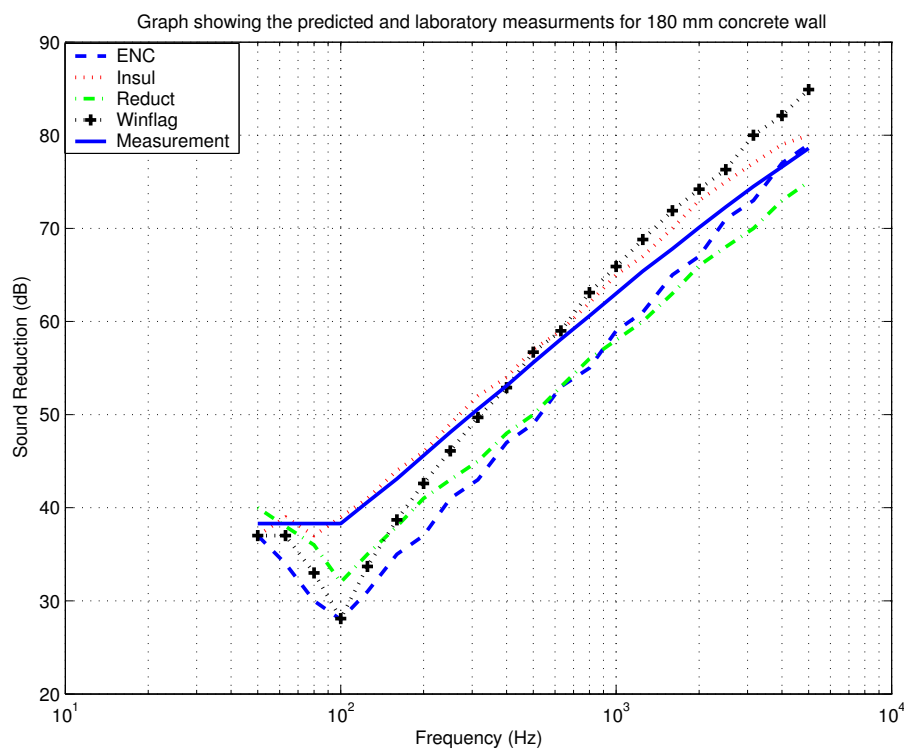


Figure 7.1. Showing both predictions and laboratory measurements for 180 mm concrete

From the above observations it is quite clear that Insul's predictions are the most accurate in this situation. Reduct can be considered to be the second most accurate program under these circumstances since it does a "better" job at simulating what happens at the critical frequency than ENC and Winflag. Also, for the higher frequencies since its predictions lie parallel to the measured ones, this indicates that

its predictions matches the trends observed from the measurements even though it may be off by approximately 6 dB. Winflag can be considered to be more accurate than ENC for this situation as its predictions for the higher frequencies better match the measured values.

7.3 Double Walls

For double wall constructions, the accuracy of these programs will be evaluated by comparing their predictions to a double wall construction composed of two sets of 12.5 mm gypsum boards on each side with 45 mm mineral wool in between them. The spacing between each set of 12.5 mm boards is 70 mm and there are also steel studs present that are 450 mm apart. These measurements were taken from a manufacturer of this wall. A comparison between the predictions generated from these programs and those measured by the manufacturer is shown in figure 7.2.

From these results the accuracy of these programs can be analyzed for the following frequency ranges.

$$f \leq f_0$$

Below the resonance frequency (i.e. 107 Hz) all of the programs produce similar results. This does not come as a surprise since it was discovered that all of the programs with the exception of Winflag all use Sharp's equation for this range. Also, since both the absorption material and the effect of studs do not affect the predictions at this frequency range, the similarity of these results are understandable. Since, the major differences between these programs occurs in the manner in which they take into account these factors.

$$f_0 \leq f \leq f_l \text{ (i.e. 107-785 Hz)}$$

From figure 7.2 it can be seen that many differences occur between the predictions generated by the various programs. From this figure, Insul is the only program that comes close to the values obtained from the measurements. Both ENC and Reduct produce similar predictions that are parallel to each other with the later being closer to the measured values. The reason for the similarity between both ENC and Reduct's predictions could originate from the fact that both programs utilizes similar forms of Sharp's original theories to deal with the effect of studs, within this frequency range. Winflag's predictions does not seem to be reasonable. From these predictions one can conclude that Insul is the most accurate for this frequency range followed by Reduct, then ENC and finally by Winflag.

$$f \geq f_l$$

Within this frequency range both Insul and Winflag's predictions accurately simulate the results obtained from the measurements. They also provide an excellent prediction of what happens around the critical frequency (i.e. ≈ 2911 Hz). Reduct

also does a fair job at simulating what happens at the critical frequency, while ENC's predictions does not come close. From the results obtained from Insul, Reduct and ENC the effect of the improvements made on Sharp's original model for studs can be seen. As his original theories which are utilized by ENC did not produce accurate results. However, the improvements made by Bodlund (as used in Reduct) and the subsequent improvements made by Rindel (as used by Insul) prove to be more accurate in this case.

From these results one can conclude that Insul and Winflag are the most accurate within this frequency range followed by Reduct then by ENC.

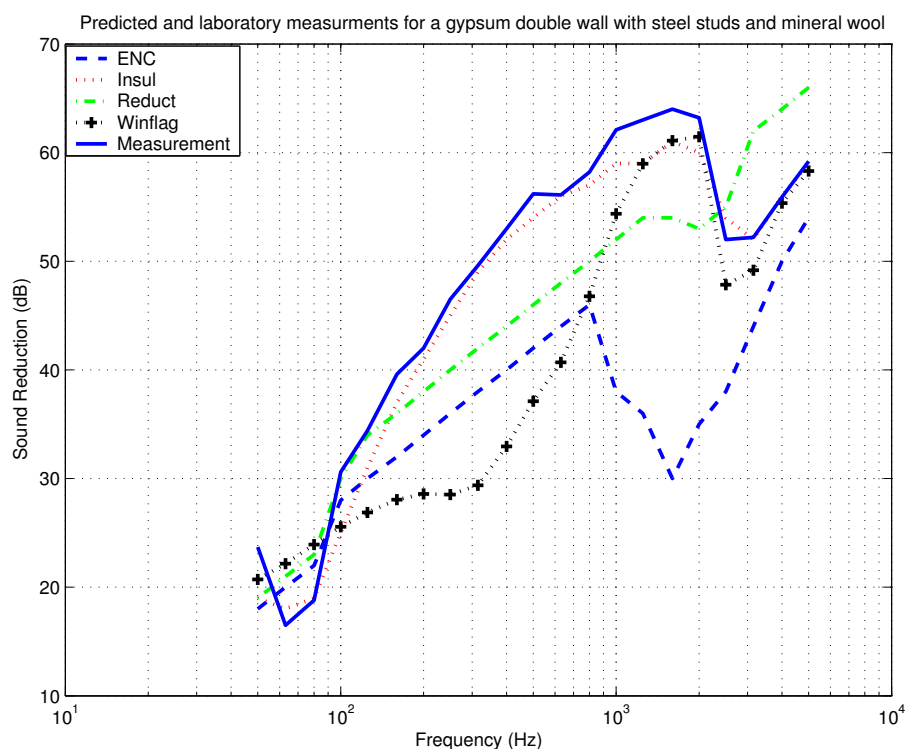


Figure 7.2. Showing both predictions and laboratory measurements for a gypsum double wall construction with steel studs and mineral wool

From the above observations it is quite clear that Insul's predictions are the most accurate over all frequency ranges for this double wall construction. Reduct can be considered to be the second most accurate program for this construction as it produced reasonable results over the entire frequency range. Winflag's predictions, can be considered to be the third most accurate because of the large discrepancies between its values and the measured values between the frequency range $f_0 \leq f \leq f_l$, even though it did produce somewhat better results that Reduct for $f \geq f_l$. ENC's predictions for this construction does not seem to be accurate.

7.4 Summary and Conclusion

From the discussion made in the sections above the various programs were ranked according to how they performed within each frequency range for both the single and double wall construction. These results can be seen in Table 7.1. Within this table a score of 3 was given to the most accurate program while 0 represented the least accurate. In the case of a tie, all affected programs were given the same score.

Frequency Range	Program			
	Insul	Reduct	ENC	Winflag
$f \leq f_c$	3	3	3	3
$f \approx f_c$	3	2	1	1
$f \geq f_c$	3	0	1	2
$f \leq f_0$	3	3	3	3
$f_0 \leq f \leq f_l$	3	2	1	0
$f \geq f_l$	3	2	0	3
Total	18	12	9	12

Table 7.1. Ranking of the various building element programs

From Table 7.1 it can be seen that Insul can be considered to be the most accurate of all the programs. Reduct and Winflag can be considered to be the second most accurate, followed by ENC. As a result, Insul can be considered to be the best of all of these building element programs to use in conjunction with Bastian or independently. If one has the option of being able to choose two of these building element programs to use within an acoustical consultancy, then Insul and Winflag will be the best combination. This is because even though Winflag and Reduct are considered to be equally as good in terms of its predictions, Winflag has more features that will allow it to be an addition to Insul. Since Insul and Reduct have essentially the same features having both programs will be redundant. In the case of ENC, one can recommend that it be used as a "utility" program to perform minor calculations that may be useful to the consultant and should not be used as the primary program in an investigation.

8 Case Study 1: Prediction and Measurement of Airborne Sound Insulation in a Class room

8.1 Introduction

Within the previous section it was discovered that Insul was the most reliable building element program investigated within this thesis. In this section Insul's predictions will be used in conjunction with Bastian to predict the sound insulation within a classroom. Bastian has obviously been evaluated independently by its developers. The results from such work show that its predictions are accurate. This has been done ironically to the point where it has been used to certify the accuracy of predictions made according to the EN12354 standard. As in Simmon's work which dealt with the uncertainty of measured and calculated sound insulation in buildings [36]. In this section the accuracy of the predicted in situ values given by Bastian will be investigated and it will be shown that it is possible to make an accurate prediction of the sound insulation within a room by only using these programs.

8.2 Measurements

The measurement were carried out in two class rooms in a high school outside of Gothenburg in Sweden. Both the source and receiving rooms are approximately $190m^3$. Both rooms are similarly built with the same materials in each room as shown in figure 8.1 while the construction of the walls, floors and ceilings are shown in table 8.1;

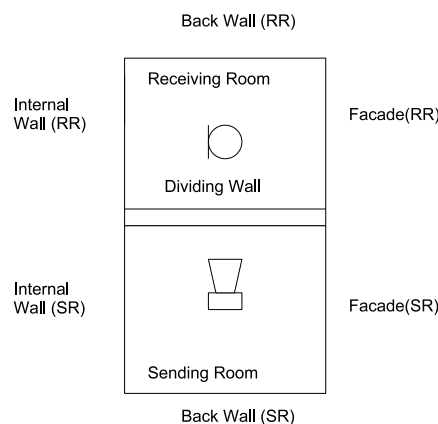


Figure 8.1. Schematic of the rooms measured during this case study I

Element	Composition	Properties
Dividing wall	Composed of two sets of 12.5 mm gypsum boards on each side with 45mm mineral wool in between them. The spacing between each set of 12.5 mm boards is 70 mm. There are also steel studs present that are 450mm apart	Gypsum- Surface Mass= $9\frac{kg}{m^2}$ each. Critical Frequency= 2911 Hz
Corridor wall	180mm prefabricated concrete	$E=35\text{ GPa}$ $\eta = 0.01$ $\rho = 2400\frac{kg}{m^3}$
Facade wall	From the the inside of the classroom going out this wall is composed of 70mm concrete followed by a 150mm layer of cellular plastic then a 130 mm layer of concrete	Cellular plastic- $E = 1.8 * 10^3 Pa$ $\rho = 20\frac{kg}{m^3}$ $\eta = 0.001$
Joists and Ceiling	2mm Linoleum Floor mat 40-50 mm Concrete slab, 265 mm hallow concrete element followed by a 300 mm air gap then 18 mm mineral wool absorbent	
Floor	From inside of the classroom going downwards in the following order: 2mm Linoleum Floor mat, 140 mm Concrete, 70mm cellular plastic, ground/earth	

Table 8.1. Description of the room investigated in case study I

For these measurements 3 microphone positions 1 meter apart were used to measure the reverberation time of the rooms. The sweep method as outline by the ISO 140 standard was then used to measure the sound reduction of the room. A summary of all of the equipment used for these measurements is outlined within table 8.2. While the result obtained from both Insul's and Bastian's predictions compared to these measured values will be discussed in the following section.

Item	Manufacturer	Type	Internal Description
Precision sound analyser	Brüel & Kjaer	2260	AL 124
Noise generator	IVIE	IE-20A	GB 004
Acoustical Calibrator	Brüel & Kjaer	4231	KU 075
Power Amplifier	Norsonic AS	260	FK 040
Loudspeaker	Norsonic AS	270	H 049

Table 8.2. Equipment used during case study I

8.3 Results

Figure 8.2 shows the predicted laboratory sound reduction predicted by Insul while figure 8.3 shows how Insul's prediction compares to the measured laboratory values (see Appendix A.5). Figure 8.3 clearly demonstrates the accuracy of the program as everything from the general shape of the curve to the suspiciously large coincidence frequency dip are modeled as discussed for this construction in section 7.3

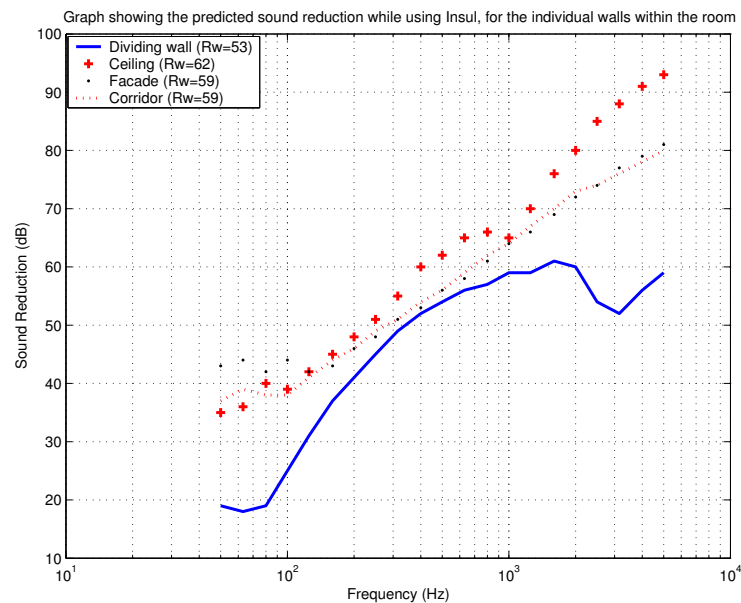


Figure 8.2. Summary of the predictions obtained while using Insul

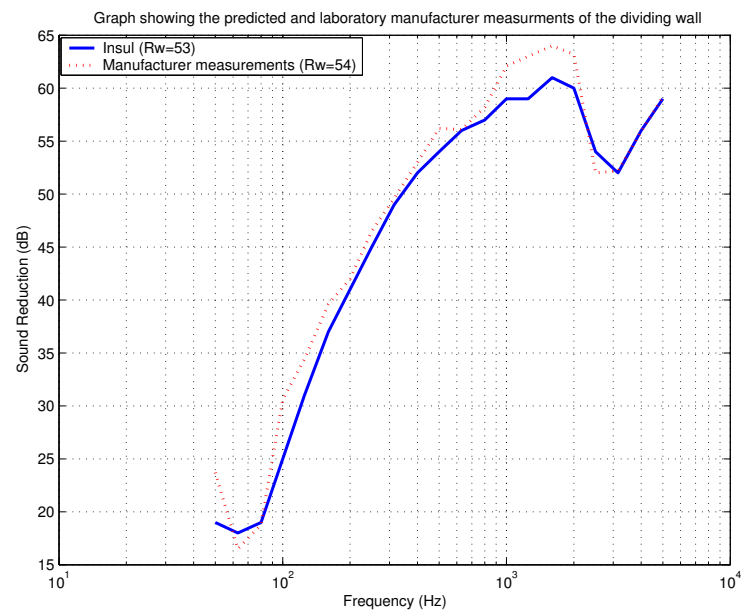


Figure 8.3. Comparison between the laboratory measurements and prediction from Insul

Figure 8.4 on the other hand shows how the laboratory predictions obtained from Insul compares to the in-situ predictions that were obtained while using Bastian. These results clearly demonstrate the effect that the room (i.e. the other four walls), junctions and other elements (e.g. Windows) has on the transmission loss of the dividing wall. As a reduction in the weighted sound reduction index from 53 to 50 dB can be seen. Such a decrease was expected based on the theories that were outlined within section 2.3. The accuracy of the prediction made from the combination of both Insul and Bastian can only really be seen from figure 8.5 as this compares the measured in-situ values to the predicted ones. Even though this graph indicates that below the fundamental resonance frequency (i.e. ≈ 107 Hz) the predicted values were much higher than the measured ones, it still indicates that the predictions were very accurate as the rest of the graph seem to coincide with the measurements. Also, the fact that the difference between the measured and predicted weighted sound reduction was only 2 dB further testifies to its accuracy. This 2dB difference lies well within the range expected of comparisons made from predictions based on the EN12354-1 standard and measurements as the standard indicates that;

A comparison with measurement results gathered in different laboratories over the last thirty years show that the measured results lie in a range around the given lines from -4dB till +8dB. (EN12354-1:2000, page 33)

The obtained results are therefore acceptable according to this range mentioned within the standard.

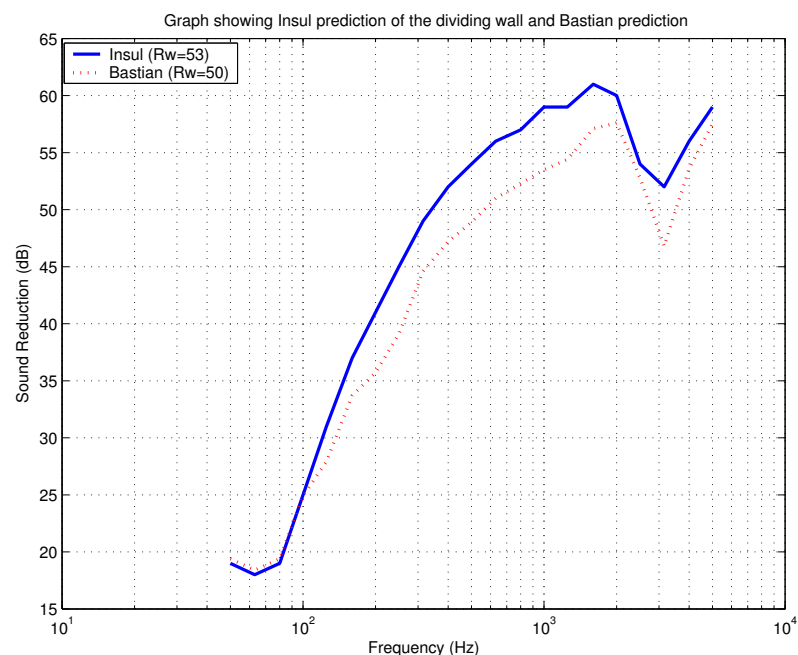


Figure 8.4. Comparison between Insul's prediction for the dividing wall and Bastian predictions for the entire room

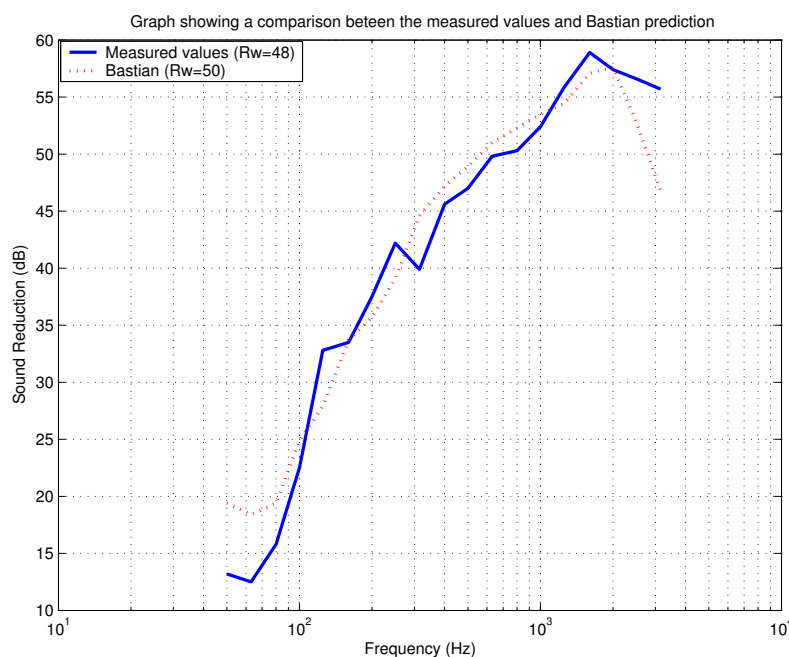


Figure 8.5. Comparison between the measured values and those predicted by Bastian

8.4 Conclusion

Based on the results obtained, the calculation model used by Bastian to convert laboratory values into in-situ values has been shown to be accurate. The discrepancies that occurred between the predicted and measured values for the low frequencies are understandable as measurement uncertainties usually occur within this range. Also, based on the accuracy of the results obtained, it has been shown that it is possible to make accurate predictions by combining the predictions generated from a building element program with Bastian. This however is based on the assumption that these input values are accurate. The usefulness of being able to do this combination can prove to be extremely beneficial to consultants as measurement data for the various building elements are not always available. This can save a lot of time and money during the design phase of a project.

Bastian's value to an acoustic consultant reaches further than its calculation model that allows it to predict the in-situ sound reduction. As this calculation model could simply be derived from the EN12354 standard as shown in section 2.3. A large portion of its true worth comes from its extensive data base of measured values which can be useful in a variety of situations. The benefits of having these values alone makes Bastian worth the cost. Based on the reliability of the predictions generated, its data base, and from the fact that it is the only sound insulation program investigated within this thesis to accurately calculate the in-situ sound reduction. One can conclude that Bastian should definitely be the first choice if one

has to choose from all of these programs.

Part II

Design of Silent Rooms

9 Introduction: Design of silent rooms

In Part I of this thesis the accuracy as well as the theoretical basis of the various sound insulation programs were verified and analyzed. In this part, the knowledge gained from this analysis will be used in the design of a silent room, by using these programs in the design. This will be done mainly through a case study where the class room investigated in part I will be converted into a music room. The discussion made within this case study will be limited to the features that are available within the programs. Before this is done however, the definition of a silent room, some general techniques of how to design such rooms as well as some practical suggestions of what is needed for minimum sound insulation will be given.

9.1 General Techniques

For the design of silent rooms, the first thing that must be established is, exactly what is a silent room and how silent is silent. For the purpose of this discussion a silent room can be defined simply as any room where a particular noise level as well as acoustic properties are desired. The required silence may be determined on an individual basis depending on specific personal requirements. However, standardized requirements will be used in this case. The techniques outlined within this section may be applied to any room (i.e. bedroom, living room, studio etc.). The purpose of the discussion is to give a general idea of some of the things that should be thought of when designing such rooms. Furthermore, the discussion should be considered to be a guide and not a detailed explanation of everything that is required to be done.

The Design of silent rooms is an extremely broad topic as it involves more than simply improving the sound insulation within a room. Even though a proper understanding of the basics of sound insulation as outlined in section 1.4 is helpful, and can prevent someone from making simple errors such as the use of light-weight walls to insulate rooms, other factors play important roles. This is because, in the design of a silent room one cannot simply consider the reduction of noise as the only criteria for measuring the success in the design of such a room as this may actually make the situation even more unpleasant. For example, in a situation where one needs to make a bedroom quite one can simply apply a few sound insulating techniques, add the amount of absorbers needed and actually make it extremely quite that very little background noises can be heard. This, may be judged as a successful design since the external noise was eliminated. However, this situation may actually have caused more harm, since the person using the bedroom may be disturbed from their sleep by the slightest noise that can be perceived, since almost all background noise was eliminated and small sounds may appear to be magnified. A further example can be given for the case where one wants to design a silent room for the purposes of playing a musical instrument. One can just simply have thick bare concrete walls to insulate

this room from other rooms and this may also be considered to be successful design of a silent room. However, with only thick bare concrete walls, echoes, coloration of the sound etc. may occur. Therefore making the situation impractical for its use. As a result, the simple point that can be derived from these two examples is that in the design of any silent room other factors other than the sound insulation needs to be considered. Some of these factors include;

- Room shape and its size
- Reverberation times and frequency curves
- Absorbers, reflectors diffusers etc
- External noise i.e Traffic Noise, residential noise
- Purpose of the room for Music, speech, home audio, home library etc.
- Psychoacoustical metrics

All of these factors affect the design of the room as it affects how different aspects of how the sound in the room is perceived. These factors should not be viewed as separate parameters since they are all interconnected. For example, the purpose of the room will determine the physio-acoustic metrics as well as the reverberation time needed, which will be affected by the size of the room as well as the amount of absorbers, reflectors etc. present. With these factors in mind, some of the general steps that can be taken for the design of a non existing room according to the book *Acoustical Designing in Architecture* [25], in the following chronological order are as follows.

1. Select a site in the quietest surroundings consistent with other requirements
2. Make a noise survey to determine how much sound insulation will be required
3. Determine how to control noise sources within the building (i.e. both airborne and structure borne noise)
4. Design the shape and size of the room that will ensure the most advantageous flow of sound and will enhance the aesthetic qualities of speech and music
5. Select and distribute absorptive and reflective materials that will provide optimum conditions for growth, decay, and steady state distribution in each room
6. Supervise the installation of acoustical plaster, plastic absorbents, or other materials whose absorptivity is dependent on the manner of application
7. Use competent engineers for the installation of sound amplification equipment if necessary

8. Inspect the finished building and do test to determine whether the requirements for sound insulation, sound absorption as well as other acoustical properties have met the demands
9. Leave maintenance instructions concerning how the acoustical materials should be cleaned, how the furniture in the building must be arranged to ensure good acoustics and how sound amplification equipment should be maintained.

The above steps were mentioned for good room acoustics but can also be applied for the design of a silent room as some of the same principles apply. In the situation where the room already exist, the steps and considerations outlined in figure 9.1 in conjunction with the relevant steps mentioned above for a non-existing room could be used.

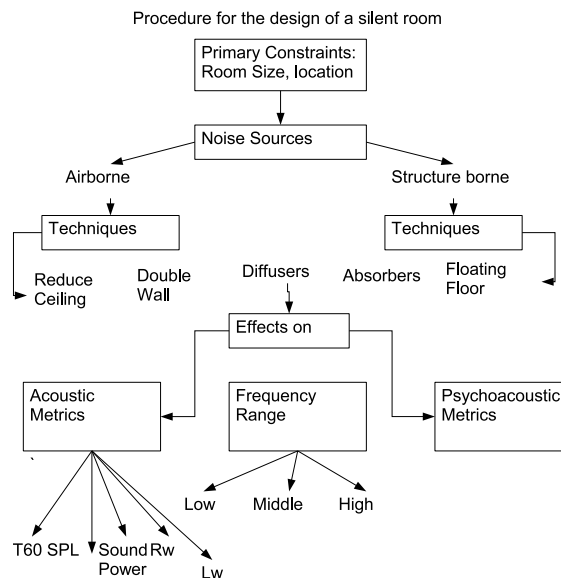


Figure 9.1. Summary of some of the different factor that need to be considered in the design of a silent room,

Figure 9.1 essentially indicates that once the primary constraints of the room is established one must evaluate the noise sources present, then use the appropriate technique to reduce these levels. While considering these techniques, their effects on the indicated measures should be known/considered. Although figure 9.1 only gives a few examples of some of the different measures that can be considered as well as some of the techniques that can be used to reduce the noise level, it is still quite useful as its purpose is to give the reader an idea of the line of thought that could be used. Using the guide outlined in figure 9.1 as well as the procedure given for a non-existing room the desired sound insulation and acoustical conditions within the room can be achieved.

Practically in order to archive the minimum sound insulation within a particular room careful consideration must be paid to the construction materials that are used

as well as the noise sources present. Both of these factor are considered in figure 9.2 which gives the type of constructions required for particular listening conditions when certain noise sources are present. The constructions indicated will produce the minimum sound insulation requirements. According to the book Acoustical Design in Architecture [25] table 9.2 can be used as follows;

After an estimate or survey of the exterior noise conditions, the appropriate level on the scale on the left is selected. The point is connected by a straight line through a point on the scale to the right which corresponds to the desired noise conditions. Then the point of intersection of this straight line with that of the center scale determines the approximate minimum insulation required. The weight...of a single rigid partition will provide this insulation...[Acoustical Design in Architecture [25], page 219]

For example for a room designed for discussions or quiet dining in an area where there moderate traffic is present then from figure 9.2, it can be seen that at a single wall of a least $98 \frac{kg}{m^2}$ or a double glazing with 0.6 kg glass and 0.025 m spacing is required. This will produce the minimum sound insulation.

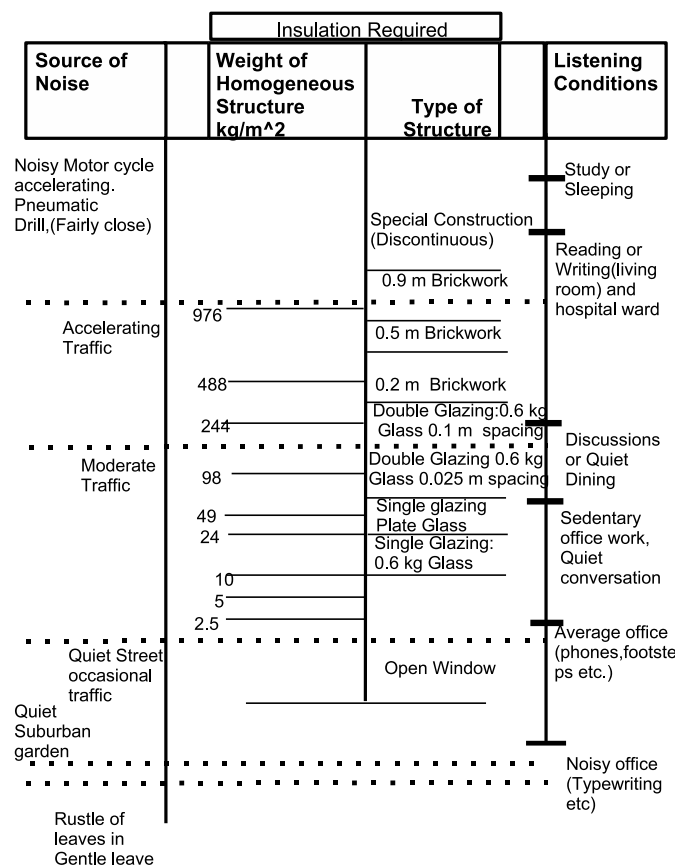


Figure 9.2. Showing the required sound insulation for different situations(taken from[25])

9.2 Case Study II: Conversion of a classroom to a music room

The following case study utilizes the knowledge gained from the investigation into the theoretical basis and accuracy of the various programs to convert an ordinary classroom into a music room. The final design and recommendation of the changes that needs to be made for this conversion will meet the Swedish standards to ensure that persons in the neighboring rooms are not disturbed. In this process it is assumed that the music room will be used primarily for piano playing. As a result the sound source considered will be piano. The steps outlined in figure 9.1 are included within the following steps.

Step 1 : Create a model of the current classroom

This was done in part 1 of this thesis. From this, it was predicted that the weighted sound reduction of this classroom will be 50 dB. This fulfills the Swedish the SS 02 52 68 standard class A requirement for an ordinary classroom. During this phase the knowledge gained during the analysis into the different sound insulation programs should be used to create an accurate model.

Step 2 : Outline any constraints

In this case the primary constraints are the room size and location since these have already been defined. In a real life situations other constraints may include financial as well as construction constraints (e.g. like being able to break down one of the walls). Some of these other constraints will also be mentioned when trying to justify the use of a particular technique over another.

Step 3 : Analyze the sound sources present as well as the predicted levels in both the sending and receiving rooms

For this investigation it will be assumed that the only noise source comes from a piano. The sound level generated from this piano were taken from measurements that are stored within Bastian's database. When this source is used the sound pressure level in both the sending and receiving rooms for the current classroom construction can be seen in figure 9.3. From this figure it can be seen that the sound source is highest in the middle frequency range (i.e. 100 to ≈ 1000 Hz). However, one can also see that based on this original construction there is a large reduction in the sound pressure levels within the receiving room for frequencies greater than 100 Hz. Little reduction takes place within the lower frequencies. As a result, from this observation, one may immediately want to suggest that either more mass needs to be added to the dividing wall or a low frequency absorber should be used to further reduce the low frequency levels. Further analysis, will determine which of these steps or other alternatives can be used.

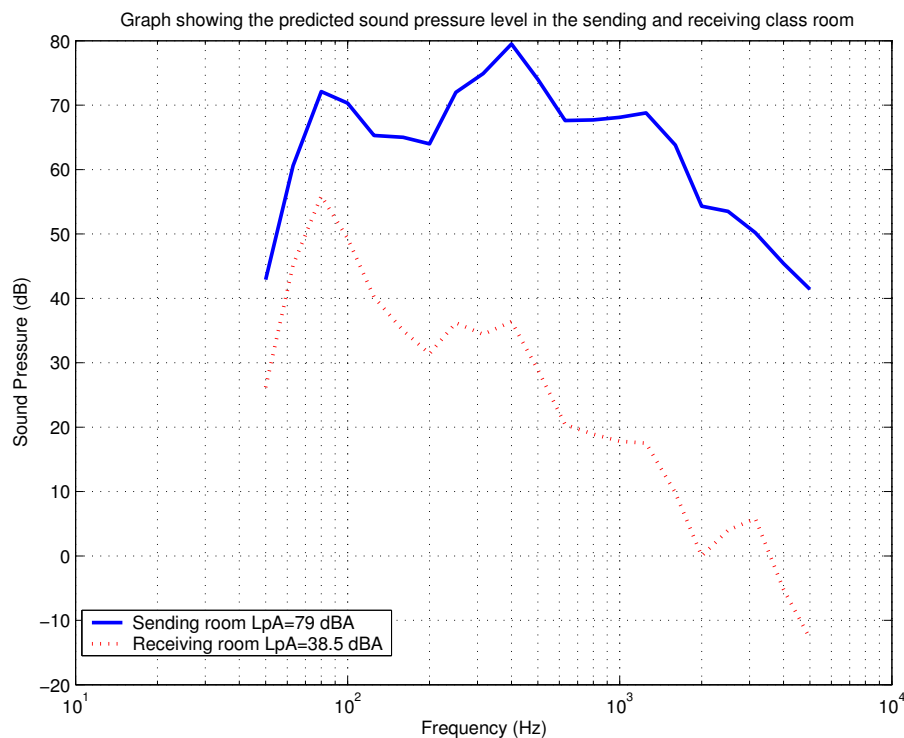


Figure 9.3. Showing the current sound pressure levels in the sending and receiving rooms without any adjustments

Step 4 : Outline the desired goals

In this case the design goal is to convert the current classroom into a music room so that it meets the Swedish SS 0252 68 requirements to be considered a class B type music room. Using the piano as the noise source, Bastian predicts that the sound pressure within the receiving room will be 38.5 dB(A) as shown in figure 9.3. Therefore, the primary goal of this investigation is to use reduce the level in the receiving room to 30 dB(A). It is quite clear, from figure 9.3 that special attention is needed for frequencies less than 500 Hz, as above this frequency the level in the receiving room is less than 30 dB(A).

Step 5 : Analysis the sound reduction or the normalized level difference due to each element within the model

In Bastian's prediction, either the sound reduction or normalized level difference for each element is given as part of its report depending on the calculation parameter selected. This information should be used to investigate which elements need to be adjusted in order to achieve the desired sound pressure level in the receiving room. For the current situation the normalized level difference per path for each element included into the model for the classroom is shown in table 9.1. From this it can be seen that the four weakest paths occurs through the dividing wall, window, floor and ceiling. As a result different techniques such as those outlined within figure 9.1 should be applied to each of these elements beginning from the

weakest element. However, in this case slight improvement can be made by simply removing the windows from the model. When this is done the sound pressure level in the receiving room falls to 37.6 dB(A). Practically this can be achieved by simply covering the windows within the room with drapes or curtains equivalent to the absorption area of the rest of the facade wall.

Element	Weighted normalized level difference(Dn,w)
Separating element	50.1
Window	51.0
Facade	75.8
Corridor wall	67
Floor	53.2
Ceiling	61

Table 9.1. Weighted normalized level difference per path

Step 6 : Apply relevant sound improvement techniques to the weakest elements first

The relevant improvement techniques should be applied to the weakest elements first. Continuing from the improvements obtained from simply removing the window from the model the following shows how the different techniques can be combined to achieve the desired goal. This will be done element by element.

Dividing wall

From the results shown within figure 9.3 in step 3 it was suspected that additional mass had to be added to the dividing wall as very little reduction occurred within the low frequency range. Since the sound reduction of this double wall is mostly dependent on its mass within this range, little improvement can be obtained without additional mass being added. As a result, one could either break down the wall and rebuild a new one or add an additional wall lining to the wall. Since breaking down the dividing wall may prove to be costly the later option will be considered. The wall lining utilized considered was a P 6 60 mm gypsum board, 12.5 mm on lightweight bricks (1.0 300 mm, render 2*15 mm) which is stored within Bastian's database. The improvement obtained from the addition of this wall lining can be seen from the reduction of the sound pressure level in the receiving room from 37.6 dB(A) to 33 dB(A). This reduction can be seen in figure 9.4. From this it can be seen that some further reduction did occur within the middle frequency range but more reduction is still need for under 500 Hz. As the sound pressure level within this range is still above 30 dB(A).

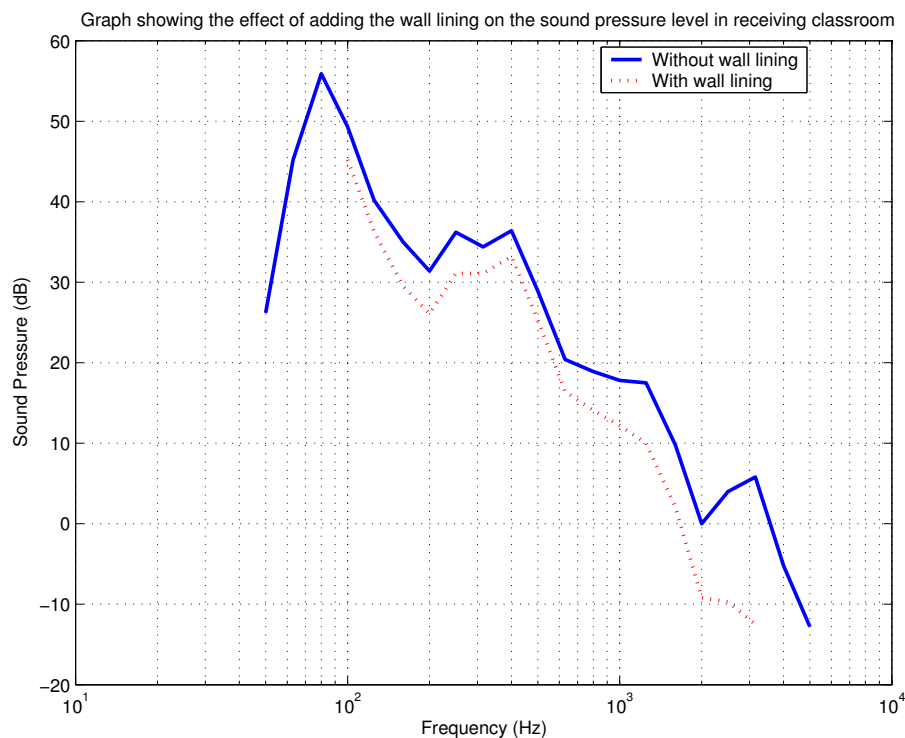


Figure 9.4. The effect of having the wall lining on the sound pressure level in the receiving room

Floor

The next element to be consider is the floor. In order to reduce the sound transmitted into the receiving room through the floor the sound reduction through the floor must be analyzed. From Bastian's report it can be seen that the normalized level difference through the floor via the flanking element (i.e. 33) is 63.5 while as compared to 70.5 through the direct path. From this, one may assume that the flanking path is the cause of the low normalized level difference through the floor. In order to verify this assumption, the velocity level difference through the junctions has to be analyzed. From figure 9.5 difference in the velocity level difference through the flanking path (i.e. Ff) and through the separating elements (i.e. paths Fd and Df) can clearly be seen. From this one suggestion on how to improve these results could be to simply isolate the flanking path of the floor. This isolation is done within Bastian by simply changing the junction type from a rigid T to one where an isolation layer is present on the flanking paths (junction number 10 in Bastian). The improvement in the velocity level difference from having this isolation can be seen in figure 9.6. This improvement is translated into a further reduction in the sound pressure level from 33 dB(A) to 30.2 dB(A).

Even though the isolation of the flanking paths of the floor reduces the sound pressure level to the point where it is practically meets the goal. Isolating the flanking path of the floor within a room might be costly depending on the construction of the class room. It may be cheaper and easier to simply install a floating floor to

solve this problem. When this alternative option is consider through the use of a calcium sulphate 40 mm, 73T 13/10 mm floating floor Bastian simulates that the sound pressure level should drop to 29.1 dB(A) as opposed to the 30.2 dB(A) when the floor’s flanking paths are simply isolated.

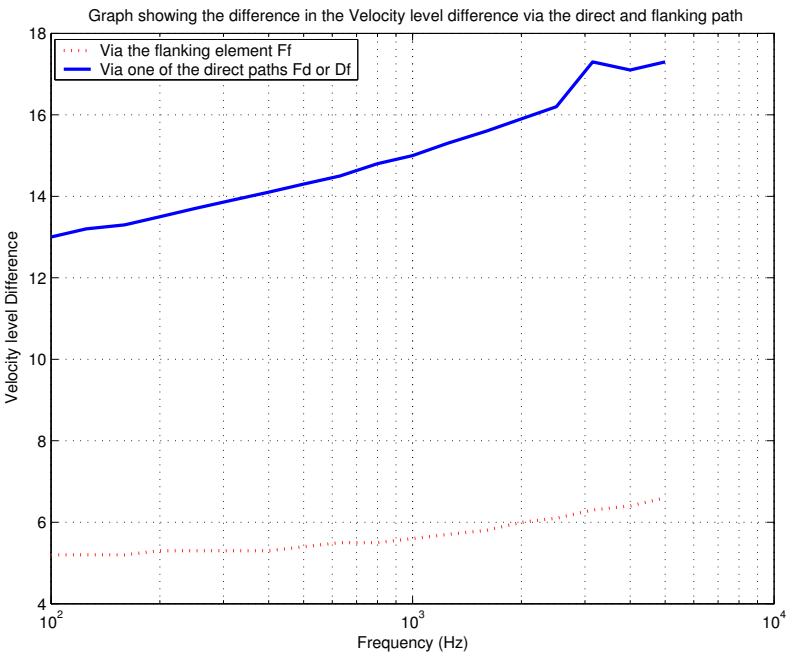


Figure 9.5. Showing the difference in the velocity level difference via the direct and flanking path

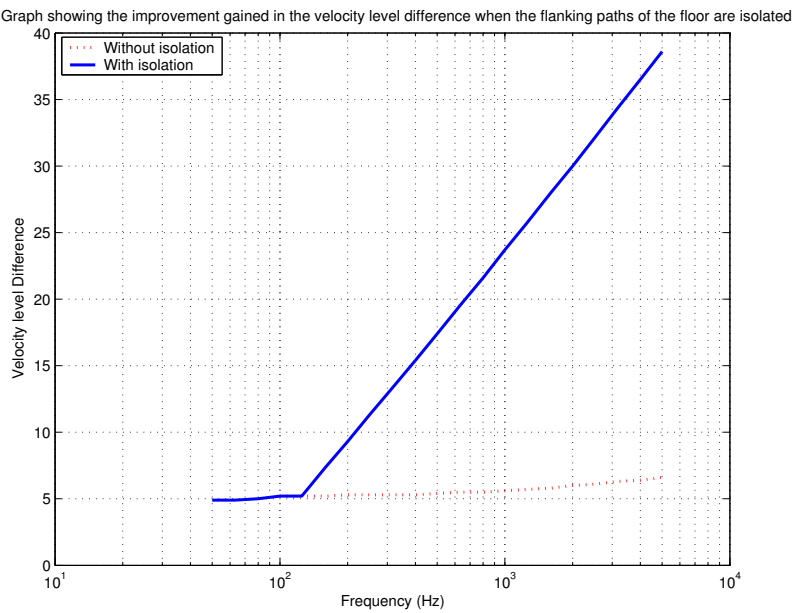


Figure 9.6. Showing the improvement in the velocity level difference after isolating the flanking path

Ceiling

If further reduction is desired so that the classroom can be classified as a class A (i.e. $L_{pA} = 26 \text{ dB(A)}$) then one may consider adding a suspended ceiling. If a gypsum board 12.5 mm thick is suspended with a height of 1 m then Bastian simulates that the sound pressure level in the receiving room will drop to 28.1 dB(A). This 1 dB(A) improvement that is obtained when the suspended ceiling is combined with the floating floor may not be worth it economically. Alternatively one can add thick drapes into the room to further reduce the sound pressure level. It is certainly possible to obtain a further 2 or 3 dB(A) reduction if drapes are combined with the suggested techniques in order to reach the level required for class A.

Step 7 : Decide upon the best combination of techniques to use

From step six it was shown that it is possible to achieve the desired sound pressure level within the room. Now one has to decide on which combination of techniques to implement. Financial and physical constraints will influence the combination of techniques that one chooses. However, it is recommended that the techniques that affect the weakest paths should be considered first as done in step six.

Step 8 : Implement and the techniques selected and consider the physiological parameters

After selecting the best possible combination of techniques, they should be implemented and any additional problems with the sound quality within the music room should be dealt with. Some possible problems as well as their solutions that one might encounter are given within figure 9.7.

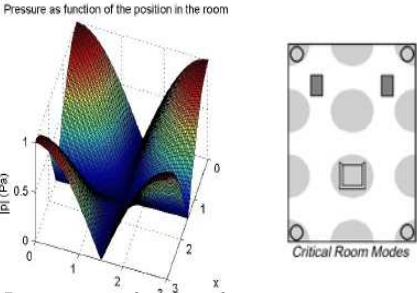

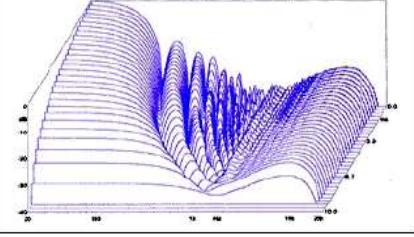
Potential Issues	Solutions
<p>The problem of “0 mode”: is caused when the standing waves create a low register response that is unequal according to the position in the room</p>  <p>Pressure as a function of position in the room</p>	<p>Study the modes in a room, place your listening position and subwoofer in order to avoid being on the junction of 2 or 3 modes at the same frequency.</p> <p>A diffraction of Schroeder presents a series of openings with different depths. Placing it on the side, opposite to the screen, this direction of the part is being a length varying between “x” m and “x+1.5” m (a depth of 1.50 m allowed an effectiveness until a low frequency of approximately 70 Hz). This eliminates any possibility of formation from a mode in the longitudinal direction of the room. It will be simply dissipated behind an acoustically transparent mural fabric, assembled on a removable frame work</p> 
 <p>Pressure as a function of position in the room</p> <p>Comb filtering : the axial, tangential and oblique reflections generated by the different modes in the room create null pressure</p>	<p>Non-parallel sides in order to have a room without mode of resonance at the low frequencies (just 2° is sometimes enough)</p> <p>Reflectors placed in an oblique way on the ceiling. This will solve the local modal problem according to the height.</p> <p>Comb filtering effects are reduced by placing acoustically absorptive materials at the reflection points responsible for the interfering waves. The materials must be of a size and type to properly address the frequencies of each specific problem. Rearranging the speaker setup will simply shift the locations of reflections and alter the problem frequencies, but does not remove the problem.</p>
<p>The shortest reflections (typically inferior to 20 ms after the directed waves): they have direct effects on the response of the loudspeakers, which they disturb seriously. In the room, we want an acoustic close to <i>LeDe</i> (“Live end-Dead end”) and avoid the <i>Haas</i> effect (2 same sounds with temporal decay).</p>	<ul style="list-style-type: none"> - Reduction of the background sound - Insulation in double hull - Cancellation of the smallest reflection but preservation of the semi-long reflections, before echo (between 20 ms and 50 ms)
<p>The echo “flotter” (generally between 2 parallel sides)</p>	<p>Judicious locations of absorbed and/or diffracted panels</p>

Figure 9.7. Showing some of the potential problems and solutions that may be encountered during the design of a room for home theater

These potential problems cannot be predicted from any of the information given from the various sound insulation programs studied within this thesis. They are just being mentioned here as potential issues that one might encounter during the implementation of the design that are based on the various programs.

9.3 Conclusion: Design of Silent Rooms

From the case study above it was shown how it is possible to convert the given ordinary class room into a music room. From this the usefulness of the various sound insulation programs can be seen as all of the predictions were done with the combination of information obtained from Insul and Bastian. This implies that the entire analysis could have been carried out during the design phase of this project. A fact that testifies to the usefulness of these programs, as their predictions can directly influence the choices that one will have to make while doing such a project.

This study also shows the importance of understanding the theoretical basis of the programs. Without this understanding, proper adjustments to the various aspects of Bastian's report, such as the velocity level difference and the flanking transmission per path could not be done. This also applies to the building element programs. As it was discovered throughout this investigation into the accuracy and the theoretical basis of these programs, that it is crucial, that careful attention be paid to the input values entered when creating models with these programs.

Finally from all of the work presented within this thesis, one can conclude that even though all of the programs investigated are based on well established theories, the accuracy and reliability of these programs vary. Also, it takes a proper understanding of the theoretical basis of the respective programs to effectively manipulate their predictions in order to meet the requirements for a particular investigation. However, once this is done effectively, accurate models can be generated. The usefulness and benefits of the amount of time and money that could be saved can then be seen. Since the models are generated both quickly and accurately. Two facts that should appeal to any acoustician.

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A Appendix

A.1 Monolithic wall matlab code used by EN12354-1

```
%Jason Cambridge
%Matlab code for EN12354

close all
clear all
clc

f=[63,125,250,500,1000,2000,4000];
frd=[50,63,80,100,125,160,200,250,315,400,500,630,...
      800,1000,1250,1600,2000,2500,3150,4000,5000];

%*****EN12354 Data*****
EnC260mm=[43,42,51,59,67,74,75];
EnLC120mm=[33,36,34,35,44,53,56];

l1=4;
l2=3;
S=l1*l2;
po=1.2;
co=340;
m1=598;
vlong=3500;
t=0.26;
fc=(co^2/(1.8*vlong*t));
rho=2400;
E=(12*rho)/((fc.*2.*pi.*t)/(co^2))^2;
B=E*t^3/12;
Cb=((B.*2.*pi.*frd)/(rho.*S)).^0.25;
bL=Cb./frd;
nt=0.006;
%*****Radiation Factor*****
for s=1:length(frd)

ko(s)=(2.*pi.*frd(s))./340;
V(s)=-0.964-(0.5+(l2/(pi.*l1))).*log((l2/l1))+...
      (5.*l2/(2.*pi.*l1))-(1./(4.*pi.*l1.*l2.*ko(s).^2));
sigmaf(s)=0.5.*(log(ko(s).*sqrt(l1*l2))-V(s));
if sigmaf(s)>2
    sigmaf(s)=2;
end
end
%*****Critical frequency*****

fp=vlong/(5.5*t);%from correction term
```

```

fc2=fc*(4.05*((t.*frd)./vlong)+sqrt(1+(4.05*((t.*frd)./vlong))));
fc3=2.*fc.*((frd./fp).^3);
fcrt=ones(1,length(frd))*fc;
for n=1:length(frd);
    if frd(n)>fc & frd(n)<fp
        fcrt(n)=fc2(n);
    elseif frd(n)>fc & frd(n)>fp
        fcrt(n)=fc3(n);
    end
end

%*****Determination of Sigma*****
sigma1=1./(sqrt(1-fcrt./frd));
sigma2=4*l1*l2*(frd./co).^2;
sigma3=sqrt((2.*pi.*frd.*(l1+l2))/(16*co));
f11=(co.^2)./(4.*fcrt).*(1/l1^2+1/l2^2);

lambda=sqrt(frd./fcrt);
for m=1:length(frd)
    delta1(m)=(((1-lambda(m).^2).*log((1+lambda(m))/(1-lambda(m)))...
        +2.*lambda(m)))./((4*pi^2).*((1-lambda(m).^2).^1.5));
    if frd(m)>fcrt(m)/2
        delta2(m)=0;
    else
        delta2(m)=(8.*co.^2.*(1-2.*lambda(m).^2))./(fcrt(m)...
            .^2.*pi^4.*l1.*l2.*lambda(m).*sqrt(1-lambda(m).^2))
    end
    sigma4(m)=(2*(l1+l2))/((l1*l2)).*((co/fcrt(m)).*delta1(m))+delta2(m);
end
for n=1:length(frd)
    if f11(n)<=fcrt(n)/2 & frd(n)>=fcrt(n)
        sigma(n)=sigma1(n);

    elseif f11(n)<=fcrt(n)/2 & frd(n)<fcrt(n)

        sigma(n)=sigma4(n);
    elseif f11(n)<=fcrt(n)/2 & f11>frd(n) & sigma(n)>sigma2(n)
        sigma(n)=sigma2(n)

    end

    if f11(n)>fcrt(n)/2 & frd(n)<fcrt(n) & sigma2(n) <sigma3(n)
        sigma(n)=sigma2(n);

    elseif f11(n)>fcrt(n)/2 & frd(n)>fcrt(n) & sigma1(n)<sigma3(n)
        sigma(n) =sigma1(n);
    elseif f11(n)>fcrt(n)/2
        sigma(n) =sigma3(n);
    end
end

for n=1:length(frd)
    if sigma(n)>2
        sigma(n)=2;

```

```

end
end
%*****Evaluation Transmission factor*****

ntot=nt+(m1./(485.*sqrt(frd)));
ntot3=nt+(m1./(485.*sqrt(f)));
X=sqrt(31.1/fc);
Y=44.3*(fc/m1);
alpha=1/3*((2*sqrt(X*Y)*(1+X)*(1+Y))./(X*(1+Y)^2+2*Y*(1+X^2)))^2;
alphak=alpha*(1-0.9999*alpha);
S=t*l1;
ntot2=nt+((2.*po.*co.*sigma)./(2.*pi.*frd.*m1))...
+(co./(pi^2*S*sqrt(frd.*fcrt))*(((2*t+2*l1)*alphak)*2+((2*t+2*l2)*alphak)*2));
for n=1:length(frd)
    if frd(n)>(fcrt(n)+0.15*fcrt(n))
        T(n)=(((2*po*co)./(2.*pi.*frd(n)*m1)).^2).*...
            ((pi.*fcrt(n).*sigma(n).^2)./(2.*frd(n).*ntot(n)));

        elseif frd(n)>=(fcrt(n)-0.15*fcrt(n)) & frd(n)<=(fcrt(n)+0.1*fcrt(n))
            T(n)=(((2*po*co)./(2.*pi.*frd(n)*m1)).^2).*((pi*sigma(n).^2)./(2*ntot(n)));

        elseif frd(n)<(fcrt(n)-0.15*fcrt(n))
            T(n)=(((2*po*co)./(2.*pi.*frd(n)*m1)).^2).*((2.*sigma(n).+((l1+l2)^2)/(l1^2+l2^2)...
                *sqrt(fcrt(n)./frd(n)).*((sigma(n).^2)./ntot(n))));
    end
end

R=-10*log10(T);

%*****Bastian Data*****
BasC260mm=[33.6,35.0,45.6,45.0,46.8,48.8,50.9,53.0,55.3,57.5,59.9...
,62.3,64.7,66.9,68.4,69.9,71.5,73.0,72.7,72.4,72.1];
BasC=10.^(BasC260mm./10);
for i=1:length(BasC)/3
    (1+(i-1)*3:i*3);
    BasCV(i)=(sum(BasC(1+(i-1)*3:i*3)))/3;
    RCV(i)=(sum(T(1+(i-1)*3:i*3)))/3;
end

BasC260mm_T=10*log10(BasCV);
R_T=-10*log10(RCV);
BasLC= [31.0375 32.1031 30.9461 41.0671 48.3904 53.8932 59.4728]
%*****Insul Data*****
InC260mm=[40,46,53,61,69,75,80];
%C260mmI=[41,40,41,44,46,49,51,54,56,59,61,64,67,69,72,74,75,77,79,80,82];
InLC120mm=[35,35,32,40,48,56,62];

%*****Plots*****
figure(1)
semilogx(f,EnC260mm)
%semilogx(f,EnLC120mm)
semilogx(f,EnC260mm,'linewidth',2)
hold on

```

```

semilogx(f,round(R_T),'r:','linewidth',2)
xlabel('Frequency (Hz)')
ylabel('Sound reduction (dB)')
legend('EN12354','Cambridge_{EN12354}')
title('Graph showing the predicted reduction index for 260 mm, 2300 kg/m^3, Concrete')
grid on

figure(2)
semilogx(f,round(R_T),'r:','linewidth',2)
hold on
semilogx(f,BasC260mm_T,'k','linewidth',2)
xlabel('Frequency (Hz)')
ylabel('Sound Reduction (dB)')
legend('Cambridge_{EN12354}','Bastian')
title('Graph showing the predicted reduction index for 260 mm, 2300 kg/m^3, Concrete')
grid on

figure (3)
semilogx(f,round(R_T),'r:','linewidth',2)
hold on
semilogx(f,InC260mm,'g','linewidth',2)
xlabel('Frequency (Hz)')
ylabel('Sound Reduction (dB)')
legend('Cambridge_{EN12354}','Insul')
title('Graph showing the predicted reduction index for 260 mm, 2300 kg/m^3, Concrete')
grid on

```

A.2 Monolithic wall matlab code used by Bastian

```

%Jason Cambridge
%Bastian Evaluation
clear all
close all

%Frequency
f=[63,125,250,500,1000,2000,4000];
frd=[50,63,80,100,125,160,200,250,315,400,500,630,800,1000,1250,...
    1600,2000,2500,3150,4000,5000];

%size of the plate
l1=4;
l2=3;
%E=5*10^9;
nt=0.006;
co=340;
po=1.2;
t=0.26;
%B=E*h^3/12;
rho=2300;***
m11=rho*t;
vlong=3500;
fc=(co^2/(1.8*vlong*t));%Critical frequency
Blambdac=co/fc; %Critical Wavelength
U=2*(l1+l2); %perimeter
S=l1*l2; %area
sigmafc1=sqrt(l1/Blambdac)+sqrt(l2/Blambdac);% Radiation Factor at fc according to Maidanik
fref=1000;%reference frequency
if l1<l2
    sigmafc2=0.45*sqrt(U/Blambdac)*((l1/l2)^0.25);
else
    sigmafc2=0.45*sqrt(U/Blambdac)*((l2/l1)^0.25);% Radiation Factor at fc according to Timmel
end

for i=1:length(frd)

    %alpha
    alph(i)=sqrt(frd(i)./fc);

    %g1
    if f<0.5*fc%Check
        g1(i)=(4/pi^4).*(1-2.*alph(i).^2).*(1./(sqrt(alph(i)).*sqrt(1-alph(i))));
    else
        g1(i)=0;
    end

    %g2
    g2(i)=(1/(4*pi^2)).*((1-alph(i)).*log((1+alph(i))./(1-alph(i))))...
        +2.*alph(i)./(1-alph(i)).^(3/2);

    %sigma

```

```

sigma1(i)=(Blambdac^2/S).*(2.*g1(i)+(U./Blambdac).*g2(i));
if sigma1(i)>1
    sigma1(i)=1;
end
sigma2(i)=sqrt(l1/Blambdac)+sqrt(l2/Blambdac);
sigma3(i)=1./sqrt(1-(fc./frd(i)));
if sigma3(i)>sigma2(i)
    sigma3(i)=sigma2(i)
end

if frd(i)<(fc/(10^(1/20)))
    sigma(i)=sigma1(i);
elseif frd(i)>(fc/(10^(1/20))) & frd(i)<(fc*10^(1/20))
    sigma(i)=sigma2(i);
elseif frd(i)>(fc*10^(1/20)) & sigma3(i)<=sigma2(i)
    sigma(i)=sigma3(i);
end

if frd(i)<(fc/(10^(1/20))) & sigma1(i)<sigmac2
    sigmaTc(i)=sigma1(i);
elseif frd(i)<(fc/(10^(1/20))) & sigma1(i)>sigmac2
    sigmaTc(i)=sigmac2(i);
elseif frd(i)>(fc/(10^(1/20))) & frd(i)<(fc*10^(1/20))
    sigmaTc(i)=sigmac2;
elseif frd(i)>(fc*10^(1/20)) & sigma3(i)>sigmac2 & sigmac2<1
    sigmaTc(i)=1;
elseif frd(i)>(fc*10^(1/20)) & sigma3(i)>sigmac2 & sigmac2>1
    sigmaTc(i)=sigmac2;
elseif frd(i)>(fc*10^(1/20)) & sigma3(i)<sigmac2
    sigmaTc(i)=sigma3(i);
end

if frd(i)<(fc/(10^(1/20)))
    nrad(i)=(2.*po.*co.*sigmaTc(i))./(pi*frd(i)*m11);
elseif frd(i)>(fc/(10^(1/20))) & frd(i)<(fc*10^(1/20))
    nrad(i)=(po.*co.*sigmaTc(i))./(pi*frd(i)*m11);
elseif frd(i)>(fc*10^(1/20))
    nrad(i)=(po.*co.*sigmaTc(i))./(pi*frd(i)*m11);
end
mframe(i)=0.4*2400
fcframe(i)=46

Kij(i)=5.7+5.7*(log10(mframe(i)./m11))^2
alphak(i)=2*sqrt((fcframe(i)/fref))*10^(-Kij(i)/10)
nperilab(i)=(co/(pi^2*S*sqrt(frd(i)*fc)))*U*alphak(i)
%ntot(i)=nt+(m11./(485.*sqrt(frd(i))));
ntot(i)=nt+nrad(i)+nperilab(i)
if frd(i)<(fc/(10^(1/20)))
    Rb(i)=20*log10((pi*frd(i)*m11)./(po*co))-3
elseif frd(i)>(fc/(10^(1/20))) & frd(i)<(fc*10^(1/20))
    Rb(i)=0;
elseif frd(i)>(fc*10^(1/20))

```



```

        Rb(i)=0;
    end
    if frd(i)<(fc/(10^(1/20)))
        Rn(i)=Rb(i)-10.*log10(1+(2.55*sigmafc2^2*pi*fc)./(ntot(i)*frd(i)));
    elseif frd(i)>(fc/(10^(1/20))) & frd(i)<(fc*10^(1/20))
        Rn(i)=0 ;
    elseif frd(i)>(fc*10^(1/20))
        Rn(i)=0;
    end
    if frd(i)<(fc/(10^(1/20)))
        Rmin(i)=10*log10((pi*frd(i)*m11)/(po*co))...
            +10*log10((pi*S*sqrt(frd(i)*fc))/(U*co));
    elseif frd(i)>(fc/(10^(1/20))) & frd(i)<(fc*10^(1/20))
        Rmin(i)=0 ;
    elseif frd(i)>(fc*10^(1/20))
        Rmin(i)=0;
    end

    if Rn(i)>=Rb(i)
        Rlow(i)=Rb(i)
    elseif Rn(i)<=Rb(i) & Rn(i)<=Rmin(i)
        Rlow(i)=Rmin(i)
    elseif Rn(i)<=Rb(i) & Rn(i)>=Rmin(i)
        Rlow(i)=Rn(i)
    end

    if frd(i)<(fc/(10^(1/20)))
        Rct(i)=0;
    elseif frd(i)>(fc/(10^(1/20))) & frd(i)<(fc*10^(1/20))
        Rct(i)=20*log10((frd(i)*m11/(po*co))...
            +10*log10(2*pi*ntot(i))-20*log10(sigmafc2) ;
    elseif frd(i)>(fc*10^(1/20))
        Rct(i)=0;
    end

    if frd(i)<(fc/(10^(1/20)))
        Rst(i)=0;
    elseif frd(i)>(fc/(10^(1/20))) & frd(i)<(fc*10^(1/20))
        Rst(i)=0 ;
    elseif frd(i)>(fc*10^(1/20))
        Rst(i)=20*log10((2*pi*frd(i)*m11)/(2*po*co))...
            +10*log10((frd(i))/fc)+10*log10(((2*ntot(i))/pi));
    end

    Rsum(i)=Rlow(i)+Rct(i)+Rst(i);

    Rdon(i)=Rsum(i)+5*((pi*frd(i)*min(l1,l2))/(2.3*co))^-0.72;

    if 36.5-10*log10(frd(i)*fc*t^2)>0
        Rhe(i)=Rdon(i)
    else
        Rhe(i)=Rdon(i)+36.5-10*log10(frd(i)*fc*t^2)
    end

```

```

end
Rlun(i)=(20*log10((rho*vlong)/(4*po*co))+10*log10(ntot(i)/0.02))
if Rlun(i)>Rdon(i)
    R(i)=Rdon(i)
else
    R(i)=Rlun(i)
end

if Rlun(i)<Rhe(i)
    R2(i)=Rlun(i)
else
    R2(i)=Rhe(i)
end
end
Bas=10.^(R./10);
Bas2=10.^(R2./10)
for i=1:length(frd)/3
    (1+(i-1)*3:i*3);
    BasCV(i)=(sum(Bas(1+(i-1)*3:i*3)))/3;
    BasCV2(i)=(sum(Bas2(1+(i-1)*3:i*3)))/3;
end

Bas_T=10*log10(BasCV)
Bas_T2=10*log10(BasCV2)

semilogx(frd,R)

hold on
semilogx(frd,R2,'r')
hold on
semilogx(frd,R,'k')
grid on

EnC260mm=[43,42,51,59,67,74,75]
BasC260mm_T =[41.4365 47.1417 53.4334 60.3313 66.9218 71.6485 72.4069]
bas=[33.6,35.0,45.6,45.0,46.8,48.8,50.9,53.0,55.3,57.5,59.9,62.3,64.7...
,66.9,68.4,69.9,71.5,73.0,72.7,72.4,72.1];
BasLC= [31.0375 32.1031 30.9461 41.0671 48.3904 53.8932 59.4728]

figure(2)

semilogx(f,Bas_T2,'k','linewidth',2)
hold on
semilogx(f,BasC260mm_T,'r:', 'linewidth',2)
grid on
frd2=[100,125,160,200,250,315,400,500,630,800,1000,1250,1600,2000,2500,3150]
ref=[33,36,39,42,45,48,51,52,53,54,55,56,56,56,56,56]
xlabel('Frequency (Hz)')
ylabel('Sound Reduction (dB)')
legend('Cambridge_{Bastian}','Database')
title('Graph showing the predicted reduction index for 260 mm, 2300 kg/m^3, Concrete using Bastian')

```

A.3 Matlab code of suspected Insul theory

```
%Jason Cambridge
%Matlab code used by Insul

close all
clear all
f=[63,125,250,500,1000,2000,4000];
frd=[50,63,80,100,125,160,200,250,315,400,500,630,800,1000,...
    1250,1600,2000,2500,3150,4000,5000];

l1=7;
l2=4;
S=l1*l2;
po=1.2;
co=340;
m1=598;
vlong=3500;
t=0.26;
fc=(co^2/(1.8*vlong*t));
rho=2400;
%E=(12*rho)/((fc.*2.*pi.*t)/(co^2))^2
E=3.5*10^9
p1=2300;
fc2=(co^2/(2*pi*t))*sqrt(12*p1/E);

InC260mm=[40,46,53,61,69,75,80]
EnC260mm=[43,42,51,59,67,74,75]
omegac=2*pi*fc;
omega=2*pi.*f
nt=0.006
ntot=nt+(m1./(485.*sqrt(f)))
for n=1:length(f)
    R1low(n)=20*log10(m1*f(n))-48;
    R1cr(n)=20*log10(m1*f(n))+10*log10((ntot(n).*f(n))./(fc))-44
    if f(n)<fc
        R1(n)=R1low(n)
    else
        R1(n)=R1cr(n)
    end
    S1=l1*l2;
    ko(n)=(2.*pi.*f(n))./340
    deltaR(n)=-log10(log(ko(n).*S1.^0.5)+20.*log10((1-(omega(n)./omegac).^2)))
    if f(n)<200
        R1sw(n)=R1(n)+deltaR(n)
    else
        R1sw(n)=R1(n)
    end
end

semilogx(f,R1,'k--','linewidth',2)
hold on
    semilogx(f,R1sw,'r:','linewidth',2)
hold on
    semilogx(f,InC260mm,'linewidth',2)
```

```

hold on

xlabel('Frequency (Hz)')
ylabel('Redution Index (Db)')
legend('Cambridge_{without Swell correction}'...
      , 'Cambridge_{with Swell correction}', 'Insul Data with Swell Correction')
title('Insul prediction data for the reduction index for 260 mm, 2300 kg/m^3, Concrete')
grid on

%*****Double wall constructions*****

m2=9;
m3=m2;
fc2=2911;
fc3=2911
c=340
omegac2=2*pi*fc2;
omega2=2*pi.*f;

nt2=0.01
ntot2=nt2+(m2./(485.*sqrt(f)))

for n=1:length(f)
    R2low(n)=20*log10(m2*f(n))-48;
    R2cr(n)=20*log10(m2*f(n))+10*log10((ntot2(n).*f(n))./(fc2))-44
    if f(n)<fc2
        R2(n)=R2low(n)
    else
        R2(n)=R2cr(n)
    end
end

fo=90
d=0.07
fl=55/d
for n=1:length(f)
    if f(n)<fo
        R4(n)=20*log10(f(n)*(m2+m3))-47
    elseif f(n)>fo & f(n)<fl
        R4(n)=R2(n)+R2(n)+20*log10(f(n).*d)-29
    elseif f(n)>fl
        R4(n)=R2(n)+R2(n)+6
    end
end
end
single=[15,18,33,46,52,50,48]

figure
semilogx(f,R4,'k')
hold on
semilogx(f,single,'r:')

grid on

b=0.45

```

```

lambdac=fc2*co
k=(2/pi)*l1*lambdac
S=l1*l2
for n=1:length(f)
    Z(n)=(2*(1+j)*m2*co*(f(n)/fc2)^0.5)/7
    Z1(n)=real(Z(n))
    v1(n)=Z(n)/(Z(n)+Z(n))
    if f(n)>fo & f(n)<f1
        v2(n)=f(n)^2
    else
        v2(n)=f(n)
    end
    W(n)=((15*k)/S)*(v1(n)*v2(n))^2
    RB(n)=10*log10(1+W(n))
    K(n)=20*log10(m2*((Z(n)+Z(n))/Z(n))*(m2+m3))
    Rst(n)=10*log10(b*fc2)+K(n)-18
end
R7=R4-RB
%Lr=0.0125
%fc3=(m2*fc3+m3*fc2)/(m2+m3)
%fc1=((m2*sqrt(fc3)+m3*sqrt(fc2))/(m2+m3))^2

sigmaA1=22*10^3
y=(omega./co)*0.189.*(po.*f/sigmaA1).^(-0.595)+((omega.*i)./co)...
    .*(1+0.0978*((po.*f)./sigmaA1).^(-0.7))

alpha=real(y)
beta=imag(y)
fc1=fc2
spacing=0.450
deltaRD=10*log10(spacing*fc2)+20*log10(m2/(m2+m3))-18
fc11=[(m2*sqrt(fc2)+m3*sqrt(fc1))/(m2+m3)]^2
deltaRm=10*log10((S/12)*(pi*fc11)/(2*c))

    k=omega./co
for n=1:length(f)
    if f(n)>f1
        Rab(n)= R2(n)+R2(n)+8.6*alpha(n).*d+20*log10(beta(n)./k(n))
    else
        Rab(n)=R4(n)
    end
end
end

for n=1:length(f)
    if f(n)<0.5*f1
        R5(n)=R4(n)
        R6(n)=Rab(n)
    elseif f(n)>0.5*f1 & f(n)<f1
        R5(n)=R4(n)-deltaRD
        R6(n)=Rab(n)-deltaRD
    else
        R5(n)=R4(n)-deltaRm
        R6(n)=Rab(n)-deltaRm
    end
end

```

```

end

figure
    semilogx(f,R4,'h','linewidth',2)
hold on
semilogx(f,Rab,'g-.','linewidth',2)
hold on
semilogx(f,R5,'r:', 'linewidth',2)
hold on
semilogx(f,R6,'y--','linewidth',2)
hold on
semilogx(f,single,'linewidth',2)
xlabel('Frequency (Hz)')
ylabel('Sound Reduction (dB)')
legend('Cambridge_{double panel} ', 'Cambridge_{double panel with Rockwool}'...
        , 'Cambridge_{double panel with steel studs}'...
        , 'Cambridge_{double panel with steel studs and rockwool}'...
        , 'Insul prediction double panel with steel studs and rockwool' )
title('Comparision between Insul and calculated values ')
grid on

%*****The effect of Different types of Studs*****
Timber=[14,14,14,17,21,26,30,33,35,37,39,41,42,44,45,47,45,40,38,42,45]
TimberS=[14,14,14,18,22,27,32,36,39,43,45,46,48,50,51,53,52,46,44,48,51]
Steel=[14,14,14,18,22,27,32,26,41,45,48,48,51,52,53,56,54,47,45,49,53]
RubberI=[14,14,14,18,22,27,32,37,42,47,51,51,54,56,57,60,58,50,48,53,58]
Point=[16,17,18,16,24,29,33,37,42,45,48,49,51,53,52,54,52,44,41,45,50]
figure
semilogx(frd,Timber,'h','linewidth',2)
hold on
semilogx(frd,TimberS,'r+', 'linewidth',2)
hold on
semilogx(frd,Steel,':', 'linewidth',2)
hold on
semilogx(frd,RubberI,'g--','linewidth',2)
hold on
semilogx(frd,Point,'linewidth',2)
xlabel('Frequency (Hz)')
ylabel('Sound Reduction(dB)')
legend('Timber Studs', 'Timber Staggered', 'Steel Studs'...
        , 'Rubber Isolation', 'Point Connection' )
title('Showing the effects of different types of studs')
grid on

```

A.4 Matlab code of suspected Reduct theory

```
%Jason Cambridge

clear all
close all

f2=[50,63,80,100,125,160,200,250,315,400,...
    630,800,1000,1250,1600,2000,2500,3150,4000,5000]
Concrete_E40=[40,38,36,32,35,38,41,43,45,48,50,...
    53,56,58,60,63,66,68,70,73,75]

c=393
p=1.29
nint=0.01
fc=87
m=432
Rm=20*log10(m*f2)-48
Rfc=20*log10((pi.*m*f2)/(p*c))+10*log10((2*nint*f2)/(pi*fc))
for n=1:length(f2)
    if f2(n)<0.6*fc
        R1(n)=Rm(n)
    elseif f2(n)>0.6*fc & f2(n)<2*fc
        R1(n)=Rm(n)+10*log10(0.01)+8
    elseif f2(n)>2*fc
        R1(n)=Rfc(n)
    end
end

figure
semilogx(f2,R1,'linewidth',2)
hold on
semilogx(f2,Concrete_E40,'r:', 'linewidth',2)
xlabel('Frequency (Hz)')
ylabel('Sound Reduction (dB)')
legend('Cambridge_{Reduct}'...
    , 'Reduct')
title('Reduct prediction data for the reduction index for 180 mm, 2400 kg/m^3, Concrete')
grid on

%*****Field Correction*****
Tsitu=[0.208 0.183 0.163 0.147 0.13 0.115 0.102 0.09 0.079...
    0.07 0.061 0.054 0.047 0.041 0.036 0.031 0.027 0.023 0.02 0.017 0.015]
Tlab=[0.569 0.503 0.446 0.412 0.358 0.313 0.273 0.237 0.205 0.177 0.152 ...
    0.13 0.111 0.095 0.080 0.068 0.057 0.048 0.04 0.033 0.028]
corr=-10*log10(Tsitu./Tlab)
deviation=5-corr
C=(corr+5)./corr
K=log10(f2)
D=ones(size(f2))
E=5*D
L=corr*-1
G=[corr;E]
H=std(G,0,1)
A=[f2;Tsitu;Tlab;corr;deviation;H]
B=A'
```

```
figure
errorbar(K,Concrete_E40,H)
xlabel('Frequency (Hz)')
ylabel('Sound Reduction (dB)')
%title('Error associatedReduct prediction data for the reduction index for 180 mm
%, 2400 kg/m^3, Concrete')
grid on
```


A.5 Manufacturers measurement of the dividing wall in Case Study 1



Enhet/Department
Fysik och Elteknik
Handläggare/Handled by
Tore Bergkvist

RAPPORT
Datum/Date
2000-08-25
Ert datum/Your date

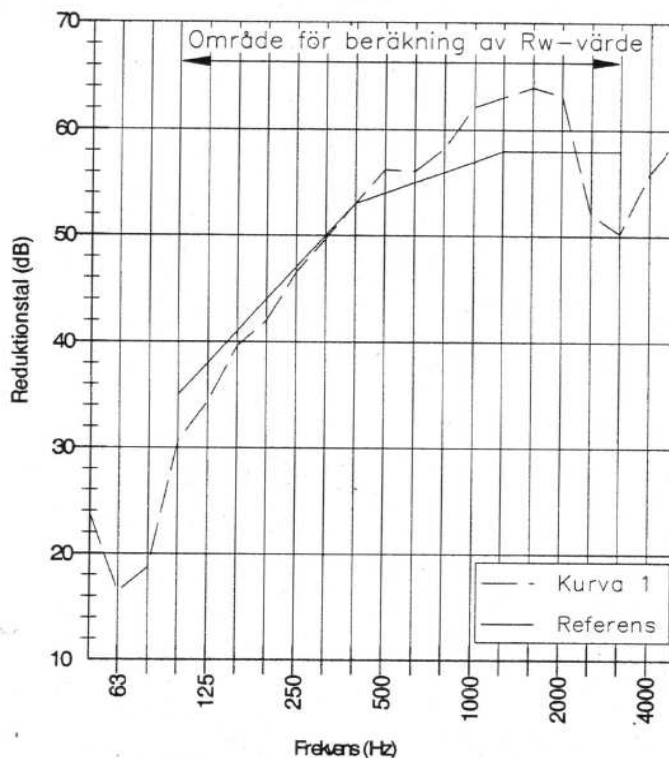
Bilaga -09
Beteckning/Reference
P007732
Er referens/Your reference
Bodil Almberg

Uppdragsgivare:
Provobjekt:
Montering:
Lufttemperatur

Bestämning av luftljudsisolering i laboratorium enligt SS EN ISO 140-3:95
Gyproc AB
Vägg typ: 70/XR70 (450) 202 M45
Utförd av uppdragsgivaren
23°C
Mätdatum: 2000-08-23

Resultat:

Provöppningsarea samt modul: 10,96 m², enrumsmont. enkelvägg
Kurva 1 - Normalt montage och utan tejptätning
Kurva 2 - Referenskurva



Frekvens (Hz)	Kurva 1 (dB)
50	23,7
63	16,5
80	18,8
100	30,6
125	34,4
160	39,6
200	42
250	46,5
315	49,6
400	53
500	56,2
630	56,1
800	58,2
1000	62,1
1250	63
1600	64
2000	63,2
2500	52
3150	50,2
4000	55,9
5000	59,2

Rw	54
(C; Ctr)	(-2;-7)
50-3150	(-7;-18)
50-5000	(-6;-18)
Rmedel	51,3
Sum. Avv.	26,1
Max. Avv.	7,8
Frekvens	3150

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Akustik

Jarl Olofsson
Tekniskt ansvarig

Tore Bergkvist
Teknisk handläggare

SP Sveriges Provnings- och Forskningsinstitut / SP Swedish National Testing and Research Institute
SP Staatliche Materialprüfungs- und Forschungsanstalt • SP Institut national d'essai des matériaux et de recherches

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A.6 Classroom Measurement of elements in Case Study 1

