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SUSTAINABLE THERMAL AND ACOUSTIC RETROFITTING OF FAÇADE WALLS

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Engineering Acoustics

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MASTER'S DISSERTATION

SUSTAINABLE THERMAL AND ACOUSTIC RETROFITTING OF FAÇADE WALLS

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Abstract

Faced with an acute problem of housing options during the 1960s, the Swedish government introduced a nationwide campaign of ‘A Million New Homes’. In order to achieve the aim of the campaign, the construction of these homes depends on cheap and fast building methods which do not result in the homes being energy efficient nor are they equipped with good acoustical properties. As time progress and society evolved, there is a growing need for these old homes to meet new energy efficient standards as well as improve the acoustics properties of homes.

Previous studies have predominantly focused on retrofitting options to improve the energy efficiency of old buildings. A large number of recommendations are currently available for retrofitting options to promote energy saving. However, limited work has been done to cover improvements in sound pressure levels. This paper therefore hopes to bridge the gap in existing research of retrofitting old homes to achieve a balance improvement in both the thermal and acoustical properties.

The focus in this paper will be on 3 key façade constructions that are pertinent during the 1960s-era – namely the heavy façade (element built and autoclaved aerated concrete blocks outside a load-bearing concrete) and lightweight façade (built as a curtain or infill wall) constructions. The motivation of analysing the heavy façade vs light façade constructions is to highlight the differences in consideration required when retrofitting different types of original façades.

During the analysis, the paper will firstly look into the energy and acoustical performance of the original façade constructions. This was then compared against simulated performances of two different proposed retrofitting options. The performances are evaluated on both retrofitting the outside and the inside of the façade wall. The proposed retrofitting options provide some insights as to the improvements of the thermal and acoustical properties expected when the façades of these buildings are retrofitted with added insulating materials.

Based on the outcome of the analysis, the study in this paper found that for heavy façade constructions, the retrofitting options proposed resulted in an improvement of both the thermal and acoustical properties of the buildings. However, the retrofitting option 2 which has a thicker and heavier retrofit structure results in a more superior improvements of the building and in particular a lower resonance frequency. In contrast, when looking at the complex original construction made of lightweight façade, the proposed retrofitting option improves the thermal properties; however it does not improve the acoustical properties of the building. An improved sound reduction index comes with a heavy construction structure. This therefore highlights that in such an original structure, it would be easy to improve the thermal properties; however more serious consideration is required during a retrofitting process in order to result in an improvement for the acoustical properties of the building.

In conclusion, the paper highlights that there are merits to retrofitting old buildings in order to achieve both a balanced improvement in thermal and acoustical properties. It is however much easier when the original structure is of a heavy façade instead of a lightweight façade.

Preface

This master's thesis report is done in connection with the 5 year Masters Programme in Civil Engineering from the Faculty of Engineering, Lund University (LTH). I would like to extend my deepest gratitude to my supervisor Delphine Bard from the Acoustics Department of Lund University for guiding me through the work required to achieve this paper. I would also like to thank WSP Acoustics Sweden and in particular Klas Hagberg for all the extended support rendered during the course of this study. Finally, I would like to thank my family, my beautiful wife Diana and my friends for the support and love provided to me while I achieve this new milestone in life.

Henric Lundh
Lund, April 2017

Contents

1 Introduction

1.1 Background

Today's urbanization of society increases traffic and makes people live closer to each other. With a growing population faced across many countries in the world, the cities are expected to be denser and this increases the number of people who are exposed to noise. According to various surveys done around the world, there are an increasing number of residential noise complaints in the recent years (Chepesiuk, 2005). There have been many adverse impacts of noise towards the well-being of humans. For example, previous studies have shown that being exposed to noise causes humans to stress, which can lead to cardiovascular disease. More of these impacts will be further explained in Chapter 2.2.3 of this paper (Eriksson et.al, 2013). As a result, it is of great importance that the noise level is being controlled at an acceptable level within residential buildings to ensure that humans' well-being is maintained. In order to achieve an acceptable and tolerable sound level indoors, buildings are required to be equipped with better sound insulation.

At the same time, we are also faced with a decline in the amount of natural resources, more significantly the non-renewable resources such as minerals and oil, which would result in the scarcity of energy (WWF, n.d). As the world's population grows, the demand for these non-renewable resources far exceeds the available resources. These resources are the main contributors of the energy sources there are today. As the world grows and globalizes, there are more and more demand for energy, which eventually adds a growing strain to the overall supply. As a result, there is an increasing focus around the world for eco-friendly buildings that helps to minimize the human footprint on the planet. These eco-friendly buildings are aimed at reducing the overall energy needs in order for it to meet human requirements and one of the efforts is diverted towards energy efficiency. To make a building more energy efficient, there are a number of solutions which could potentially be the focus. These includes having improved thermal insulation to ensure that the building retains or releases sufficient heat in order to obtain the optimal temperature suitable for human well-being. In this way, less energy is wasted and more energy could be conserved and used for other greater needs. It should be highlighted that the European Union has also identified buildings to be the largest segment where energy savings can be achieved.

In today's renovation works, there has been great focus on energy efficiency by having more efficient heat and ventilation systems as well as using materials that could achieve improved thermal insulation within the construction, so as to reduce the usage of heat and promote energy savings. This paper aims to bridge the large number of research with the focus of thermal insulation together with that of sound insulation during a retrofitting implementation of old buildings. In order to build a concrete example, this paper will focus on the retrofitting implementations of Swedish residential buildings built in the 1960s, which requires improvement to both its thermal and acoustical insulating properties. The focus will be on reducing sound pressure levels in buildings combined with good energy efficiency to create a sustainable acoustic and thermic retrofitting. Retrofitting focusing on both heat and sound insulation will create a liveable indoor environment that is suitable in today's urban society and will continue to be sustainable even for future generations.

1.2 1960s building technique in Sweden

During the 1960s, the Swedish government introduced the campaign of Sweden's Million New Homes, which aimed at remedying the acute issue faced at that point in time – the shortage of housing. The aim of the campaign was to ensure that affordable housing options were created to cater to the growing Swedish middle class society. As a result, many new suburbs were created all over the country. In order to create these buildings fast, the constructions of these residential buildings neglected both the location of these projects as well as the use of proper technology during the construction. As a result, these low cost productions resulted in an after effect of building deterioration even after a short lifespan of only 40-50 years. The photo highlighted in figure 1.1 provide an idea of an example of the residential buildings constructed in this time period. The buildings are generally simple, plain and built high to achieve the aim of the Swedish Million New Homes campaign.

Today, these residential buildings built in the period of 1960s, are linked to some of the countries least energy efficient constructions. Over the years, Sweden faced an increasing demand for energy to ensure continuity in the daily running of its society. While at the same time, the oil crisis that has plagued Europe in the early 2000s has caused the supply of energy to be more expensive. This has greatly impacted Sweden as oil represented 71% of its total energy supplies. Therefore the government's focus was greatly on promoting efficient and cost-efficient energy across all segments of the society. This was further fuelled by the European Union's directive towards development of more renewable energy as well as being more effective and efficient in the energy usage. The government provided a goal of reducing energy consumption in residential buildings by 20% before 2020 compared to the baseline of 1995 (EU European Commission, n.d.) The focus has greatly been on preserving fully functioning buildings while improving the efficiency of these buildings. Throughout this sub-chapter, a great deal of detail has been directed towards thermal savings rather than noise insulation. This basically implies that the main driver of a retrofitting implementation was fuelled by the need to save energy. That being said however, provides a good opportunity to coincide this with improving the sound insulation. The idea is to ensure that while there is ample focus on reducing energy, there is also a desire to ensure that whichever method or material used is also consequentially targeting the acoustical aspects of the building.

As a result some years ago, the European Union introduced and financed a project lead with collaboration with the SP Technical Research Institute of Sweden entitled SQUARE (System for Quality Assurance during Retrofitting of Existing buildings). The aim of the project is to improve the number of energy efficient buildings based on the existing constructions around the country. One of the many areas of the project was looking specifically at the constructions during the Swedish Million New Homes campaign where these are known to be big consumers of energy. With proper renovation and conversions, these buildings will allow for lower energy consumption while at the same time ensure improvements to the overall indoor environment.

During the Swedish Million New Homes campaign the construction work had to be fast, efficient and cheap. Full size building elements were built in factories; often in temporary factories close to the building sites and these elements were then lifted in place by big cranes and assembled together with other parts to form the overall structure. If there is a lack of special care during the assembling process of joining these elements together, the critical points of potential issues with the building will be at the connecting points where the building elements were joined together. One example of a potential issue is a weaker sound reduction index between apartments resulting from leakages.

Figure 1.1. Typical façade of a dwelling from the 1970th with an element built façade construction (Adapted from www.byggteknikförlaget.se).

There are many different constructions used during this period. This master thesis is focusing on three different types of façade constructions, all with a load bearing structure of concrete both in the building's floors and internal walls:

- Element built façade construction of concrete
- Autoclaved aerated concrete blocks outside a load bearing concrete façade
- Light weight façade elements built as a curtain wall or infill wall

The first type of façade construction that we will be looking at is the Element-built façade construction of concrete. This is a common method of constructing a building during this era. One example to illustrate this is the 6 storey high element built dwelling in Stockholm that was completed in 1970 (see example of façade structure in figure 1.2). Element built houses are built in big scale, normally more than four floors and with a number of building blocks surrounding a courtyard where the crane could rotate and place elements on the surrounding buildings. The radius of the crane therefore defined the size of the courtyards. The structure in the building is carried up by internal walls and floors of 200 mm concrete as the load bearing structure. The façade in this structure is a ready-made sandwich element built up with 120 mm of concrete internally followed by 100 mm of cellular plastic for thermal insulation and a final layer of non-structural support 60 mm concrete placed on the outside in order to provide thermal insulation due to the changing weather (Björk et.al, 2002). Floor plates, internal walls and the façade are all elements created in a factory that are assembled at the building site. While this type of construction is cheap and efficient to build, there are disadvantages in the final product. Some of these disadvantages in the construction include sound leakages between flats via the assembly points, and the thermal leakages between the façade elements at the assembly points.

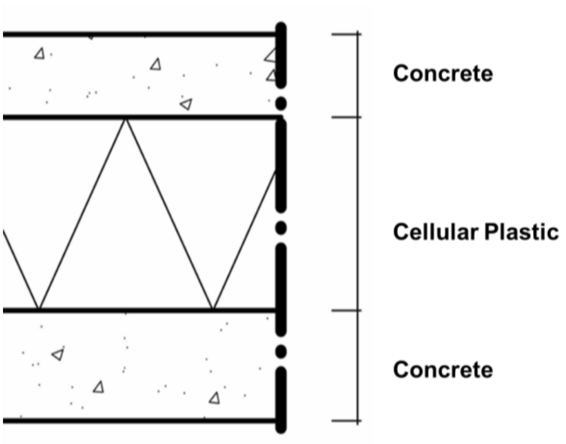

Figure 1.2. Construction 1: Element built façade construction of concrete, from BASTIAN.

Moving on, the other popular choice of construction during this time period is the autoclaved aerated concrete blocks outside a load bearing concrete façade. An example of this is a building that was built during the same era which is a 9 storey high dwelling completed in 1964 in Stockholm (see example of façade structure in figure 1.3). In this type of building construction, the façade is made of 150 mm of autoclaved aerated concrete placed outside a 150 mm concrete wall moulded together with internal walls of 150 mm concrete and floors of 160 mm concrete creating a massive and heavy structure (Björk et.al, 2002). On top of the concrete floors; 30 mm of mineral wool and 50 mm of sand were placed, sealed with another layer of 50 mm of concrete in order to avoid heat leakages spreading in the floors but also helps in improving airborne and impact sound insulation. This façade has very poor thermal insulation due to the lack of mineral wool or cellular plastic, the only thermal insulation layer is the aerated concrete with very limited thermal resistance. Since the façade and the load bearing structure are moulded together, there is less leakages at the assembly points. However, as a result of the thin concrete walls, these buildings have the disadvantage of having a restricted sound reduction index between apartments.

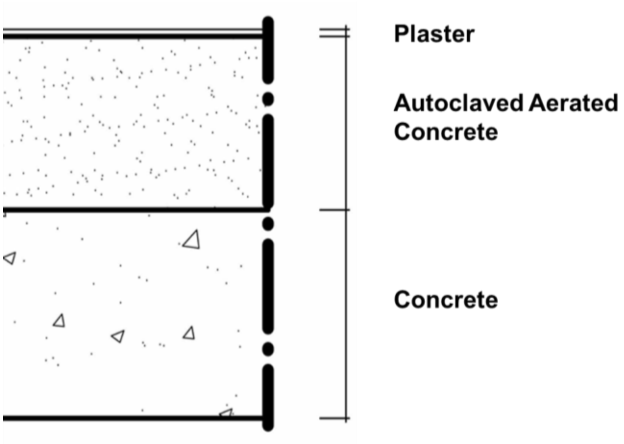

Figure 1.3. Construction 2: Autoclaved aerated concrete blocks outside a load bearing concrete façade, from BASTIAN.

Finally, the last type of construction that will be covered in this paper is the light weight façade elements built as a curtain wall or infill wall. Buildings which are built using this method typically come in smaller scale, normally three floor or less, often had a light weight façade instead of a heavy structure. An example of this type of smaller building construction is the 3 storey high dwelling in Nacka completed in 1970 (see example of façade structure in figure 1.4). The core of these residential buildings are made out of internal support bearing 160 mm concrete walls and 190 mm concrete floors moulded on the building site. The façade elements are factory built as a frame for every room and lifted in place before being assembled to the load bearing structure. The façade elements are built up with an internal 13 mm thick gypsum board placed on 120 mm wooden studs with mineral wool covered with a 9 mm thick weather board of Internit (Internit is a fibre cement consisting of asbestos) and an external 19 mm thick wooden panel mounted on 19 mm thick laths creating an air gap (Björk et.al, 2002). The façade is built either inside the load bearing concrete structure as an Infill wall inside the concrete frame, creating a heat bridge via the structure; outside the structure as a Curtain wall to cover the heat bridge, causing sound leakages via the façade; or most commonly as a combination of the two.

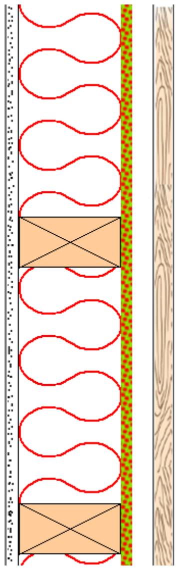

Figure 1.4. Construction 3: Light weight façade elements, from BASTIAN.

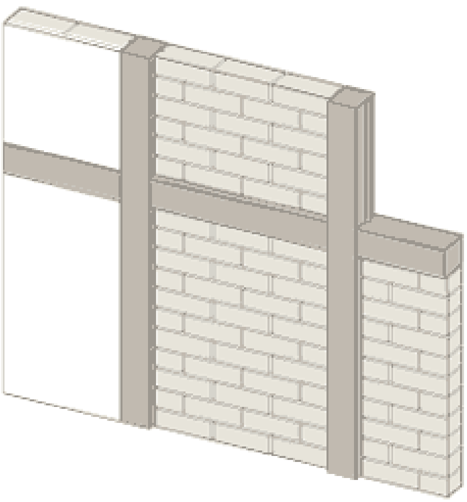

Figure 1.5. Infill wall of heavy filling, (adapted from www.earthbuilding.info).

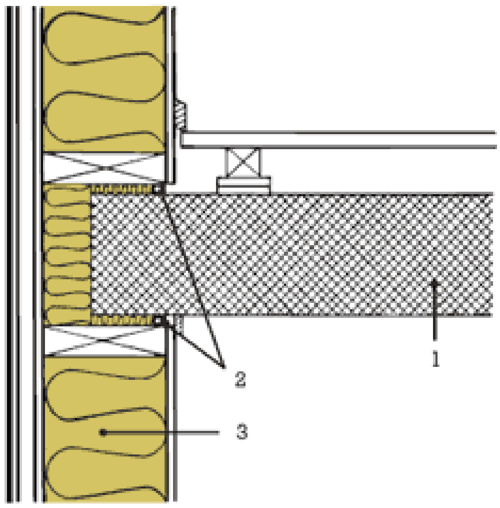

Figure 1.6. Combination of Curtain wall and Infill wall (adapted from www.rockwool.se).

1.3 Objective

The aim of this master thesis is to investigate and improve façade elements in buildings built during the period of Swedish Million Homes campaign in the 1960s. Previous studies have tested and studied the various properties of thermal and acoustic on a façade. However, it was often noticed that most literature covers one aspect of insulation, either choosing to focus on acoustics or thermal with small linkage to the other. The focus will mainly be to bridge the two concepts of sound insulation and thermal insulation during a retrofitting project. This paper aims to discuss the importance of these two concepts while providing suggestions of an optimal method and materials used to obtain the best result of retrofitting the façade of an old building.

1.4 Method

For the interest of this research, this paper focuses on a deductive research approach. This includes various literature reviews, which will assist to provide some understanding of the concepts and theoretical framework of the topics herewith being acoustics and thermal insulation as well as a description overview of the building technology behind the 1960s housing in Sweden. These literature reviews serve as a good platform for new hypotheses to be created. It gives a good idea of various instances and variables which one needs to keep in mind when retrofitting a façade.

Due to the lack of funding to physically carry out the experiments as well as the short time frame faced when carrying out this paper, physical experiments are deemed not feasible to further enhance the findings or test new concepts in relation to the fields of acoustic and thermal insulation in a retrofitted environment. Therefore, this paper will focus on computer simulation which is a flexibility yet effective method to deliver some conclusive contributions to this paper.

Through the use of simulations, various hypotheses can be created in order for a specific conclusion to be made with respect to the type of materials that could possibly be used when a building's façade needs to be retrofitted. Although one may argue that simulations might not be fully conclusive, with the advancement of technology, the existing simulation programs such as BASTIAN and INSUL, which will primarily be used in this paper, offer close to reality findings without adding unnecessary cost or resources. Simulation provides an effective alternative in getting results for a scientific question and this method also allows for various variables to be tested quickly and easily (Maria, 1997).

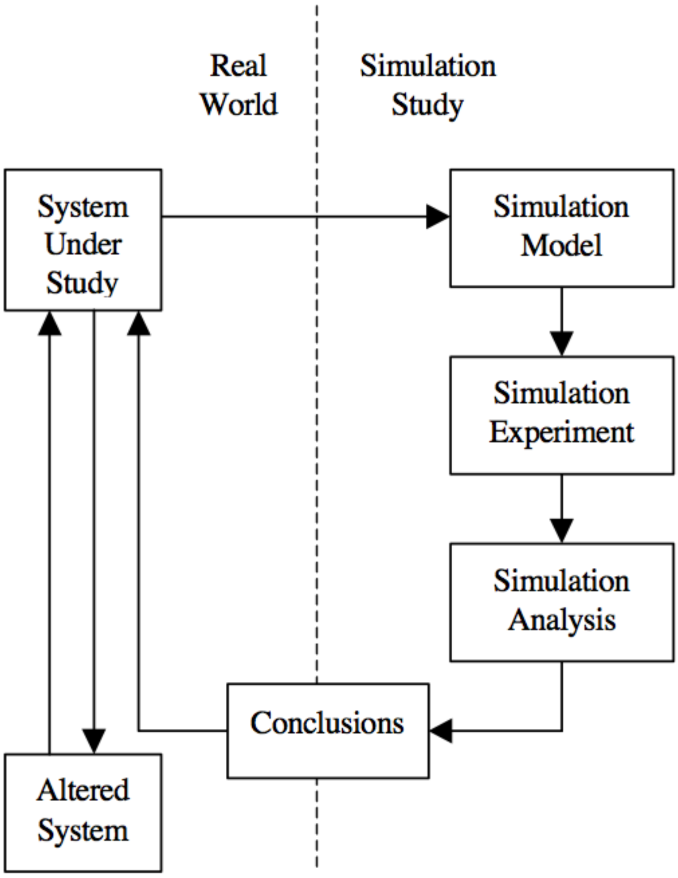

Figure 1.7. Adapted from Introduction to modelling and simulation, Maria 1997.

1.5 Scope

The focus in this master thesis will be on the façade elements in dwellings. The importance of flooring, roofs, doors and windows will only be included up to necessary depth in order to support the main research area and not form the basis of this paper.

The acoustical section will be based according to the standards listed below:

- SS-EN 12354-3, Building acoustics – Estimation of acoustic performance of buildings from the performance of elements – Part 3: Airborne sound insulation against outdoor sound
- Swedish Building Regulations, Regelsamling för byggande, BBR 23
- SS 25267:2015, Acoustics – Sound classifications of spaces in buildings – Dwellings

While this paper will base the thermal section according to the standard listed below:

- SS EN ISO 6946, Building components and building elements – Thermal resistance and thermal transmittance – Calculation method
- Swedish Building Regulations, Regelsamling för byggande, BBR 23

The standards used above are required for any buildings in Sweden to pass the regulations stated by the Swedish National Board of Housing, Building and Planning (Boverket) and to a large extent covers the regulations stated by the European Union Commission.

1.6 Research limitations

As previously indicated, the overall lack of funding as well as time and physically limitations, it will be difficult to carry out the measurements of a true retrofitting work. In order to come up with a concrete conclusion, many rounds of measurements are needed with varying materials and variables which will result not only in costs but also time. Unfortunately, the lack of funding and suitable project site where different materials could be tested and measured did not allow for this. As a result, this paper will limit itself by computer simulations to reach a reasonable conclusion for this study.

1.7 Outline of this paper

The outline of this paper is as follow: In Chapter 2, the paper explains the fundamentals of acoustics including the requirements in Swedish buildings and how people get affected by noise. In chapter 3 the paper brings up the theory behind the thermal and energy calculations, the requirements for buildings in Sweden and also how the thermal condition affects humans and the environment. Chapter 4 explains the methodology of the calculations and what calculations that have been made for the case study. Chapter 5 explains the different case studies and chapter 6 shows the result of the different retrofitting methods. Chapter 7 discusses and concludes the findings in the paper.

2 Sound and acoustics

2.1 Airborne sound reduction

Airborne sound reduction gives an indication on how good the partition separating two rooms are in reducing the sound from one room to the other. A high sound reduction for the partition reduces the sound better than a low sound reduction and less sound will travel between the two rooms.

2.1.1 Sound reduction index

Sound waves traveling in a medium are defined by the elasticity, density and the mass in the media. When the wave is entering into a new medium some of the wave's intensity will be reflected and some will be transmitted through the medium. A small amount of the wave's intensity will also be absorbed in the new medium and transformed into heat energy (Nilsson et.al, 2008). The ratio between these wave intensities is described in equation (2.1).

$$\Pi_i = \Pi_r + \Pi_t + \Pi_a \tag{2.1}$$

where Π_i is the incoming effect of the wave [W]

Π_r is the reflected effect of the wave [W]

Π_t is the transmitted effect of the wave [W]

Π_a is the absorbed effect of the wave [W]

By taking the ratio between the transmitted effect of the wave and the incoming effect of the wave, the sound transmission coefficient is found according to equation (2.2).

$$\tau = \frac{\Pi_t}{\Pi_i} \tag{2.2}$$

To define how good the sound insulation is in a specific building element, the sound transmission loss is used, and this is also called the sound reduction index. The sound reduction index is based on the ratio between the incoming sound effect and the sound effect transmitted through the wall (Nilsson et.al, 2008), and can be calculated with equation (2.3).

$$R = 10 \cdot \log\left(\frac{\Pi_i}{\Pi_t}\right) = 10 \cdot \log\left(\frac{1}{\tau}\right) = -10 \cdot \log \tau \tag{2.3}$$

2.1.2 Sound reduction index between two rooms

The relation between the transmission loss and the sound pressure level in two rooms defines the sound reduction index between two rooms. In the room where a sound source is being generated, the sending room, the average sound pressure p_1 [Pa] is giving the sound power incident on the wall (Jacobsen et.al, 2007), calculated with the following equation:

$$\Pi_i = I_{inc} \cdot S = \frac{\mathrm{p_1}^2 \cdot S}{4 \cdot \rho \cdot c} \tag{2.4}$$

where I_{inc} is the incident sound intensity [W/m^2]

ρ is the density of the medium, in this instance air [kg/m^3]

c is the speed of sound in the medium, in this instance air [m/s]

S is the area of the test specimen (the wall) [m^2]

In the other room, the receiving room, the sound pressure p_2 is giving the sound power transmitted into the room by the following equation.

$$\Pi_t = \frac{\mathrm{p_2}^2 \cdot A_2}{4 \cdot \rho \cdot c} \tag{2.5}$$

where A_2 is the absorption area in the receiving room [m^2]

Using these two equations, (2.4) and (2.5), in equation (2.3) gives the following expression:

$$R = 10 \cdot \log\left(\frac{\mathrm{p_1} \cdot S}{\mathrm{p_2} \cdot A_2}\right) = L_1 - L_2 + 10 \cdot \log\left(\frac{S}{A_2}\right) \tag{2.6}$$

where L_1 is the sound pressure level in the sending room [dB]

L_2 is the sound pressure level in the receiving room [dB]

The last term determines the sound pressure that is absorbed in or transmitted out from the receiving room. Since the sound reduction index should give the same result regardless if the receiving room is fully furnished or not, this term removes the influence of the receiving room.

Instead of using weighted sound reduction index between apartments in dwellings, the standardized sound level difference is used due to differences affected to volume. The standardized sound level difference is calculated according to the following expression (SIS,2015):

$$D = L_1 - L_2 + 10 \cdot \log\left(\frac{T}{T_0}\right) \tag{2.7}$$

where T is the reverberation time in the receiving room [s]

T_0 is the reference reverberation time; for dwellings $T_0 = 0{,}5\ s$.

2.1.3 Measured sound reduction index

To measure the sound reduction index between two rooms (or outside into a room through the façade) a speaker is placed in the sending room that emits very loud noise in every frequency in the octave bands or the one-third-octave bands. The sound pressure level is measured in both rooms determining L_1 and L_2. The noise must be significantly louder than any potential background noise to give an accurate estimation of the sound reduction index in the test specimen. If the background noise is loud in the receiving room, it is measured and deducted from the sound pressure level during the test. When L_1 and L_2 are determined, the reverberation time in the receiving room is measured and is being used to establish the equivalent sound absorption area according to equation (2.8) below (Sabine's equation, found in SS-EN ISO 16283:2014), which is used in the last term in equation (2.6).

$$A_2 = \frac{0.16 \cdot V}{T_{60}} \tag{2.8}$$

where V is the volume of the receiving room [m^3]

T_{60} is the reverberation time [s]

With these measurements, the sound reduction index for the test specimen can be calculated for every third octave band. The last term in equation (2.6) takes into account the lost sound effect due to absorption in the receiving room and adds it back, this to only portray the wall and not the sound effect that is absorbed by the room.

2.1.4 Weighted sound reduction index

In order to compare the sound reduction index in different building elements a single-numbered quantity is being rated. The single-numbered quantity, which also is known as the weighted sound reduction index is established by SS-EN ISO 717-1:2013. The weighted sound reduction index is established from the reference values (see table 2.1 and diagram 2.1), which is compared with the sound reduction index spectrum already established previously.

Table 2.1. Reference values for airborne sound

Frequency [Hz]	Reference values [dB]
100	33
125	36
160	39
200	42
250	45
315	48
400	51
500	52
630	53
800	54
1000	55
1250	56
1600	56
2000	56
2500	56
3150	56

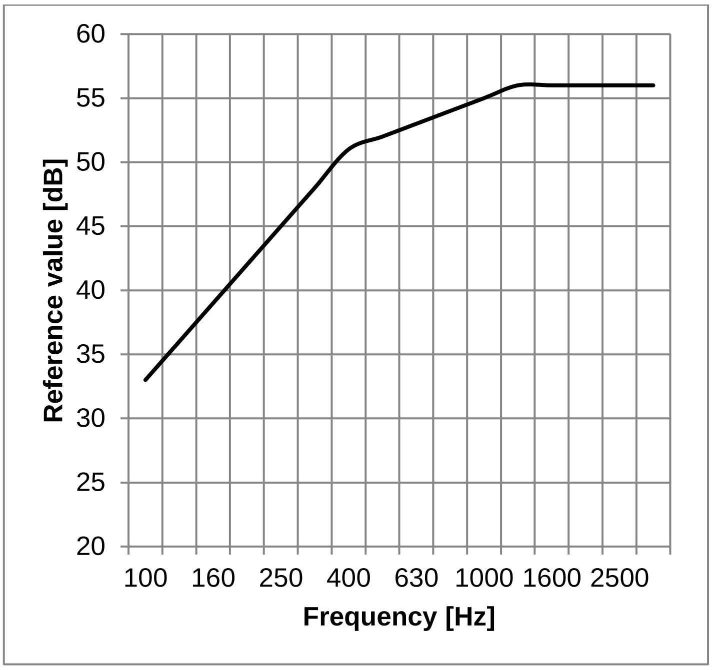

Diagram 2.1. Reference curve for airborne sound

By moving the reference curve towards the previously established sound reduction index with steps of 1 dB until the sum of unfavourable deviations is as close to 32 dB as possible, but not exceeding. Meaning that the value from the previously established sound reduction index is subtracted from the reference curve and then summing all unfavourable deviations. Only the unfavourable deviations shall be summed and they only appear when the previously established sound reduction index is less than the reference value (Nilsson et.al, 2008).

The weighted sound reduction index is now the reference value at 500 Hz, which is 52dB, added together with the number of decibels that the reference curve was shifted, see equation (2.9).

$$R'_W = 52 + x \qquad (2.9)$$

where x is the steps that the reference curve is shifted
R'_W is the weighted sound reduction index, ‘ (prime) stands for in-situ [dB]

2.1.5 Spectrum adaption terms

To take into account the characteristics of different sound spectra, the spectrum adaption term is added to the single-number, in this case known as R_W. The spectrum adaption term is added to adjust the A-weighted sound pressure level from different noise sources, C for pink noise and C_{tr} for urban traffic noise according to SS-EN ISO 717-1. It is calculated according to equation (2.10).

$$C_j = X_{Aj} - X_W \tag{2.10}$$

where j is the subscript for the two sound spectra, 1 (pink noise) and 2 (traffic noise)

X_{Aj} is calculated in equation (2.11)

X_W is the weighted value, in this case the weighted sound reduction index

$$X_{Aj} = -10 \cdot \log \sum 10^{(L_{ij} - X_i)/10} \tag{2.11}$$

where i is the subscript for the octave bands

L_{ij} is the sound level for the different frequencies given in table 2.2

X_i is the sound reduction index for the different frequencies

Table 2.2. Sound level spectra to calculate the adaption terms, No. 1 for C and No. 2 for C_{tr}. Note that all levels are A-weighted

Frequency [Hz]	Sound levels, L_{ij} [dB]	
	Spectrum No. 1	Spectrum No. 2
100	-29	-20
125	-26	-20
160	-23	-18
200	-21	-16
250	-19	-15
315	-17	-14
400	-15	-13
500	-13	-12
630	-12	-11
800	-11	-9
1000	-10	-8
1250	-9	-9
1600	-9	-10
2000	-9	-11
2500	-9	-13
3150	-9	-15

2.1.6 Combined sound reduction index

A façade element is often built up by several sub elements e.g. wall, windows, doors etc. which all of them are having different properties hence different sound reduction indexes. To calculate the transmission coefficient for the total wall the sound intensity incident on the total element is assumed to be evenly distributed. If that is true, the total incident sound power on the element is calculated according to the formulae below collected from Fundamentals of acoustics and noise control (Jacobsen et.al, 2007):

$$\Pi_i = \sum_{i=1}^{n} S_i \cdot I_{inc} = S \cdot I_{inc} \tag{2.12}$$

where S is the area of total element [m^2]

The sound power transmitted through the element is:

$$\Pi_\tau = \sum_{i=1}^{n} \tau_i \cdot S_i \cdot I_{inc} \tag{2.13}$$

According to equation (2.2) the resulting sound transmission coefficient through the total element is calculated by:

$$\tau_{res} = \frac{\Pi_t}{\Pi_i} = \frac{1}{S} \cdot \sum_{i=1}^{n} \tau_i \cdot S_i \tag{2.14}$$

where i is the index of the sub element

S_i is the area of the sub element [m^2]

This will give, according to equation (2.3) that the resulting sound reduction index for the total element is:

$$R_{res} = -10 \cdot \log \tau_{res} = -10 \cdot \log\left(\frac{1}{S} \cdot \sum_{i=1}^{n} S_n \cdot 10^{-R_n/10}\right) \tag{2.15}$$

where R_n is the known weighted sound reduction index of the sub element [dB]

Using these equations it is easy to see that even a small area with a low sound reduction index severely reduces the total sound reduction index. By sealing all potential leakages in an element the sound reduction index can be heavily improved.

2.1.7 Sound reduction index in a single wall

During the analytical calculations of the sound reduction index of a single wall, these calculations can be divided into five different regions where each region has different ways of determining the sound reduction index. The frequency of where each region starts and ends is depending on the type and thickness of the wall (Ljunggren et.al, 2016).

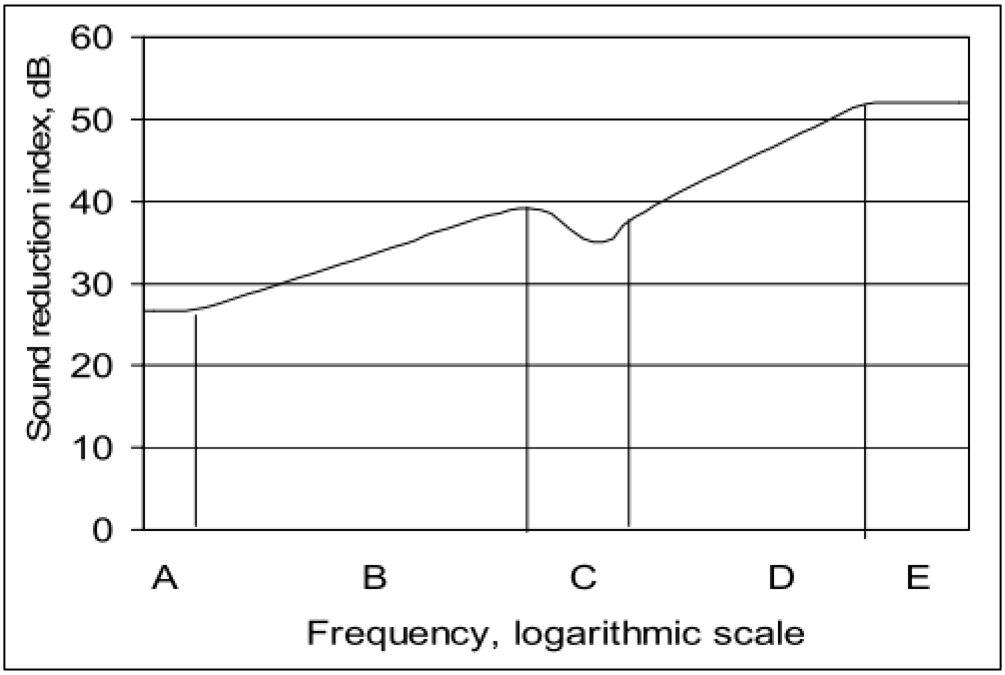

Figure 2.1. Different regions of sound reduction index in a single wall (Ljunggren et.al, 2016)

Region A: Very low frequencies

At very low frequencies the stiffness of the wall controls the sound reduction in the wall. This normally happens at frequencies below 80 Hz. Theoretically the sound reduction index actually decreases with increasing frequency in this area, but that is not always the case (Ljunggren et.al, 2016).

Region B: The mass law region

In the mass law region the sound reduction index is dominated by the mass of the wall and it typically increases with 6 dB per octave (Nilsson et.al, 2008). The sound reduction index for this region can be calculated according to Ljunggren et.al (2016) with the following equation:

$$R_B = 20 \cdot \log\left(\frac{\omega \cdot m''}{2 \cdot \rho \cdot c}\right) - 10 \cdot \log\left(\ln\left(\frac{\omega \cdot m''}{2 \cdot \rho \cdot c}\right)^2\right) \quad (2.16)$$

where ω is the angular frequency given by $2 \cdot \pi \cdot f$

$$R_B = 20 \cdot \log\left(\frac{2 \cdot \pi \cdot f \cdot m''}{2 \cdot \rho \cdot c}\right) - 10 \cdot \log\left(\ln\left(\frac{2 \cdot \pi \cdot f \cdot m''}{2 \cdot \rho \cdot c}\right)^2\right) \quad (2.17)$$

where f is the frequency [Hz]

m'' is the surface mass of the wall [kg/m^2]

ρ is the density of air [kg/m^3]

c is the speed of sound in air [m/s]

ρ is the density of air [kg/m^3]

The sound reduction index for the mass law can be simplified according to the following equation (Nilsson et.al, 2008):

$$R_B = 20 \cdot \log\left(\frac{\pi \cdot f \cdot m''}{2 \cdot \rho \cdot c}\right) \quad (2.18)$$

These equations are valid only up to the critical frequency which starts the next region.

Region C: The coincidence region

Coincidence is occurring when the wavelength in the air coincides with the wavelength of the bending waves in the wall. The lowest frequency where coincidence appears is at the critical frequency which can be calculated with the following equation according to Ljunggren et.al (2016).

$$f_c = \frac{K_c}{h} \tag{2.19}$$

where h is the thickness of the wall [m]

K_c is a factor determined by the material of the wall and is calculated with:

$$K_c = 60000 \cdot \sqrt{\frac{\rho_w}{E}} \tag{2.20}$$

where ρ_w is the density of the material in the wall [kg/m^3]

E is the dynamic Young's modulus [N/m^2]

The sound will incident on the wall in different angles and will make the wall oscillate. Depending on what frequency and incident angle the wave has, different oscillations will occur and sound will easier be transmitted through the wall (Nilsson et.al, 2008).

Region D: The high frequency region

Reaching the high frequency region, when $f > f_c$, the sound reduction index increases with 7-9 dB per octave. The sound reduction index can be calculated with two different formulae depending on if the partition wall is the whole separating element or if the separating wall is larger than just the separating element (the sending room is wider than the receiving room). At the second case, vibrations in the wall will spread evenly over the whole wall and the sound reduction index becomes larger (Ljunggren et.al, 2016).

For the first case, where the sending room is as wide as the receiving room, the sound reduction index can be calculated as followed:

$$R_D = 20 \cdot \log(m'') + 30 \cdot \log(f) - 10 \cdot \log(f_c) + 10 \cdot \log(\eta) - 45 \tag{2.21}$$

where m'' is the surface mass of the wall [kg/m^2]

f is the frequency [Hz]

f_c is the critical frequency [Hz]

η is the loss factor

For the second case, where the sending room is wider than the receiving room, the sound reduction index is compensated for the area which gives the vibration loss according to:

$$R_D = 20 \cdot \log(m'') + 30 \cdot \log(f) - 10 \cdot \log(f_c) + 10 \cdot \log(\eta) - 45 + 10 \cdot \log\left(\frac{S}{S_s}\right) \tag{2.22}$$

Where S is the total area of the wall [m]

S_S is the area of the separating wall [m]

Region E: Very high frequencies

The sound reduction index for very high frequencies can be determined with the following equation:

$$R_E = 20 \cdot \log\left(\frac{\rho_w \cdot c_w}{\rho \cdot c}\right) + 10 \cdot \log\left(\frac{\eta}{\eta_0}\right) \tag{2.23}$$

where ρ_w is the density of the material in the wall [kg/m^3]

c_w is the propagation speed in of a longitudinal wave right through the wall [m/s]

ρ is the density of air [kg/m^3]

c is the propagation speed in air [m/s]

η is the loss factor of the wall

η_0 is a reference value of the loss factor, $\eta_0 = 0{,}02$

This region is determined from the frequency where $R_D = R_E$ and following R_E for a couple of octaves (Ljunggren et.al, 2016).

2.1.8 Sound reduction index in a double wall

Double wall without connections

A double wall without connections between the two plates in the wall and the cavity filled with mineral wool can be found in figure 2.2.

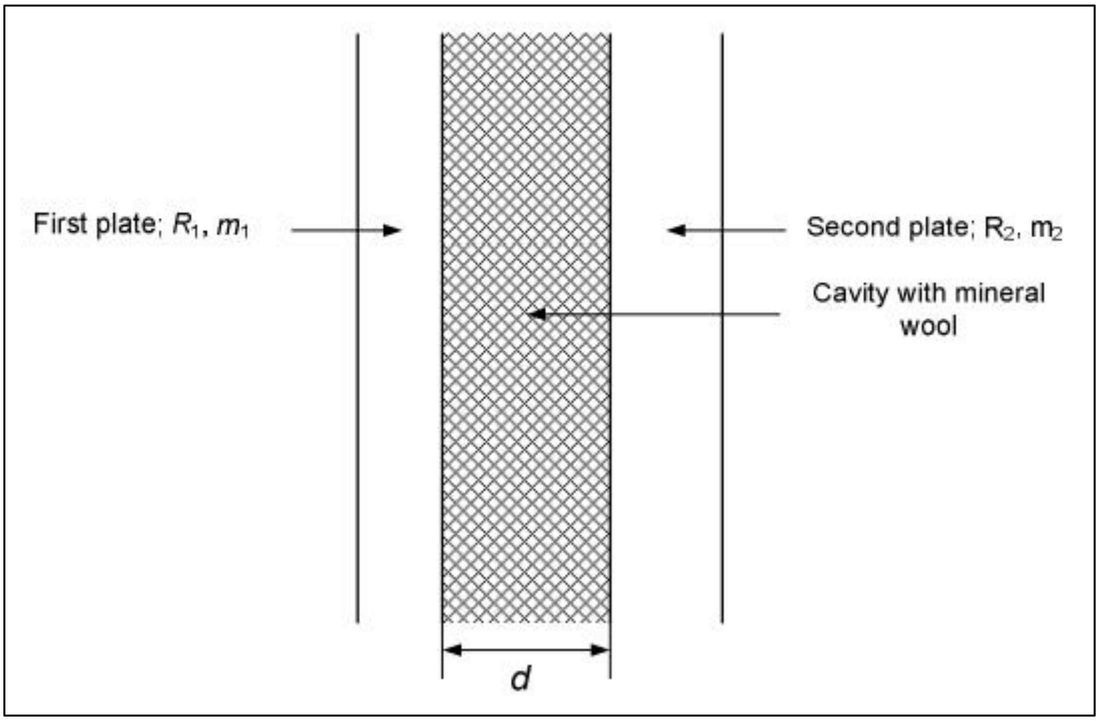

Figure 2.2. Double wall without connections. Cavity thickness d, sound reduction index for each plate R_n and surface weight for each plate m_n (Ljunggren et.al, 2016).

In order to obtain the sound reduction index for the double wall in an analytical calculation, the following equations can be used (Ljunggren et.al, 2016).

For $f < f_0$:

$$R_{double} = R_1 + 17 \cdot \log\left(\frac{m_1 + m_2}{m_1}\right) \tag{2.24}$$

For $f_0 < f < f_1$:

$$R_{double} = R_1 + R_2 + 20 \cdot \log(f \cdot d) - 29 \tag{2.25}$$

For $f > f_1$

$$R_{double} = R_1 + R_2 + 6 \tag{2.26}$$

where R_1 is the sound reduction index for the first plate [dB]

R_2 is the sound reduction index for the second plate [dB]

m_1 is the surface mass for the first plate [kg/m^2]

m_2 is the surface mass for the second plate [kg/m^2]

d is the thickness of the cavity [m]

The resonance frequency for the system f_0 can be calculated according to:

$$f_0 = \frac{116}{\sqrt{d \cdot \frac{2 \cdot m_1 \cdot m_2}{m_1 + m_2}}} \tag{2.27}$$

f_1 is the frequency where R_{double} in equation (2.25) is equal to R_{double} in equation (2.26).

Retrofitting a heavy wall

When retrofitting a heavy wall with a light wall, for example a gypsum wall, the improvement of the sound reduction index can be calculated for the wall construction (Ljunggren et.al, 2016):

For $f < f_0$:

$$\Delta R \approx 0 \tag{2.28}$$

For $f_0 < f < f_1$:

$$\Delta R = R_2 + 20 \cdot \log(f \cdot d) - 29 \tag{2.29}$$

For $f > f_1$

$$\Delta R = R_2 + 6 \tag{2.30}$$

Where f_0 (with cavity absorption) can be calculated according to:

$$f_0 = \frac{82}{\sqrt{d \cdot \frac{2 \cdot m_1 \cdot m_2}{m_1 + m_2}}} \tag{2.31}$$

Where f_0 (without cavity absorption) can be calculated according to:

$$f_0 = \frac{60}{\sqrt{d \cdot \frac{2 \cdot m_1 \cdot m_2}{m_1 + m_2}}} \tag{2.32}$$

2.2 Swedish standards in residential buildings

2.2.1 Sound classification

To maintain satisfied requirements in sound insulation there are four levels of sound classifications according to the Swedish Standard SS 25267:2015 from SIS, Swedish Standards Institute. There are different requirements for different parts of the building, and since this master thesis is focusing on retrofitting of façades the only area of interest is the requirements from outdoor sound and requirements between apartments.

Sound class A has the highest sound reduction index and it responds to very good sound reduction. Sound class B responds to significantly better sound reduction than sound class C which is the minimum requirement for new buildings according to the Swedish Building Regulations, BBR 23. Sound class D is only used for renovations of old buildings where sound class C cannot be achieved for a reasonable cost and without greater impact of the building e.g. for listed buildings. The sound class is decided based on the value of the weighted sound reduction index R'w and it will be explained in the subsequent sections.

2.2.2 Requirements from outdoor sound

In general, except for some exceptions outside windows and doors on external corridors and nearby footpaths, there are no restrictions on the sound reduction index for a façade. In order to fulfil the requirements on equivalent and maximum sound pressure level, all façade constructions such as outer wall, windows and doors should be equipped with a sufficient sound reduction index based on the outside noise levels from traffic or other sources.

The requirements regarding noise in buildings are established by the Public Health Agency of Sweden, which has the responsibility for health issues at national level. The requirements according to the Public Health Agency of Sweden and also the minimum requirements according to BBR 23 state that the equivalent sound pressure level indoor cannot exceed 30 dBA based on the A-weighted sound pressure level (A-weighted sound pressure level accounts for the loudness perceived by the human ear) and the maximum sound pressure level cannot exceed 45 dBA. (Folkhälsomyndigheten, 2014). This also corresponds to the minimum requirements according to the sound classification, sound class C (BBR). The requirements according to the Swedish Standard SS 25267:2015 state that the sound pressure level indoors cannot exceed 26 dBA equivalent and 41 dBA maximum for sound class B and also 22 dBA equivalent and 37 dBA maximum for sound class A. However, sound class D, shares the requirements with sound class C (BBR) since both are based on the maximum sound pressure level humans are allowed to be exposed of according to The Public Health Agency of Sweden (SIS, 2015).

Table 2.3. Highest allowed sound pressure levels from outdoor sound in apartments, according to SS 25267:2015.

	Sound class			
	A	**B**	**C (BBR)**	**D**
Equivalent sound pressure level, $L_{A,eq,24h}$ [dBA]	22	26	30	30
Maximum sound pressure level, $L_{A,Fmax}$ [dBA]	37	41	45	45

2.2.3 Requirements between apartments

On the contrary to the requirements from outdoor sound, there are sharp requirements for the sound level difference when measuring sound between apartments. The minimum requirements between apartments in new built residential building have been set by BBR 23 to be $D_{nT,w} + C_{50-3150} = 52\ dB$ for normal walls and floors between apartments. There are however special requirements for different parts of the building e.g. walls towards garages and commercial facilities. All specific requirements for the different parts of a building can be found in BBR 23. As this paper is only interested in looking at the sound requirements between apartments, only this specific requirement is spelled out here. Similar as the earlier point on requirements for outdoor sound, there are also higher standards, sound class A and B where the requirements are stricter than the 52 dB highlighted above, namely 60 dB for sound class A and 56 dB for sound class B. There are also requirements according to sound class D at 48 dB. These requirements for better sound class can be found in the Swedish Standard SS 25267:2015 (Boverket, 2016).

Table 2.4. Highest allowed sound level difference between apartments, according to SS 25267:2015.

	Sound class			
	A	**B**	**C (BBR)**	**D**
Sound level difference between apartments, $L_{A,eq,24h}$ [dBA]	60	56	52	48[1]
1) Requirements refer to $D_{nT,w} + C_{100-3150}$				

2.3 Effect of noise in residential buildings

There are several impacts of noise in residential buildings. In this segment of the paper, we will discuss among others the impact of noise towards property prices and human health. This segment aims to provide some insights on some of the reasons why sound insulation is an important consideration when constructing residential buildings.

Noise and its impact on health

There are two classifications of noise impacts on health; one being auditory and the other non-auditory. Auditory noise effect results in either a temporary loss of hearing or an eventual permanent loss of hearing. Non-auditory effects are those that are not directly related to hearing itself or the hearing organs but the other health consequences of exposure to noise on the human body.

- **Auditory Effects**

Auditory noise effect could result from a one-time loud impulse sound or a long-term exposure to noise above a certain decibel level. These exposures result in damages of the eardrums or the cochlea resulting in eventual permanent hearing loss. In a report done by World Health Organization, it was estimated that approximately 10% of the world's population are exposed to negative environment with high sound pressure levels that could eventually lead to some form of hearing loss (Basner et al, 2013).

- **Non-auditory Effects**

Contrastingly, as mentioned, non-auditory effects are the health effects of noise, which does not directly impact the hearing organ. Some of these effects include sleep disturbance and annoyance. In a research done by the World Health Organization, they found that environmental noise has a negative impact on the healthy well-being among Europeans. Referring to figure 2.3, it was found that environmental noises impose the greatest negative effect on the quality of sleep of humans followed by emotional annoyance.

Adequate and quality sleep is important in achieving daytime alertness and also contributes to the performance level of daily tasks. Environmental noise was medically tested to result in psychological reaction during sleep, which interferes with normal and quality sleep cycle therefore impeding daily alertness and productivity (Basner et al, 2013).

In addition, humans who are exposed to long-term noise tend to experience high emotional annoyance. In medical terms, annoyance refers to an emotional state, which is linked to anger, depression and/or a sense of helplessness. In a study driven by the European Union Commission, who uses a survey method to analyse the impact of traffic noise on the general emotions of participants, it was found that most participants tend to regard hearing traffic noise as an emotional annoyance and makes them feel depressed. (European Environmental Agency, 2010) This is further explained by the fact that traffic or aircraft noise tend to distort the quality of humans daily activities such as conversations or watching television. Therefore when this quality is distorted, the noise, which contributed to such an environment, is deemed as the devil source. (Stansfeld et.al, 2003)

Moreover, environmental noise is also linked to concrete medical implications namely cardiovascular disease which includes ischaemic heart disease, high blood pressure as well as stroke. Long term exposure to noise results in a charge up of the autonomic nervous systems and causes the heart to beat faster (Basner et al, 2013).

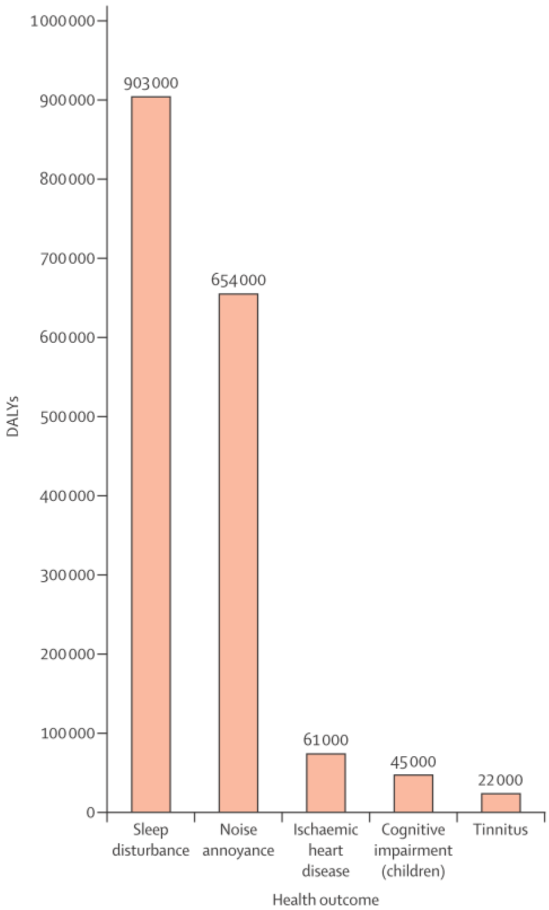

Figure 2.3. DALYs attributed to environmental noise exposure in Europe, DALYs=Disability-adjusted life years (Basner et al, 2013).

Noise impact on property prices and valuation

Many previous studies have studied the relationship between noise and property prices. Often, the results are coherent and indicate that people are willing to pay for properties, which have lower noise pollution or with better sound insulation. This is logical if we consider the health and environmental impacts of noise as mentioned above. In short, people generally have a steeper utility curve when comparing properties with different noise transmission and tend to see a higher marginal benefit from paying more to attain satisfaction from their homes.

In a study carried out by Wilhelmsson (2000), which studied the impact of traffic sound on the property prices in a Stockholm suburb, it was found that houses with less sound insulation are sold at a discount of almost 30% compared with properties that have good sound insulation. In his study, Wilhelmsson (2000) controls for other factors that could potentially affect the prices of properties among others property tax, location and size of houses. With this, he could somewhat accurately study the impact of sound insulation on the property prices. The theory behind this finding focuses on the idea that people attribute higher value and, are generally willing to pay for houses, which have specific properties. These properties include better sound insulation as noise is generally related to disturbance and something negative.

The study indicated above is also consistent with the findings from Andersson et al (2009). In their paper, they aim to highlight the impact on property value as a result of different sources of noise, herewith being traffic and railway noise. As a method, they focus on hedonic econometrics regression, which showed statistically significant correlation between noise indicators and property value. From their findings as shown in figure 2.4, it simply indicates that properties with higher noises coming from traffic and railway tend to have lower price valuation.

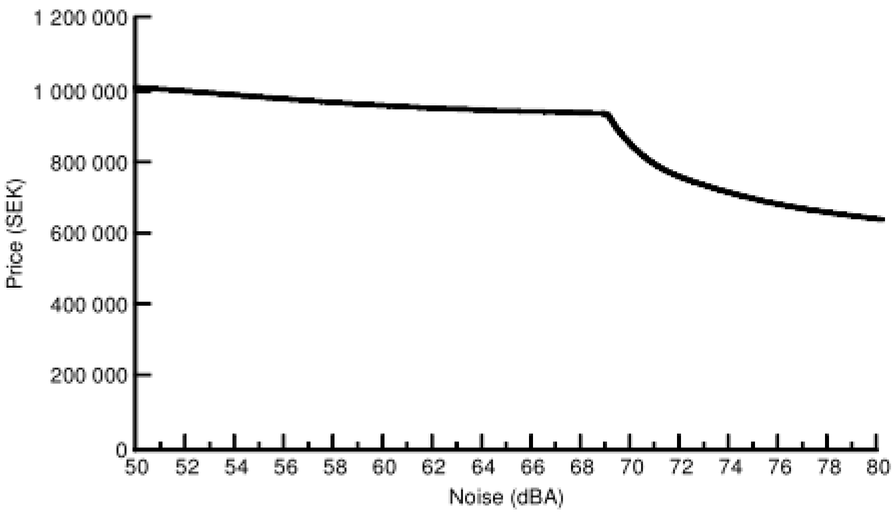

Figure 2.4. Property prices on a standard property in locations with different noise levels (Wilhelmsson, 2010).

3 Thermal insulation

3.1 Thermal transmittance

To define how good a building element is in terms of thermal insulation, the thermal resistance is determined. The thermal resistance, also known as R-value, defines how much heat energy is transmitted through the building element per square meter and has the unit $\mathrm{m^2K/W}$. In buildings however, the U-value, thermal transmittance, is mostly used, defined as the inverse of the R-value and has the unit $\mathrm{W/(m^2K)}$. The U-value, is calculated according to the equation (3.1). Note that a low U-value responds to good insulation, whereas a high U-value responds to poor insulation.

$$U = \frac{1}{R} = \frac{1}{d/\lambda} = \frac{\lambda}{d} \tag{3.1}$$

where d is the thickness of the element [m]

λ is the thermal conductivity [W/mK]

3.2 Thermal conductivity

Thermal conductivity is a material constant and describes the ability of a material to conduct heat, see table 3.1 for commonly used materials in constructions. A material that easily conducts heat gives a high U-value and is therefore a poor heat insulation. Considering that, materials with low conductivity are used for insulation in buildings.

Table 3.1. List of some materials and their thermal conductivity according to Boverket, 2007.

Material	Thermal conductivity $[\mathrm{W/(mK)}]$
Autoclaved Aerated Concrete	0.20
Bricks	0.60
Cellular plastic	0.04
Concrete	1.20
Gypsum	0.22
Internit	0.60
Mineral wool (glass)	0.037
Mineral wool (stone)	0.033
Wood	0.14

3.3 Total thermal transmittance

In the case where a number of materials are put together into one building element, the total thermal transmittance is dependent on each individual material. For example, if we look at a layered wall, the total thermal transmittance is simply the sum of all the materials' thermal conductivity and its thickness (Rosvall, 2010) as shown according to the following equations:

$$R_{tot} = R_1 + R_2 + \cdots + R_n = \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + \cdots + \frac{d_n}{\lambda_n} \tag{3.2}$$

$$U = \frac{1}{R_{se} + R_{tot} + R_{si}} \tag{3.3}$$

where R_{se} is the external surface resistance

R_{si} is the internal surface resistance

The surface resistance is a constant when calculating the thermal resistance when going from open air to a solid material. The surface resistance is an air film of each side of the wall that is added to the total thermal transmittance. For a wall R_{se} is 0,04 m^2K/W and R_{si} is 0,13 m^2K/W.

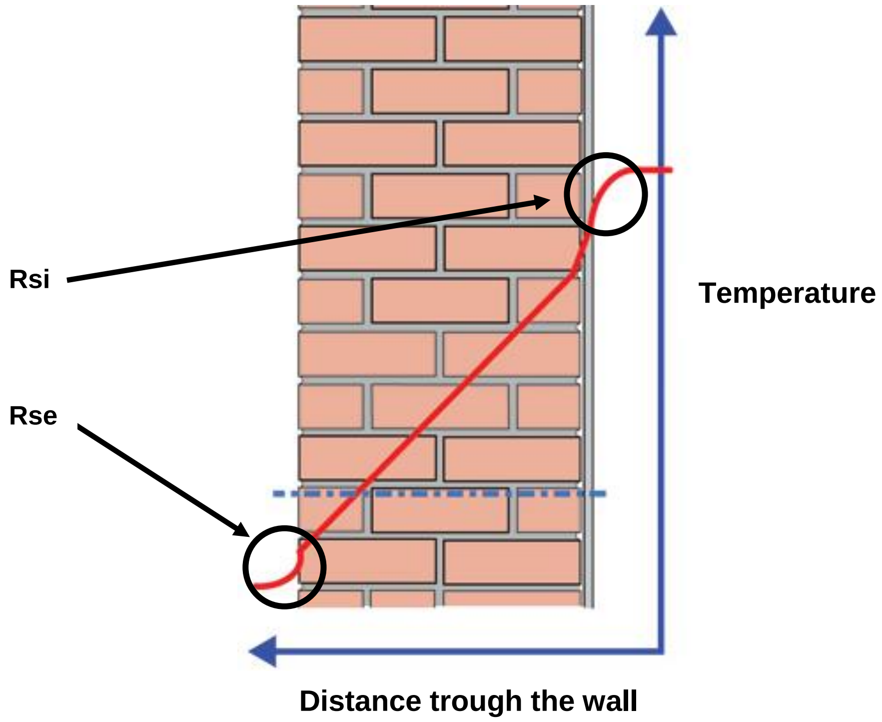

Figure 3.1. The surface resistance on the inside (Rsi) and on the outside (Rse). Red curve is showing the temperature trough the wall (Adapted from buildingscience.com).

For a more complex building element which consists of several materials in the same layer, two different calculation methods can be used: *The Thermal Transmittance method* and *The Thermal Conductivity method*. Both methods are based on the previous equation (3.3), but the order of operations is different. As a matter of fact, these two methods give a slightly different result, where the thermal transmittance method slightly underestimates the total thermal transmittance and the thermal conductivity method slightly overestimates the total thermal transmittance (Rosvall, 2010). A combined thermal transmittance is therefore calculated with the following formula:

$$U = \frac{2 \cdot U_\lambda \cdot U_U}{U_\lambda + U_U} \qquad (3.4)$$

where U_λ is the thermal transmittance calculated with the thermal transmittance method

U_U is the thermal transmittance calculated with the thermal conductivity method

3.3.1 Thermal transmittance method

In the thermal transmittance method the building element is studied orthogonal from the thermal flow. In this manner the building element is getting different areas with different thermal transmittance. For example, as shown in figure 3.2, in a double wall with vertical and horizontal wooden beams, there will be four small segments with a thermal transmittance for only wood, there will be four long segments for one layer wood and one layer mineral wool, and there will be one big segment with only mineral wool from both layers (Rosvall, 2010).

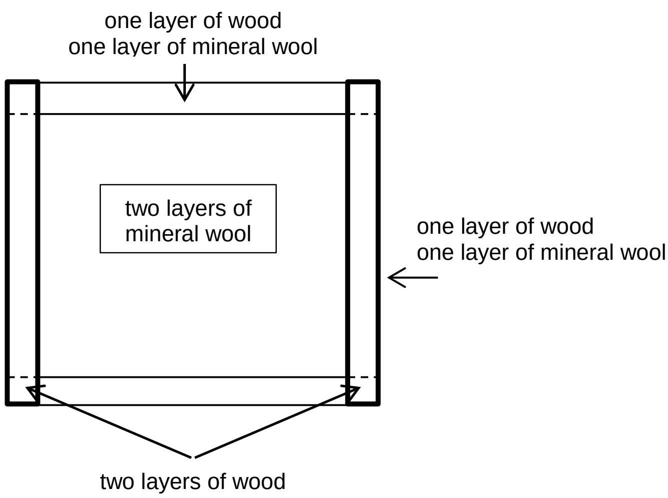

Figure 3.2. Building element studied orthogonal from the thermal flow showing the different areas.

For each segment a thermal resistance is calculated based on its thickness and its thermal conductivity. The thermal resistance and thermal conductivity are calculated on each individual thickness layer, and then added together. When the thermal resistance for each segment is known a total thermal resistance is calculated (Rosvall, 2010) according to the following equation:

$$R_U = \sum_{i}^{n} A_i \cdot R_i \qquad (3.5)$$

where R_U is the thermal resistance for the total area composed of n materials [m^2K/W]

i is the index of the sub element

A_i is the area for each segment in percentage

R_i is the thermal transmittance for each segment, including the surface resistances [m^2K/W]

The thermal transmission is now calculated as previously according to equation (3.3).

3.3.2 Thermal conductivity method

In the thermal conductivity method the building element is studied through the cross section instead of orthogonal from the thermal flow. In this method a combined thermal conductivity for each layer is calculated instead of a combined thermal resistance for each segment. For a layer with only one material the normal method is used according to equation (3.2). Layers with different materials, for example a wooden beam wall where mineral wool is placed between the wooden beams, a thermal conductivity for the whole layer is calculated. A percentage of each material in the layer is calculated and multiplied with the thermal conductivity of the material itself. Adding all materials in the layer will give a combined thermal conductivity for the whole layer (Rosvall, 2010) according to the following equation:

$$\lambda_{combined} = \sum_{i}^{n} \alpha_i \cdot \lambda_i \qquad (3.6)$$

where α_i is the percentage of the material of the total layer composed by n materials

λ_i is the thermal conductivity of the material in each layer [W/mK]

With the calculated thermal conductivities for the layers together with the layers thickness, the thermal transmittance can be calculated as previously according to equation (3.2) followed by (3.3).

3.4 Energy calculation

An energy calculation to determine how much heat energy that is transmitted through the façade element can be done after the thermal transmittance has been established. The heat energy transmitted through the wall is simply calculated multiplying the thermal transmittance with the area and the degree hours (Neuman, 2015).

$$E = U \cdot A \cdot \theta_{\Sigma h} \tag{3.7}$$

where E is the energy transmitted trough the wall [W]

U is the combined thermal transmittance of the wall [W/m^{2}K]

A is the area of the wall [m^2]

$\theta_{\Sigma h}$ is the degree hours [K]

The degree hours are the amount of hours during a year that the building has to use a heating system. In Sweden, 17 ºC is normally used as the breaking point when estimating the degree hours. 17 ºC is picked in order to calculate how many hours that the heating system has to be in use in order to get 20 ºC indoors. 17 ºC is then set in order to consider internal heat such as humans and appliances (lamps, fridge, stove etc.) but also sun radiation through the windows. For every hour the outdoor average temperature is below 17 ºC the degree hours are counting. Therefore the degree hours are dependent on where the house is located. For example the degree hours are 80 000 Kh in Malmö and 92 000 Kh in Stockholm (Neuman, 2015).

3.5 Retrofitting methods

When retrofitting a wall there are two methods that can be chosen from; retrofitting on the inside and retrofitting on the outside of the wall. Adding insulation on the inside of the existing wall is easier than adding insulation on the outside, since wooden or steel beams can be placed on the inside of the wall with an insulating material in between, not affecting the exterior façade. On the down side, along with losing out of room space in the rooms, adding thermal insulation on the inside of the wall will make the existing wall colder and therefore more sensitive towards moist in the wall. In many walls there is a vapour barrier, a plastic foil that prevents the moist inside the building from going through the wall due to difference in relative humidity on both sides of the wall. If the retrofitted insulation material on the inside is thicker than one third of the wall, the plastic foil will be too cold compared to the temperature inside the room and water will condensate on the inside of the plastic foil and creating a huge risk of mould growth inside the wall (SP, n.d.). However, in old buildings a vapour barrier is often missing without causing any harm to the wall due to the poor insulation, which gives a warm wall where no condensation will occur. Therefore it is of great importance that the retrofitted insulation material isn't too thick or that a new vapour barrier is installed together with a removal of the old one. The biggest risk with a retrofitting on the inside is that the dew point is shifted further into the construction and mould growth will occur.

Retrofitting an insulation material on the outside of the wall is more favourable than adding an insulation material on the inside, although it is a greater impact of the exterior façade. When adding an insulation material on the outside the existing wall is getting warmer and therefore drier than before. Moving the dew point further out in the construction will reduce the risk of mould growth in the façade (Bolist, n.d.). It is of great importance that a vapour barrier, if missing, is added to prevent moist from entering the construction from the inside, which otherwise will enter the construction and give mould growth when the dew point is reached. On the outside of the façade there should be an existing air gap that lets the precipitation that enters the construction pour out and dry up. Without a sufficient air gap, water from precipitation will enter the construction and increasing the risk of mould growth and also freezing damages if the water isn't being dried out. When the retrofitted insulating material is added it is important that the existing façade is removed and the air gap is shifted further out for sufficient heat insulation since cold air will be entering the air gap. With an air gap inside from an insulation layer, the construction will keep cold and adding more insulation will not make a difference and the thermal transmittance will remain the same. A new air gap must be installed outside the retrofitted insulation material but inside the new façade layer to protect the construction.

All in all, the retrofitting method from the outside is preferred due to the risks with a cold façade causing mould growth. However, retrofitting on the outside is a great impact of the building and often requires a planning permission from the municipality. Therefore retrofitting on the inside is often a cheaper and easier solution and can be done in one room at the time.

A common building method the early 2000th was the so called exterior insulation and finish system (EIFS). This method was built without the air gap and the EIFS itself was the weather barrier. In some cases in Sweden these façades have been suffering from severe moisture damages and mould growth and many façades have been replaced. These façades should always be retrofitted on the outside of the wall creating an air gap and preventing water from entering the construction.

3.6 Swedish standards in residential buildings

3.6.1 Climate zones

In an attempt to reduce the human carbon and energy footprint and saving energy to the best possible extend, Sweden's restrictions on the specific energy use is measured in kWh per square meter and year. Due to the differences in the climate across the country, Sweden breaks the overall country into 4 distinct parts or climate zones where each zone has relatively similar average outside temperature. Climate zone I is far north and climate Zone IV is the southernmost part of Sweden. Depending on the average temperature in the climate zone and the national required thermal transmittance described in section 3.6.2, the maximum building's specific energy use per year spreads from 115 kWh/m^2 in climate zone I, 100 kWh/m^2 in climate zone II, 80 kWh/m^2 in climate zone III and 75 kWh/m^2 in climate zone IV.

Figure 3.3. Four climate zones in Sweden (adapted from www.nibe.se).

3.6.2 Requirements for thermal insulation

The requirements regarding energy management in buildings are, similar to the requirements for noise, established by The Public Health Agency of Sweden. The requirements state that a new built dwelling with several apartments in the building should not have a thermal transmittance exceeding $0{,}4\ \mathrm{W/m^2K}$ as an average for the whole building envelope, including roof, foundation, walls, doors and windows. Since windows and doors always have a significantly higher thermal transmittance and are the weakest point in the building envelope, the other parameters have to be well below the average requirement.

When altering or renovating a building, if the average thermal transmittance does not meet the requirement, the values should be pursued for the alteration according to the following table:

Table 3.2. Pursued thermal transmittance for different parameters according to Boverket, 2016.

$\boldsymbol{U_i}$	$[\boldsymbol{W/m^2K}]$
U_{roof}	0,13
U_{wall}	0,18
U_{floor}	0,15
U_{window}	1,2
U_{door}	1,2

There are a number of exceptions in which the building envelope is allowed to not reach the requirements when altering a building, but it is of great importance that the thermal transmittance is not getting higher than before the alteration (Boverket, 2016).

3.7 Thermal impact in residential building

While many civil engineering research has discussed the importance of maintaining and ensuring thermal insulation properties during construction of buildings, less of these papers touch upon the impact of lacking thermal insulation on human health as well as environmental consequences. In this section, two important impacts on health when there is lacking thermal insulation in residential buildings are discussed.

Health impact of thermal discomfort

The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE), states that the thermal comfort is the state of mind of a person that is fully satisfied with the thermal environment that he or she is in (ASHRAE Standard, 2004). In other words, it is the state when the human body is functioning well and it is not defined as a single particular temperature but rather a range. It is a subjective judgement that differs according to different individuals, where a particular temperature might be the perfect point for one individual but others might feel satisfaction at a degree higher or lower. Many different factors affect the level of thermal comfort and these include the level of human activity, the relative air movement, air temperature as well as the level of humidity. Therefore, due to the fact that humans tend to spend most of their time being indoors, it is important to ensure that the building has proper thermal insulation. A better-insulated building has the ability to balance out the various factors to arrive at an environment where the occupants are satisfied (Sookchaiya, 2010).

Thermal discomfort occurs whenever an individual is in a state of dissatisfaction with the temperature of the environment he or she is in. There have been many different studies that look into the health impacts of thermal discomfort. In a study done by the US Green Building Council, it was found that by having a better thermal insulated house, there is generally a higher level of thermal comfort. Thermal comfort, in turn, contributes to happier and healthier occupants (Opitz, n.d.). The logic behind this assumption is that, when an individual is satisfied psychologically with the environment he or she is in, he or she tends to be able to function well and be productive in their daily life.

In a different study done by University College London for Friends of Earth (Marmot Review Team, 2011), it was reported a strong correlation between living in cold temperatures and death. In the report, which was based on figures from United Kingdom, it was found that each degree Celsius drop below 18 degree Celsius, contributes to an additional 3500 deaths. These deaths result from issues with the respiratory and circulatory systems in addition to the well-known factors such as influenza and hypothermia. Cold weather conditions can cause the heart to work harder and therefore people who are prone to living under cold weather conditions are more susceptible to circulatory and cardiovascular health issues, which could result in death. In contrast, hypothermia is developed when cold weather conditions result in the drop of body temperature well below the standard 37 degrees Celsius, an individual may experience confusion and fatigue (Guly, 2011). Over time, an individual who is exposed to cold living conditions develops what it is called chronic hypothermia and this can cause severe mental impairment. To further support the findings above, in a separate research done by Shelter (2006), it was found that the impact of mental health is greatest among children living in bad housing conditions with lacking thermal insulation. The study found that children living in badly insulated housing during cold weather tend to develop anxiety, often feel depressed and are slower in their cognitive development.

While previous studies has mainly focused its efforts on highlighting the importance of thermal discomfort resulting from cold temperature, little emphasis has been put on impacts of living in a warm home. With the latest incidences of heat waves and persistent long periods of warm weather, additional focus has been added on ensure that waste heat is released from the residential buildings therefore keeping homes cool and comfortable for the occupants. In a study done by Kosatsky (2005) it was found that the heat wave which occurred in Europe in 2003, resulted in excess death in many of the major European cities. Some of the factors contributing to the increase level of mortality include heat exhaustion and heat stroke. It was argued that in a hot environment it takes much shorter to cause a significant health impact as compared to being exposed in a cold environment. An individual tends to be drained off its natural liquid as it forces itself to cool down in a warm environment. This leads to a drop in the level of body liquid available, which eventually leads to dehydration. In turn, dehydration causes the body to be weaker and an individual tends to feel more lethargic than normal. An extensive level of dehydration can lead to heat stroke, which is also considered as a serious heat illness. A heat stroke has many implications and some of them include cardiovascular and respiratory failure, which can lead to death (Utton, n.d.) (Department of Health, 2011).

The previously summarized findings from previous research have given some indication on the importance of thermal insulation in balancing out the environment in a residential home in order to obtain an optimal living environment for its occupants. A home that is too hot or too cold could bring detrimental health impacts.

Environmental impact

Countries around the world are coming together to pledge support towards energy efficiency projects. Within the European Union, the Commission has recently announced its promise to reduce the use of energy and promote various energy efficiency projects within the various member countries. This comes at a period where the world is facing environmental issues surrounding the depletion of energy resources as well as global warming. Energy efficiency is deemed to be one of the most effective ways of reducing carbon dioxide emission, which causes global warming. In addition, the introduction of energy efficiency reduces the speed of energy resource depletion, which is an important aspect while the world continues to develop renewable energy resources as a substitution for the depletion of coals and minerals. This is crucial because the lack of focus on saving the current available resources will potentially lead to a complete depletion of non-renewable energy resources at a much faster pace than the world can expect.

According to the European Environmental Agency (2015), residential buildings contribute about 26.6% of the total energy consumption in Europe (see figure 3.4). With the pledge for increased energy efficiency, the European Union highlights that the residential and the household sector have the highest potential of energy savings. Due to the natural climate in Europe, the highest source of energy consumption is heating to mitigate the cold outside temperature. Therefore, the implementation of thermal insulation to improve the thermal comfort indoors enables lower energy to be used therefore contributing positively towards saving global energy resources. Old houses in Europe can be retrofitted to further improve the thermal insulation properties. By doing this, the need for additional heating elements can be reduced by about 30-50% (European Environmental Agency, 2015).

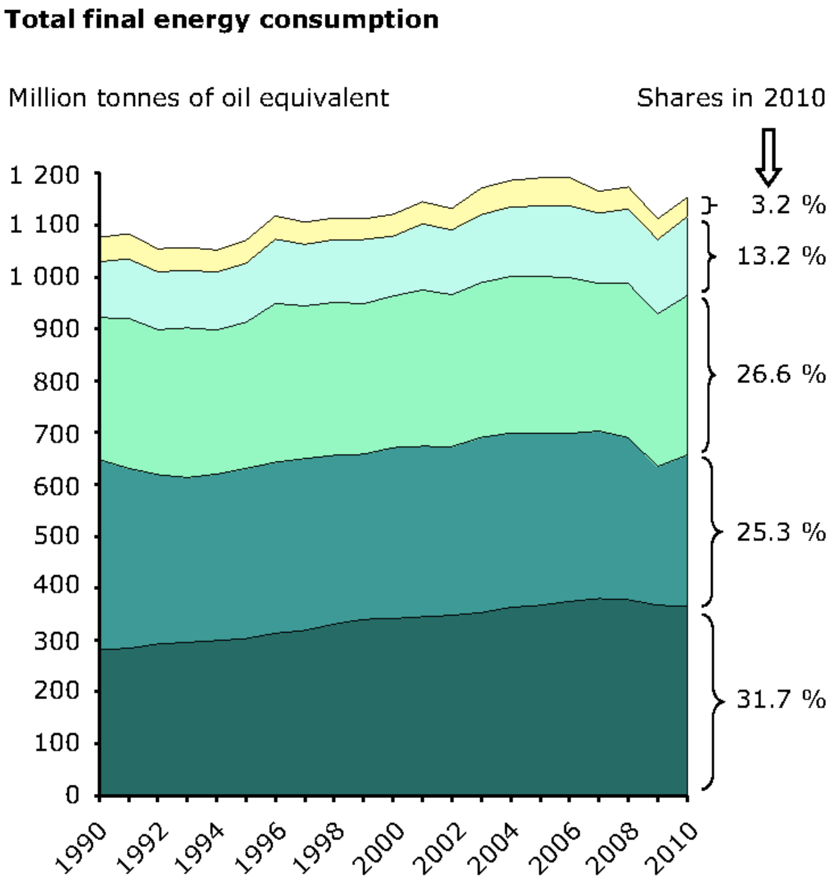

Figure 3.4. Total final energy consumption (European Environmental Agency, 2015).

In a separate study done by European Alliance of Companies in Energy Efficiency (EuroACE) it was found that improving insulation in European houses contribute to a large reduction of carbon dioxide emission within the European region as well as reduces the need for additional heating demand by about 20%. This finding highlights the importance of thermal insulation in residential buildings (XCO2, n.d.).

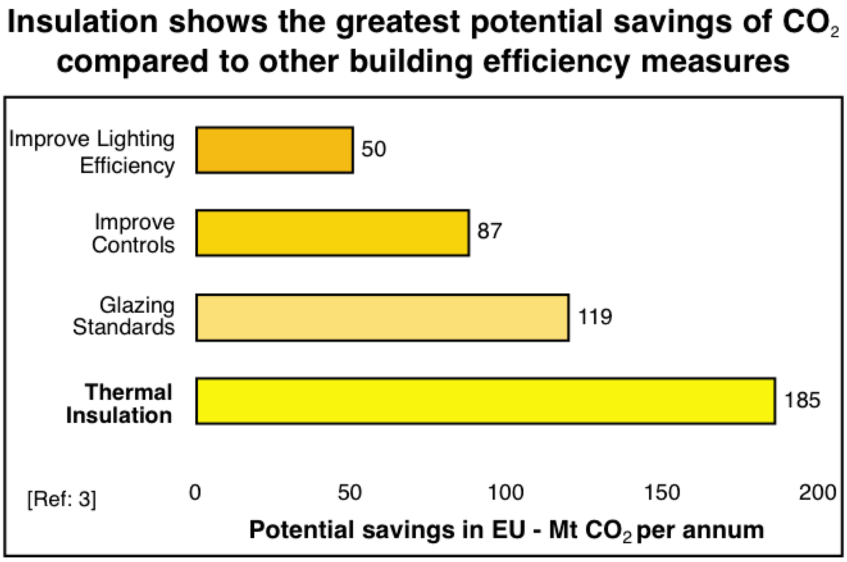

Figure 3.5. Insulation shows the greatest potential of saving CO_2, (XCO2, n.d.)

Based on economics theory of supply and demand, an increasing strain on the supply of available energy resources while at the same time an increase in demand due to increasing population and higher industrial activities, will result in an increase in the prices for energy. The less focus there is on energy efficiency would mean additional energy cost borne by home owners as they try to keep their house warm (in the case of European countries) or cool (in the case of tropical Asian countries). Figure 3.5, which was adapted from the European Statistics Commission, indicates a clear trend line of the energy prices for household consumption in Europe. On average, between the year 2008 to 2016, energy prices have increased by 30% within the scope of European Union (Eurostat, 2016).

Figure 3.6. Energy prices in Europe, 2008-2016 (Eurostat, 2016)

4 Methodology

4.1 Details of calculations

The calculations for the research presented here will compare how different retrofitting methods will affect the default configuration of the façade constructions. The first calculations to be done are therefore the properties of the default configuration according to the following:

- Sound reduction index from outdoor sound
- Sound level difference between apartments
- Thermal transmittance
- Heat energy transmission

For the three different façade constructions as mentioned in section 1.2 based on the 1960s building technique in Sweden, different retrofitting methods will be investigated. As a short recap, the 3 different façade constructions that are used in this study are:

1. Element built façade construction of concrete
2. Autoclaved aerated concrete blocks outside a load bearing concrete façade
3. Light weight façade elements built as a Curtain wall or Infill wall

For the two heavy concrete façade constructions, retrofitting will be made as two different case studies; one retrofitting on the inside and one retrofitting on the outside of the façade. Both retrofitting will be carried out with gypsum boards on wooden or steel studs placed separated from the wall. The cavities will be filled with mineral wool for absorption and for thermal insulation. This retrofitting method is simple and the most conventional way to do a retrofitting. The acoustic calculations, sound reduction index from outdoor sound and sound level difference between apartments, will be carried out in the computer software BASTIAN and sometimes altered in the computer software INSUL. Both software are selected as they are most commonly used by building acoustic consultants in Sweden and as such justifies their reliability of providing comprehensive results in previous building projects.

The third construction is based on a double leaf construction and is therefore more complex. Adding an extra layer will create a triple leaf construction which might cause reductions in some frequencies. This construction will be modelled in the computer software INSUL to come to a recommendation of a good way to increase the sound reduction index from outdoor sound and decrease the thermal transmittance.

For all three constructions, the thermal calculations for thermal transmittance and the heat energy transmission will be done through manual calculations based on standard thermal equations.

4.2 INSUL

4.2.1 Background

INSUL is a program that predicts the sound insulation of e.g. walls and is developed by Marshall Day Acoustics which is a consultant firm founded in 1981, New Zeeland. INSUL also predicts sound insulation for other types of building elements such as floors, ceilings and windows.

The INSUL version used in this thesis is INSUL 8.0.7 from 2015. Through the many updates, INSUL has been improved and compared with laboratory tests to provide accuracy for a wide range of constructions (Marshall Day Acoustics, 2017).

4.2.2 Usage

In INSUL, the building element is built up in a graphic window. The building element, in this case a wall, consists of panels and frameworks that are being alternate layered. The panels and frameworks can be constructed with several materials from a database and varied with different thickness etc. If needed, new materials can be added to INSUL, but it requires several material constants to be accurate.

INSUL calculates the sound reduction index, including a weighted value, for a building element based on the materials used. When new materials are added or changed, INSUL evaluates these changes and models the materials using elastic plate theory (Marshall Day Acoustics, 2017).

4.2.3 Output

When the building element is built up, INSUL calculates the sound reduction index in one-third-octave bands and shows the result in a table for each frequency and also in a resulting diagram. INSUL also calculates the weighted sound reduction index including the two spectrum adaption terms, C for pink noise and C_{tr} for urban traffic noise.

4.2.4 Limitations and restrictions

It is important to remember that INSUL is a predictive tool and it is thus not a substitute for any measurements. When calculations in INSUL have been compared to actual measurements, an accuracy divergence within 3 dB has been perceived for most constructions. However, the accuracy is decreasing with the number of panels in the construction, and for triple panel constructions the uncertainty may be as high as 5 dB (Marshall Day Acoustics, 2017).

When using INSUL as a prediction tool, the given sound reduction index cannot be trusted and INSUL tends to overestimate the construction. This overestimation arises from the fact that INSUL is not based on measurements but strictly based on the calculations from the density and thickness of the different materials. However, having an initial construction with a known sound reduction index, either from a physical measurement or from a computer software such as BASTIAN, INSUL can be used to alter the construction and to calculate the differences of the two.

4.3 BASTIAN

4.3.1 Background

BASTIAN is a program that predicts the sound transmission between rooms and from the exterior and is developed by DataKustik which is a manufacturer of software for emission prediction founded in 1991, Germany. BASTIAN calculates both airborne and impact sound transmission and is commonly used to investigate the building acoustic properties (DataKustik, 2014).

The version used in this thesis is 2.3.103 and contains several databases of materials, which are used in the calculations.

4.3.2 Usage

The graphic layout in BASTIAN is a 3D layout and consists of two rooms (for indoor sound transmission and impact sound) or one room and an outside area (for external sound transmission). The included building elements are defined with dimensions and junctions from pre-defined solutions as well as different materials from the built in database. The building elements consist of a basic element and additional layers that make the model more closely resemble a real life scenario.

New building elements can be added to BASTIAN's database and used in the structure. The new building elements are added with the sound reduction for each one-third-octave but also the critical frequency and the mass per unit area. To know the sound reduction index for each frequency, the building element has to be tested throughout measurements, but the building element can also be built up with different layered materials in INSUL and then imported and used in BASTIAN.

4.3.3 Output

When all building elements are mounted, BASTIAN is calculating the weighted sound reduction index for each building element included a total sound reduction index for the whole structure between the rooms or from outside. The result can be displayed as a weighted sound reduction index, as a normalized sound level difference or as a standardized sound level difference, all with or without different spectrum adaption terms. With the weighted sound reduction index for each building element, it is easy to see which one of the building elements is the weakest. Same result is showed for impact sound. Both the airborne sound reduction and the impact sound level can be shown in a resulting diagram.

BASTIAN calculates according to the European standard EN 12354 parts 1-3; airborne sound insulation between rooms, Impact sound insulation between rooms and airborne sound insulation against outdoor sound (DataKustik, 2014).

4.3.4 Database

BASTIAN includes several databases on building elements. In the databases there are several different building elements such as walls and flooring, and in the BASTIAN-specific Data there are more than 1600 different building elements, and there are more than 2000 different building elements from the Nordic and European market in total (Simmons, n.d.)

4.3.5 Limitations and restrictions

As any other modelling program it is important to remember that it is only an approximation of the construction. The more complex the construction, the more difficult is will be to build it up in BASTIAN in order to get an accurate result. Creating a model in BASTIAN requires great experience in building acoustics (Simmons, n.d.).

4.4 Previous research findings

Previous studies have investigated the varying degree of the different building materials and their acoustics and/or thermal insulation properties. This segment of the paper aims to highlight some of the findings, which will be validated in the simulation investigation in the upcoming chapter.

Autoclaved Aerated Concrete

In a scientific research paper done by Schnitzler (2006), he argues that an Autoclaved Aerated Concrete (AAC) can be designated as a sustainable building material while preserving the important building properties such as thermal and acoustical insulation. Invented in Sweden in 1923 by Johann Eriksson (Wittmann, 1992), the AAC structure is made up of lightweight aggregate concrete materials such as silica, cement and aluminium powder, which react together to form a structure that contains microscopic hydrogen bubbles. Another major factor to note is that this structure is autoclaved using steam and high pressure instead of being left to dry.

AAC is argued to have strong thermal insulation properties thus reducing energy waste through external façades of a building. With the way it is manufactured as described above, the structure with its millions of microscopic hydrogen bubbles has a high ability to retain heat energy. These bubbles trap the heat internally and do not transmit it externally very quickly. It was further argued that AAC is best used in places where there are major fluctuations between the outdoor and indoor temperature (Schnitzler, 2006). Moreover, the AAC not only focuses on saving heat waste but is also a good material for sound insulation. In scientific experiment carried out by Szudrowicz, et al (n.d.), which studied the sound insulation properties of a single AAC walls, they found that AAC walls are generally compliant with the sound reduction requirements though they act as better insulators when the density of the walls are at lower levels of 340 kg/m^3 when it was at higher levels such as 700 kg/m^3.

Mineral Wool

There are mainly two types of mineral wool, the first is known as stone wool, which is created from a mixture of volcanic rock and recycled natural minerals such as slag and coke, and a second type of mineral wool known as glass wool. Glass wool uses the same manufacturing technique as cotton candy and is comprised of fibre glass such as limestone and soda ash. Findings from many previous studies have proved the thermal and acoustical insulation properties of both types of mineral wools (Vrána, 2007).

During the manufacturing stage of these mineral wools, it is important to ensure there is proper and sufficient representation of gas phase within the structure. These gas phases improve the insulating power within the structure of the material and prevent any convective heat transfer out and into the building (Vrána, 2007). In a separate study done by Zach et all (2011), which focused on the sound insulation properties of mineral wool, it was found that mineral wool is an excellent acoustic insulating material with many additional positive properties including energy efficiency as well as good thermal conductivity. In a different study done by Srivatava, et al (n.d.), which investigated the thermo-acoustical properties of mineral wool at various densities and temperatures, it was found that under various differing conditions, mineral wool satisfies its thermo-acoustical insulation properties. By testing differing densities, the study was able to control the effectiveness of mineral wool in its use as a thermal insulation material – bearing in mind that at higher density, the material tends to lose its thermal conductivity.

Concrete

One of the most common building materials is concrete. Ever since it was firstly introduced to the world many years ago, it has been used in various structures such as buildings, bridges and pavements. Up to date, concrete has been the most widely used building material over and beyond any other materials such as steel, aluminium and mineral wool (Crow, 2008). Concrete is composed of cement, water and small granular materials. During the manufacturing process, cement and water come together to form a paste, which when the mixture eventually dries and hardens, holds the small granular materials together to form a large, solid structure.

Due to the fact that concrete is one of the most common building materials, previous research has focused on the various properties of concrete including its thermal and acoustical properties to be used as part of a building structure. In a previous research carried out by Wadsö, et al (2012), which tested the thermal properties of standard concrete, it was found that the thermal conductivity of concrete is dependent on the degree of water-cement ratio which influences the amount of moisture and hydration in the particular concrete structure. It was tested that the more hydrated the concrete, the less air gaps are filling the structure and this improves the degree of thermal conductivity. In addition, within the same paper, the authors tested concrete with varying degree of aggregates (small, granular materials) to figure out if these have any impact on the level of thermal conductivity of concrete. It was found that using different aggregates could potential result in a higher degree of thermal conductivity within a concrete structure. For example, the study found that changing the aggregate from magnetite to graphite, the thermal conductivity of the concrete structure increases significantly. This indicates that the material of the aggregate itself contributes to the level of thermal conductivity of a particular concrete and this is an important factor when choosing material in a retrofitting activity.

Moving on towards an evaluation of acoustical properties for a concrete structure, this paper summarizes the findings from two previous studies, which studied the effectiveness of concrete structures in isolating noise. The first research was done by Warnock (1999), which studied the acoustical properties of concrete floors in minimizing impact sound. It was found that concrete being a hard material, does not offer any cushion for these impact noises. In order to obtain a more acceptable result, the study suggested that concrete floorings are modified with softer materials, which could act as both cushion and absorb noise from being further transferred from one area to another. In addition, a separate research from Warnock (1998) found that a concrete block is only effective in its sound absorption properties when the concrete block is thick enough. This however results in impracticality during the construction of the building and is therefore not preferred. In conclusion, the study indicates that while concrete does possess certain sound insulating properties, it is only effective when the mass per unit area is high enough which unfortunately does not make sense during the construction itself. Therefore, concrete is often used in connection with other materials in order to achieve the right sound insulation effects while balancing the practicality of executing the construction works.

Cellular plastic

In the recent years, a new type of building materials have regained popularity within the industry; cellular plastics (also known by other names such as foamed plastic or expanded plastic). The structure is typically made up of components such as polyurethane, extruded polystyrene or expanded polystyrene and the resulting structure is basically a rigid foam plastic that has good insulation properties. Within the building industry, the two most common type of cellular plastics used are XPS (Extruded Polystyrene) and EPS (Expanded Polystyrene). EPS is a type of cellular foam which is more known as closed-cell insulation and exists typically in white colour. On the other hand, XPS is a rigid insulation structure made using an extruded method and comes in different colours (Akovali, 2005).

During the production process of expanded polystyrene (XPS), the raw materials, polystyrene molecules, are melted and blowing agents are injected in the process under high pressure. The mixture including the blowing agent is then removed from the extruder and the drop in pressure causes the material to turn into foam.

In comparison, the production method for EPS (expanded polystyrene) is almost the same as that of XPS except for one process. In the XPS, the plastic molecules are melted and liquified. However, for the production for EPS, the plastic molecules are rather expanded and then moulded together to form the final shape (Ueno, 2011).

This foamed plastic basically acts as an air tight cover over the surface of the material which is applied on. This way, the foamed plastic tightly covers the holes where the energy is lost through. As a result, these foamed plastic has many advantages such as easy to transport to construction sites due to its lightweight in comparison to other building materials and they are also easy to install. However, above all, cellular plastic are generally favoured due to its low thermal conductivity and they are thus perfect materials in light of the energy conservation and green initiatives (Akovali, 2005). Between the two types of cellular plastic, XPS tends to perform better in thermal insulation. From previous research, XPS has been shown to generate a higher R-value than EPS. This results from the dense structure of the end product and also due to the point that in its natural form EPS soaks up moisture further reducing its R-value (Ueno, 2011).

On a separate point, while polystyrene is a generally known to be a good thermal insulator, it is however a bad sound insulator. The physical properties of plastic and polystyrene allow for a better sound diffusor rather than absorber. Due to its closed-cell nature of the resulting structure, the material in itself will only result in limited success for sound insulation.

Gypsum boards

Today’s building industry sees an increasing usage of gypsum board within the construction of various structures. Gypsum board stands for a type of material, which is made up of gypsum core with an exterior consisting of a different material – typically paper. The use of this material chosen over plywood or fibreboard is due to its core advantage of being fire resistance. In addition, gypsum board also has other advantages such as sound insulation, versatility and durability (EuroGypsum, 2015).

Gypsum can be found in its crystalline form within the sedimentary rock formations. This crystalline mineral is sent to the manufacturing factory where it is dried of its natural water content and finally crushed into small solid powder. Upon contact with water, this small solid gypsum powder is then recharged and the slurry resulting paste is spread onto of cardboard or hard paper to form the gypsum board (EuroGypsum, 2015).

A a gypsum board needs to be used in connection with another material before it is able to harness its full insulation properties. In a typical wall construction, steel or wood studs are used to fasten gypsum boards on each side, leaving a cavity area between the two boards. This cavity area is then either left empty or insulation materials can be stuffed in between to improve the insulating power of this wall structure. Typically, materials such as glass fibre, mineral wools or cellular fibres are used to fill the space (see figure 4.1).

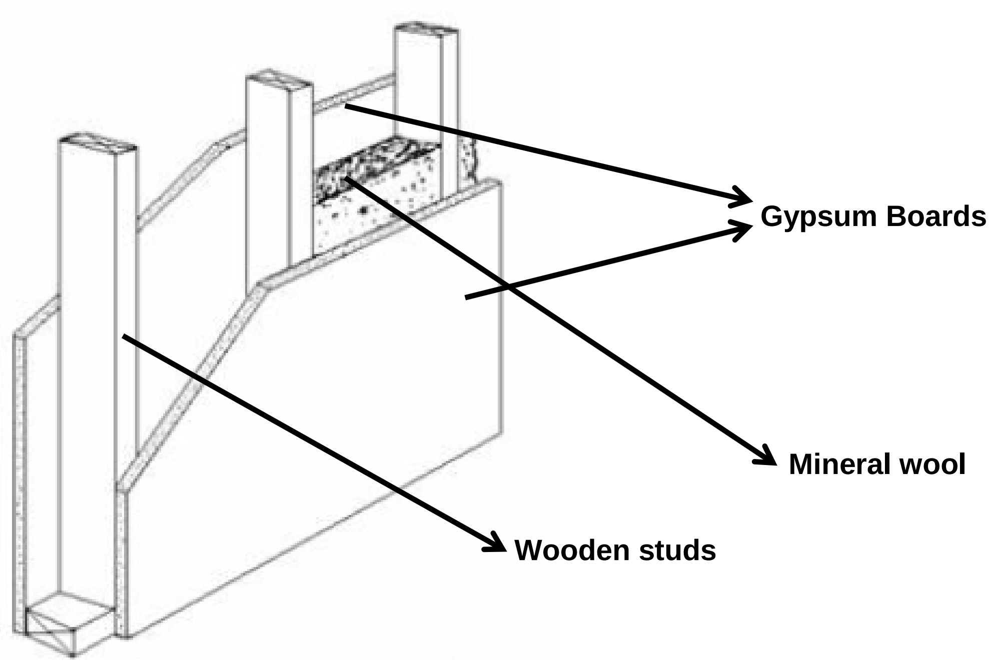

Figure 4.1. Example of material in a gypsum wall.

In a study done by Warnock and Quirt (1997), it was found that the insulating properties of the gypsum walls together with the cavity filled material, only improves when the gypsum boards are isolated from each other. This basically indicates the need of these steel or wood studs which keep the gypsum boards apart from each other instead of locked together. In the study, they also looked into the importance of the construction of the insulation material as they fill up the cavity between the gypsum walls. In that section of the research, it was found that sound reduction was increased when the thickness of the sound absorbing material was increased and that it was also more effective when the cavity was filled completely across the whole inner surface instead of partially. In the same study, it was also shown that the depth of the cavity helps to improve the sound reduction effect and this depth was more critical in a wall structure where no additional insulation material was used to fill the cavity (i.e. when the cavity was left empty). Finally, the study also found that adding additional layers of gypsum board within the wall structure (as an intermediate layer between the two outer boards) worsened the overall sound reduction power of the structure. The factors resulting in this finding primarily lie on the fact that adding an additional layers only reduces the depth of the cavity and allows sound bypass the insulation materials.

In regards to the thermal resistance properties of gypsum walls, the cavity between the two gypsum board traps the heat and therefore delaying the time of temperature transfer to the overall system. In a separate study done by researchers from Universidad Politécnica de Madrid (UPM), they have develop and patented a new type of gypsum board that could help to reduce the energy consumption of a building by as high as 40%. With this new finding, this material is argued to be able to store up to five times the thermal energy of a typical gypsum board therefore improve its thermal properties even further (Madrimasd, 2012).

5 Case studies of pre-retrofit scenarios

5.1 Default configuration of the construction

As mentioned earlier, there are three different example buildings that will be modelled in this paper in order to come up with a recommendation. In order to compare how different retrofitting methods are influencing the constructions, it is important that the default setup of the constructions is the same during the different simulations.

The basic setup for the façade calculations is a room with a 4 meter long façade wall. The room is 3 meters deep and 2,5 meters high. Hence, when comparing the sound reduction index from outdoors to indoors the area of the partition is 4x2,5 meters. When comparing how the different retrofitting methods are affecting the sound reduction index between apartments two rooms with the same dimensions are placed next to each other's, i.e. the area of the partition is 3x2,5 meters.

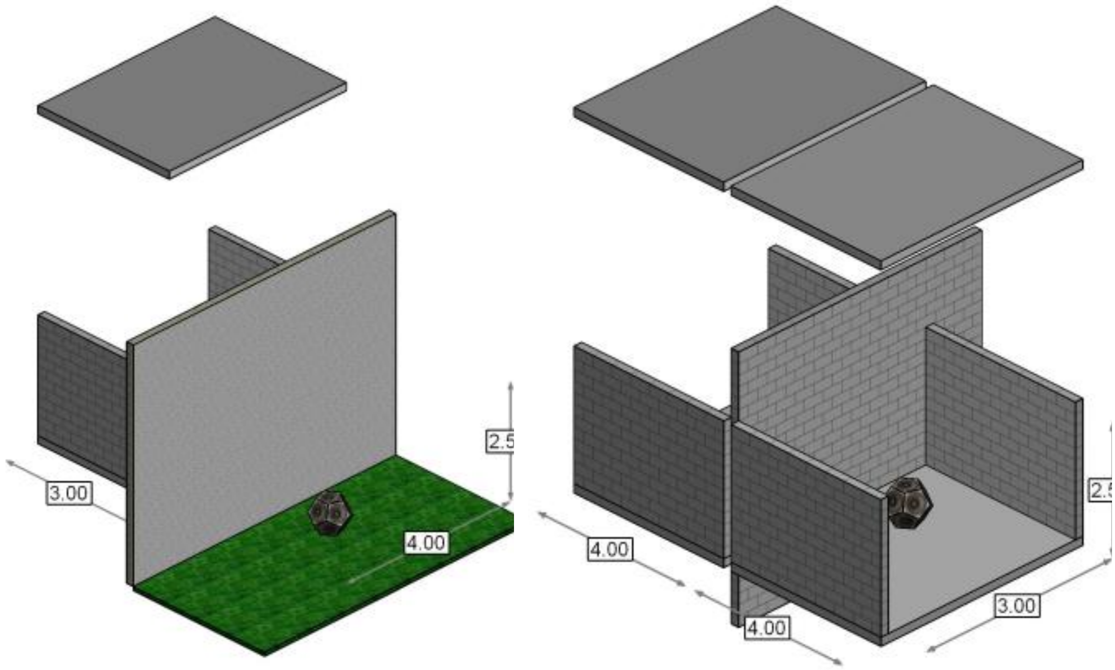

Figure 5.1. Default setup of the construction. Setup for sound reduction index from outdoor sound (left), and sound level difference between apartments (right).

5.2 Sound properties based on the default setup

5.2.1 Construction 1: Element built façade construction

The first construction in the study is an element built façade construction of concrete. The floors and load bearing walls are made up of 200 mm homogeneous concrete elements. The façade is made out of sandwich elements consisting of a non-structural supporting 60 mm concrete on the outside, followed with a 100 mm thick cellular plastic for thermal insulation. Inside the cellular plastic, a load bearing 120 mm thick concrete layer that holds up the floor structure (see figure 1.2).

All the elements are assembled together on the building site creating a steady construction where the floor elements are resting on the internal walls, the façades and in some cases load bearing pillars where the span is large. However, since the building consists of different elements it is of great importance that the façade element is properly reinforced and moulded together with the floor slabs and internal walls in order to reduce the flanking transmission and achieve proper junction reduction. Due to the fast and sloppy building process during the Million New Homes campaign in the 1960s many elements are not properly reinforced. In the default setup of this construction both extremes will be calculated; one with properly reinforced façade construction at the junctions, and one without.

The sound reduction index from outdoor sound for this construction is calculated with the data given above in BASTIAN according to the construction model in the left part of figure 5.1 giving the weighted apparent sound reduction index[1] $R'_{45°,w} + C_{tr} = 40\ dB$ as seen in the following table and resulting diagram.

For the following and all further tables and resulting diagrams regarding sound reduction index from outdoor sound d is the direct sound transmitting trough the façade wall, f1 and f2 is the two internal walls on both sides of the room, f3 and f4 is the floor and the ceiling of the room.

tau	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	R'45°,w + C
d	38.1	38.3	34.5	36.0	34.4	35.9	32.9	33.5	33.3	34.1	40.4	44.4	48.1	49.3	54.0	58.7	61.3	64.1	66.1	70.2	70.8	40.2
f1	51.2	51.3	49.4	50.4	50.5	53.6	54.3	56.8	59.0	61.7	67.1	71.3	75.4	78.2	82.7	87.4	90.8	94.2	97.3	101.5	103.8	62.4
f2	51.2	51.3	49.4	50.4	50.5	53.6	54.3	56.8	59.0	61.7	67.1	71.3	75.4	78.2	82.7	87.4	90.8	94.2	97.3	101.5	103.8	62.4
f3	48.3	48.4	46.5	47.3	47.8	50.9	51.6	54.2	56.3	59.0	64.4	68.6	72.8	75.6	80.1	84.7	88.1	91.7	94.8	98.9	101.2	59.6
f4	48.3	48.4	46.5	47.3	47.8	50.9	51.6	54.2	56.3	59.0	64.4	68.6	72.8	75.6	80.1	84.7	88.1	91.7	94.8	98.9	101.2	59.6
Total	37.0	37.2	33.7	35.1	33.8	35.5	32.7	33.4	33.2	34.1	40.3	44.3	48.1	49.3	54.0	58.7	61.3	64.1	66.1	70.2	70.8	40.1

Figure 5.2. Sound reduction from outdoor sound in 1/3 octave bands, default setup construction 1, exported from BASTIAN.

[1] $R'_{45°,w}$ differs from R'_{w} where the angle sound incidence is 45° to symbolise the average of sound incidences from all angles.

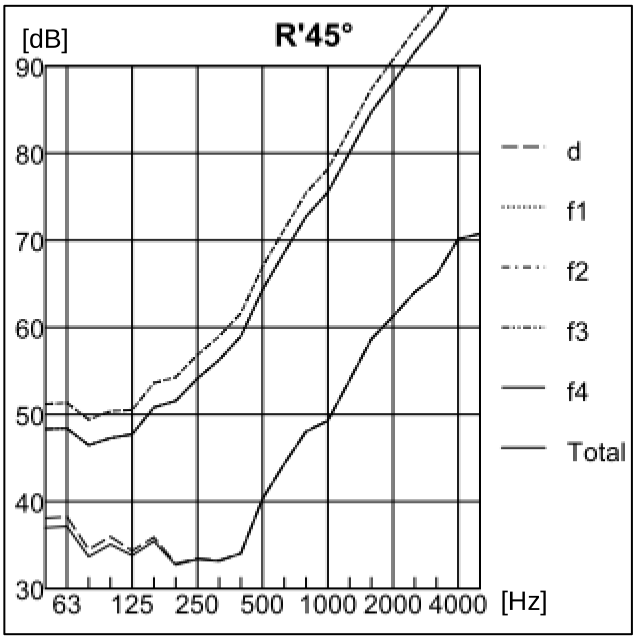

Figure 5.3. Sound reduction from outdoor sound $R'_{45°,w} + C_{tr}$, default setup construction 1, resulting diagram.

The result in the table of 1/3 octave bands and in the resulting diagram indicates that the sound reduction from outdoor sound is weak in the frequencies below 500 Hz which is the dominating frequencies from traffic noise. The weighted sound reduction is therefore poor with regard to the correction term for traffic noise, C_{tr}, the most important correction for outdoor sound when the building is located near high density roads.

The sound level difference between apartments is calculated with the same construction data above, but instead with the right part of figure 5.1. The first calculation, with properly reinforced façade construction, gives the weighted standardized sound level difference $D_{nT,w} + C_{50-3150} = 56\ dB$ as seen in the following table and resulting diagram.

For the following and all further tables and resulting diagrams regarding sound level difference between apartments d is the direct sound transmitting trough the partition wall separating the apartments, f1 is the internal wall of the rooms, f2 is the façade wall, f3 and f4 is the floor and the ceiling of the room.

tau	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	DnT,w (0.5 s) + C50-
d	40.4	40.4	40.4	40.9	42.6	44.7	47.2	49.8	52.3	54.8	57.3	59.8	62.3	64.7	67.2	69.5	71.9	74.1	76.3	78.5	80.5	59.0
f1	50.2	50.2	50.2	50.6	52.5	55.0	57.5	60.1	62.6	65.2	67.7	70.3	72.8	75.3	77.8	80.3	82.7	85.0	87.4	89.6	91.8	69.3
f2	44.3	44.3	44.4	44.7	45.1	45.4	47.9	50.6	53.1	55.7	58.3	61.0	63.7	66.3	69.0	71.6	74.2	76.7	79.3	81.8	84.1	60.3
f3	49.2	49.0	49.0	49.1	51.6	54.0	56.6	59.2	61.7	64.2	66.8	69.3	71.8	74.4	76.8	79.3	81.7	84.1	86.3	88.5	90.7	68.3
f4	49.2	49.0	49.0	49.1	51.6	54.0	56.6	59.2	61.7	64.2	66.8	69.3	71.8	74.4	76.8	79.3	81.7	84.1	86.3	88.5	90.7	68.3
Total	37.9	37.9	37.9	38.3	39.8	41.3	43.9	46.4	49.0	51.5	54.1	56.6	59.2	61.7	64.2	66.7	69.1	71.5	73.8	76.0	78.2	55.9

Figure 5.4. Sound level difference between apartments in 1/3 octave bands with properly reinforced façade construction, default setup construction 1, exported from BASTIAN.

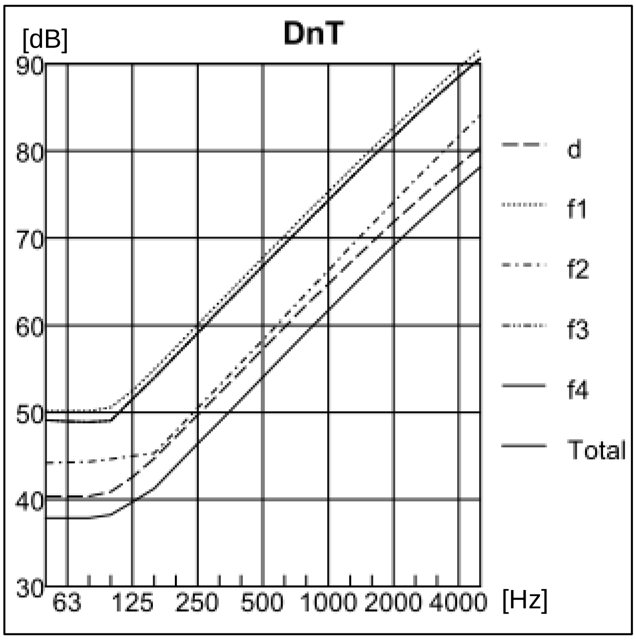

Figure 5.5. Sound level difference between apartments $D_{nT,w} + C_{50-3150}$ with properly reinforced façade construction, default setup construction 1, resulting diagram.

The direct sound here is slightly dominant in low frequencies. In medium high to high frequencies the flanking transmission via the façade is influencing the total sound level difference.

Considering the often poor reinforcement of the façade construction, the second calculation, gives the weighted standardized sound level difference $D_{nT,w} + C_{50-3150} = 52\ dB$ as seen in the following table and resulting diagram.

tau	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	DnT,w (0.5 s) + C50-
d	40.4	40.4	40.4	40.9	42.6	45.0	47.7	50.4	53.0	55.6	58.2	60.8	63.3	65.7	68.2	70.6	72.9	75.0	77.2	79.3	81.3	59.6
f1	50.2	50.2	50.2	50.6	52.5	55.0	57.5	60.1	62.6	65.2	67.7	70.3	72.8	75.3	77.8	80.3	82.7	85.0	87.4	89.6	91.8	69.3
f2	37.3	37.4	37.4	37.7	37.8	37.7	40.3	43.0	45.6	48.3	50.9	53.6	56.3	59.0	61.7	64.3	67.0	69.6	72.2	74.8	77.2	52.8
f3	49.2	49.0	49.0	49.1	51.6	54.0	56.6	59.2	61.7	64.2	66.8	69.3	71.8	74.4	76.8	79.3	81.7	84.1	86.3	88.5	90.7	68.3
f4	49.2	49.0	49.0	49.1	51.6	54.0	56.6	59.2	61.7	64.2	66.8	69.3	71.8	74.4	76.8	79.3	81.7	84.1	86.3	88.5	90.7	68.3
Total	35.1	35.1	35.1	35.5	36.2	36.8	39.4	42.1	44.6	47.3	49.9	52.6	55.2	57.9	60.5	63.1	65.7	68.2	70.7	73.1	75.4	51.7

Figure 5.6. Sound level difference between apartments in 1/3 octave bands with poor reinforced façade construction, default setup construction 1, exported from BASTIAN.

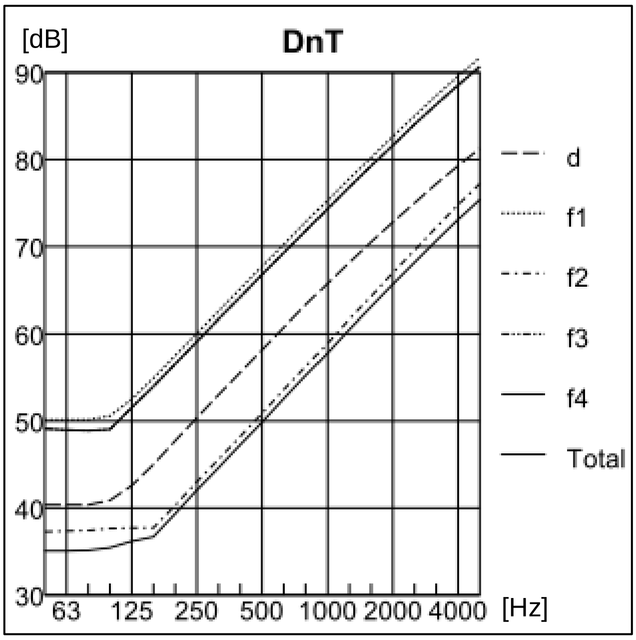

Figure 5.7. Sound level difference between apartments $D_{nT,w} + C_{50-3150}$ with poor reinforced façade construction, default setup construction 1, resulting diagram.

As seen in the table of 1/3 octave bands and in the resulting diagram, it is no longer the direct sound that is dominating in any of the frequencies i.e. not the sound transmitting through the 200 mm thick internal wall. Instead, the result shows that the sound level difference is dominated by the flanking transmission via the façade due to the poor reduction in the junction with a non-proper reinforcement of the façade element. This is the scenario that will be investigated further when retrofitting the façade.

5.2.2 Construction 2: Façade with autoclaved aerated concrete

The second construction in the study is an autoclaved aerated concrete façade with a load bearing inner layer of normal concrete. The structure is carried up by 160 mm concrete floors, 150 mm thick internal walls of concrete and the inner façade layer of 150 mm concrete, all reinforced and moulded on the building side creating a proper reduction in the junctions. The only thermal insulation is the outer layer of 150 mm autoclaved aerated concrete in the façade that is moulded together with the inner layer of concrete (see figure 1.3).

Inside each apartment, the floor is covered with 30 mm mineral wool and 50-80 mm of sand below a wooden floor or another thin layer of concrete with plastic carpets on top. This is done so as to increase the thermal comfort on the floor but also the impact sound which would be very poor with only 160 mm thick concrete structure.

The sound reduction index from outdoor sound for this construction is calculated with the given data in BASTIAN giving the weighted apparent sound reduction index $R'_{45°,w} + C_{tr} = 47\ dB$ as seen in the following table and resulting diagram.

tau	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	R'45°,w + C
d	38.4	39.4	40.5	41.5	42.2	41.7	42.6	40.2	40.3	43.1	45.8	48.5	51.3	54.0	56.7	59.7	62.4	65.2	68.0	70.9	73.7	47.6
f1	49.8	50.3	50.9	51.4	51.7	52.5	54.2	54.3	55.6	58.3	60.9	63.5	66.2	68.8	71.4	74.1	76.7	79.3	81.8	84.4	86.8	61.1
f2	49.8	50.3	50.9	51.4	51.7	52.5	54.2	54.3	55.6	58.3	60.9	63.5	66.2	68.8	71.4	74.1	76.7	79.3	81.8	84.4	86.8	61.1
f3	51.4	52.4	53.5	54.5	55.3	55.1	55.5	53.8	53.9	55.3	56.6	58.5	60.4	62.2	65.1	68.1	70.9	73.8	76.7	79.7	83.1	59.4
f4	61.4	62.4	63.4	64.4	65.3	65.0	65.5	63.8	63.8	65.2	66.6	68.4	70.3	72.2	75.0	78.0	80.9	83.8	86.7	89.6	93.0	69.4
Total	37.6	38.6	39.6	40.5	41.1	40.9	41.8	39.7	39.9	42.6	45.2	47.8	50.5	53.1	55.8	58.8	61.5	64.3	67.1	70.0	72.8	46.9

Figure 5.8. Sound reduction from outdoor sound in 1/3 octave bands, default setup construction 2, exported from BASTIAN.

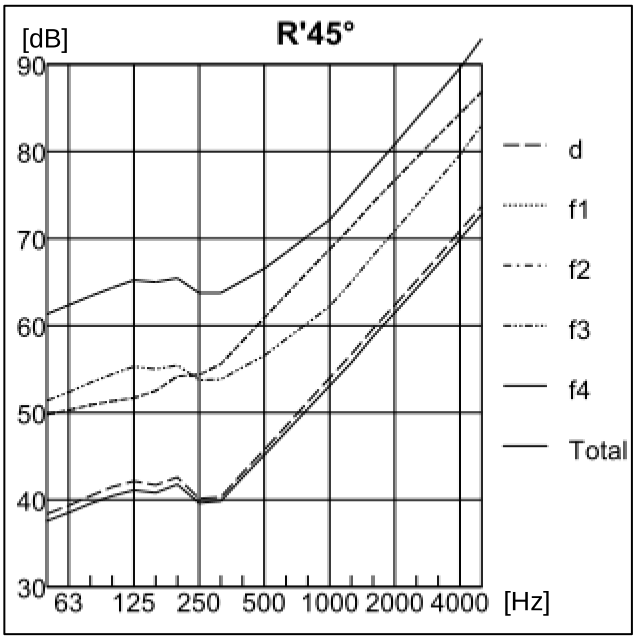

Figure 5.9. Sound reduction from outdoor sound $R'_{45°,w} + C_{tr}$, default setup construction 2, resulting diagram.

The result in the table of 1/3 octave bands and in the resulting diagram shows that the sound reduction from outdoor sound starts growing after 315 Hz. The weighted sound reduction is therefore better compared to the previous calculation of construction 1.

Also the sound level difference between apartments is calculated with the same construction data, just as for construction 1. The weighted standardized sound level difference between the two apartments is calculated to $D_{nT,w} + C_{50-3150} = 53\ dB$ as seen in the following table and resulting diagram.

tau	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	DnT,w (0.5 s) + C50
d	38.8	38.8	38.6	38.6	38.7	40.8	43.3	45.9	48.4	50.8	53.4	55.9	58.4	60.8	63.3	65.8	68.1	70.5	72.8	74.9	77.0	55.2
f1	48.2	48.3	48.2	48.2	48.2	50.3	52.8	55.4	58.0	60.5	63.1	65.7	68.2	70.8	73.4	75.9	78.4	80.9	83.3	85.6	87.9	64.8
f2	45.2	45.3	45.2	45.2	45.2	47.3	49.8	52.4	55.0	57.5	60.1	62.7	65.2	67.8	70.4	72.9	75.4	77.9	80.3	82.6	84.9	61.8
f3	46.8	46.8	46.7	46.7	46.9	49.4	52.1	54.6	57.2	59.7	62.3	64.9	67.5	70.0	72.6	75.1	77.5	80.0	82.4	84.7	87.0	64.0
f4	46.8	46.8	46.7	46.7	46.9	49.4	52.1	54.6	57.2	59.7	62.3	64.9	67.5	70.0	72.6	75.1	77.5	80.0	82.4	84.7	87.0	64.0
Total	36.6	36.6	36.4	36.4	36.5	38.7	41.2	43.8	46.4	48.8	51.4	53.9	56.4	58.9	61.5	63.9	66.3	68.8	71.1	73.3	75.4	53.2

Figure 5.10. Sound level difference between apartments in 1/3 octave bands, default setup construction 2, exported from BASTIAN.

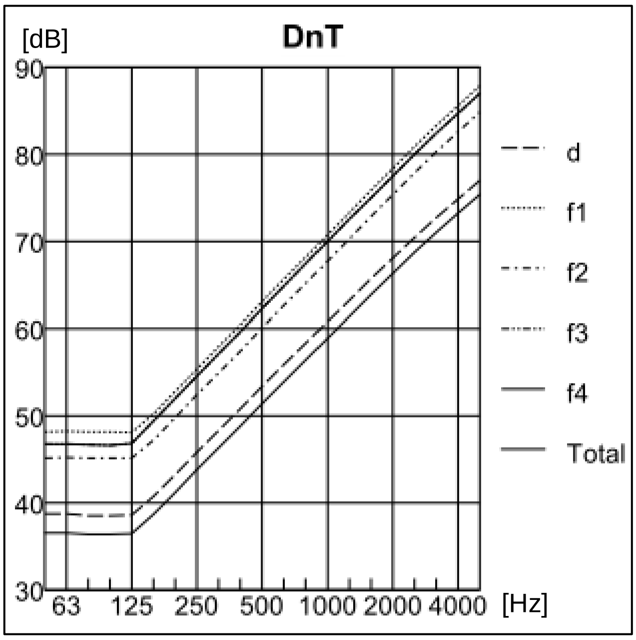

Figure 5.11. Sound level difference between apartments $D_{nT,w} + C_{50-3150}$, default setup construction 3, resulting diagram.

In this construction the direct sound via the 150 mm thick concrete wall is dominating the total sound level difference. The properly reinforced and moulded junctions are reducing the flanking transmission via the façade compared to construction 1 and this, together with the thin walls is making the direct sound dominating.

5.2.3 Construction 3: Light weight façade elements

Finally, the third construction that is being investigated is a light weight façade element, built up with a 13 mm thick gypsum board internally on 120 mm thick wooden studs with mineral wool in between, followed by a 9mm thick weather board of Internit an air gap and finally a 19 mm wooden façade panel on 19 mm lath (see figure 1.4). The load bearing structure is made out of 160 mm concrete walls and 190 mm concrete floors moulded on the building site.

In this construction it is of great importance how the façade elements are assembled with the rest of the construction. If the façade element is placed far out as a curtain wall the flanking transmission, or even leakages, will be dominating the sound level difference between the apartments. On the other extreme, if the façade element instead is placed further in order to break the flank and the concrete walls are going too far out in the façade, it will result in a thermal bridge and the thermal insulation will be poor.

The sound reduction index from outdoor sound is calculated with the given data in BASTIAN giving the weighted apparent sound reduction index $R'_{45°,w} + C_{tr} = 28\ dB$ as seen in the following table and resulting diagram.

tau	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	R'45°,w + C
d	15.8	11.1	15.2	13.4	17.3	20.4	20.9	21.4	25.8	29.0	29.9	32.7	33.8	35.0	34.5	36.7	39.3	42.1	48.1	50.8	54.6	27.7
f1	59.4	57.0	59.1	58.2	60.1	63.1	64.6	66.1	69.6	72.4	74.1	76.8	78.6	80.4	81.4	83.7	86.2	88.8	92.9	95.4	98.4	72.1
f2	59.4	57.0	59.1	58.2	60.1	63.1	64.6	66.1	69.6	72.4	74.1	76.8	78.6	80.4	81.4	83.7	86.2	88.8	92.9	95.4	98.4	72.1
f3	57.4	55.0	57.1	56.2	58.6	61.7	63.3	64.8	68.2	71.1	72.8	75.5	77.3	79.1	80.1	82.4	84.9	87.5	91.6	94.0	97.0	70.7
f4	57.4	55.0	57.1	56.2	58.6	61.7	63.3	64.8	68.2	71.1	72.8	75.5	77.3	79.1	80.1	82.4	84.9	87.5	91.6	94.0	97.0	70.7
Total	15.8	11.1	15.2	13.4	17.3	20.4	20.9	21.4	25.8	29.0	29.9	32.7	33.8	35.0	34.5	36.7	39.3	42.1	48.1	50.8	54.6	27.7

Figure 5.12. Sound reduction from outdoor sound in 1/3 octave bands, default setup construction 3, exported from BASTIAN.

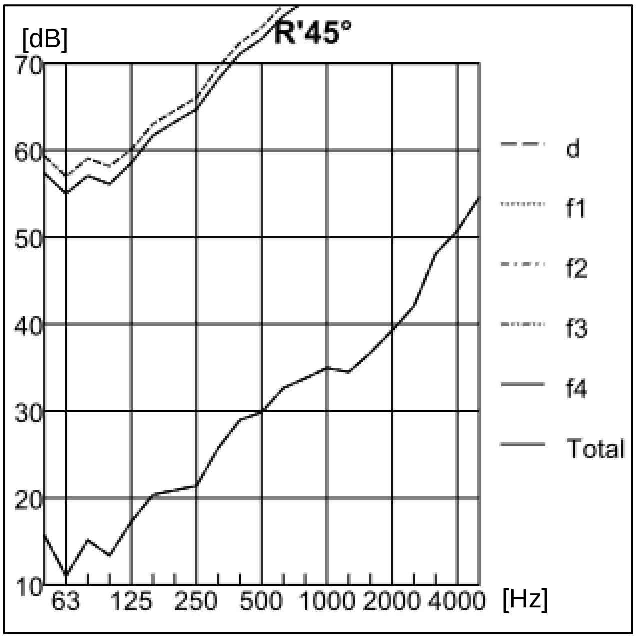

Figure 5.13. Sound reduction from outdoor sound $R'_{45°,w} + C_{tr}$, default setup construction 3, resulting diagram.

As seen the sound reduction index from outdoor sound is really poor due to the very light and thin façade. This façade construction is therefore not recommended near any high density roads. The sound reduction index from outdoor sound is not dependent on how the façade is placed, as a curtain wall or infill wall, since the façade element itself is so poor.

The sound level difference between apartments is, as mentioned, very dependent on the flaking transmission via the façade. Therefore, the three different cases are considered; one with a total infill wall and no flanking transmission, one with a total curtain wall and there are leakages via the façade, one where the flank is partly fractioned but the façade element is protecting the internal walls and minimizing the thermal bridge.

For the case with a total infill wall that completely fractions the flanking transmission, the weighted standardized sound level difference between the two apartments is calculated to $D_{nT,w} + C_{50-3150} = 56\ dB$ as seen in the following table and resulting diagram.

tau	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	DnT,w (0.5 s) + C50
d	40.7	40.5	40.4	40.4	40.6	43.4	45.9	48.4	51.0	53.4	55.9	58.3	60.9	63.2	65.6	68.0	70.3	72.6	74.8	76.9	79.0	57.7
f1	49.1	49.2	49.0	49.0	49.0	51.8	54.4	56.9	59.5	62.0	64.6	67.1	69.8	72.2	74.8	77.3	79.8	82.3	84.6	86.9	89.2	66.3
f2	55.9	53.6	56.0	55.3	57.7	61.0	62.5	64.0	67.9	71.0	72.6	75.4	77.0	78.6	78.7	80.8	83.3	85.9	91.2	93.7	97.2	74.1
f3	49.4	49.4	49.1	49.2	49.9	53.0	55.6	58.1	60.6	63.2	65.7	68.2	70.7	73.2	75.7	78.1	80.6	82.9	85.2	87.4	89.6	67.3
f4	49.4	49.4	49.1	49.2	49.9	53.0	55.6	58.1	60.6	63.2	65.7	68.2	70.7	73.2	75.7	78.1	80.6	82.9	85.2	87.4	89.6	67.3
Total	39.1	38.9	38.8	38.8	39.2	42.0	44.5	47.0	49.6	52.1	54.5	57.0	59.5	61.9	64.3	66.6	69.0	71.4	73.6	75.8	77.9	56.3

Figure 5.14. Sound level difference between apartments in 1/3 octave bands with façade construction as an infill wall, default setup construction 3, exported from BASTIAN.

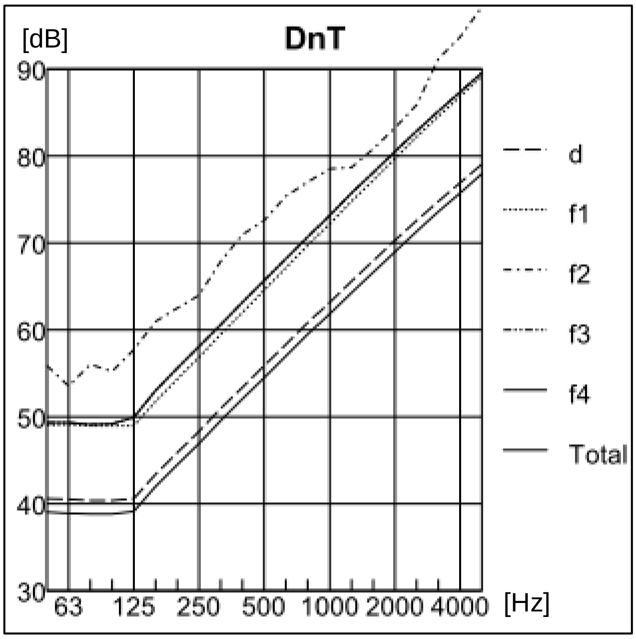

Figure 5.15. Sound level difference between apartments $D_{nT,w} + C_{50-3150}$ with façade construction as an infill wall, default setup construction 3, resulting diagram.

Since the flanking transmission via the façade is fractioned and the other junctions are moulded with the separating wall, the direct sound is dominating the total sound level difference.

For the second case with a curtain wall the weighted standardized sound level difference between the two apartments is calculated to $D_{nT,w} + C_{50-3150} = 30\ dB$ as seen in the following table and resulting diagram.

tau	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	DnT,w (0.5 s) + C50
d	40.8	40.7	40.5	40.5	40.7	43.5	46.0	48.5	51.0	53.5	55.9	58.4	60.9	63.3	65.7	68.0	70.4	72.7	74.8	76.9	79.1	57.8
f1	49.1	49.2	49.0	49.0	49.0	51.8	54.4	56.9	59.5	62.0	64.6	67.1	69.8	72.2	74.8	77.3	79.8	82.3	84.6	86.9	89.2	66.3
f2	14.6	9.9	14.0	12.2	16.1	19.2	19.7	20.2	24.6	27.8	28.7	31.5	32.6	33.8	33.3	35.5	38.1	40.9	46.9	49.6	53.4	30.5
f3	49.4	49.4	49.1	49.2	49.9	53.0	55.6	58.1	60.6	63.2	65.7	68.2	70.7	73.2	75.7	78.1	80.6	82.9	85.2	87.4	89.6	67.3
f4	49.4	49.4	49.1	49.2	49.9	53.0	55.6	58.1	60.6	63.2	65.7	68.2	70.7	73.2	75.7	78.1	80.6	82.9	85.2	87.4	89.6	67.3
Total	14.6	9.9	14.0	12.2	16.1	19.2	19.7	20.2	24.6	27.8	28.7	31.5	32.6	33.8	33.3	35.5	38.1	40.9	46.9	49.6	53.4	30.5

Figure 5.16. Sound level difference between apartments in 1/3 octave bands with façade construction as a curtain wall, default setup construction 3, exported from BASTIAN.

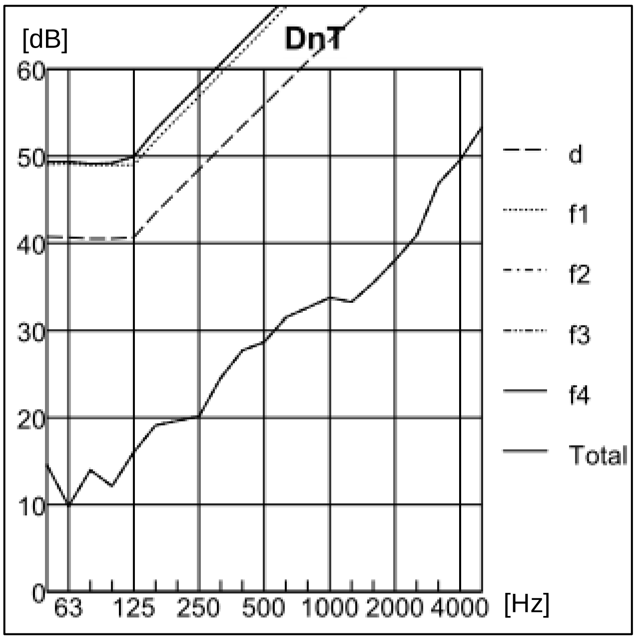

Figure 5.17. Sound level difference between apartments $D_{nT,w} + C_{50-3150}$ with façade construction as a curtain wall, default setup construction 3, resulting diagram.

As expected the flanking transmission via the façade is totally dominating the total sound level difference. In this case there is a huge leakage at the assembly point that it is almost possible to see through.

For the third case, where the façade element is a combination of a curtain wall and infill wall, the weighted standardized sound level difference between the two apartments is calculated to $D_{nT,w} + C_{50-3150} = 54\,dB$ as seen in the following table and resulting diagram.

tau	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	DnT,w (0.5 s) + C50
d	40.7	40.6	40.5	40.5	40.7	43.5	45.9	48.4	51.0	53.4	55.9	58.3	60.9	63.2	65.6	67.9	70.3	72.6	74.8	76.9	79.0	57.7
f1	49.1	49.2	49.0	49.0	49.0	51.8	54.4	56.9	59.5	62.0	64.6	67.1	69.8	72.2	74.8	77.3	79.8	82.3	84.6	86.9	89.2	66.3
f2	42.0	37.3	41.4	39.6	43.5	46.6	47.1	47.6	52.0	55.2	56.1	58.9	60.0	61.2	60.8	63.0	65.6	68.3	74.3	77.0	80.8	57.9
f3	49.4	49.4	49.1	49.2	49.9	53.0	55.6	58.1	60.6	63.2	65.7	68.2	70.7	73.2	75.7	78.1	80.6	82.9	85.2	87.4	89.6	67.3
f4	49.4	49.4	49.1	49.2	49.9	53.0	55.6	58.1	60.6	63.2	65.7	68.2	70.7	73.2	75.7	78.1	80.6	82.9	85.2	87.4	89.6	67.3
Total	37.4	35.1	37.0	36.3	37.9	40.8	42.7	44.3	47.7	50.4	52.3	54.9	56.8	58.6	59.2	61.4	64.0	66.6	71.0	73.4	76.2	54.1

Figure 5.18. Sound level difference between apartments in 1/3 octave bands with façade construction as a combination of a curtain wall and infill wall, default setup construction 3, exported from BASTIAN.

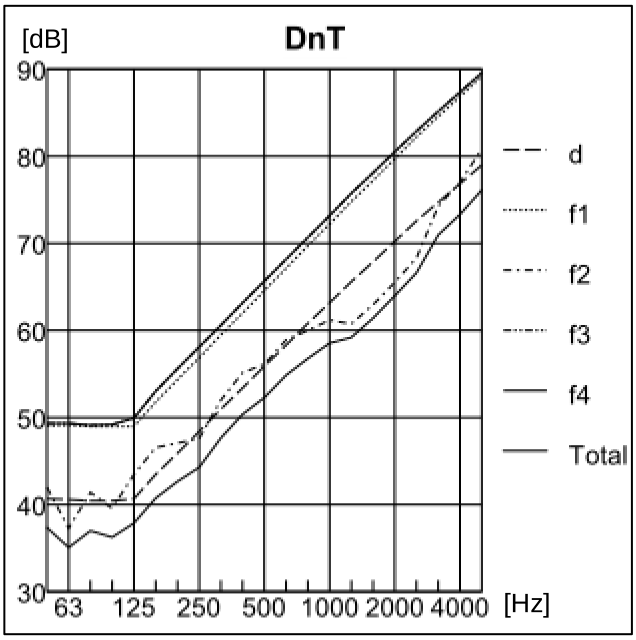

Figure 5.19. Sound level difference between apartments $D_{nT,w} + C_{50-3150}$ with façade construction as a combination of a curtain wall and infill wall, default setup construction 3, resulting diagram.

As seen the sound level difference in this case is dominated by both the direct sound and the flanking transmission via the façade, just as the construction is built.

When comparing these three cases, the first two is very unlikely to be found in situ. The first case will cause mould growth in the façade and it have to be changed relatively quickly. The second case will cause complaints by neighbours due to sound leakages, but also air leakages and smells that come with it from the other apartment due to the poor connection at the assembly point. Therefore it is the third case, the combination of a curtain wall and infill wall that will be further investigated for retrofitting.

5.3 Thermal properties on the default setup

Thermal transmittance is calculated for each construction with the method described in chapter 3 with the data mentioned. The material constants as well as the surface resistance are as given in the same chapter.

In order to compare the three setups, and to see the difference when retrofitting the constructions, thermal bridges will not be taken into consideration due to the complexity and that the result of the retrofitting will be measured per square meter.

5.3.1 Construction 1: Element built façade construction

The façade of the first construction is as mentioned a sandwich element build up with 60 mm concrete on the outside, followed with a 100 mm thick layer of cellular plastic and a 120 mm thick concrete layer (see figure 1.2).

The thermal transmittance is determined for the construction according to the following calculations:

$$R_1 = \frac{d_{concrete,60}}{\lambda_{concrete}} + \frac{d_{cellular\ plastic,100}}{\lambda_{cellular\ plastic}} + \frac{d_{concrete,120}}{\lambda_{concrete}}$$

$$R_1 = \frac{60 \cdot 10^{-3}}{1{,}2} + \frac{100 \cdot 10^{-3}}{0{,}04} + \frac{120 \cdot 10^{-3}}{1{,}2} = 2{,}65\ m^2 \cdot K/W$$

$$U_1 = \frac{1}{R_{se} + R_1 + R_{si}} = \frac{1}{0{,}04 + 2{,}65 + 0{,}13} = 0{,}355\ W/m^2 \cdot K$$

The calculated thermal transmittance is thereby determined as $0{,}355\ \mathrm{W/m^2 \cdot K}$. This can be compared to the requirement for new built dwellings, wich states the thermal transmittance should not exceed $0{,}4\ \mathrm{W/m^2K}$ as an average for the whole building giving us some margin. However, since $0{,}4\ \mathrm{W/m^2K}$ is the average for the whole building, also counting on windows which has severely lower thermal transmittance, it is not a good result. The recommended thermal transmittance for a wall when retrofitting is instead as low as $0{,}18\ \mathrm{W/m^2K}$ meaning that this wall needs to be retrofitted in order to pass today's building standard requirements.

5.3.2 Construction 2: Façade with autoclaved aerated concrete

The second façade construction only consists of 150 mm autoclaved aerated concrete (AAC) followed by 150 mm of normal concrete (see figure 1.3).

The thermal transmittance is determined for the construction according to the following calculations:

$$R_2 = \frac{d_{\mathrm{AAC},150}}{\lambda_{\mathrm{AAC}}} + \frac{d_{concrete,150}}{\lambda_{concrete}}$$

$$R_2 = \frac{150 \cdot 10^{-3}}{0{,}20} + \frac{150 \cdot 10^{-3}}{1{,}2} = 0{,}875\ m^2 \cdot K/W$$

$$U_2 = \frac{1}{R_{se} + R_2 + R_{si}} = \frac{1}{0{,}04 + 0{,}875 + 0{,}13} = 0{,}957\ W/m^2 \cdot K$$

The calculated thermal transmittance for the second construction, $0{,}957\ \mathrm{W/m^2 \cdot K}$, is as seen significantly poorer. The value can be compared that modern windows and doors should have a thermal transmittance at $1{,}2\ \mathrm{W/m^2 \cdot K}$, not that much higher than this wall. Retrofitting this façade is more a must than a recommendation in order to get any thermal comfort indoors.

5.3.3 Construction 3: Light weight façade elements

The last construction in the study is a more complex construction. The third construction has 120 mm thick wooden studs with mineral wool in between. On the inside there is a layer of 13 mm gypsum and on the outside a 9 mm layer of a Internit weather board. The construction also has a wooden façade panel outside a ventilated air gap (see figure 1.4). The airgap in this construction is assumed to be well ventilated according to SS-EN ISO 6946 and can therefore be disregarded during the determination of the thermal transmission.

To determine the thermal transmission for a combined construction, with more than one material in each layer, two different methods are used:

Thermal transmittance method

First the thermal resistance for the wooden segment and the mineral wool segment is calculated:

$$R_{wood} = R_{se} + R_{internit} + R_{wood} + R_{gypsum} + R_{si}$$

$$R_{wood} = R_{se} + \frac{d_{internit,9}}{\lambda_{internit}} + \frac{d_{wood,120}}{\lambda_{wood}} + \frac{d_{gypsum,13}}{\lambda_{gypsum}} + R_{si}$$

$$R_{wood} = 0{,}04 + \frac{9 \cdot 10^{-3}}{0{,}60} + \frac{120 \cdot 10^{-3}}{0{,}14} + \frac{13 \cdot 10^{-3}}{0{,}22} + 0{,}13 = 1{,}10\ m^2 \cdot K/W$$

$$R_{mineral\ wool} = R_{se} + R_{internit} + R_{mineral\ wool} + R_{gypsum} + R_{si}$$

$$R_{mineral\ wool} = R_{se} + \frac{d_{internit,9}}{\lambda_{internit}} + \frac{d_{mineral\ wool,120}}{\lambda_{mineral\ wool}} + \frac{d_{gypsum,13}}{\lambda_{gypsum}} + R_{si}$$

$$R_{mineral\ wool} = 0{,}04 + \frac{9 \cdot 10^{-3}}{0{,}60} + \frac{120 \cdot 10^{-3}}{0{,}037} + \frac{13 \cdot 10^{-3}}{0{,}22} + 0{,}13 = 3{,}49\ m^2 \cdot K/W$$

After that the area for the wood segment and for the mineral wool segment is calculated:

$$A_{wood} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

$$A_{mineral\ wool} = \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

And finally the segment partitions are weighted in with the thermal resistances:

$$R_{3,U} = A_{wood} \cdot R_{wood} + A_{mineral\,wool} \cdot R_{mineral\,wool}$$

$$R_{3,U} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 1{,}10 + \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 3{,}49 = 3{,}31\; m^2 \cdot K/W$$

$$U_{3,U} = \frac{1}{R_{3,U}} = \frac{1}{3{,}31} = 0{,}302\; W/m^2 \cdot K$$

Thermal conductivity method

First the percentage of wood versus mineral wool is calculated and then used to determine a combined thermal conductivity for the layer with both wooden studs and mineral wool:

$$a_{wood} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

$$a_{mineral\,wool} = \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

$$\lambda_{wood+mineral\,wool} = \alpha_{wood} \cdot \lambda_{wood} + \alpha_{mineral\,wool} \cdot \lambda_{mineral\,wool}$$

$$\lambda_{wood+mineral\,wool} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 0{,}14 + \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 0{,}037 = 0{,}045\; W/m \cdot K$$

When the thermal conductivity for the combined layer is calculated, the total thermal resistance can be calculated:

$$R_{3,\lambda} = \frac{d_{internit}}{\lambda_{internit}} + \frac{d_{wood+mineral\,wool}}{\lambda_{wood+mineral\,wool}} + \frac{d_{gypsum}}{\lambda_{gypsum}}$$

$$R_{3,\lambda} = \frac{9 \cdot 10^{-3}}{0{,}60} + \frac{120 \cdot 10^{-3}}{0{,}045} + \frac{13 \cdot 10^{-3}}{0{,}22} = 2{,}76\; m^2 \cdot K/W$$

When the thermal resistance is calculated, the thermal transmittance can be calculated:

$$U_{3,\lambda} = \frac{1}{R_{se} + R_{3,\lambda} + R_{si}} = \frac{1}{0{,}04 + 2{,}76 + 0{,}13} = 0{,}342\; W/m^2 \cdot K$$

Combined thermal transmittance

When the thermal transmittance is calculated with both methods, the combined thermal transmittance is calculated:

$$U_3 = \frac{2 \cdot U_{3,U} \cdot U_{3,\lambda}}{U_{3,U} + U_{3,\lambda}}$$

$$U_3 = \frac{2 \cdot 0{,}302 \cdot 0{,}342}{0{,}302 + 0{,}342} = 0{,}321\ W/m^2 \cdot K$$

The thermal transmittance is thereby determined at $0{,}321\ \mathrm{W/m^2 \cdot K}$ for the third construction. This can be compared to construction 1 with a similar thermal transmittance ($0{,}355\ \mathrm{W/m^2 \cdot K}$). Construction 3 has slightly thicker thermal insulating layer but also has thermal bridges via the wooden studs in the façade.

6 Post-retrofit scenarios and key findings

6.1 Retrofitting options

For the first two façade constructions an extra layer can be retrofitted on the inside or the outside. These two façade constructions will be retrofitted with two different options, retrofitting option 1 and retrofitting option 2, and the results will be compared to highlight the best retrofitting method.

Since the third façade construction is already a double leaf construction as mentioned earlier, the façade construction is therefore more complex. Adding an extra layer will create a triple leaf construction which might cause reductions in some frequencies. As a result, a different retro-fitting option will be reviewed.

6.1.1 Retrofitting option 1

The first retrofitting consists of a 13 mm gypsum board on 45 mm studs placed 15 mm separated from the concrete façade element, with a total cavity of 60 mm which is filled with mineral wool as seen in figure 6.1.

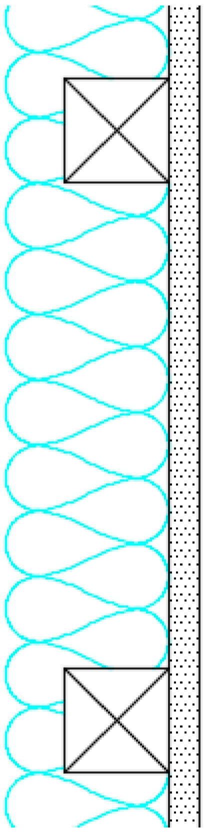

Figure 6.1. Retrofitting option 1. 13 mm gypsum board, 45 mm studs, 60 mm cavity with mineral wool

6.1.2 Retrofitting option 2

For the second retrofitting construction, the studs are increased to a thickness of 70 mm and 2 gypsum boards are added instead of one. The total cavity for this retrofitting is 95 mm thick and filled with mineral wool as seen in figure 6.2.

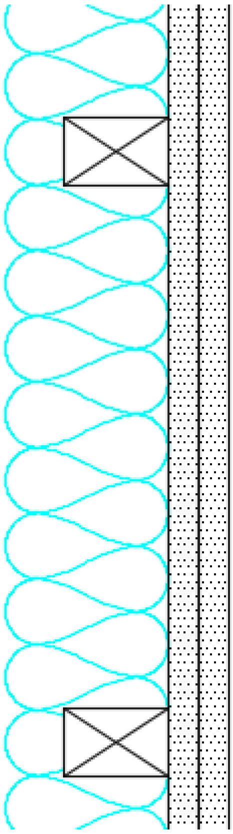

Figure 6.2. Retrofitting option 2. 2x13 mm gypsum boards, 70 mm studs, 95 mm cavity with mineral wool.

6.1.3 Retrofitting for double leaf constructions

This construction will be modelled by changing the outer part and the inner parts by the façade construction to find a good way to increase the sound reduction index from outdoor sound and decrease the thermal transmittance.

For the retrofitting on the inside, the existing gypsum board will be removed and an extra layer of 45 mm wooden studs and mineral wool will be added. The new wooden studs can be placed horizontal in order to minimize the head bridges via the wood. On the new wooden studs two 13 mm thick gypsum boards will be added.

For the retrofitting on the outside, the outer façade layer (the wood panel) will be kept the same in order to be able to compare the retrofitting results without being affected with the outer façade layer. Changing the outer façade layer e.g. to bricks will significantly increase the sound reduction index. As a result, for the retrofitting on the outside, the Interit board must be removed due to the health aspect of those boards. Instead of adding a new board, an extra layer of 45 mm wooden studs and mineral wool will be added outside the existing ones where the studs are placed horizontal to minimize heat bridges. The Internit layer will be replaced with a more modern layer of a outer gypsum board that can break the wind inside the air gap.

6.2 Construction 1: Element built façade construction

6.2.1 Using retrofitting option 1

Impact on acoustic result

For the first retrofitting, option 1, as seen in figure 6.1 the sound reduction index from outdoor sound for the total construction is calculated giving the weighted apparent sound reduction index $R'_{45°,w} + C_{tr} = 45\ dB$ as seen in the following table and resulting diagram.

tau	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	R'45°,w + C
d	38.1	37.3	29.5	32.0	33.4	40.3	38.6	40.5	41.0	42.3	48.7	52.9	56.6	57.9	61.7	67.5	71.0	74.8	77.8	82.9	84.6	46.1
f1	51.2	51.3	49.4	50.4	50.5	53.6	54.3	56.8	59.0	61.7	67.1	71.3	75.4	78.2	82.7	87.4	90.8	94.2	97.3	101.5	103.8	62.4
f2	51.2	51.3	49.4	50.4	50.5	53.6	54.3	56.8	59.0	61.7	67.1	71.3	75.4	78.2	82.7	87.4	90.8	94.2	97.3	101.5	103.8	62.4
f3	48.3	48.4	46.5	47.3	47.8	50.9	51.6	54.2	56.3	59.0	64.4	68.6	72.8	75.6	80.1	84.7	88.1	91.7	94.8	98.9	101.2	59.6
f4	48.3	48.4	46.5	47.3	47.8	50.9	51.6	54.2	56.3	59.0	64.4	68.6	72.8	75.6	80.1	84.7	88.1	91.7	94.8	98.9	101.2	59.6
Total	37.0	36.4	29.2	31.6	32.9	39.3	38.0	40.0	40.6	42.0	48.4	52.6	56.3	57.7	61.5	67.3	70.7	74.5	77.5	82.6	84.3	45.7

Figure 6.3. Sound reduction from outdoor sound in 1/3 octave bands for construction 1 using retrofitting option 1, exported from BASTIAN.

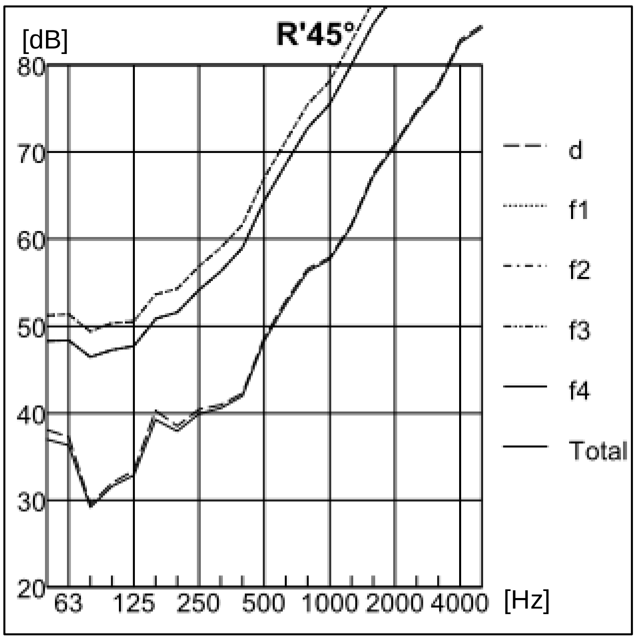

Figure 6.4. Sound reduction from outdoor sound $R'_{45°,w} + C_{tr}$ for construction 1 using retrofitting option 1, resulting diagram.

The sound level difference between apartments is calculated with the same retrofitting data, giving the weighted standardized sound level difference $D_{nT,w} + C_{50-3150} = 53\ dB$ as seen in the following table and resulting diagram.

tau	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	DnT,w (0.5 s) + C50
d	40.4	40.2	39.0	39.8	42.4	45.7	48.4	51.0	53.5	56.0	58.5	61.0	63.5	65.9	68.3	70.6	72.9	75.1	77.3	79.3	81.3	59.8
f1	50.2	50.2	50.2	50.6	52.5	55.0	57.5	60.1	62.6	65.2	67.7	70.3	72.8	75.3	77.8	80.3	82.7	85.0	87.4	89.6	91.8	69.3
f2	37.3	35.4	27.7	29.9	35.9	46.2	51.3	56.6	60.6	64.3	67.1	70.3	73.1	75.9	77.0	81.8	86.3	90.8	95.4	100.0	104.6	55.3
f3	49.2	49.0	49.0	49.1	51.6	54.0	56.6	59.2	61.7	64.2	66.8	69.3	71.8	74.4	76.8	79.3	81.7	84.1	86.3	88.5	90.7	68.3
f4	49.2	49.0	49.0	49.1	51.6	54.0	56.6	59.2	61.7	64.2	66.8	69.3	71.8	74.4	76.8	79.3	81.7	84.1	86.3	88.5	90.7	68.3
Total	35.1	33.8	27.3	29.4	34.7	42.1	45.5	48.7	51.4	54.1	56.6	59.2	61.7	64.1	66.4	69.0	71.4	73.7	75.9	78.0	80.1	53.0

Figure 6.5. Sound level difference between apartments in 1/3 octave bands for construction 1 using retrofitting option 1, exported from BASTIAN.

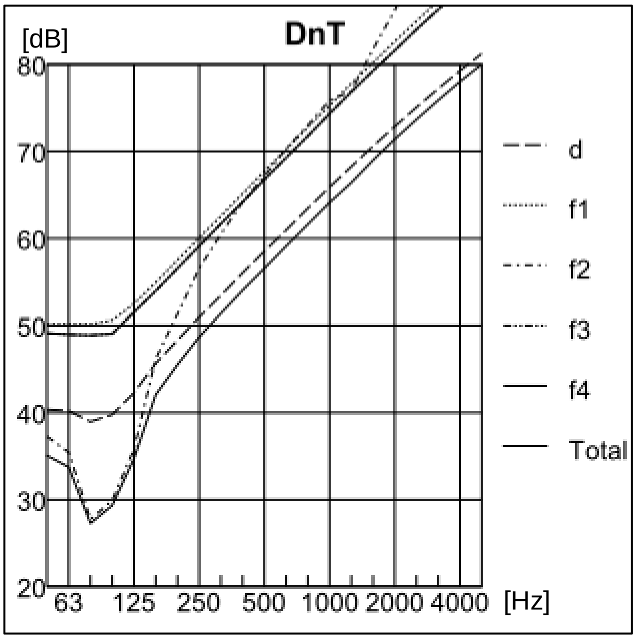

Figure 6.6. Sound level difference between apartments $D_{nT,w} + C_{50-3150}$ for construction 1 using retrofitting option 1, resulting diagram.

Comparing retrofitting on the inside or on the outside

Comparing how the façade construction changes between the default configuration, retrofitting on the inside and retrofitting on the outside is done in INSUL showing a theoretical estimation on how the sound reduction index changes.

The following figure shows the difference between the default configuration for façade construction 1 with the retrofitting option 1 on the inside and on the outside. As seen in figure 6.7, the sound reduction index from outdoor sound is almost the same in all frequencies regardless of where the retrofitting is placed, except for the frequencies between 125 Hz and 315 Hz where the retrofitting on the outside is slightly better.

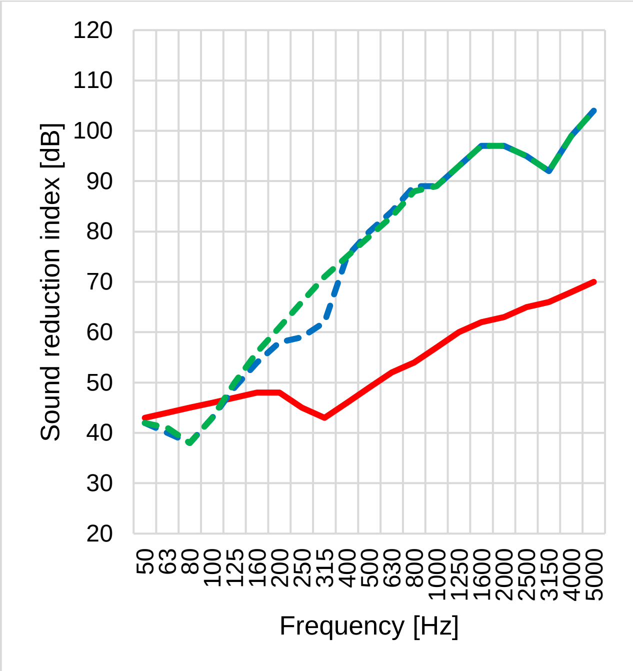

Figure 6.7. Difference between default configuration (red), retrofitting on the inside (blue dotted) and retrofitting on the outside (green dotted).

Impact on thermal results

The thermal transmittance for construction 1 using retrofitting option 1 increased due to the added layers of insulation materials. Since the façade construction after the retrofitting is a complex construction with studs and mineral wool in the same layer, both the thermal transmittance method and the thermal conductivity method have to be used.

The thermal transmittance for construction 1 with retrofitting option 1 is calculated manually and results in $U_{c1,r1} = 0{,}229\ W/m^2 \cdot K$.

Based on this results, we can infer that the energy transmitted through the wall (10 m^2), for a house located in Malmö, saves $E = 100\ kWh$ per year for the wall before and after retrofitting. The implication of this will be discussed in the next chapter. Detailed calculations can be found in Appendix 2a.

6.2.2 Using retrofitting option 2

Impact on acoustic result

The sound reduction index from outdoor sound for this construction is calculated giving the weighted apparent sound reduction index $R'_{45°,w} + C_{tr} = 52\ dB$ as seen in the following table and resulting diagram.

tau	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	R'45°,w + C
d	33.1	36.3	34.5	43.3	44.4	50.2	48.3	49.9	50.3	51.4	57.8	61.9	65.7	66.9	70.8	76.5	80.1	83.8	86.8	92.0	93.7	55.8
f1	51.2	51.3	49.4	50.4	50.5	53.6	54.3	56.8	59.0	61.7	67.1	71.3	75.4	78.2	82.7	87.4	90.8	94.2	97.3	101.5	103.8	62.4
f2	51.2	51.3	49.4	50.4	50.5	53.6	54.3	56.8	59.0	61.7	67.1	71.3	75.4	78.2	82.7	87.4	90.8	94.2	97.3	101.5	103.8	62.4
f3	48.3	48.4	46.5	47.3	47.8	50.9	51.6	54.2	56.3	59.0	64.4	68.6	72.8	75.6	80.1	84.7	88.1	91.7	94.8	98.9	101.2	59.6
f4	48.3	48.4	46.5	47.3	47.8	50.9	51.6	54.2	56.3	59.0	64.4	68.6	72.8	75.6	80.1	84.7	88.1	91.7	94.8	98.9	101.2	59.6
Total	32.7	35.6	33.7	39.9	40.6	44.6	44.4	46.6	47.8	49.5	55.5	59.7	63.6	65.4	69.5	74.8	78.4	82.0	85.0	89.9	91.8	52.8

Figure 6.8. Sound reduction from outdoor sound in 1/3 octave bands for construction 1 using retrofitting option 2, exported from BASTIAN.

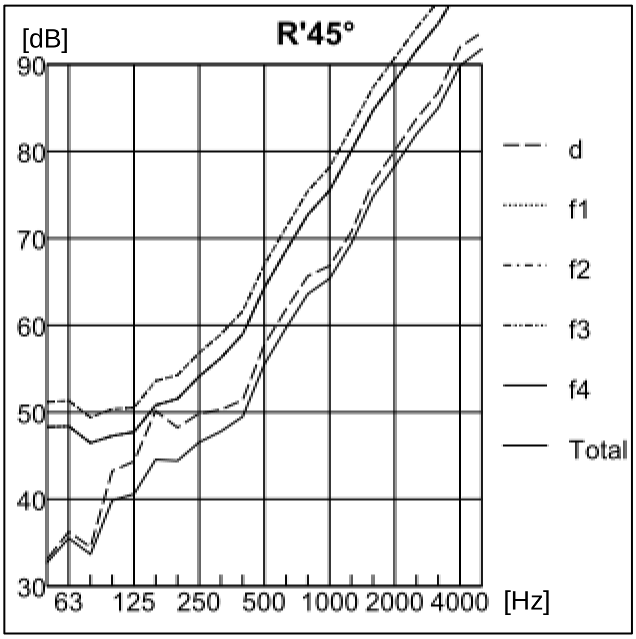

Figure 6.9. Sound reduction from outdoor sound $R'_{45°,w} + C_{tr}$ for construction 1 using retrofitting option 2, resulting diagram.

The sound level difference between apartments is calculated with the same retrofitting data, giving the weighted standardized sound level difference $D_{nT,w} + C_{50-3150} = 57\ dB$ as seen in the following table and resulting diagram.

tau	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	DnT,w (0.5 s) + C50-
d	39.0	40.0	40.4	41.6	43.6	46.1	48.6	51.1	53.6	56.1	58.6	61.1	63.5	65.9	68.3	70.7	72.9	75.1	77.3	79.3	81.3	60.2
f1	50.2	50.2	50.2	50.6	52.5	55.0	57.5	60.1	62.6	65.2	67.7	70.3	72.8	75.3	77.8	80.3	82.7	85.0	87.4	89.6	91.8	69.3
f2	27.6	33.5	37.4	50.9	55.6	63.1	67.7	72.4	76.3	79.9	83.1	86.4	89.6	92.5	94.1	98.8	103.4	107.8	112.3	117.0	121.6	64.1
f3	49.2	49.0	49.0	49.1	51.6	54.0	56.6	59.2	61.7	64.2	66.8	69.3	71.8	74.4	76.8	79.3	81.7	84.1	86.3	88.5	90.7	68.3
f4	49.2	49.0	49.0	49.1	51.6	54.0	56.6	59.2	61.7	64.2	66.8	69.3	71.8	74.4	76.8	79.3	81.7	84.1	86.3	88.5	90.7	68.3
Total	27.2	32.4	35.1	39.6	41.8	44.4	47.0	49.5	52.0	54.5	57.0	59.5	62.0	64.4	66.9	69.2	71.5	73.8	76.0	78.1	80.1	57.6

Figure 6.10. Sound level difference between apartments in 1/3 octave bands for construction 1 using retrofitting option 2, exported from BASTIAN.

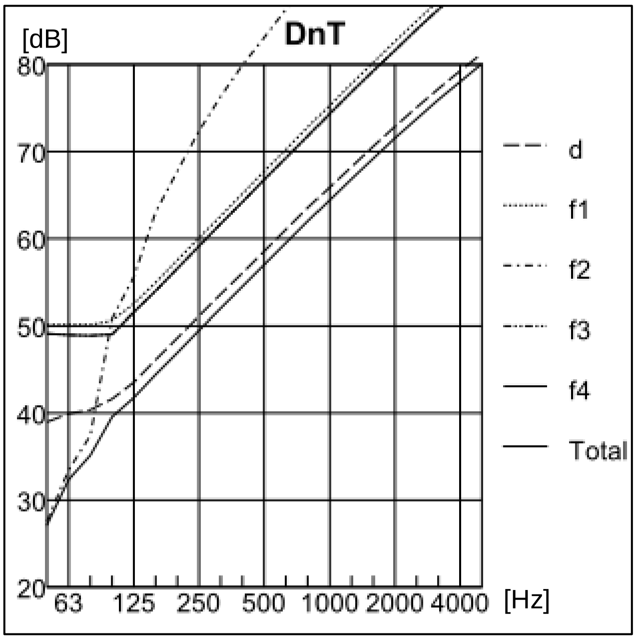

Figure 6.11. Sound level difference between apartments $D_{nT,w} + C_{50-3150}$ for construction 1 using retrofitting option 2, resulting diagram.

Comparing retrofitting on the inside or on the outside

The following figure shows the difference between the default configuration for façade construction 1 with the retrofitting option 2 on the inside and on the outside. Similar to the retrofitting option 1, the sound reduction index from outdoor sound is almost the same in all frequencies regardless of where the retrofitting is placed, except for the frequencies between 125 Hz and 315 Hz where the retrofitting on the outside is slightly better.

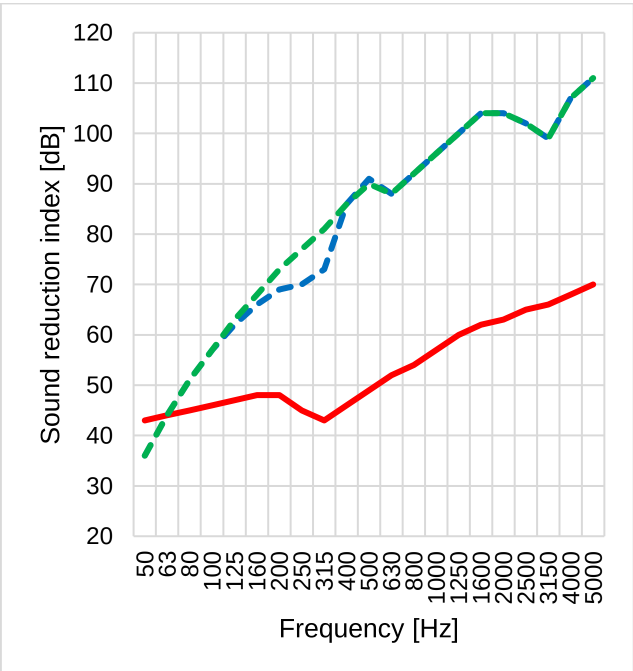

Figure 6.12. Difference between default configuration (red), retrofitting on the inside (blue dotted) and retrofitting on the outside (green dotted).

Impact on thermal results

For the retrofitting option 2 the thermal transmittance is calculated to $U_{c1,r2} = 0{,}199\ W/m^2 \cdot K$. The energy transmitted through the wall before compared to after the retrofitting saves $E = 124\ kWh$ per year for the wall. Detailed calculations can be found in Appendix 2b.

6.3 Construction 2: Façade with autoclaved aerated concrete

6.3.1 Using retrofitting option 1

Impact on acoustic result

The sound reduction index from outdoor sound for this construction is calculated giving the weighted apparent sound reduction index $R'_{45°,w} + C_{tr} = 51\ dB$ as seen in the following table and resulting diagram.

tau	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	R'45°,w + C
d	38.4	38.4	35.5	37.5	41.2	46.1	48.3	47.2	48.0	51.3	54.1	57.0	59.8	62.6	64.4	68.5	72.1	75.9	79.7	83.6	87.5	52.9
f1	49.8	50.3	50.9	51.4	51.7	52.5	54.2	54.3	55.6	58.3	60.9	63.5	66.2	68.8	71.4	74.1	76.7	79.3	81.8	84.4	86.8	61.1
f2	49.8	50.3	50.9	51.4	51.7	52.5	54.2	54.3	55.6	58.3	60.9	63.5	66.2	68.8	71.4	74.1	76.7	79.3	81.8	84.4	86.8	61.1
f3	51.4	52.4	53.5	54.5	55.3	55.1	55.5	53.8	53.9	55.3	56.6	58.5	60.4	62.2	65.1	68.1	70.9	73.8	76.7	79.7	83.1	59.4
f4	61.4	62.4	63.4	64.4	65.3	65.0	65.5	63.8	63.8	65.2	66.6	68.4	70.3	72.2	75.0	78.0	80.9	83.8	86.7	89.6	93.0	69.4
Total	37.6	37.7	35.2	37.1	40.3	44.1	46.0	45.1	45.9	48.6	51.0	53.5	56.0	58.3	60.7	64.1	67.1	70.2	73.3	76.3	79.4	50.4

Figure 6.13. Sound reduction from outdoor sound in 1/3 octave bands for construction 2 using retrofitting option 1, exported from BASTIAN.

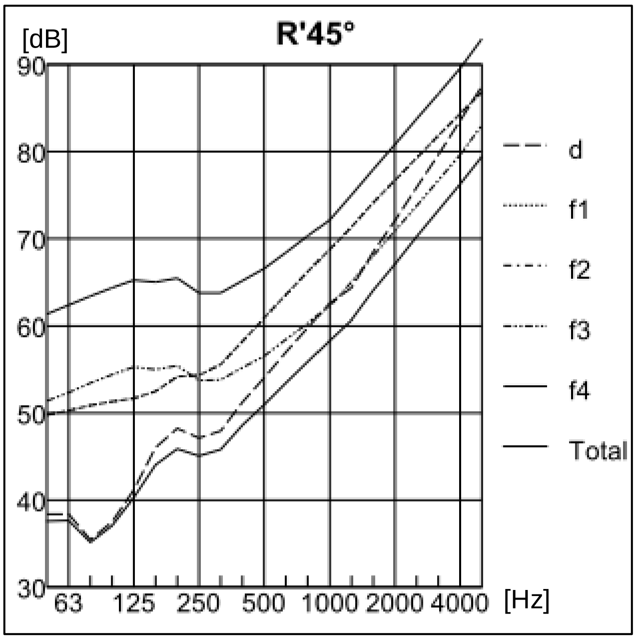

Figure 6.14. Sound reduction from outdoor sound $R'_{45°,w} + C_{tr}$ for construction 2 using retrofitting option 1, resulting diagram.

The sound level difference between apartments is calculated with the same retrofitting data, giving the weighted standardized sound level difference $D_{nT,w} + C_{50-3150} = 53\ dB$ as seen in the following table and resulting diagram.

tau	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	DnT,w (0.5 s) + C50
d	38.8	38.6	37.7	37.9	38.5	41.1	43.6	46.3	48.8	51.2	53.8	56.3	58.7	61.2	63.7	66.1	68.5	70.9	73.1	75.3	77.3	55.5
f1	48.2	48.3	48.2	48.2	48.2	50.3	52.8	55.4	58.0	60.5	63.1	65.7	68.2	70.8	73.4	75.9	78.4	80.9	83.3	85.6	87.9	64.8
f2	45.2	43.7	36.9	38.6	43.6	53.4	57.6	61.8	65.2	68.2	71.0	73.8	76.3	79.0	80.5	84.3	87.8	91.4	94.9	98.3	101.7	63.0
f3	46.8	46.8	46.7	46.7	46.9	49.4	52.1	54.6	57.2	59.7	62.3	64.9	67.5	70.0	72.6	75.1	77.5	80.0	82.4	84.7	87.0	64.0
f4	46.8	46.8	46.7	46.7	46.9	49.4	52.1	54.6	57.2	59.7	62.3	64.9	67.5	70.0	72.6	75.1	77.5	80.0	82.4	84.7	87.0	64.0
Total	36.6	36.3	33.7	34.5	36.2	39.4	42.0	44.7	47.2	49.7	52.3	54.8	57.3	59.8	62.3	64.7	67.1	69.6	71.9	74.1	76.2	53.7

Figure 6.15. Sound level difference between apartments in 1/3 octave bands for construction 2 using retrofitting option 1, exported from BASTIAN.

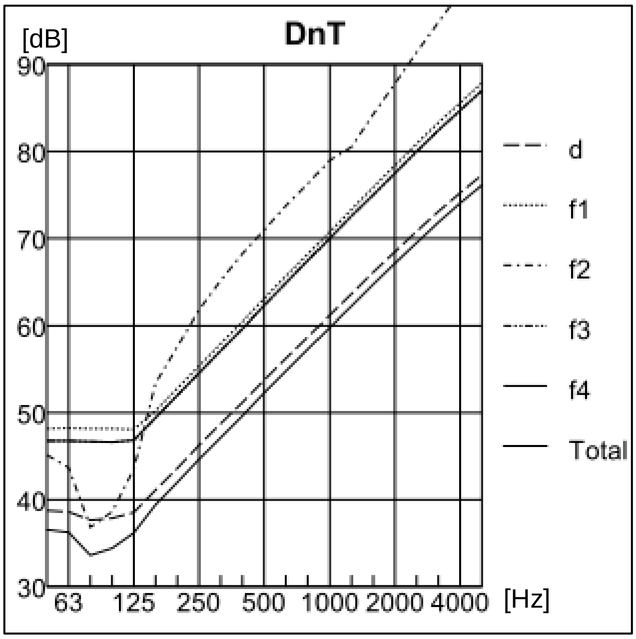

Figure 6.16. Sound level difference between apartments $D_{nT,w} + C_{50-3150}$ for construction 2 using retrofitting option 1, resulting diagram.

Comparing retrofitting on the inside or on the outside

The following figure shows the difference between the default configuration for façade construction 2 with the retrofitting option 1 on the inside and on the outside. Similar to construction 1, the sound reduction index from outdoor sound is almost the same in all frequencies regardless of where the retrofitting is placed, except for the frequencies between 80 Hz and 250 Hz where the retrofitting on the outside is slightly better.

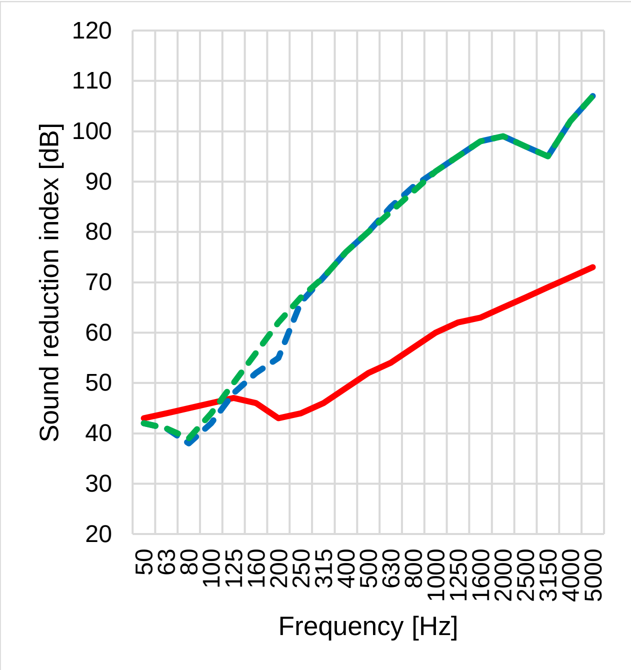

Figure 6.17. Difference between default configuration (red), retrofitting on the inside (blue dotted) and retrofitting on the outside (green dotted).

Impact on thermal results

For the retrofitting option 1 the thermal transmittance is calculated to $U_{c2,r1} = 0{,}387\ W/m^2 \cdot K$. The energy transmitted through the wall before compared to after the retrofitting saves $E = 456\ kWh$ per year for the wall. Detailed calculations can be found in Appendix 2c.

6.3.2 Using retrofitting option 2

Impact on acoustic result

The sound reduction index from outdoor sound for this construction is calculated giving the weighted apparent sound reduction index $R'_{45°,w} + C_{tr} = 57\ dB$ as seen in the following table and resulting diagram.

tau	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	R'45°,w + C
d	33.4	37.4	40.5	48.8	52.2	56.0	58.0	56.6	57.3	60.4	63.2	66.0	68.9	71.6	73.5	77.5	81.2	84.9	88.7	92.7	96.6	62.6
f1	49.8	50.3	50.9	51.4	51.7	52.5	54.2	54.3	55.6	58.3	60.9	63.5	66.2	68.8	71.4	74.1	76.7	79.3	81.8	84.4	86.8	61.1
f2	49.8	50.3	50.9	51.4	51.7	52.5	54.2	54.3	55.6	58.3	60.9	63.5	66.2	68.8	71.4	74.1	76.7	79.3	81.8	84.4	86.8	61.1
f3	51.4	52.4	53.5	54.5	55.3	55.1	55.5	53.8	53.9	55.3	56.6	58.5	60.4	62.2	65.1	68.1	70.9	73.8	76.7	79.7	83.1	59.4
f4	61.4	62.4	63.4	64.4	65.3	65.0	65.5	63.8	63.8	65.2	66.6	68.4	70.3	72.2	75.0	78.0	80.9	83.8	86.7	89.6	93.0	69.4
Total	33.1	36.8	39.6	45.0	46.5	47.7	49.1	48.5	49.3	51.5	53.5	55.7	57.9	60.0	62.7	65.7	68.5	71.4	74.2	77.1	80.1	55.1

Figure 6.18. Sound reduction from outdoor sound in 1/3 octave bands for construction 2 using retrofitting option 2, exported from BASTIAN.

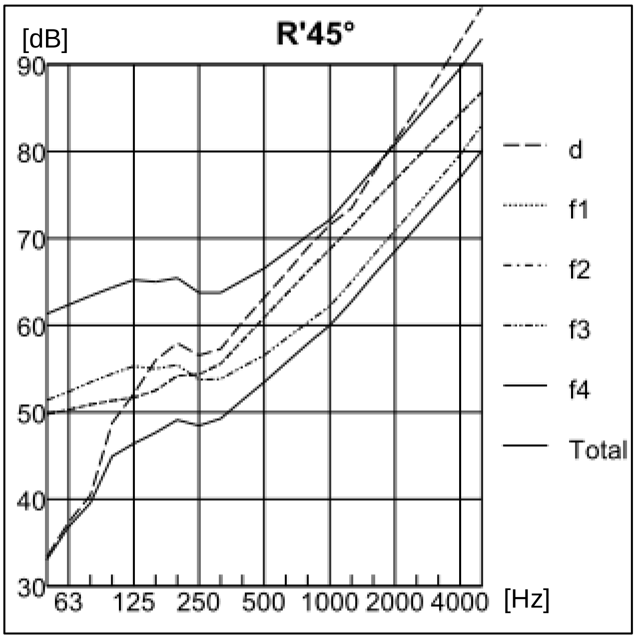

Figure 6.19. Sound reduction from outdoor sound $R'_{45°,w} + C_{tr}$ for construction 2 using retrofitting option 2, resulting diagram.

The sound level difference between apartments is calculated with the same retrofitting data, giving the weighted standardized sound level difference $D_{nT,w} + C_{50-3150} = 54\ dB$ as seen in the following table and resulting diagram.

tau	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	DnT,w (0.5 s) + C50
d	37.9	38.5	38.6	38.9	39.1	41.3	43.8	46.3	48.8	51.3	53.9	56.3	58.8	61.3	63.7	66.2	68.5	70.9	73.1	75.3	77.3	55.7
f1	48.2	48.3	48.2	48.2	48.2	50.3	52.8	55.4	58.0	60.5	63.1	65.7	68.2	70.8	73.4	75.9	78.4	80.9	83.3	85.6	87.9	64.8
f2	36.9	42.1	45.2	54.9	57.9	64.6	68.3	72.0	75.1	77.9	80.7	83.3	85.9	88.5	90.3	93.8	97.3	100.8	104.2	107.6	110.9	71.6
f3	46.8	46.8	46.7	46.7	46.9	49.4	52.1	54.6	57.2	59.7	62.3	64.9	67.5	70.0	72.6	75.1	77.5	80.0	82.4	84.7	87.0	64.0
f4	46.8	46.8	46.7	46.7	46.9	49.4	52.1	54.6	57.2	59.7	62.3	64.9	67.5	70.0	72.6	75.1	77.5	80.0	82.4	84.7	87.0	64.0
Total	33.7	35.9	36.4	37.2	37.4	39.7	42.2	44.8	47.3	49.8	52.4	54.9	57.4	59.9	62.4	64.8	67.2	69.6	71.9	74.1	76.2	54.2

Figure 6.20. Sound level difference between apartments in 1/3 octave bands for construction 2 using retrofitting option 2, exported from BASTIAN.

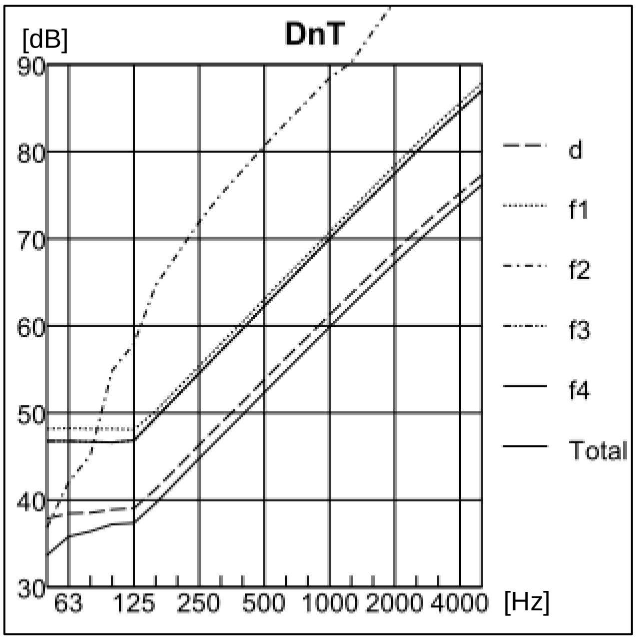

Figure 6.21. Sound level difference between apartments $D_{nT,w} + C_{50-3150}$ for construction 2 using retrofitting option 2, resulting diagram.

Comparing retrofitting on the inside or on the outside

The following figure shows the difference between the default configuration for façade construction 2 with the retrofitting option 2 on the inside and on the outside. Similar to the retrofitting option 1, the sound reduction index from outdoor sound is almost the same in all frequencies regardless of where the retrofitting is placed, except for the frequencies between 63 Hz and 250 Hz where the retrofitting on the outside is slightly better.

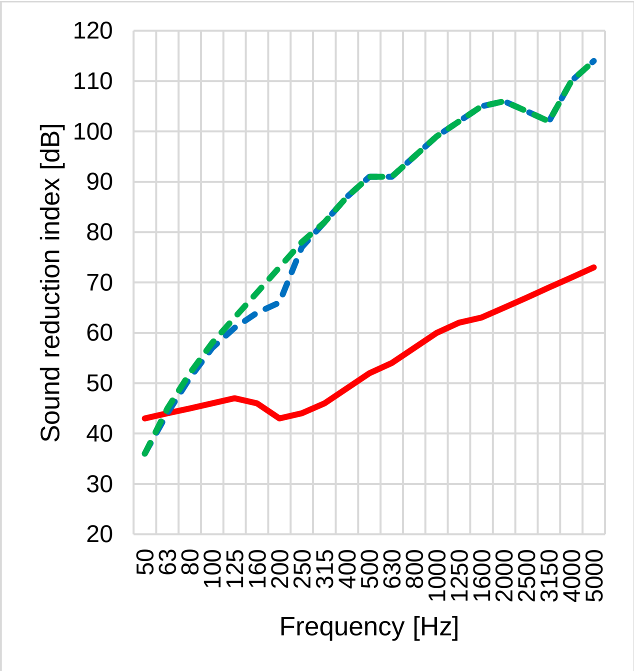

Figure 6.22. Difference between default configuration (red), retrofitting on the inside (blue dotted) and retrofitting on the outside (green dotted).

Impact on thermal results

For the retrofitting option 1 the thermal transmittance is calculated to $U_{c2,r2} = 0{,}308\ W/m^2 \cdot K$. The energy transmitted through the wall before compared to after the retrofitting saves $E = 519\ kWh$ per year for the wall. Detailed calculations can be found in Appendix 2d.

6.4 Construction 3: Light weight façade elements

6.4.1 Retrofitting on the inside

Impact on acoustic result

The sound reduction index from outdoor sound for this construction is calculated giving the weighted apparent sound reduction index $R'_{45°,w} + C_{tr} = 32\ dB$. The difference between the default configuration and the retrofitting on the inside is seen in the following diagram. As seen in figure 6.23 there is only a slight increase of the sound reduction index from outdoor sound when the light weight façade is retrofitted on the inside due to the limited change of the weight and the thickness of the façade.

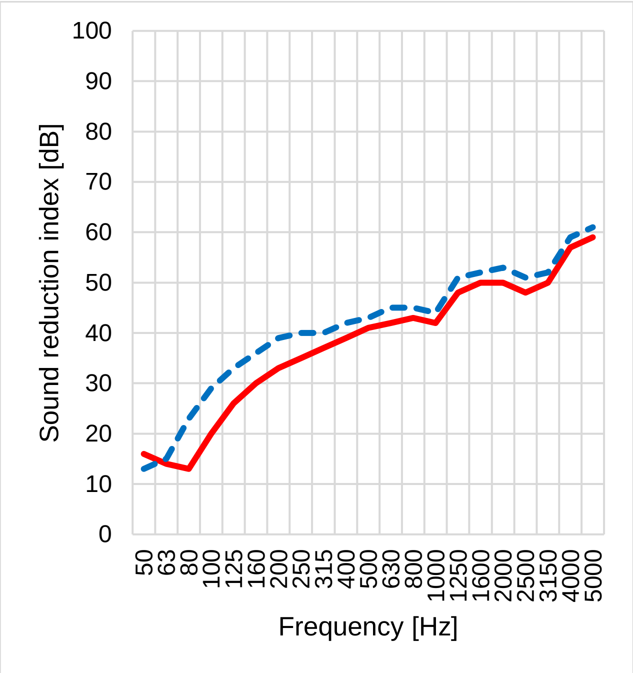

Figure 6.23. Difference between default configuration (red) and retrofitting on the inside (blue dotted).

Impact on thermal results

For the retrofitting on the inside for the third construction, the thermal transmittance is calculated to $U_{c3,ri} = 0{,}236\ W/m^2 \cdot K$. The energy transmitted through the wall before compared to after the retrofitting saves $E = 67\ kWh$ per year for the wall. Detailed calculations can be found in Appendix 2e.

6.4.2 Retrofitting on the outside

Impact on acoustic result

The sound reduction index from outdoor sound for this construction is calculated giving the weighted apparent sound reduction index $R'_{45°,w} + C_{tr} = 29\ dB$. The difference between the default configuration and the retrofitting on the inside is seen in the following diagram. Similar to the retrofitting on the inside, there is only a slight increase of the sound reduction index from outdoor sound for the retrofitting on the outside of the light weight facade as seen in figure 6.24. This is again due to the limited change of the weight and the thickness of the façade.

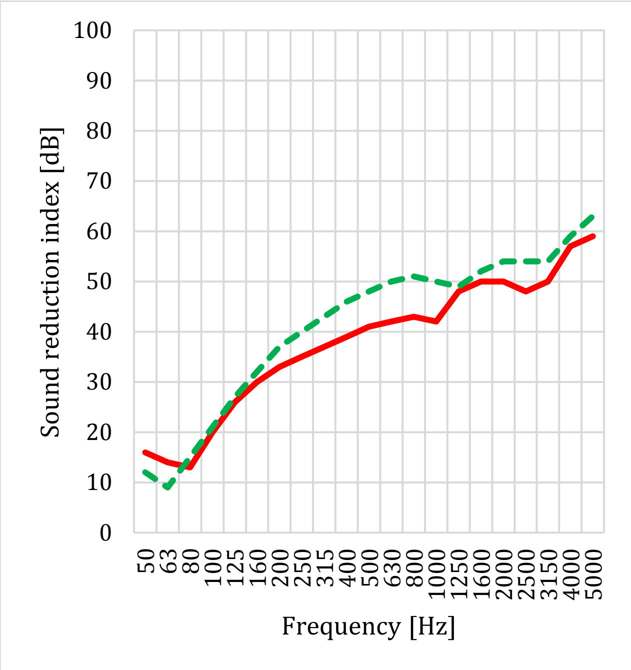

Figure 6.24. Difference between default configuration (red) and retrofitting on the outside (green dotted).

Impact on thermal results

For the retrofitting on the outside for the third construction, the thermal transmittance is calculated to $U_{c3,ru} = 0{,}239\ W/m^2 \cdot K$. The energy transmitted through the wall before compared to after the retrofitting saves $E = 66\ kWh$ per year for the wall. Detailed calculations can be found in Appendix 2f.

6.5 Summary of results

6.5.1 Acoustic summary

The results of the retrofitting for the acoustic parameters for all three façade constructions result are summarised in the following tables:

Table 6.1. Result of retrofitting regarding acoustic properties for façade construction 1 and 2.

	Construction 1		Construction 2	
	$R'_{45°,w} + C_{tr}$ $[dB]$	$D_{nT,w,50}$ $[dB]$	$R'_{45°,w} + C_{tr}$ $[dB]$	$D_{nT,w,50}$ $[dB]$
Default configuration	40	52	47	53
Retrofitting 1, inside	45	53	51	53
Retrofitting 1, outside	45	52	51	53
Retrofitting 2, inside	52	57	55	54
Retrofitting 2, outside	52	52	55	53

Table 6.2. Result of retrofitting regarding acoustic properties for façade construction 3.

	Construction 3	
	$R'_{45°,w} + C_{tr}$ $[dB]$	$D_{nT,w,50}$ $[dB]$
Default configuration	28	54
Retrofitting inside	32	–
Retrofitting outside	29	–

6.5.2 Thermal summary

The results of the retrofitting for the thermal properties (thermal transmittance and energy saved) for all three façade constructions result is summarised in the following tables:

Table 6.3. Result of retrofitting regarding thermal properties for façade construction 1 and 2.

	Construction 1		Construction 2	
	U $[W/m^2 \cdot K]$	E $[kWh]$	U $[W/m^2 \cdot K]$	E $[kWh]$
Default configuration	0,355	–	0,957	–
Retrofitting 1	0,229	100	0,387	456
Retrofitting 2	0,199	124	0,308	519

Table 6.4. Result of retrofitting regarding thermal properties for façade construction 3.

	Construction 3	
	U $[W/m^2 \cdot K]$	E $[kWh]$
Default configuration	0,321	–
Retrofitting inside	0,236	67
Retrofitting outside	0,239	66

6.6 Reliability and validity of method

6.6.1 Reliability

The reliability issue concerning this study involves 2 different dimensions – the reliability of the data used and the reliability of the method used in the overall analysis. The paper has firstly ensured that the acoustics data used in this study was reliable as they were extracted from a very reliable source, which is the BASTIAN Database, a database used by all Acoustics Consultants in Sweden. In addition, this paper has also ensured that selected building examples used in the simulated calculations are typical for the 1960s-era and concrete data behind the constructions are correct and available. This has been ensured through cross-referencing with the extensive research done previously in Björk et al (2002). These are done to ensure consistency and a higher degree of reliability of the data used. Finally, the simulated calculations were done through the highly renown computer programs such as BASTIAN and INSUL, which are programs used by building acoustic consultants, ensuring an optimal accuracy in terms of the calculation methods. As such, both the data and method used have been verified to ensure that a high degree of reliability was maintained.

6.6.2 Validity

The methodology and concepts used in this paper are largely based on theoretical physics and acoustical terms developed by highly renowned physicians and engineers from decades before. As such, while studying this topic, the concepts borrowed from those findings are assumed to be applicable and valid. The paper has to a large extent also crosschecked that the data retrieved on the building constructions of the example buildings used is also consistent with the general construction type from the 1960s-era in Sweden. Therefore, we have ensured that the methodology and data are highly valid in this study. However, a point to note is that considering this study is the first of its kind – there is no concrete way for us to benchmark the findings from this paper against any other previous studies. However, hopefully through the detailed guidance of how the simulation calculations are carried out, further research building on this paper can be easily managed. Also, considering that it is not possible for us to retrofit an actual 1960s building or façade due to cost and support constraints, the method used is based on simulations which might possibly lead to our results not matching completely in reality.The validity from this paper can be further improved through performing physical measurements of 1960s buildings in Sweden.

7 Conclusion and discussion

In this section, the paper discusses some of the findings from the simulated analyses from Chapter 6. In order to effectively provide some additional insights, the paper looks at the two different types of constructions – heavy façade vs light façade and the implications of the findings on future retrofitting methods targeted towards these respective constructions.

7.1 Retrofitting of heavy façade constructions

Both the weighted apparent sound reduction for the façade construction when regarding sound from outdoors and the weighted standardized sound level difference are increasing or remaining the same value before and after the retrofitting for the first and second façade constructions. However, when studying the graphs of the apparent sound reduction and the standardized sound level difference, they show a decrease in some areas. The decrease in the graphs is at the same frequency for both façade constructions when using either of the retrofitting methods. The first retrofitting method is having a relatively high decrease at 80 Hz. The second retrofitting method is giving a decrease at 50 Hz. Both these decreases correlate with the mass-air-mass frequency, the resonance frequency, for the retrofitted constructions, 83 Hz for the first retrofitting option and 47 Hz for the second retrofitting option. Although the weighted apparent sound reduction and the weighted standardized sound level difference increases, a decrease in a single frequency band causing a dip can influence the acoustic comfort by creating disturbances when more sound transmits trough the construction in those frequencies. Therefore, when retrofitting and adding a new layer to the existing constructions, the resonance frequency should be aimed to be as low as possible not to impact the weighted apparent sound reduction or weighted standardized sound level difference that are calculated down to 50 Hz for dwellings in Sweden. The resonance frequency is depending on the surface weight of the layers on both sides of the cavity as well as the thickness of the cavity. The retrofitted construction can therefore be designed to minimize the resonance frequency by increasing the surface weight of the retrofitted construction and/or the thickness of the cavity.

When the flanking transmission is dominating the sound level difference between apartments, for example with poor junctions in the construction or a weak façade construction, a retrofitting on the inside is increasing the sound level difference between apartments more than if the flanking transmission is low. As seen in the result, the retrofitting on the inside for the first construction is increasing the sound level difference between apartments more than for the second construction. The reason for this is that the dominating flanking transmission for the first construction is decreasing and more sound are instead traveling as direct sound through the partition wall separating the apartments and not via the façade.

As a conclusion, if the flanking transmission is high or if there are leakages in the junction, retrofitting is recommended to be installed on the inside to reduce the flanking transmission or to seal the leakages. However, if the sound level difference between the apartments is sufficient before any retrofitting, the retrofitting should be placed on the outside not to reduce the sound level difference in any frequencies. A reduction of the sound level difference in a single frequency band will cause sound to transmit through and it can be very disturbing although the weighted value is equally good or even better than before the retrofitting.

When evaluating the thermal properties, there are no difference considering the thermal transmittance if the retrofitting is placed on the inside or on the outside of the façade construction. The single factor affecting the thermal transmittance is the thickness of the insulating material. A thicker mineral wool will decrease the thermal transmittance, but a heavier surface weight of any layer or having two instead of one layer of gypsum boards will not affect the thermal transmittance more than just a fraction. Also the heat energy transmitted through the façade is directly correlated to the thickness of the insulating material. For the case study where the façade area is 10 m^2, the first retrofitting for the first construction saves 100 kWh per year. It can seem to be a small saving due to what impact the retrofitting have to the construction in regards to the work, but a three room apartment (two bedrooms, one living room and one kitchen) where the façade area is assumed to be the same in every room the energy saved is 400 kWh per year for just that apartment. Considering a building with 20 apartments, the energy saved is as much as 8000 kWh per year. With the energy price of approximately 1 SEK/kWh the money saved is 8000 SEK per year. For the second construction with the second retrofitting method, the energy saved is 519 kWh per room which gives 2076 kWh per apartment and 41520 kWh for the walls in the whole building with 20 apartments. The money saved is now 41520 SEK per year for a dwelling located in Malmö. If the dwelling is located further north where the demand of heating is larger, the energy (and money) that can be saved every year will increase further. Note that these numbers only reflect the energy saving trough the wall. If windows would be changed in the dwellings, the energy saved could be significantly higher. This is not only a cost benefit but will definitely contribute positively to the overall human energy footprint given the depleting amount of natural resources in the world.

When comparing the new values for the thermal transmittance after the retrofitting with the recommended values in the Swedish Building Regulations, BBR, there is still a huge difference. To reach the recommended thermal transmittance of 0,18 W/m^2K according to BBR the retrofitted insulating layer has to be at least 110 mm for the first construction and 184 mm for the second construction. These thicknesses are very big and if retrofitted, it will change the design of the building and cause problems around the windows with deep openings in the façade waist.

As mentioned earlier, there are other advantages of where the retrofitting should be placed on a façade construction. The main risk of retrofitting on the inside is that the façade is getting colder and moist will get further in to the construction and might cause mould growth or freezing damages on the façade. Retrofitting on the outside is therefore preferred to reduce the risks of a cold and wet construction. Another important aspect of placing the retrofitting on the outside is that any thermal bridges will be covered with the new façade insulation and will influence the wall lesser. Considering the second façade construction, where the concrete walls between apartments are moulded together with the concrete façade and only a layer of autoclaved aerated concrete on the outside. Placing a retrofitting on the inside of this construction, the façade construction will remain cold and the low temperature will spread to the concrete walls and floors due to the thermal bridges. Retrofitting on the outside will reduce the thermal bridges and the climate inside will be more pleasant.

The acoustic and the thermal characteristics go somewhat hand in hand where a retrofitting on the outside is to be preferred. There should be only two cases where the retrofitting should be placed on the inside of a heavy façade construction:

- Huge flanking transmission via the façade or leakages at the junctions
- When the façade appearance should not be changed

If the building, or the façade itself, is listed as historic and should not be altered the retrofitting has to be done in the inside. However, due to the risks of an internal retrofitting the façade can be destroyed after a few years. When this is the case, further investigations should be done and maybe a retrofitting of the façade should not be done at all.

7.2 Retrofitting of light weight façade constructions

Reviewing the case studies the retrofitting indicates that an increase of the cavity thickness and just a slight increase of the surface mass hardly affect the apparent sound reduction index. The sound level difference between apartments has not been studied due to the complexity of the design. However, when retrofitting a light weight façade construction it is of great importance that the junctions are designed with special care in order not to get any leakages or flanking transmission via the façade. The design of junctions when retrofitting should be investigated further in a deeper research.

On the other side, the thermal transmittance is decreasing with the thicker insulating material. The energy saved is not as much as for the two first constructions, which depends on that the thermal transmittance was already better in the default configuration. In order to reach the recommended values for thermal transmittance the insulating material has to increase with at least 110 mm.

The conclusion is that without making a light weight façade heavy, it is difficult to get a good sound reduction index. Since the single factor that is affecting the thermal transmittance is how thick the insulating material is, the wall can pass the recommended values according to BBR by making the wall thicker. Unfortunately, making the façade construction thicker will not increase the apparent sound reduction index more than marginally. By making the insulating layer thicker and therefore the cavity thicker, the resonance frequency will decrease slightly. However, since the resonance frequency is also depending on the surface mass of the layers around the cavity, the construction has to increase its weight in order to get a significantly higher apparent sound reduction index. Because of this, the single easiest way to increase the apparent sound reduction index for the façade construction is to replace the outer layer with a heavy structure, for example a brick wall. An outer layer of bricks together with a thick insulating material in the wall will increase both the acoustic and the thermal properties, however, this would go against the property of the structure of being light and cheap.

As a summary, for light weight façade constructions the acoustic properties and the thermal properties does not go hand in hand, and the retrofitting process is more complex than for the heavy façade constructions.

7.3 Final recommendations and way forward

Through the simulations done in this paper, the author hopes to provide some key insights as to how a retrofitting process can be done to better improve the qualities of old buildings. To tear down a building and build a new greener one is tempting. However, with that also comes high cost and not to mention the negative impacts that has on the environment. There are many articles indicating the higher emission of greenhouse gases when a new building is constructed and when old ones are torn down. Beyond that, there is also a cultural aspect of not preserving old buildings as it sometimes can form the heritage of the area. Intrinsically, retrofitting should be seen as a positive alternative to tearing down buildings and creating a new one. It can reach the positive outcome comparable to a greener new building if done correctly. As shown in Chapter 6 of this paper and in the discussion points above, it is relatively straight forward for a heavy façade construction from the 1960s-era. That being said, the paper also highlights that retrofitting would be harder and more complex when the building is built on a light façade. More caution and analysis has to be done to balance the impact of chosen materials against its effect on acoustical and thermal properties. This could perhaps be an area for future research. On a last note, this entire paper is built on simulations through renowned software programs and the way to prove and disprove the findings would be through physical implementation to an actual building and a post-retrofit measurement. As such, the hope is that this paper provides for the basic fundamental insights for any actual retrofitting projects that are looking towards improving and preserving 1960s buildings in Sweden.

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Appendix 1a: Façade construction 1 - Calculations for outdoor sound

GROUND CONFIGURATION, facade construction 1:

Sound reduction from outdoor sound, per construction part

Frequency [Hz]	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	R'45°,w + Ctr
d [dB]	38,1	38,3	34,5	36	34,4	35,9	32,9	33,5	33,3	34,1	40,4	44,4	48,1	49,3	54	58,7	61,3	64,1	66,1	70,2	70,8	40,2
f1 [dB]	51,2	51,3	49,4	50,4	50,5	53,6	54,3	56,8	59	61,7	67,1	71,3	75,4	78,2	82,7	87,4	90,8	94,2	97,3	101,5	103,8	62,4
f2 [dB]	51,2	51,3	49,4	50,4	50,5	53,6	54,3	56,8	59	61,7	67,1	71,3	75,4	78,2	82,7	87,4	90,8	94,2	97,3	101,5	103,8	62,4
f3 [dB]	48,3	48,4	46,5	47,3	47,8	50,9	51,6	54,2	56,3	59	64,4	68,6	72,8	75,6	80,1	84,7	88,1	91,7	94,8	98,9	101,2	59,6
f4 [dB]	48,3	48,4	46,5	47,3	47,8	50,9	51,6	54,2	56,3	59	64,4	68,6	72,8	75,6	80,1	84,7	88,1	91,7	94,8	98,9	101,2	59,6
Total [dB]	37	37,2	33,7	35,1	33,8	35,5	32,7	33,4	33,2	34,1	40,3	44,3	48,1	49,3	54	58,7	61,3	64,1	66,1	70,2	70,8	40,1

Retrofitting option 1:

Sound reduction from outdoor sound, per construction part

Frequency [Hz]	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	R'45°,w + Ctr
d [dB]	38,1	37,3	29,5	32	33,4	40,3	38,6	40,5	41	42,3	48,7	52,9	56,6	57,9	61,7	67,5	71	74,8	77,8	82,9	84,6	46,1
f1 [dB]	51,2	51,3	49,4	50,4	50,5	53,6	54,3	56,8	59	61,7	67,1	71,3	75,4	78,2	82,7	87,4	90,8	94,2	97,3	101,5	103,8	62,4
f2 [dB]	51,2	51,3	49,4	50,4	50,5	53,6	54,3	56,8	59	61,7	67,1	71,3	75,4	78,2	82,7	87,4	90,8	94,2	97,3	101,5	103,8	62,4
f3 [dB]	48,3	48,4	46,5	47,3	47,8	50,9	51,6	54,2	56,3	59	64,4	68,6	72,8	75,6	80,1	84,7	88,1	91,7	94,8	98,9	101,2	59,6
f4 [dB]	48,3	48,4	46,5	47,3	47,8	50,9	51,6	54,2	56,3	59	64,4	68,6	72,8	75,6	80,1	84,7	88,1	91,7	94,8	98,9	101,2	59,6
Total [dB]	37	36,4	29,2	31,6	32,9	39,3	38	40	40,6	42	48,4	52,6	56,3	57,7	61,5	67,3	70,7	74,5	77,5	82,6	84,3	45,7
Difference d:	0	-1	-5	-4	-1	4,4	5,7	7	7,7	8,2	8,3	8,5	8,5	8,6	7,7	8,8	9,7	10,7	11,7	12,7	13,8	5,9
Difference tot:	0	-0,8	-4,5	-3,5	-0,9	3,8	5,3	6,6	7,4	7,9	8,1	8,3	8,2	8,4	7,5	8,6	9,4	10,4	11,4	12,4	13,5	5,6

Retrofitting option 2:

Luftljudsisolering, per konstruktion/byggnadsdel

Frequency [Hz]	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	R'45°,w + Ctr
d [dB]	33,1	36,3	34,5	43,3	44,4	50,2	48,3	49,9	50,3	51,4	57,8	61,9	65,7	66,9	70,8	76,5	80,1	83,8	86,8	92	93,7	55,8
f1 [dB]	51,2	51,3	49,4	50,4	50,5	53,6	54,3	56,8	59	61,7	67,1	71,3	75,4	78,2	82,7	87,4	90,8	94,2	97,3	101,5	103,8	62,4
f2 [dB]	51,2	51,3	49,4	50,4	50,5	53,6	54,3	56,8	59	61,7	67,1	71,3	75,4	78,2	82,7	87,4	90,8	94,2	97,3	101,5	103,8	62,4
f3 [dB]	48,3	48,4	46,5	47,3	47,8	50,9	51,6	54,2	56,3	59	64,4	68,6	72,8	75,6	80,1	84,7	88,1	91,7	94,8	98,9	101,2	59,6
f4 [dB]	48,3	48,4	46,5	47,3	47,8	50,9	51,6	54,2	56,3	59	64,4	68,6	72,8	75,6	80,1	84,7	88,1	91,7	94,8	98,9	101,2	59,6
Total [dB]	32,7	35,6	33,7	39,9	40,6	44,6	44,4	46,6	47,8	49,5	55,5	59,7	63,6	65,4	69,5	74,8	78,4	82	85	89,9	91,8	52,8
Difference d:	-5	-2	0	7,3	10	14,3	15,4	16,4	17	17,3	17,4	17,5	17,6	17,6	16,8	17,8	18,8	19,7	20,7	21,8	22,9	15,6
Difference tot:	-4,3	-1,6	0	4,8	6,8	9,1	11,7	13,2	14,6	15,4	15,2	15,4	15,5	16,1	15,5	16,1	17,1	17,9	18,9	19,7	21	12,7

Appendix 1b: Façade construction 1 - Calculations between apartments

GROUND CONFIGURATION, facade construction 1:

Sound level difference between apartments, per construction part

Frequency [Hz]	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	DnT,w (0.5 s) + C50-3150
d [dB]	40,4	40,4	40,4	40,9	42,6	45	47,7	50,4	53	55,6	58,2	60,8	63,3	65,7	68,2	70,6	72,9	75	77,2	79,3	81,3	59,6
f1 [dB]	50,2	50,2	50,2	50,6	52,5	55	57,5	60,1	62,6	65,2	67,7	70,3	72,8	75,3	77,8	80,3	82,7	85	87,4	89,6	91,8	69,3
f2 [dB]	37,3	37,4	37,4	37,7	37,8	37,7	40,3	43	45,6	48,3	50,9	53,6	56,3	59	61,7	64,3	67	69,6	72,2	74,8	77,2	52,8
f3 [dB]	49,2	49	49	49,1	51,6	54	56,6	59,2	61,7	64,2	66,8	69,3	71,8	74,4	76,8	79,3	81,7	84,1	86,3	88,5	90,7	68,3
f4 [dB]	49,2	49	49	49,1	51,6	54	56,6	59,2	61,7	64,2	66,8	69,3	71,8	74,4	76,8	79,3	81,7	84,1	86,3	88,5	90,7	68,3
Total [dB]	35,1	35,1	35,1	35,5	36,2	36,8	39,4	42,1	44,6	47,3	49,9	52,6	55,2	57,9	60,5	63,1	65,7	68,2	70,7	73,1	75,4	51,7

Retrofitting 1:

Sound level difference between apartments, per construction part

Frequency [Hz]	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	DnT,w (0.5 s) + C50-3150
d [dB]	40,4	40,2	39	39,8	42,4	45,7	48,4	51	53,5	56	58,5	61	63,5	65,9	68,3	70,6	72,9	75,1	77,3	79,3	81,3	59,8
f1 [dB]	50,2	50,2	50,2	50,6	52,5	55	57,5	60,1	62,6	65,2	67,7	70,3	72,8	75,3	77,8	80,3	82,7	85	87,4	89,6	91,8	69,3
f2 [dB]	37,3	35,4	27,7	29,9	35,9	46,2	51,3	56,6	60,6	64,3	67,1	70,3	73,1	75,9	77	81,8	86,3	90,8	95,4	100	104,6	55,3
f3 [dB]	49,2	49	49	49,1	51,6	54	56,6	59,2	61,7	64,2	66,8	69,3	71,8	74,4	76,8	79,3	81,7	84,1	86,3	88,5	90,7	68,3
f4 [dB]	49,2	49	49	49,1	51,6	54	56,6	59,2	61,7	64,2	66,8	69,3	71,8	74,4	76,8	79,3	81,7	84,1	86,3	88,5	90,7	68,3
Total [dB]	35,1	33,8	27,3	29,4	34,7	42,1	45,5	48,7	51,4	54,1	56,6	59,2	61,7	64,1	66,4	69	71,4	73,7	75,9	78	80,1	53
Difference f2:	0	-2	-9,7	-7,8	-1,9	8,5	11	13,6	15	16	16,2	16,7	16,8	16,9	15,3	17,5	19,3	21,2	23,2	25,2	27,4	2,5
Difference tot:	0	-1,3	-7,8	-6,1	-1,5	5,3	6,1	6,6	6,8	6,8	6,7	6,6	6,5	6,2	5,9	5,9	5,7	5,5	5,2	4,9	4,7	1,3

Retrofitting 2:

Sound level difference between apartments, per construction part

Frequency [Hz]	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	DnT,w (0.5 s) + C50-3150
d [dB]	39	40	40,4	41,6	43,6	46,1	48,6	51,1	53,6	56,1	58,6	61,1	63,5	65,9	68,3	70,7	72,9	75,1	77,3	79,3	81,3	60,2
f1 [dB]	50,2	50,2	50,2	50,6	52,5	55	57,5	60,1	62,6	65,2	67,7	70,3	72,8	75,3	77,8	80,3	82,7	85	87,4	89,6	91,8	69,3
f2 [dB]	27,6	33,5	37,4	50,9	55,6	63,1	67,7	72,4	76,3	79,9	83,1	86,4	89,6	92,5	94,1	98,8	103,4	107,8	112,3	117	121,6	64,1
f3 [dB]	49,2	49	49	49,1	51,6	54	56,6	59,2	61,7	64,2	66,8	69,3	71,8	74,4	76,8	79,3	81,7	84,1	86,3	88,5	90,7	68,3
f4 [dB]	49,2	49	49	49,1	51,6	54	56,6	59,2	61,7	64,2	66,8	69,3	71,8	74,4	76,8	79,3	81,7	84,1	86,3	88,5	90,7	68,3
Total [dB]	27,2	32,4	35,1	39,6	41,8	44,4	47	49,5	52	54,5	57	59,5	62	64,4	66,9	69,2	71,5	73,8	76	78,1	80,1	57,6
Difference f2:	-9,7	-3,9	0	13,2	17,8	25,4	27,4	29,4	30,7	31,6	32,2	32,8	33,3	33,5	32,4	34,5	36,4	38,2	40,1	42,2	44,4	11,3
Difference tot:	-7,9	-2,7	0	4,1	5,6	7,6	7,6	7,4	7,4	7,2	7,1	6,9	6,8	6,5	6,4	6,1	5,8	5,6	5,3	5	4,7	5,9

Appendix 1c: Façade construction 2 - Calculations for outdoor sound

GROUND CONFIGURATION, facade construction 2:
Sound reduction from outdoor sound, per construction part

Frequency [Hz]	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	R'45°,w + Ctr
d [dB]	38,4	39,4	40,5	41,5	42,2	41,7	42,6	40,2	40,3	43,1	45,8	48,5	51,3	54	56,7	59,7	62,4	65,2	68	70,9	73,7	47,6
f1 [dB]	49,8	50,3	50,9	51,4	51,7	52,5	54,2	54,3	55,6	58,3	60,9	63,5	66,2	68,8	71,4	74,1	76,7	79,3	81,8	84,4	86,8	61,1
f2 [dB]	49,8	50,3	50,9	51,4	51,7	52,5	54,2	54,3	55,6	58,3	60,9	63,5	66,2	68,8	71,4	74,1	76,7	79,3	81,8	84,4	86,8	61,1
f3 [dB]	51,4	52,4	53,5	54,5	55,3	55,1	55,5	53,8	53,9	55,3	56,6	58,5	60,4	62,2	65,1	68,1	70,9	73,8	76,7	79,7	83,1	59,4
f4 [dB]	61,4	62,4	63,4	64,4	65,3	65	65,5	63,8	63,8	65,2	66,6	68,4	70,3	72,2	75	78	80,9	83,8	86,7	89,6	93	69,4
Total [dB]	37,6	38,6	39,6	40,5	41,1	40,9	41,8	39,7	39,9	42,6	45,2	47,8	50,5	53,1	55,8	58,8	61,5	64,3	67,1	70	72,8	46,9

Retrofitting option 1:
Sound reduction from outdoor sound, per construction part

Frequency [Hz]	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	R'45°,w + Ctr
d [dB]	38,4	38,4	35,5	37,5	41,2	46,1	48,3	47,2	48	51,3	54,1	57	59,8	62,6	64,4	68,5	72,1	75,9	79,7	83,6	87,5	52,9
f1 [dB]	49,8	50,3	50,9	51,4	51,7	52,5	54,2	54,3	55,6	58,3	60,9	63,5	66,2	68,8	71,4	74,1	76,7	79,3	81,8	84,4	86,8	61,1
f2 [dB]	49,8	50,3	50,9	51,4	51,7	52,5	54,2	54,3	55,6	58,3	60,9	63,5	66,2	68,8	71,4	74,1	76,7	79,3	81,8	84,4	86,8	61,1
f3 [dB]	51,4	52,4	53,5	54,5	55,3	55,1	55,5	53,8	53,9	55,3	56,6	58,5	60,4	62,2	65,1	68,1	70,9	73,8	76,7	79,7	83,1	59,4
f4 [dB]	61,4	62,4	63,4	64,4	65,3	65	65,5	63,8	63,8	65,2	66,6	68,4	70,3	72,2	75	78	80,9	83,8	86,7	89,6	93	69,4
Total [dB]	37,6	37,7	35,2	37,1	40,3	44,1	46	45,1	45,9	48,6	51	53,5	56	58,3	60,7	64,1	67,1	70,2	73,3	76,3	79,4	50,4
Difference d:	0	-1	-5	-4	-1	4,4	5,7	7	7,7	8,2	8,3	8,5	8,5	8,6	7,7	8,8	9,7	10,7	11,7	12,7	13,8	5,3
Difference tot:	0	-0,9	-4,4	-3,4	-0,8	3,2	4,2	5,4	6	6	5,8	5,7	5,5	5,2	4,9	5,3	5,6	5,9	6,2	6,3	6,6	3,5

Retrofitting option 2:
Luftljudsisolering, per konstruktion/byggnadsdel

Frequency [Hz]	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	R'45°,w + Ctr
d [dB]	33,4	37,4	40,5	48,8	52,2	56	58	56,6	57,3	60,4	63,2	66	68,9	71,6	73,5	77,5	81,2	84,9	88,7	92,7	96,6	62,6
f1 [dB]	49,8	50,3	50,9	51,4	51,7	52,5	54,2	54,3	55,6	58,3	60,9	63,5	66,2	68,8	71,4	74,1	76,7	79,3	81,8	84,4	86,8	61,1
f2 [dB]	49,8	50,3	50,9	51,4	51,7	52,5	54,2	54,3	55,6	58,3	60,9	63,5	66,2	68,8	71,4	74,1	76,7	79,3	81,8	84,4	86,8	61,1
f3 [dB]	51,4	52,4	53,5	54,5	55,3	55,1	55,5	53,8	53,9	55,3	56,6	58,5	60,4	62,2	65,1	68,1	70,9	73,8	76,7	79,7	83,1	59,4
f4 [dB]	61,4	62,4	63,4	64,4	65,3	65	65,5	63,8	63,8	65,2	66,6	68,4	70,3	72,2	75	78	80,9	83,8	86,7	89,6	93	69,4
Total [dB]	33,1	36,8	39,6	45	46,5	47,7	49,1	48,5	49,3	51,5	53,5	55,7	57,9	60	62,7	65,7	68,5	71,4	74,2	77,1	80,1	55,1
Difference d:	-5	-2	0	7,3	10	14,3	15,4	16,4	17	17,3	17,4	17,5	17,6	17,6	16,8	17,8	18,8	19,7	20,7	21,8	22,9	15
Difference tot:	-4,5	-1,8	0	4,5	5,4	6,8	7,3	8,8	9,4	8,9	8,3	7,9	7,4	6,9	6,9	6,9	7	7,1	7,1	7,1	7,3	8,2

Appendix 1d: Façade construction 2 - Calculations between apartments

GROUND CONFIGURATION, facade construction 2:

Sound level difference between apartments, per construction part

Frequency [Hz]	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	DnT,w (0.5 s) + C50-3150
d [dB]	38,8	38,8	38,6	38,6	38,7	40,8	43,3	45,9	48,4	50,8	53,4	55,9	58,4	60,8	63,3	65,8	68,1	70,5	72,8	74,9	77	55,2
f1 [dB]	48,2	48,3	48,2	48,2	48,2	50,3	52,8	55,4	58	60,5	63,1	65,7	68,2	70,8	73,4	75,9	78,4	80,9	83,3	85,6	87,9	64,8
f2 [dB]	45,2	45,3	45,2	45,2	45,2	47,3	49,8	52,4	55	57,5	60,1	62,7	65,2	67,8	70,4	72,9	75,4	77,9	80,3	82,6	84,9	61,8
f3 [dB]	46,8	46,8	46,7	46,7	46,9	49,4	52,1	54,6	57,2	59,7	62,3	64,9	67,5	70	72,6	75,1	77,5	80	82,4	84,7	87	64
f4 [dB]	46,8	46,8	46,7	46,7	46,9	49,4	52,1	54,6	57,2	59,7	62,3	64,9	67,5	70	72,6	75,1	77,5	80	82,4	84,7	87	64
Total [dB]	36,6	36,6	36,4	36,4	36,5	38,7	41,2	43,8	46,4	48,8	51,4	53,9	56,4	58,9	61,5	63,9	66,3	68,8	71,1	73,3	75,4	53,2

Retrofitting 1:

Sound level difference between apartments, per construction part

Frequency [Hz]	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	DnT,w (0.5 s) + C50-3150
d [dB]	38,8	38,6	37,7	37,9	38,5	41,1	43,6	46,3	48,8	51,2	53,8	56,3	58,7	61,2	63,7	66,1	68,5	70,9	73,1	75,3	77,3	55,5
f1 [dB]	48,2	48,3	48,2	48,2	48,2	50,3	52,8	55,4	58	60,5	63,1	65,7	68,2	70,8	73,4	75,9	78,4	80,9	83,3	85,6	87,9	64,8
f2 [dB]	45,2	43,7	36,9	38,6	43,6	53,4	57,6	61,8	65,2	68,2	71	73,8	76,3	79	80,5	84,3	87,8	91,4	94,9	98,3	101,7	63
f3 [dB]	46,8	46,8	46,7	46,7	46,9	49,4	52,1	54,6	57,2	59,7	62,3	64,9	67,5	70	72,6	75,1	77,5	80	82,4	84,7	87	64
f4 [dB]	46,8	46,8	46,7	46,7	46,9	49,4	52,1	54,6	57,2	59,7	62,3	64,9	67,5	70	72,6	75,1	77,5	80	82,4	84,7	87	64
Total [dB]	36,6	36,3	33,7	34,5	36,2	39,4	42	44,7	47,2	49,7	52,3	54,8	57,3	59,8	62,3	64,7	67,1	69,6	71,9	74,1	76,2	53,7
Difference f2:	0	-1,6	-8,3	-6,6	-1,6	6,1	7,8	9,4	10,2	10,7	10,9	11,1	11,1	11,2	10,1	11,4	12,4	13,5	14,6	15,7	16,8	1,2
Difference tot:	0	-0,3	-2,7	-1,9	-0,3	0,7	0,8	0,9	0,8	0,9	0,9	0,9	0,9	0,9	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,5

Retrofitting 2:

Sound level difference between apartments, per construction part

Frequency [Hz]	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	DnT,w (0.5 s) + C50-3150
d [dB]	37,9	38,5	38,6	38,9	39,1	41,3	43,8	46,3	48,8	51,3	53,9	56,3	58,8	61,3	63,7	66,2	68,5	70,9	73,1	75,3	77,3	55,7
f1 [dB]	48,2	48,3	48,2	48,2	48,2	50,3	52,8	55,4	58	60,5	63,1	65,7	68,2	70,8	73,4	75,9	78,4	80,9	83,3	85,6	87,9	64,8
f2 [dB]	36,9	42,1	45,2	54,9	57,9	64,6	68,3	72	75,1	77,9	80,7	83,3	85,9	88,5	90,3	93,8	97,3	100,8	104,2	107,6	110,9	71,6
f3 [dB]	46,8	46,8	46,7	46,7	46,9	49,4	52,1	54,6	57,2	59,7	62,3	64,9	67,5	70	72,6	75,1	77,5	80	82,4	84,7	87	64
f4 [dB]	46,8	46,8	46,7	46,7	46,9	49,4	52,1	54,6	57,2	59,7	62,3	64,9	67,5	70	72,6	75,1	77,5	80	82,4	84,7	87	64
Total [dB]	33,7	35,9	36,4	37,2	37,4	39,7	42,2	44,8	47,3	49,8	52,4	54,9	57,4	59,9	62,4	64,8	67,2	69,6	71,9	74,1	76,2	54,2
Difference f2:	-8,3	-3,2	0	9,7	12,7	17,3	18,5	19,6	20,1	20,4	20,6	20,6	20,7	20,7	19,9	20,9	21,9	22,9	23,9	25	26	9,8
Difference tot:	-2,9	-0,7	0	0,8	0,9	1	1	1	0,9	1	1	1	1	1	0,9	0,9	0,9	0,8	0,8	0,8	0,8	1

Appendix 2a: Façade construction 1

Thermal calculations for retrofitting 1

Thermal transmittance method

First the thermal resistance for the wooden segment and the mineral wool segment is calculated:

$$R_{wood} = R_{se} + R_{concrete} + R_{cellular\ plastic} + R_{concrete} + R_{mineral\ wool} + R_{wood} + R_{gypsum} + R_{si}$$

$$R_{wood} = R_{se} + \frac{d_{concrete,60}}{\lambda_{concrete}} + \frac{d_{cellular\ plastic,100}}{\lambda_{cellular\ plastic}} + \frac{d_{concrete,120}}{\lambda_{concrete}} + \frac{d_{mineral\ wool,15}}{\lambda_{mineral\ wool}} + \frac{d_{wood,45}}{\lambda_{wood}} + \frac{d_{gypsum,13}}{\lambda_{gypsum}} + R_{si}$$

$$R_{wood} = 0{,}04 + \frac{60 \cdot 10^{-3}}{1{,}2} + \frac{100 \cdot 10^{-3}}{0{,}04} + \frac{120 \cdot 10^{-3}}{1{,}2} + \frac{15 \cdot 10^{-3}}{0{,}037} + \frac{45 \cdot 10^{-3}}{0{,}14} + \frac{13 \cdot 10^{-3}}{0{,}22} + 0{,}13 = 3{,}606\ m^2 \cdot K/W$$

$$R_{mineral\ wool} = R_{se} + \frac{d_{concrete,60}}{\lambda_{concrete}} + \frac{d_{cellular\ plastic,100}}{\lambda_{cellular\ plastic}} + \frac{d_{concrete,120}}{\lambda_{concrete}} + \frac{d_{mineral\ wool,60}}{\lambda_{mineral\ wool}} + \frac{d_{gypsum,13}}{\lambda_{gypsum}} + R_{si}$$

$$R_{mineral\ wool} = 0{,}04 + \frac{60 \cdot 10^{-3}}{1{,}2} + \frac{100 \cdot 10^{-3}}{0{,}04} + \frac{120 \cdot 10^{-3}}{1{,}2} + \frac{60 \cdot 10^{-3}}{0{,}037} + \frac{13 \cdot 10^{-3}}{0{,}22} + 0{,}13 = 4{,}501\ m^2 \cdot K/W$$

After that the area for the wood segment and for the mineral wool segment is calculated:

$$A_{wood} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

$$A_{mineral\ wool} = \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

And finally the segment partitions are weighted in with the thermal resistances:

$$R_{1,1,U} = A_{wood} \cdot R_{wood} + A_{mineral\ wool} \cdot R_{mineral\ wool}$$

$$R_{1,1,U} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 3{,}606 + \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 4{,}501 = 4{,}434\ m^2 \cdot K/W$$

$$U_{1,1,U} = \frac{1}{R_{1,1,U}} = \frac{1}{4{,}434} = 0{,}226\ W/m^2 \cdot K$$

Thermal conductivity method

First the percentage of wood versus mineral wool is calculated and then used to determine a combined thermal conductivity for the layer with both wooden studs and mineral wool:

$$a_{wood} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

$$a_{mineral\ wool} = \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

$$\lambda_{wood+mineral\ wool} = \alpha_{wood} \cdot \lambda_{wood} + \alpha_{mineral\ wool} \cdot \lambda_{mineral\ wool}$$

$$\lambda_{wood+mineral\ wool} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 0{,}14 + \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 0{,}037 = 0{,}045\ W/m \cdot K$$

When the thermal conductivity for the combined layer is calculated, the total thermal resistance can be calculated:

$$R_{1,1,\lambda} = \frac{d_{concrete,60}}{\lambda_{concrete}} + \frac{d_{cellular\ plastic,100}}{\lambda_{cellular\ plastic}} + \frac{d_{concrete,120}}{\lambda_{concrete}} + \frac{d_{mineral\ wool,15}}{\lambda_{mineral\ wool}} + \frac{d_{wood+mineral\ wool,45}}{\lambda_{wood+minearl\ wool}} + \frac{d_{gypsum,13}}{\lambda_{gypsum}}$$

$$R_{1,1,\lambda} = \frac{60 \cdot 10^{-3}}{1{,}2} + \frac{100 \cdot 10^{-3}}{0{,}04} + \frac{120 \cdot 10^{-3}}{1{,}2} + \frac{15 \cdot 10^{-3}}{0{,}037} + \frac{45 \cdot 10^{-3}}{0{,}045} + \frac{13 \cdot 10^{-3}}{0{,}22} = 4{,}121\ m^2 \cdot K/W$$

When the thermal resistance is calculated, the thermal transmittance can be calculated:

$$U_{1,1,\lambda} = \frac{1}{R_{se} + R_{1,1,\lambda} + R_{si}} = \frac{1}{0{,}04 + 4{,}121 + 0{,}13} = 0{,}233\ W/m^2 \cdot K$$

Combined thermal transmittance

When the thermal transmittance is calculated with both methods, the combined thermal transmittance is calculated:

$$U_{1,1} = \frac{2 \cdot U_{1,1,U} \cdot U_{1,1,\lambda}}{U_{1,1,U} + U_{1,1,\lambda}} = \frac{2 \cdot 0{,}226 \cdot 0{,}233}{0{,}226 + 0{,}233} = 0{,}229\ W/m^2 \cdot K$$

Energy calculation

With the new thermal transmittance, the energy saved for an area can be calculated with the difference from the precious thermal transmittance:

$$E_{1,1} = \left(U_1 - U_{1,1}\right) \cdot A \cdot \theta_{\Sigma h}$$

$$E_{1,1} = (0{,}355 - 0{,}229) \cdot 10 \cdot 80000 = 100291\ Wh \approx 100\ kWh$$

Appendix 2b: Façade construction 1

Thermal calculations for retrofitting 2

Thermal transmittance method

First the thermal resistance for the wooden segment and the mineral wool segment is calculated:

$$R_{wood} = R_{se} + R_{concrete} + R_{cellular\ plastic} + R_{concrete} + R_{mineral\ wool} + R_{wood} + R_{gypsum} + R_{si}$$

$$R_{wood} = R_{se} + \frac{d_{concrete,60}}{\lambda_{concrete}} + \frac{d_{cellular\ plastic,100}}{\lambda_{cellular\ plastic}} + \frac{d_{concrete,120}}{\lambda_{concrete}} + \frac{d_{mineral\ wool,15}}{\lambda_{mineral\ wool}} + \frac{d_{wood,70}}{\lambda_{wood}} + \frac{d_{gypsum,26}}{\lambda_{gypsum}} + R_{si}$$

$$R_{wood} = 0{,}04 + \frac{60 \cdot 10^{-3}}{1{,}2} + \frac{100 \cdot 10^{-3}}{0{,}04} + \frac{120 \cdot 10^{-3}}{1{,}2} + \frac{15 \cdot 10^{-3}}{0{,}037} + \frac{70 \cdot 10^{-3}}{0{,}14} + \frac{26 \cdot 10^{-3}}{0{,}22} + 0{,}13 = 3{,}844\ m^2 \cdot K/W$$

$$R_{mineral\ wool} = R_{se} + \frac{d_{concrete,60}}{\lambda_{concrete}} + \frac{d_{cellular\ plastic,100}}{\lambda_{cellular\ plastic}} + \frac{d_{concrete,120}}{\lambda_{concrete}} + \frac{d_{mineral\ wool,85}}{\lambda_{mineral\ wool}} + \frac{d_{gypsum,26}}{\lambda_{gypsum}} + R_{si}$$

$$R_{mineral\ wool} = 0{,}04 + \frac{60 \cdot 10^{-3}}{1{,}2} + \frac{100 \cdot 10^{-3}}{0{,}04} + \frac{120 \cdot 10^{-3}}{1{,}2} + \frac{60 \cdot 10^{-3}}{0{,}037} + \frac{13 \cdot 10^{-3}}{0{,}22} + 0{,}13 = 5{,}235\ m^2 \cdot K/W$$

After that the area for the wood segment and for the mineral wool segment is calculated:

$$A_{wood} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

$$A_{mineral\ wool} = \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

And finally the segment partitions are weighted in with the thermal resistances:

$$R_{1,2,U} = A_{wood} \cdot R_{wood} + A_{mineral\ wool} \cdot R_{mineral\ wool}$$

$$R_{1,2,U} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 3{,}844 + \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 5{,}235 = 5{,}131\ m^2 \cdot K/W$$

$$U_{1,2,U} = \frac{1}{R_{1,2,U}} = \frac{1}{5{,}131} = 0{,}195\ W/m^2 \cdot K$$

Thermal conductivity method

First the percentage of wood versus mineral wool is calculated and then used to determine a combined thermal conductivity for the layer with both wooden studs and mineral wool:

$$a_{wood} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

$$a_{mineral\,wool} = \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

$$\lambda_{wood+mineral\,wool} = \alpha_{wood} \cdot \lambda_{wood} + \alpha_{mineral\,wool} \cdot \lambda_{mineral\,wool}$$

$$\lambda_{wood+mineral\,wool} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 0{,}14 + \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 0{,}037 = 0{,}045\ W/m \cdot K$$

When the thermal conductivity for the combined layer is calculated, the total thermal resistance can be calculated:

$$R_{1,2,\lambda} = \frac{d_{concrete,60}}{\lambda_{concrete}} + \frac{d_{cellular\,plastic,100}}{\lambda_{cellular\,plastic}} + \frac{d_{concrete,120}}{\lambda_{concrete}} + \frac{d_{mineral\,wool,15}}{\lambda_{mineral\,wool}} + \frac{d_{wood+mineral\,wool,70}}{\lambda_{wood+minearl\,wool}} + \frac{d_{gypsum,26}}{\lambda_{gypsum}}$$

$$R_{1,2,\lambda} = \frac{60 \cdot 10^{-3}}{1{,}2} + \frac{100 \cdot 10^{-3}}{0{,}04} + \frac{120 \cdot 10^{-3}}{1{,}2} + \frac{15 \cdot 10^{-3}}{0{,}037} + \frac{70 \cdot 10^{-3}}{0{,}045} + \frac{26 \cdot 10^{-3}}{0{,}22} = 4{,}739\ m^2 \cdot K/W$$

When the thermal resistance is calculated, the thermal transmittance can be calculated:

$$U_{1,2,\lambda} = \frac{1}{R_{se} + R_{1,2,\lambda} + R_{si}} = \frac{1}{0{,}04 + 4{,}739 + 0{,}13} = 0{,}204\ W/m^2 \cdot K$$

Combined thermal transmittance

When the thermal transmittance is calculated with both methods, the combined thermal transmittance is calculated:

$$U_{1,2} = \frac{2 \cdot U_{1,2,U} \cdot U_{1,2,\lambda}}{U_{1,2,U} + U_{1,2,\lambda}} = \frac{2 \cdot 0{,}195 \cdot 0{,}204}{0{,}195 + 0{,}204} = 0{,}199\ W/m^2 \cdot K$$

Energy calculation

With the new thermal transmittance, the energy saved for an area can be calculated with the difference from the precious thermal transmittance:

$$E_{1,2} = \left(U_1 - U_{1,2}\right) \cdot A \cdot \theta_{\Sigma h}$$

$$E_{1,2} = (0{,}355 - 0{,}199) \cdot 10 \cdot 80000 = 124322\ Wh \approx 124\ kWh$$

Appendix 2c: Façade construction 2

Thermal calculations for retrofitting 1

Thermal transmittance method

First the thermal resistance for the wooden segment and the mineral wool segment is calculated:

$$R_{wood} = R_{se} + R_{AAC} + R_{concrete} + R_{mineral\ wool} + R_{wood} + R_{gypsum} + R_{si}$$

$$R_{wood} = R_{se} + \frac{d_{AAC,150}}{\lambda_{concrete}} + \frac{d_{concrete,150}}{\lambda_{cellular\ plastic}} + \frac{d_{mineral\ wool,15}}{\lambda_{mineral\ wool}} + \frac{d_{wood,45}}{\lambda_{wood}} + \frac{d_{gypsum,13}}{\lambda_{gypsum}} + R_{si}$$

$$R_{wood} = 0{,}04 + \frac{150 \cdot 10^{-3}}{0{,}2} + \frac{150 \cdot 10^{-3}}{1{,}2} + \frac{15 \cdot 10^{-3}}{0{,}037} + \frac{45 \cdot 10^{-3}}{0{,}14} + \frac{13 \cdot 10^{-3}}{0{,}22} + 0{,}13 = 1{,}831\ m^2 \cdot K/W$$

$$R_{mineral\ wool} = R_{se} + \frac{d_{AAC,150}}{\lambda_{concrete}} + \frac{d_{concrete,150}}{\lambda_{cellular\ plastic}} + \frac{d_{mineral\ wool,60}}{\lambda_{mineral\ wool}} + \frac{d_{gypsum,13}}{\lambda_{gypsum}} + R_{si}$$

$$R_{mineral\ wool} = 0{,}04 + \frac{150 \cdot 10^{-3}}{0{,}2} + \frac{150 \cdot 10^{-3}}{1{,}2} + \frac{60 \cdot 10^{-3}}{0{,}037} + \frac{13 \cdot 10^{-3}}{0{,}22} + 0{,}13 = 2{,}726\ m^2 \cdot K/W$$

After that the area for the wood segment and for the mineral wool segment is calculated:

$$A_{wood} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

$$A_{mineral\ wool} = \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

And finally the segment partitions are weighted in with the thermal resistances:

$$R_{2,1,U} = A_{wood} \cdot R_{wood} + A_{mineral\ wool} \cdot R_{mineral\ wool}$$

$$R_{2,1,U} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 1{,}831 + \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 2{,}726 = 2{,}659\ m^2 \cdot K/W$$

$$U_{2,1,U} = \frac{1}{R_{2,1,U}} = \frac{1}{5{,}131} = 0{,}376\ W/m^2 \cdot K$$

Thermal conductivity method

First the percentage of wood versus mineral wool is calculated and then used to determine a combined thermal conductivity for the layer with both wooden studs and mineral wool:

$$a_{wood} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

$$a_{mineral\,wool} = \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

$$\lambda_{wood+mineral\,wool} = \alpha_{wood} \cdot \lambda_{wood} + \alpha_{mineral\,wool} \cdot \lambda_{mineral\,wool}$$

$$\lambda_{wood+mineral\,wool} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 0{,}14 + \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 0{,}037 = 0{,}045\, W/m \cdot K$$

When the thermal conductivity for the combined layer is calculated, the total thermal resistance can be calculated:

$$R_{2,1,\lambda} = \frac{d_{AAC,150}}{\lambda_{concrete}} + \frac{d_{concrete,150}}{\lambda_{cellular\,plastic}} + \frac{d_{mineral\,wool,15}}{\lambda_{mineral\,wool}} + \frac{d_{wood+mineral\,wool,45}}{\lambda_{wood+minearl\,wool}} + \frac{d_{gypsum,13}}{\lambda_{gypsum}}$$

$$R_{2,1,\lambda} = \frac{150 \cdot 10^{-3}}{0{,}2} + \frac{150 \cdot 10^{-3}}{1{,}2} + \frac{15 \cdot 10^{-3}}{0{,}037} + \frac{45 \cdot 10^{-3}}{0{,}045} + \frac{13 \cdot 10^{-3}}{0{,}22} = 2{,}346\, m^2 \cdot K/W$$

When the thermal resistance is calculated, the thermal transmittance can be calculated:

$$U_{2,1,\lambda} = \frac{1}{R_{se} + R_{2,1,\lambda} + R_{si}} = \frac{1}{0{,}04 + 2{,}346 + 0{,}13} = 0{,}398\, W/m^2 \cdot K$$

Combined thermal transmittance

When the thermal transmittance is calculated with both methods, the combined thermal transmittance is calculated:

$$U_{2,1} = \frac{2 \cdot U_{2,1,U} \cdot U_{2,1,\lambda}}{U_{2,1,U} + U_{2,1,\lambda}} = \frac{2 \cdot 0{,}376 \cdot 0{,}398}{0{,}376 + 0{,}398} = 0{,}387\, W/m^2 \cdot K$$

Energy calculation

With the new thermal transmittance, the energy saved for an area can be calculated with the difference from the precious thermal transmittance:

$$E_{2,1} = \left(U_2 - U_{2,1}\right) \cdot A \cdot \theta_{\Sigma h}$$

$$E_{2,1} = (0{,}957 - 0{,}387) \cdot 10 \cdot 80000 = 456327\, Wh \approx 456\, kWh$$

Appendix 2d: Façade construction 2

Thermal calculations for retrofitting 2

Thermal transmittance method

First the thermal resistance for the wooden segment and the mineral wool segment is calculated:

$$R_{wood} = R_{se} + R_{AAC} + R_{concrete} + R_{mineral\ wool} + R_{wood} + R_{gypsum} + R_{si}$$

$$R_{wood} = R_{se} + \frac{d_{AAC,150}}{\lambda_{concrete}} + \frac{d_{concrete,150}}{\lambda_{cellular\ plastic}} + \frac{d_{mineral\ wool,15}}{\lambda_{mineral\ wool}} + \frac{d_{wood,70}}{\lambda_{wood}} + \frac{d_{gypsum,26}}{\lambda_{gypsum}} + R_{si}$$

$$R_{wood} = 0{,}04 + \frac{150 \cdot 10^{-3}}{0{,}2} + \frac{150 \cdot 10^{-3}}{1{,}2} + \frac{15 \cdot 10^{-3}}{0{,}037} + \frac{70 \cdot 10^{-3}}{0{,}14} + \frac{26 \cdot 10^{-3}}{0{,}22} + 0{,}13 = 2{,}069\ m^2 \cdot K/W$$

$$R_{mineral\ wool} = R_{se} + \frac{d_{AAC,150}}{\lambda_{concrete}} + \frac{d_{concrete,150}}{\lambda_{cellular\ plastic}} + \frac{d_{mineral\ wool,85}}{\lambda_{mineral\ wool}} + \frac{d_{gypsum,26}}{\lambda_{gypsum}} + R_{si}$$

$$R_{mineral\ wool} = 0{,}04 + \frac{150 \cdot 10^{-3}}{0{,}2} + \frac{150 \cdot 10^{-3}}{1{,}2} + \frac{85 \cdot 10^{-3}}{0{,}037} + \frac{26 \cdot 10^{-3}}{0{,}22} + 0{,}13 = 3{,}460\ m^2 \cdot K/W$$

After that the area for the wood segment and for the mineral wool segment is calculated:

$$A_{wood} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

$$A_{mineral\ wool} = \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

And finally the segment partitions are weighted in with the thermal resistances:

$$R_{2,2,U} = A_{wood} \cdot R_{wood} + A_{mineral\ wool} \cdot R_{mineral\ wool}$$

$$R_{2,2,U} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 2{,}069 + \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 3{,}460 = 3{,}356\ m^2 \cdot K/W$$

$$U_{221,U} = \frac{1}{R_{2,2,U}} = \frac{1}{3{,}356} = 0{,}298\ W/m^2 \cdot K$$

Thermal conductivity method

First the percentage of wood versus mineral wool is calculated and then used to determine a combined thermal conductivity for the layer with both wooden studs and mineral wool:

$$a_{wood} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

$$a_{mineral\,wool} = \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

$$\lambda_{wood+mineral\,wool} = \alpha_{wood} \cdot \lambda_{wood} + \alpha_{mineral\,wool} \cdot \lambda_{mineral\,wool}$$

$$\lambda_{wood+mineral\,wool} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 0{,}14 + \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 0{,}037 = 0{,}045\; W/m \cdot K$$

When the thermal conductivity for the combined layer is calculated, the total thermal resistance can be calculated:

$$R_{2,2,\lambda} = \frac{d_{AAC,150}}{\lambda_{concrete}} + \frac{d_{concrete,150}}{\lambda_{cellular\,plastic}} + \frac{d_{mineral\,wool,15}}{\lambda_{mineral\,wool}} + \frac{d_{wood+mineral\,wool,70}}{\lambda_{wood+minearl\,wool}} + \frac{d_{gypsum,26}}{\lambda_{gypsum}}$$

$$R_{2,2,\lambda} = \frac{150 \cdot 10^{-3}}{0{,}2} + \frac{150 \cdot 10^{-3}}{1{,}2} + \frac{15 \cdot 10^{-3}}{0{,}037} + \frac{70 \cdot 10^{-3}}{0{,}045} + \frac{26 \cdot 10^{-3}}{0{,}22} = 2{,}964\; m^2 \cdot K/W$$

When the thermal resistance is calculated, the thermal transmittance can be calculated:

$$U_{2,2,\lambda} = \frac{1}{R_{se} + R_{2,2,\lambda} + R_{si}} = \frac{1}{0{,}04 + 2{,}964 + 0{,}13} = 0{,}319\; W/m^2 \cdot K$$

Combined thermal transmittance

When the thermal transmittance is calculated with both methods, the combined thermal transmittance is calculated:

$$U_{2,2} = \frac{2 \cdot U_{2,2,U} \cdot U_{2,2,\lambda}}{U_{2,2,U} + U_{2,2,\lambda}} = \frac{2 \cdot 0{,}298 \cdot 0{,}319}{0{,}298 + 0{,}319} = 0{,}308\; W/m^2 \cdot K$$

Energy calculation

With the new thermal transmittance, the energy saved for an area can be calculated with the difference from the precious thermal transmittance:

$$E_{2,1} = \left(U_2 - U_{2,1}\right) \cdot A \cdot \theta_{\Sigma h}$$

$$E_{2,1} = (0{,}957 - 0{,}308) \cdot 10 \cdot 80000 = 519009\; Wh \approx 519\; kWh$$

Appendix 2e: Façade construction 3

Thermal calculations for retrofitting on inside

Thermal transmittance method

First the thermal resistance for all the segments are calculated:

$$R_{wood+wood} = R_{se} + R_{internit} + R_{wood} + R_{gypsum} + R_{si}$$

$$R_{wood+wood} = R_{se} + \frac{d_{internit,9}}{\lambda_{internit}} + \frac{d_{wood,120}}{\lambda_{wood}} + \frac{d_{wood,45}}{\lambda_{wood}} + \frac{d_{gypsum,26}}{\lambda_{gypsum}} + R_{si}$$

$$R_{wood+wood} = 0{,}04 + \frac{9 \cdot 10^{-3}}{0{,}60} + \frac{120 \cdot 10^{-3}}{0{,}14} + \frac{45 \cdot 10^{-3}}{0{,}14} + \frac{26 \cdot 10^{-3}}{0{,}22} + 0{,}13 = 1{,}482\ m^2 \cdot K/W$$

$$R_{MW+wood} = R_{se} + R_{internit} + R_{MW} + R_{wood} + R_{gypsum} + R_{si}$$

$$R_{MW+wood} = R_{se} + \frac{d_{internit,9}}{\lambda_{internit}} + \frac{d_{MW,120}}{\lambda_{MW}} + \frac{d_{wood,45}}{\lambda_{wood}} + \frac{d_{gypsum,13}}{\lambda_{gypsum}} + R_{si}$$

$$R_{MW+wood} = 0{,}04 + \frac{9 \cdot 10^{-3}}{0{,}60} + \frac{120 \cdot 10^{-3}}{0{,}037} + \frac{45 \cdot 10^{-3}}{0{,}14} + \frac{26 \cdot 10^{-3}}{0{,}22} + 0{,}13 = 3{,}868\ m^2 \cdot K/W$$

$$R_{wood+MW} = R_{se} + R_{internit} + R_{wood} + R_{MW} + R_{gypsum} + R_{si}$$

$$R_{wood+MW} = R_{se} + \frac{d_{internit,9}}{\lambda_{internit}} + \frac{d_{wood,120}}{\lambda_{wood}} + \frac{d_{MW,45}}{\lambda_{MW}} + \frac{d_{gypsum,13}}{\lambda_{gypsum}} + R_{si}$$

$$R_{wood+MW} = 0{,}04 + \frac{9 \cdot 10^{-3}}{0{,}60} + \frac{120 \cdot 10^{-3}}{0{,}14} + \frac{45 \cdot 10^{-3}}{0{,}037} + \frac{26 \cdot 10^{-3}}{0{,}22} + 0{,}13 = 2{,}377\ m^2 \cdot K/W$$

$$R_{MW+MW} = R_{se} + R_{internit} + R_{mineral\ wool} + R_{mineral\ wool} + R_{gypsum} + R_{si}$$

$$R_{MW+MW} = R_{se} + \frac{d_{internit,9}}{\lambda_{internit}} + \frac{d_{MW,120}}{\lambda_{MW}} + \frac{d_{MW,45}}{\lambda_{MW}} + \frac{d_{gypsum,13}}{\lambda_{gypsum}} + R_{si}$$

$$R_{MW+MW} = 0{,}04 + \frac{9 \cdot 10^{-3}}{0{,}60} + \frac{120 \cdot 10^{-3}}{0{,}037} + \frac{45 \cdot 10^{-3}}{0{,}037} + \frac{26 \cdot 10^{-3}}{0{,}22} + 0{,}13 = 4{,}763\ m^2 \cdot K/W$$

After that the area for the segments are calculated:

$$A_{wood+wood} = (45 \cdot 10^{-3})^2 \cdot 4$$

$$A_{MW+wood} = 2 \cdot 45 \cdot 10^{-3} \cdot (1 - 45 \cdot 10^{-3} - 45 \cdot 10^{-3})$$

$$A_{wood+MW} = 2 \cdot 45 \cdot 10^{-3} \cdot (1 - 45 \cdot 10^{-3} - 45 \cdot 10^{-3})$$

$$A_{MW+MW} = (1 - 45 \cdot 10^{-3} - 45 \cdot 10^{-3})^2$$

And finally the segment partitions are weighted in with the thermal resistances:

$$R_{3,i,U} = A_{wood+wood} \cdot R_{wood+wood} + A_{MW+wood} \cdot R_{MW+wood} + A_{wood+MW} \cdot R_{wood+MW} + A_{MW+MW} \cdot R_{MW+MW}$$

$$R_{3,i,U} = (45 \cdot 10^{-3})^2 \cdot 4 \cdot 1{,}482 + 2 \cdot 45 \cdot 10^{-3} \cdot (1 - 45 \cdot 10^{-3} - 45 \cdot 10^{-3}) \cdot 3{,}868 + 2 \cdot 45 \cdot 10^{-3} \cdot (1 - 45 \cdot 10^{-3} - 45 \cdot 10^{-3}) \cdot 2{,}377 + (1 - 45 \cdot 10^{-3} - 45 \cdot 10^{-3})^2 \cdot 4{,}763 = 4{,}467\ m^2 \cdot K/W$$

$$U_{3,i,U} = \frac{1}{R_{3,U}} = \frac{1}{4{,}467} = 0{,}224\ W/m^2 \cdot K$$

Thermal conductivity method

First the percentage of wood versus mineral wool is calculated and then used to determine a combined thermal conductivity for the layer with both wooden studs and mineral wool:

$$a_{wood} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

$$a_{mineral\ wool} = \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

$$\lambda_{wood+mineral\ wool} = \alpha_{wood} \cdot \lambda_{wood} + \alpha_{mineral\ wool} \cdot \lambda_{mineral\ wool}$$

$$\lambda_{wood+mineral\ wool} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 0{,}14 + \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 0{,}037 = 0{,}045\ W/m \cdot K$$

When the thermal conductivity for the combined layer is calculated, the total thermal resistance can be calculated:

$$R_{3,i,\lambda} = \frac{d_{internit,9}}{\lambda_{internit}} + \frac{d_{minearl\ wool+wood,120}}{\lambda_{mineral\ wool+wood}} + \frac{d_{wood+mineral\ wool,45}}{\lambda_{wood+mineral\ wool}} + \frac{d_{gypsum,26}}{\lambda_{gypsum}}$$

$$R_{3,i,\lambda} = \frac{9 \cdot 10^{-3}}{0{,}60} + \frac{120 \cdot 10^{-3}}{0{,}045} + \frac{45 \cdot 10^{-3}}{0{,}045} + \frac{26 \cdot 10^{-3}}{0{,}22} = 3{,}822\ m^2 \cdot K/W$$

When the thermal resistance is calculated, the thermal transmittance can be calculated:

$$U_{3,i,\lambda} = \frac{1}{R_{se} + R_{3,\lambda} + R_{si}} = \frac{1}{0{,}04 + 3{,}822 + 0{,}13} = 0{,}250\ W/m^2 \cdot K$$

Combined thermal transmittance

When the thermal transmittance is calculated with both methods, the combined thermal transmittance is calculated:

$$U_{3,i} = \frac{2 \cdot U_{3,i,U} \cdot U_{3,i,\lambda}}{U_{3,i,U} + U_{3,i,\lambda}}$$

$$U_{3.i} = \frac{2 \cdot 0{,}224 \cdot 0{,}250}{0{,}224 + 0{,}250} = 0{,}236\ W/m^2 \cdot K$$

Energy calculation

With the new thermal transmittance, the energy saved for an area can be calculated with the difference from the precious thermal transmittance:

$$E_{3,i} = \left(U_3 - U_{3,i}\right) \cdot A \cdot \theta_{\Sigma h}$$

$$E_{3,i} = (0{,}321 - 0{,}236) \cdot 10 \cdot 80000 = 67463\ Wh \approx 67\ kWh$$

Appendix 2e: Façade construction 3

Thermal calculations for retrofitting on outside

Thermal transmittance method

First the thermal resistance for all the segments are calculated:

$$R_{wood+wood} = R_{se} + R_{gypsum} + R_{wood} + R_{gypsum} + R_{si}$$

$$R_{wood+wood} = R_{se} + \frac{d_{gypsum,9}}{\lambda_{gypsum}} + \frac{d_{wood,45}}{\lambda_{wood}} + \frac{d_{wood,120}}{\lambda_{wood}} + \frac{d_{gypsum,13}}{\lambda_{gypsum}} + R_{si}$$

$$R_{wood+wood} = 0{,}04 + \frac{15 \cdot 10^{-3}}{0{,}22} + \frac{45 \cdot 10^{-3}}{0{,}14} + \frac{120 \cdot 10^{-3}}{0{,}14} + \frac{13 \cdot 10^{-3}}{0{,}22} + 0{,}13 = 1{,}476\ m^2 \cdot K/W$$

$$R_{MW+wood} = R_{se} + R_{gypsum} + R_{MW} + R_{wood} + R_{gypsum} + R_{si}$$

$$R_{MW+wood} = R_{se} + \frac{d_{gypsum,15}}{\lambda_{gypsum}} + \frac{d_{MU,45}}{\lambda_{MU}} + \frac{d_{wood,120}}{\lambda_{wood}} + \frac{d_{gypsum,13}}{\lambda_{gypsum}} + R_{si}$$

$$R_{MW+wood} = 0{,}04 + \frac{15 \cdot 10^{-3}}{0{,}22} + \frac{45 \cdot 10^{-3}}{0{,}037} + \frac{120 \cdot 10^{-3}}{0{,}14} + \frac{13 \cdot 10^{-3}}{0{,}22} + 0{,}13 = 2{,}371\ m^2 \cdot K/W$$

$$R_{wood+MW} = R_{se} + R_{gypsum} + R_{wood} + R_{MW} + R_{gypsum} + R_{si}$$

$$R_{wood+MW} = R_{se} + \frac{d_{gypsum,15}}{\lambda_{gypsum}} + \frac{d_{wood,45}}{\lambda_{wood}} + \frac{d_{MW,120}}{\lambda_{MW}} + \frac{d_{gypsum,13}}{\lambda_{gypsum}} + R_{si}$$

$$R_{wood+MW} = 0{,}04 + \frac{15 \cdot 10^{-3}}{0{,}22} + \frac{45 \cdot 10^{-3}}{0{,}14} + \frac{120 \cdot 10^{-3}}{0{,}037} + \frac{13 \cdot 10^{-3}}{0{,}22} + 0{,}13 = 3{,}862\ m^2 \cdot K/W$$

$$R_{MW+MW} = R_{se} + R_{gypsum} + R_{MW} + R_{MW} + R_{gypsum} + R_{si}$$

$$R_{MW+MW} = R_{se} + \frac{d_{gypsum,15}}{\lambda_{gypsum}} + \frac{d_{MW,45}}{\lambda_{MW}} + \frac{d_{MW,120}}{\lambda_{MW}} + \frac{d_{gypsum,13}}{\lambda_{gypsum}} + R_{si}$$

$$R_{MW+MW} = 0{,}04 + \frac{15 \cdot 10^{-3}}{0{,}22} + \frac{45 \cdot 10^{-3}}{0{,}037} + \frac{120 \cdot 10^{-3}}{0{,}037} + \frac{13 \cdot 10^{-3}}{0{,}22} + 0{,}13 = 4{,}757\ m^2 \cdot K/W$$

After that the area for the segments are calculated:

$$A_{wood+wood} = (45 \cdot 10^{-3})^2 \cdot 4$$

$$A_{MW+wood} = 2 \cdot 45 \cdot 10^{-3} \cdot (1 - 45 \cdot 10^{-3} - 45 \cdot 10^{-3})$$

$$A_{wood+MW} = 2 \cdot 45 \cdot 10^{-3} \cdot (1 - 45 \cdot 10^{-3} - 45 \cdot 10^{-3})$$

$$A_{MW+MW} = (1 - 45 \cdot 10^{-3} - 45 \cdot 10^{-3})^2$$

And finally the segment partitions are weighted in with the thermal resistances:

$$R_{3,o,U} = A_{wood+wood} \cdot R_{wood+wood} + A_{MW+wood} \cdot R_{MW+wood} + A_{wood+MW} \cdot R_{wood+MW} + A_{MW+MW} \cdot R_{MW+MW}$$

$$R_{3,o,U} = (45 \cdot 10^{-3})^2 \cdot 4 \cdot 1{,}476 + 2 \cdot 45 \cdot 10^{-3} \cdot (1 - 45 \cdot 10^{-3} - 45 \cdot 10^{-3}) \cdot 2{,}371 + 2 \cdot 45 \cdot 10^{-3} \cdot (1 - 45 \cdot 10^{-3} - 45 \cdot 10^{-3}) \cdot 3{,}862 + (1 - 45 \cdot 10^{-3} - 45 \cdot 10^{-3})^2 \cdot 4{,}757 = 4{,}461\ m^2 \cdot K/W$$

$$U_{3,o,U} = \frac{1}{R_{3,U}} = \frac{1}{4{,}461} = 0{,}224\ W/m^2 \cdot K$$

Thermal conductivity method

First the percentage of wood versus mineral wool is calculated and then used to determine a combined thermal conductivity for the layer with both wooden studs and mineral wool:

$$a_{wood} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

$$a_{mineral\ wool} = \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}}$$

$$\lambda_{wood+mineral\ wool} = \alpha_{wood} \cdot \lambda_{wood} + \alpha_{mineral\ wool} \cdot \lambda_{mineral\ wool}$$

$$\lambda_{wood+mineral\ wool} = \frac{45 \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 0{,}14 + \frac{(600 - 45) \cdot 10^{-3}}{600 \cdot 10^{-3}} \cdot 0{,}037 = 0{,}045\ W/m \cdot K$$

When the thermal conductivity for the combined layer is calculated, the total thermal resistance can be calculated:

$$R_{3,o,\lambda} = \frac{d_{gypsum,15}}{\lambda_{gypsum}} + \frac{d_{minearl\ wool+wood,45}}{\lambda_{mineral\ wool+wood}} + \frac{d_{wood+mineral\ wool,120}}{\lambda_{wood+mineral\ wool}} + \frac{d_{gypsum,13}}{\lambda_{gypsum}}$$

$$R_{3,o,\lambda} = \frac{15 \cdot 10^{-3}}{0{,}22} + \frac{45 \cdot 10^{-3}}{0{,}045} + \frac{120 \cdot 10^{-3}}{0{,}045} + \frac{13 \cdot 10^{-3}}{0{,}22} = 3{,}816\ m^2 \cdot K/W$$

When the thermal resistance is calculated, the thermal transmittance can be calculated:

$$U_{3,o,\lambda} = \frac{1}{R_{se} + R_{3,\lambda} + R_{si}} = \frac{1}{0{,}04 + 3{,}816 + 0{,}13} = 0{,}251\ W/m^2 \cdot K$$

Combined thermal transmittance

When the thermal transmittance is calculated with both methods, the combined thermal transmittance is calculated:

$$U_{3,o} = \frac{2 \cdot U_{3,o,U} \cdot U_{3,o,\lambda}}{U_{3,o,U} + U_{3,o,\lambda}}$$

$$U_{3,o} = \frac{2 \cdot 0{,}224 \cdot 0{,}251}{0{,}224 + 0{,}251} = 0{,}239\ W/m^2 \cdot K$$

Energy calculation

With the new thermal transmittance, the energy saved for an area can be calculated with the difference from the precious thermal transmittance:

$$E_{3,o} = \left(U_3 - U_{3,o}\right) \cdot A \cdot \theta_{\Sigma h}$$

$$E_{3,o} = (0{,}321 - 0{,}239) \cdot 10 \cdot 80000 = 65657\ Wh \approx 66\ kWh$$