DEGREE PROJECT

Creative development of lightweight façade constructions in modular housing

The struggle to shut out the noise of the world

Johan Albihn

Industrial Design Engineering, master's level
2022

Luleå University of Technology
Department of Social Sciences, Technology and Arts

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MSc in INDUSTRIAL DESIGN ENGINEERING
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Acknowledgement

When reading through other students work for inspiration, I came across an acknowledgement starting with the words

> *"Much like sound, this thesis project did not—and could not have—come about in a vacuum".*
>
> \- *Anton Nordmark, 2019*

Now I'm angry that I didn't come up with it first.

Writing a master thesis, or studying at all, while working normal business hours is not something that I would recommend. I am also aware of the fact that I am better at giving advice than following it myself, which has led to a rather humble disposition towards the people who has helped me along the way. I therefore extend my heartfelt thanks…

… to Roger, who sparked the idea and made me follow through.

… to Jörgen, who with an impressive patience helped me with the really hard parts.

… to the acousticians of Tyréns who, like Baloo, taught - and still teaches me – almost everything they know. It would not have been the same thing to try and write this report without five years of trial and error to back it up.

… to Viktor, who got his diploma first and became an inspiration.

… to Maja, who always believes in me.

Without these brave souls, this master thesis project would still be left in a vacuum.

Finally, I'm going to go against the most ancient of Swedish customs, and thank me, myself, and I. For not giving up, though it was pretty near a couple of times. Now I'm going to go write something fun instead. Like poetry. Or an instruction manual for zip lock bags.

Johan Albihn
Luleå, May 2022

Abstract

Modular construction of housing is an industry on the rise. The prefabrication of construction modules gives a greater control over material consumption, promotes standardization, and lessens the disturbance during the construction time in the field.

Lindbäcks Bygg AB prefabricates housing modules in their factory at Haraholmen, Piteå. The modules are then transported to construction sites all over the country and assembled. Lindbäcks Bygg AB has made the design choice to focus on lightweight wooden constructions for their modules, which comes with its own set of challenges.

The urban densification of our city regions has led to more and more residential building being planned and constructed in areas that are submitted to high noise levels from surrounding traffic. This puts a great strain on the sound reduction of the building's façade wall construction, something that has proven to be a problem with lightweight wooden walls.

The aim of this master thesis project has been to test different solutions for lightweight façade wall constructions, and to ultimately find one or more solution that meet the requirements of the Swedish standards and regulations, as well as the needs of the tenants, and that can be implemented by Lindbäcks Bygg AB for manufacturing and assembly.

The project has therefore been carried out in two parts, one theoretical and one practical. The theoretical part has verified the problem with traffic noise levels in residential buildings and identified the critical areas of the current façade construction. The theoretical work led to a list of defining factors for the sound reduction, which in turn worked as a basis for the ideation process.

As a result, the theoretical part led to a number of different construction concepts for façade walls. The concepts were first tested theoretically through modelling and calculation, and verified with the acousticians at Tyréns Sverige AB and the engineers of Lindbäcks Bygg AB. The most promising concepts were sent on to be manufactured.

The practical part of this master thesis project was carried out mainly as acoustical measurements and the subsequent analysis, where the manufactured façade wall constructions were mounted on a free-standing module.

The result of the practical part, and of the master thesis project, were four different façade wall constructions that met the requirements for noise reduction, which were presented to Lindbäcks Bygg AB and Tyréns Sverige AB. The construction most easily implemented is a construction with an airgap between the wall panels, and this construction will now have to be structurally verified and adapted for the factory, before being utilized in future building projects.

KEYWORDS: *Acoustical engineering, façade wall construction, modular housing, traffic noise reduction, lightweight construction, industrial design engineering*

Sammanfattning

Modulärt byggande av bostäder är en bransch på frammarsch. Prefabricering av byggnadsmoduler ger en större kontroll över materialåtgången, främjar standardisering och minskar störningarna under byggtiden i fält.

Lindbäcks Bygg AB prefabricerar bostadsmoduler i sin fabrik på Haraholmen, Piteå. Modulerna transporteras sedan till byggarbetsplatser över hela landet och monteras till bostadskomplex. Lindbäcks Bygg AB har gjort designvalet att fokusera på lätta träkonstruktioner för sina moduler, vilket kommer med sin egen uppsättning utmaningar.

Förtätningen av våra stadsregioner har lett till att allt mer bostadsbyggande planeras och uppförs i områden som utsätts för höga bullernivåer från omgivande trafik. Detta utsätter byggnadens fasadväggskonstruktion för en stor akustisk belastning, något som har visat sig vara ett problem med lätta träväggar.

Syftet med detta examensarbete har varit att testa olika lösningar för lätta fasadväggskonstruktioner, och att i slutändan hitta en eller flera lösningar som uppfyller kraven i svenska standarder och föreskrifter samt hyresgästernas behov, och som kan implementeras av Lindbäcks Bygg AB för tillverkning och montering.

Projektet har därför genomförts i två delar, en teoretisk och en praktisk.

Den teoretiska delen har verifierat problemet med trafikbullernivåer i bostadshus och identifierat kritiska områden i den nuvarande fasadkonstruktionen. Det teoretiska arbetet ledde fram till en lista med kritiska faktorer för ljudreduktionen, som i sin tur fungerade som grund för designprocessen.

Som ett resultat ledde den teoretiska delen till en rad olika konstruktionskoncept för fasadväggar. Koncepten testades först teoretiskt genom modellering och beräkning, och verifierades av akustikerna på Tyréns Sverige AB och ingenjörerna på Lindbäcks Bygg AB. De mest lovande koncepten skickades vidare för tillverkning.

Den praktiska delen av detta examensarbete genomfördes främst som akustiska mätningar och efterföljande analys, där de tillverkade fasadväggkonstruktionerna monterades på en fristående modul.

Resultatet av den praktiska delen, och av examensarbetet, blev fyra olika fasadväggskonstruktioner som uppfyller kraven för ljudreduktion, vilka presenterades för Lindbäcks Bygg AB och Tyréns Sverige AB. Den konstruktion som är enklast att implementera är en konstruktion med luftspalt mellan väggpanelerna, och denna konstruktion kommer nu att behöva verifieras med avseende på ex. hållfasthet och anpassas för fabriken, innan den kan användas i framtida byggprojekt.

NYCKELORD: *Akustik, fasadväggkonstruktion, modulhus, reducering av trafikbuller, lättviktskonstruktion, teknisk design*

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1. Introduction

This is a master thesis project in Industrial design engineering at Luleå University of Technology, performed during the spring of 2022 as a part of a master's degree in Industrial design engineering with focus on Sound Design. It has been carried out in association with the Acoustic Department North of Tyréns Sverige AB and Lindbäcks Bygg AB.

The project deal with sound insulation in the façade construction of prefabricated building modules used for housing projects. The goal is to design a lightweight façade construction that satisfy the need for noise insulation even in areas with a dense traffic situation and high external noise levels.

1.1. BACKGROUND

Lindbäcks Bygg AB makes prefabricated wooden building modules in their factories in Piteå. The modules are transported to the building site and assembled. This procedure allows for lesser disturbances during the construction time, lesser risks of building defects due to the standardized modules and a smaller climate footprint thanks to a greater control over the use of building materials.

The façade construction is mostly fabricated along with the rest of the module in the factory. The construction however differs from the other walls of the module, as the acoustical load on the façade wall differs from that of the partitions between apartments or to corridors. The wall construction would also have to handle other types of loads, i.e. wind, that the inner walls won't need to cope with. The outermost layer is often a weather-proofed gypsum board, on which the surface layer, for example a wood panel or façade boards, is fastened.

The urban densification of primarily the larger city regions has led to more residential building being constructed in areas with high noise levels from road- and rail traffic. This has in turn led to new challenges in the fabrication of façade constructions in order to meet the requirements of *"Boverket's building regulations – mandatory provisions and general recommendations"* (BBR) and Swedish Standard SS25267:2015 *"Acoustics – Sound classification of spaces in buildings – Dwellings"*. These requirements are closely connected to *"General advice on indoor noise"* released in 2014 by the Public Health Agency of Sweden, developed to limit the negative impact on public health due to external noise.

The table below details the requirements set for the Sound Classes A to D in the Swedish Standard and Boverkets Building Regulations, where BBR corresponds to Sound Class C.

Table 1. Requirements regarding noise levels from traffic and other external sources, for sound class A to D (SS25267:2015 and BBR).

[dBA]	A	B	C (BBR)	D
Equivalent, $L_{A,eq}$	22	26	30	30
Maximum $L_{A,Fmax}$	37	41	45	45

Equivalent noise level means the averaged level over the 24 hours of the day. The maximum level is the peak levels that can be expected during the same day.

The requirements set in the standards are for the resulting indoor noise. This is however dependent on not only the sound insulation of the façade construction, but also the noise level outside the building. The traffic noise regulation (SFS 2015:216), determined by the Swedish Government in 2015, sets limits on the equivalent and maximum noise level of the areas where residential building is allowed to be constructed. In 2017 these levels were raised in order to allow for a higher densification of the urban areas, further increasing the importance of the façade construction.

More and more housing is built using wood or other lightweight construction materials. The alternative is appealing as it allows for shorter construction times and because the building materials are easier to handle in many ways. The new Environmental Certifications such as *"Miljöbyggnad"* or BREEAM are also easier to achieve with a lightweight construction, as wood and gypsum is considered more environmentally friendly than steel and concrete.

Buildings made of wood have a disadvantage though, compared to traditional concrete constructions. The lesser weight and inhomogeneous construction of the wood constructions have a harder time blocking out noise, especially in the lower frequencies, and the risk of acoustical weak spots due to the assembly are greater. This causes problems for Lindbäcks Bygg AB when trying to achieve sound class B for houses situated in highly trafficked areas and sets the stage for the focus of this master thesis project; to find a lightweight façade construction that meets the requirements for sound class B in buildings situated in areas with high traffic noise.

1.2. STAKEHOLDERS

The most obvious stakeholder of this project is Lindbäcks Bygg AB, who will be able to use the new facade construction in upcoming housing projects and hopefully achieve sound class B regarding noise from traffic and other external sources.

By achieving sound class B, future tenants will be directly affected. Better sound insulation means less disturbances from traffic and other external sources, and a better sound environment has proven to greatly benefit people in regards of better sleep and reduced stress, leading to better health overall.

By extension this will allow Lindbäcks Bygg AB to build a greater number of wood-based apartment buildings in densely populated areas, which will benefit the climate in the long run by reducing the amount of concrete used. The use of prefabricated modules in housing projects also increase control of building materials used, reducing waste, and decrease disturbance for people living in the vicinity due to shorter construction time on site.

Tyréns Sverige AB, Acoustic Department North, benefits greatly from this master thesis project as well. Not only does the result give valuable insight into the workings of façade constructions in the modules of Lindbäcks Bygg AB, but it also gives answers to acoustical questions that will help in future dimensioning and validation of buildings, both modular and traditionally built.

1.3. OBJECTIVE AND AIMS

The objective of the project has been to raise the quality of the acoustic environment for the tenants in modular apartments built by Lindbäcks Bygg AB. This has been achieved by a close study of the theory behind lightweight façade systems, Lindbäcks modular constructions and the documented effects of traffic noise on public health.

The master thesis attempts to answer the following questions:

- What impact does the sound environment have on public health and residential construction?
- What parameters affect the acoustic properties of a façade construction and what weaknesses can be identified in the constructions used today?
- How could a lightweight façade for modular housing be constructed in order to meet the requirements for sound class B in areas with heavy traffic, and therefore improve the acoustical environment for the tenants?

To achieve this, a context analysis has been conducted with focus on:

- The benefits and problems caused by the 2017 changes in the traffic noise regulation
- The impact of a better sound environment, in this case achieving sound class B, for the tenants of wooden buildings.
- The impact of reaching sound class B for Lindbäcks Bygg AB as a company
- How Lindbäcks Bygg AB has constructed their lightweight façades so far
- If the existing solutions of other companies could be adapted to fit the modules of Lindbäcks Bygg AB.

Furthermore, a literature review tries to shed more light on the subjects of:

- The theory behind traffic noise and it's calculation and measurement methods.
- The theory behind noise transmission and façade insulation
- The background of the planning and building act and the traffic noise regulation.
- Relevant research done regarding disturbances from traffic and external noise, and its subsequent health effects.
- Relevant research done regarding the experience of traffic noise in buildings made of wood versus concrete

Through testing and iterating, the goal has then ultimately been to find a façade construction that meet the requirements for traffic noise set up in the Swedish Standard, sound class B, and in accordance with the noise levels detailed in the updated version of the traffic noise regulation.

1.4. PROJECT SCOPE

The projects main focus has been the comparative sound insulation between the existing façade construction used in today's modules and the proposed and tested constructions.

The greatest boundary of the project was the production and montage time of the façade constructions that are to be tested. This has been done in close collaboration with representatives of Lindbäcks Bygg AB.

The project does not evaluate if the new noise levels set forth in the 2017 update of the traffic noise regulation are reasonable, and it does not address the validity of the calculation model for traffic noise or the measurement method of façade noise insulation. These are for greater minds to decide on.
Neither does the project dwell on evaluating lightweight constructions in general versus traditional concrete constructions but has instead focused on the constructions used by Lindbäcks Bygg AB and others with a similar business concept.

The façade of a residential building will more often than not have one or more windows in it. The impact of a window on the façade noise insulation will be touched on, but it is not evaluated in this project. It is of great import however, and Lindäcks Bygg has indicated that they want to follow up with research regarding the impact of windows on the proposed façade wall constructions later on.

Lastly, it is to be noted that the façade constructions have been tested on a free-standing building module, which is modified in order to resemble the final product as closely as possible. The project therefore does not evaluate the possible influence of the construction method in the factory or the possibility of errors or weak points in the assembly on site.

1.5. THESIS OUTLINE

Chapter 1 sets the background for the project as well as it's outline, goals and scope.
Chapter 2 deals with the context and answers the questions of where we are today regarding lightweight façade constructions and how achieving sound class B would affect the tenants, as well as gives an overview of existing solutions and identifies problem areas.
Chapter 3 gives us the theoretical groundwork regarding traffic noise, façade constructions and the background of the traffic noise regulation.
Chapter 4 describes the methods used in the project and their validity.
Chapter 5 handles the ideation phase, where gathered information is evaluated and the new façade constructions is designed, measured acoustically and improved on.
Chapter 6 features the evaluation and analysis the measurements and the subsequent discussions around the constructions, their relevance and the need for future work.

2. Context Analysis

A context analysis has been performed for this project as a part of the theoretical groundwork for the concept creation. The context analysis deals with the current state of affairs regarding traffic noise and Lindbäcks façade constructions, as well as the constructions used by others in the modular housing business.

This context analysis has focused on the following:

- The benefits and problems caused by the 2017 changes in the traffic noise regulation
- The impact of a better sound environment, in this case achieving sound class B, for the tenants of wooden buildings.
- The impact of reaching sound class B for Lindbäcks Bygg AB as a company
- How Lindbäcks Bygg AB has constructed their lightweight façades so far
- If the existing solutions of other companies could be adapted to fit the modules of Lindbäcks Bygg AB.

2.1. CURRENT STATE

Lindbäcks Bygg AB are currently constructing modular housing in a number of cities all over Sweden. The difference in, for example, climate, densification and demand makes it important to find modular constructions that satisfy most requirements, and that is easily adapted to meet the rest.

This is done, in example, with regards to insulation from traffic noise. Here Tyréns AB has been working on different constructions for the outer wall of the modules, which is either reinforced in the factory or as a part of the building assembly on site, in order to meet the requirements, set by the traffic situation of the building site.

As every project is unique it is important both for the acousticians and for Lindbäcks Bygg AB that the façade constructions perform as expected. An error can be a costly affair, and sometimes it's even more expensive to dimension "on the safe side". This becomes crucial in areas with high traffic load, and therefore high traffic noise, because this calls for constructions that hasn't been widely used yet. Much more so since the changes in the Traffic Noise Regulation, made in 2017.

Measurements are typically made when the building is completed, and acoustic measures are difficult and costly to perform. This creates a demand for verification of the constructions before putting them into production. This, in combination with the ambition to achieve sound class B in all of their residential buildings regardless of prerequisites, led Lindbäcks Bygg AB to initiate this master thesis project.

2.2. LINDBÄCKS FAÇADE CONSTRUCTIONS

Lindbäcks Bygg AB utilizes a standard façade construction for their current modules. As with all Lindbäcks constructions the frame is made from wooden laths and studs, cavities filled with mineral wool, and protected by gypsum or composite boards.

Below is detailed the standard façade construction, which is the baseline construction for the concept ideation of this project.

2x15 mm gypsum board "Protect"
0,2 PE-foil
220 mm wooden studs, distance 600 mm, mineral wool between
45 mm wooden laths, mineral wool between
9 mm Glasroc composite board

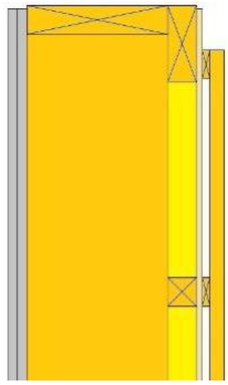


Figure 1. Standard facade wall construction used by Lindbäcks Bygg AB, here with wooden panel.

The outmost layer differs between buildings, depending on the plan and the building permit. The most common are:

- 22 mm standing wooden panel on 28 mm wooden laths
- 9 mm Cembrit façade boards on 28 mm wooden laths
- 20 mm plaster on an extra layer of 50 mm rockwool
- 87 mm brick façade on an extra layer of 50 mm rockwool

Measurements made by Tyréns AB show that that the current construction reach a sound reduction $R'_w + C_{tr}$ of about 40 dB in the field. Note that this is measurements on façades with wood panel and a window with high sound reduction installed. The façade element in itself performs slightly better.

The theoretical results of today's façade constructions can be found in table 2 below. The results are presented as change relative to the construction without the outermost layer. The façade constructions have been modelled with the use of the software Insul (ver. 8.0.9) by Marshall Day Acoustic and are presented as apparent sound reduction index (R'_w) with spectrum adaption terms.

Table 2. Theoretical results of current facade constructions, relative change to construction without the outermost layer.

[dB]	Wood	Board	Plaster	Brick
R'_w	-2	+2	+2	+11
$R'_w + C$	-3	+2	+2	+11
$R'_w + C_{tr}$	-2	+3	+3	+11
$R'_w + C_{50-3150}$	+1	+5	+7	+15
$R'_w + C_{tr50-3150}$	+5	+7	+12	+22

Table 2 show that the standard façade construction with an added wood panel is the weakest when regarding sound reduction. A façade with panel even performs worse than one without, theoretically. Sound reduction index in the field is expected to be lower than in theory.

With the 2017 changes in the Traffic Noise Regulation, the equivalent noise level at the façade could be up to 65 dBA. The maximum outside level is not regulate however, and Lindbäcks Bygg AB has encountered projects where this could go as high as 85 dBA.

Boverkets Building Regulations sets the requirements for equivalent indoor noise from traffic and other external sources to 30 dBA, maximum 45 dBA. This means a sound reduction of 40 dB minimum to meet the requirements of BBR. This leaves very little room for errors when using Lindbäcks standard façade construction with windows, based on field measurements.

For Sound class B, the requirements are tightened to an equivalent noise level indoors of 26 dBA, maximum 41 dBA. This results in a façade construction with the need to reach a sound reduction of at least 44 dB, something that is only possible right now for the standard façade construction, in theory, without a window.

For this master thesis, this means that Lindbäcks standard construction would have to be improved with at least 4 dB ($R'_w + C_{tr}$) in order to reach sound class B.

2.3. ACHIEVING SOUND CLASS B

The requirements presented in BBR is to be considered the base level regarding sound insulation in buildings. There is however a couple of reasons for Lindbäcks Bygg AB, and other similar companies, to try to achieve sound class B.

First off, sound class B means a better noise environment for the tenants. Noise levels indoors have been proven to effect general health and keeping the noise down benefits both children and adults (WHO, 1999).

This had led to a higher demand among property owners and developers for buildings that achieve sound class B. A better sound environment leads to happier tenants, which could justify higher rents, one could assume.

Finally, there is the matter of the new environmental certifications, such as *"Miljöbyggnad"* or BREEAM. Most certifications require a higher standard for many factors in a building, such as sound class B for sound. This gives companies that can build sustainable buildings that achieve sound class B an edge over the competition and becomes more attractive for future tenants.

2.4. BENCHMARKING

The traditional view on building modules is generally the construction site barracks or the temporary evacuation modules for offices in the event of renovation. The field of modular housing construction, however, is a relatively new and upcoming one.

2.4.1. Modular systems

There is currently a small number of companies that make prefabricated building modules in Sweden. This review of the market has focused on the ones manufacturing housing modules, with wooden constructions, and their façade constructions using wooden panels.

Derome (n.d) manufactures modular houses similar to Lindbäcks Bygg AB, and uses the following construction for their façade walls:

2x15 mm gypsum board
70 mm wooden studs, distance 600 mm, mineral wool between
15 mm airgap
11 mm wooden fiber board (OSB)
Plastic foil
170 mm wooden studs, distance 600 mm, mineral wool between
11 mm OSB
Wind fabric
50 mm porous façade board

Sizes (n.d) is a company who in part uses cross-laminated timber (CLT) for their module constructions. The exact dimensions and compositions of their façade walls is not open to the public at this time, however.

MOBY (n.d) builds their modules in wood but assemble them on a metal framework. This gives the house a better internal sound insulation between modules, but since the composition of their façade walls isn't open to the public, the impact of the metal frame on the sound insulation from traffic is unknown.

Moelven (n.d) constructs wooden modules for housing, as well as for example schools, offices and construction site barracks. As with the companies above, the exact composition of their constructions is not open to the public at this time.

2.4.2. Wall systems

If we look beyond the modular housing market, there are a couple of manufacturers of complete façade construction systems.

For example, **Isover** (n.d) offers two types of façade wall systems with a similar construction to the one used by Lindbäcks Bygg AB:

2x15 mm gypsum board
70 mm (alt. 45 mm) wooden studs, distance 600 mm, mineral wool between
1 mm plastic foil
195 mm (alt 175 mm) wooden studs, distance 600 mm, mineral wool between
9 mm composite board
100 mm (alt 50 mm) porous façade board
22 mm standing wooden panel on 28 mm wooden laths

Gyproc (2019) also details a couple of façade walls in their catalogue *"Gyprocs Handbok – System för lättbyggnadsteknik"*. The one constructed with wooden panel is detailed below:

12,5 mm gypsum board
Plastic foil
95-170 mm wooden studs, distance 600 mm, mineral wool between
9 mm Glasroc composite board
22 mm standing wooden panel on 38 mm wooden laths

2.4.3. Summary

It seems that the area of modular housing is a rather small and secretive part of the construction business. The conclusion that can be drawn however is that a construction with two studs of different dimensions, separated by an airgap or not, seems to be the dominating design. This seems to hold true both for modular constructions and more traditional on-site built façade walls.

Two constructions that stand out are the one with CLT in the construction, and the one with the modules mounted in a metal framework. More information, and measurement results, would be needed to verify these as valid solutions, and neither of these adhere to the historic design choices of Lindbäcks Bygg AB.

3. Theoretical concepts

In order to set a baseline for the theoretical concepts presented in this report, a literature review was performed. The literature review focused on the theory behind traffic noise calculations and measurements, the basis for the Swedish Standards and regulations, and the mathematical models used for acoustical dimensioning of lightweight façade constructions.

The literature review tries to shed more light on the subjects of:

- The theory behind traffic noise and it's calculation and measurement methods.
- The theory behind noise transmission and façade insulation
- The background of the planning and building act and the traffic noise regulation.
- Relevant research done regarding disturbances from traffic and external noise, and its subsequent health effects.
- Relevant research done regarding the experience of traffic noise in buildings made of wood versus concrete.

3.1. INDUSTRIAL DESIGN ENGINEERING

3.1.1. Industrial design

Industrial design was long seen as simply the branch of the design tree that concerns itself with products for the new industry. Products to be mass produced, and therefore need a robust, but still appealing design, easy to replicate (Industrial design, 2022-04-20). It was broadly defined as the creative processes and approaches in which a products form is determined in a large part by its mode of production (Industrial design, 2022-04-20). Industrial design has since then moved on.

The industrial designers of today have become an integral part of the product development process, concerned with the parts of the product that directly interface with the user – such as aesthetics and interfaces (Ulrich & Eppinger, 2012). The need for products and companies to stand out has prompted the design to go from an afterthought to a priority. The industrial design engineers are responsible for solving the complex problem of making a product, service or process enjoyable as well as functional (Ulrich & Eppinger, 2012).

The complexity of the problem shows itself in that a problem might not have just one solution, one final product (Wikberg Nilsson et al, 2015). Every choice leads to a different outcome, the result being no set template for the industrial design process. The process starts with the users and their needs, and the result could be something completely different than what it started out as (Wikberg Nilsson et al, 2015).

The useability and user experience should always be considered in industrial design. The ambition should be to develop products that are reliable, useful and satisfying to use (Wikberg Nilsson et al, 2015). The term human-centered design is a central part of industrial design, meaning that all design, no matter of type, should complement the users, utilize their strengths and remedy their disadvantages (Wikberg Nilsson et al, 2015).

3.1.2. Acoustic design

If the area of industrial design has gone through a transformation, it has nothing against the changes done to acoustical design and engineering. The preface of the book Designing for product sound quality (Lyon, 2000) says it quite nicely:

"Presenting a book on product design related to sound is a tricky business"

Acoustics, and sound design, is an area that has for a long time been seen as "butting in" on traditional design choices, coming in as an after-thought and upsetting the process (Lyon, 2000). It is not obvious that a product that looks good also sounds good. A nice material can creak, a machine would need extensive lubrication not to squeak and an aesthetically pleasing room can be full of disturbing echoes and noises.

In just a couple of years though, sound design has become an integral part of the design process for many companies. Companies hire entire departments of acoustic designers and acoustic engineers to make their products sound just as their product is supposed to sound (Lyon, 2000). The problem has been, and still somewhat is, that the rules of thumb that other design areas has developed through the years, are not in place yet for acoustic design (Lyon, 2000). The same goes for acoustic engineering. Sound and acoustics have gone from being a premium concept, to something that everyone, from filmmakers to architects, will have to plan for.

The classical view on sound design has been "noise control", the solution to fit dampeners or silencers in order to suppress disturbances (Lyon, 2000). Regulations and standards emanate from this view, requirements being set in "sound reduction" or "maximum noise", working with absolute levels in decibel. Building construction, that this master thesis is ultimately about, is deep in this marsh. Sound, and the disturbance from it, is a highly subjective experience. The requirements are not, and neither are the health effects from high noise levels. This is why this master thesis takes a step back to the old view of "noise control", to put the human back into focus of an industry regulated by absolute numbers.

In a way, this master thesis project also takes a step back in the evolution of industrial design. The craft, and art, of house construction are being more and more automated. The reason is the high demand for cheap apartments to be built in an astonishing pace in order to accommodate the increasing population in, and densification of, the urban areas. A higher production rate leads to tighter deadlines, which in turn has a risk of leading to worse conditions for construction workers, increases in workplace accidents and construction errors that effect the tenants of the new buildings.

For this project, design is in the process. A house built by a competent craftsman can be designed and constructed to fit the conditions of the place where it stands. A modular house, built in a factory, has to have a robust design and construction that, with minimal alterations, can fit almost any conditions. The challenge for the industrial design engineer is to find that ultimate design and construction, adapt it to the rather inflexible mold of a factory. It has to be economically and financially justifiable, and the end goal becomes to make sure that the result have real people in mind, from the ones working in the factory, through the ones assembling the building, to the end user; the tenants of the finished building.

That constitutes the connection to industrial design engineering. The thesis started with the human in the center, the drive to make the acoustic environment better for the tenants of Lindbäcks Bygg ABs modular houses. The façade constructions, that are the main focus, will have to be designed with the ergonomics of the people building them, in the factory as well as in the field, in mind. The sound design of the constructions has regulations and requirements as a framework, and acoustical measurements are used as the tool to verify that the end result satisfies the need of the end user. All of this is done with sustainability in mind, both economically and environmentally, for Lindbäcks Bygg AB, Tyréns Sverige AB and the tenants of modular apartments.

3.2. SOUND – AN INTRODUCTION

The book *"Ljud, Buller och Vibrationer"* (Anderson, 2017) gives a good overview of the concept of sound, which have been summarized below.

> Sound is the vibrations in air, or other excitable media, that our ears can pick up and, through our auditory organs, decode into relevant information. Generally, when we talk about sound we talk about sensible vibrations, such as words, music, the sound of an accelerating car or the rustling of leaves in the wind.
> When sound becomes annoying, disturbing or intelligible, we label it noise, and target it as something that has to be limited.
>
> When a sound is picked up by our ears, we register the variation in the sound pressure that we are subjected to. A harmonic tone consists of a single wavelength, the distance between two pressure maximums. A combination of tones that resonates well together is perceived as for example music and speech, whereas a dissonant combination is perceived as noise.
>
> A tones pitch, or frequency, is measured in hertz (Hz), which is easiest described as oscillations over time. Higher frequencies have a shorter wavelength and therefore a higher frequency. The opposite goes for lower frequencies. Humans are able to pick up sound ranging from 20 Hz to 20 000 Hz, which corresponds to wavelengths of 17 m down to 17 mm.
>
> The frequencies are divided into octaves, a duplication of the frequency in hertz. This in turn makes the octave scale a logarithmic scale, where the frequencies surrounding each new octave is denoted an octave band. To acousticians, who needs a more precise division when performing measurements, the octave bands are divided into thirds, named after the middle frequency of the 1/3-octave band.
>
> The human ear can pick up variations in sound pressure as small as 20 micro-Pascal (μPa). Lower frequencies require a larger sound pressure to be perceived, and vice versa. As the ratio between the most quiet and loudest

sound that we ca hear is about 10^6, sound pressure level in acoustics is generally referred to in decibel (dB).

Sound pressure level (L_p) can therefore be calculated as

$$L_p = 20log_{10}\left(\frac{p}{p_0}\right) \qquad \text{[dB]}$$

where p is the root mean square of the sound pressure, and p_0 is the reference sound pressure of 20 μPa. The decibel scale is a logarithmic scale, and this conversion makes sound easier to represent, since its level can now be given as single numbers.

The decibel scale starts at 0 dB, which is the auditory threshold for our ears. As a reference, a normal conversation at 1 m apart is about 40-60 dB and a jet engine at the same distance has a sound pressure level of about 150 dB. Noise levels of 85 dB at your ear is considered harmful over longer exposure time, and the maximum level allowed in a bedroom from outside traffic is 45 dB.

The relationship between hertz and decibel can be explained in a simplified manner. Sound is often viewed as a waveform, consisting of maximums and minimums in air pressure. The frequency (Hz) is the number of oscillations over time, the sound pressure (dB) is the height, or amplitude, of the oscillations.

Our marvellous ear has been developed to perceive sound differently over the frequency spectrum. Speech, for example, are divided into vowels and consonants. Vowels are centred around the lower frequencies, and consonants, especially the hard ones, are centred around the higher frequencies. 90 percent of the information is in the consonants, and only ten in the vowels. If we look at the energy though, the ratio is reversed. Therefore, nature for example gave us ear canals that corresponds to the wavelengths for the important frequencies and dampens the others. This results in that we don't perceive low and high frequencies equally, but they can still be equally harmful to us.

In order to remedy this, and to properly represent all frequencies important to us, the acoustic decibel scale utilizes weightings for sound pressure level, the most notable being A- and C-rating. A-rating is the most widely used by acousticians, as it corrects the linear noise curve of measurement equipment to the perceived curve of our ears. If the sound measured have a lot of low frequency disturbance, the C-rating is used to represent the effect of low frequencies and vibrations more closely.

3.3. TRAFFIC NOISE

Traffic noise is, as the name suggests, the noise made by passing traffic. By traffic is meant both road-, rail- and air traffic. This project will focus mainly on road traffic, as this is by far the most common problem area in the urban densification of today. Noise from the other traffic types is calculated, dimensioned for and measured in the same way, but calculation models can differ.

It should be noted that the requirements set forth in Boverkets building regulations and the Swedish Standard 25267:2015 are for sound insulation from traffic AND other external sources. Other external sources can for example be adjacent industries, schools and playfields, or even ventilation outlets on the building or a loud party on the neighboring balcony. Traffic is however the standard parameter considered when dimensioning façade noise insulation, and the other sources are factored in when relevant.

When developing a new urban area, traffic noise is one of the defining factors in applying for building permits. At this stage, interested parties look at the noise levels outside, first at ground level for the area and later on at the façade of the planned building. The traffic noise regulation stipulates the highest allowed noise levels at the façade of the building, which the developers, and later the acousticians, have to relate to (SFS 2015:216).

Traffic noise at this stage can either be measured or calculated, with calculation being the standard choice of action. Accurately measuring traffic noise is an arduous task, prone to error, and since the building isn't there yet, façade noise cannot be predicted using measurements. Calculation instead has the ability to adjust for increased traffic flow and give more accurate noise levels in a larger area, as well as predict façade noise levels for the whole building.

Traffic noise calculations are generally done by engineers in the planning stage, using specialized software such as SoundPlan and CadnaA where you make a calculation model in 3D including information about terrain, traffic conditions, the layout of roads, and the placement and geometry of buildings. Traffic noise levels at the façade, as well as to the surrounding environment, is then calculated using the calculation models detailed in *"Nordic calculation model for road traffic noise"* by the Swedish Environmental Protection Agency.

Acousticians use the result of the traffic noise calculations as a basis for dimensioning the façade constructions of the new buildings. They have to take into account the sound insulation of the façade wall as well as any windows and vents. The mission is to dimension the aggregate façade construction so that the predicted noise level inside the building meets the requirements in Boverkets building regulations and the Swedish Standard.

When dimensioning traffic noise insulation, the acoustician has to be aware of a couple of different spectrum adaption, or correction, terms. These are detailed in SS-EN ISO 717-1:2020 *"Acoustics - Rating of sound insulation in buildings and building elements – Part 1: Airborne sound insulation"*.

C-correction accounts for the low frequencies of the traffic noise and its effect on the sound insulation of the construction element. C-correction is applied to noise from traffic driving over 70 km/h, or rail traffic. When the speed limit is below 70 km/h, the low frequencies are even more dominant, and the spectrum adaption term C_{tr} is used instead. The sound reduction capability of for example a window is therefore given with both the terms C and C_{tr}, to account for both possibilities.

C and C_{tr} deal with the frequencies between 100-3150 Hz. If a building is situated near a source with an even lower frequency spectrum, like idling buses or a large number of heavy trucks, the frequencies between 50-100 Hz becomes more relevant to disturbance and health. Therefore $C_{50-3150}$ or $C_{tr,50-3150}$ can be used instead to account for this. The inclusion of the lowest frequencies is not a requirement in the standards but could be an important factor to the acoustical environment for the tenants of the finished building (Public Health Agency 2019).

Lastly, the resulting traffic noise indoors are to be measured in the finished building. The measurement method is detailed in the report *"Noise from Road Traffic – Measurement Method"* (Swedish Environmental Protection Agency, 1987) and requires a microphone measuring the sound pressure level inside the building during at least 500 car passes. The cars have to be counted, and the number of heavy trucks or other larger vehicles noted, as well as any disturbances. The sound pressure level during the measurement time is then adjusted to match a whole day, as the requirements are given.

It should be noted that, when verifying the acoustical parameters of a building in accordance with BBR, the acoustician is often on site before construction is fully completed. Disturbances are great during the workday and measuring the traffic noise levels indoor at night does not accurately represent the final levels. The engineering method of measurement is therefore used, utilizing a loudspeaker as the sound source instead of traffic. Briefly put, the apparent sound reduction of the façade is measured instead, and then compared to the calculated traffic noise levels predicted for the building. This is the method used for the measurements in this project and it will be further explained farther into this report.

3.4. FAÇADE NOISE INSULATION

Façade noise insulation is a measurement of how well a façade construction limits the spread of external noise into a building. In this way, it is similar to the acoustical concept of airborne noise insulation, which covers the spread of sound between two rooms or apartments in the same building (Anderson, 2017). The difference has mainly to do with measurement- and evaluation methods.

When determining sound reduction, we look at a couple of different reduction indexes (Swedish Standard Institute, 2016). For airborne sound insulation we have sound reduction index (R) and level difference (D).

Sound reduction index is calculated using the formula below:

$$R = L_s - L_r + 10\log\left(\frac{S}{A_r}\right) \quad \text{[dB]}$$

Where L is the sound pressure level in the room with the source (L_s) and in the receiving room (L_r). A_r is the equivalent sound absorption in the receiving room, gathered from the reverberation time, and S is the area of the partition. Since the sound reduction is different for different frequencies, the resulting single number quantity of the sound reduction index is weighted. The method used is detailed in SS-EN ISO 717-1:2020 *"Acoustics - Rating of sound insulation in buildings and building elements – Part 1: Airborne sound insulation"*, and the weighting results in the more commonly used term R_w. To further complicate things, R_w represents the sound reduction index measured in a controlled environment or lab. Field measurements are presented as the apparent sound reduction index R'_w.

The calculation of level difference is not unlike that of sound reduction. It is however as default standardized with a reference value depending on the reverberation time (D_{nT}):

$$D_{nT} = L_s - L_r + 10\log\left(\frac{T}{T_0}\right) \qquad \text{[dB]}$$

Where T is the reverberation time in the receiving room and T_0 is a reference reverberation time of 0,5 s. The level difference is the weighted in the same way as the apparent sound reduction index, resulting in the common term $D_{nT,w}$.

Acousticians use sound reduction index when dimensioning the façade insulation of a new building. The apparent sound reduction index is known for many standard façade constructions, and the suppliers of windows and other façade elements specifies sound reduction in their technical data.

When acoustically verifying a building through measurement, it is not uncommon to utilize a simplified method, using the standardized level difference. A loudspeaker acts as the source outside the building, and the resulting level difference is easily applied to the projected traffic noise levels and the requirements indoor.

However, for estimation of façade noise insulation in accordance with the current standard SS EN ISO 12354-3:2017 (Swedish Standard Institute, 2017), the apparent sound reduction index R'_{45} should be used instead of R'_w or $D_{nT,w}$. The denotation 45 means that the sound source is a loudspeaker with the angle of incidence of 45°, and is evaluated as

$$R'_{45} = R' - 1{,}5 \qquad \text{[dB]}$$

where the subtraction of 1,5 dB from the "regular" R' has to do with the incidence angle in combination with the pressure maximum of the sound wave that occurs at the boundary point that is the facade.

The traffic noise regulation (SFS 2015:216) states that the equivalent noise from road- and rail traffic shouldn't exceed 60 dB at the façade of a building, 65 dB for apartments under 35 m^2. This means that a façade construction has to have an effective sound insulation R'_w (with spectrum adaption term C or C_{tr}) of 30 dB for BBR, 34 dB for sound class B.

With an equivalent noise level of 65 dBA, it is not uncommon to see maximum noise levels at the façade of up 85 dBA. With a requirement for maximum indoor traffic noise of 45 dBA, this means that a façade construction needs to be made with an effective sound insulation of up to 40 dB (44 dB for sound class B). With a window or vent in the façade this number goes up even further.

3.5. THE PLANNING AND BUILDING ACT

In 2010, the Swedish Government ratified *"The Planning and Building Act"* (SFS 2010:900). The act gathers provisions regarding planning of land and water, and on construction and building. The provisions are worded with the aim to...

> *"...with regard to the freedom of the individual, promote a societal development with equal and good social living conditions and a good and long-term sustainable living environment for the people in today's society and for future generations."*

Regarding noise, the act states the following in §6a:

> *"When planning and in matters concerning building permits in accordance with this Act, residential buildings shall*
> *1. located on land suitable for the purpose, taking into account the possibilities for preventing nuisance to human health in terms of ambient noise, and*
> *2. be designed and placed on the intended ground in a manner appropriate to the possibilities for preventing nuisance to human health in relation to ambient noise."*

In this case, inconvenience to human health means a health or hygiene disorder which can affect health negatively and which cannot be regarded as minor or temporary.

The result of the Planning and Building Act is that developers have to take noise, among other things, into account during the planning and development stages of new buildings. During later stages, the tenets of the Planning and Building Act are complemented by the Traffic Noise Regulation and Boverkets Building Regulations.

3.6. THE TRAFFIC NOISE REGULATION

As a complement to the Planning and Building Act, the Swedish Government ratified the Traffic Noise Regulation in 2015 (SFS 2015:216). The regulation details requirements regarding outdoor traffic noise from road-, rail- and air traffic.

The regulation states that:

> *"The provisions in §§ 3-8 shall be applied in the assessment of whether the requirement for prevention of inconvenience to human health in chapter 2 §6a of the Planning and Building Act (2010: 900) is complied with*
> *1. when planning,*
> *2. in matters of building permits, and*
> *3. in matters of prior notice."*

This means, for example, that the noise levels detailed in the regulation are to be accounted for when planning the placement and layout of a new building, and when detailing the facade construction in order to meet the requirements for traffic noise indoors.

§3 of the original regulation specifies that the noise levels from road- and rail traffic should not exceed an equivalent of 55 dBA at the building's facade, and an equivalent noise level of 50 dBA (maximum 70 dBA) at a balcony or building adjacent patio. Due to a will to increase urban densification, these requirements were raised in 2017 (SFS 2017:359) to 60 dBA at the facade. An exception was also added for apartments smaller than 35 m^2, where an equivalent noise level of 65 dBA is allowed at the facade.

§4 adds that IF the requirement of 60 dBA at the building's facade is exceeded, half of the living spaces of each affected apartment should be situated facing a side of the building where the equivalent facade noise level doesn't exceed 55 dBA, as well as 70 dBA maximal noise level between the hours 22.00 and 06.00, called a noise protected side.

Noteworthy for this master thesis is the fact that the traffic noise regulation doesn't mention the maximum noise level at the facade, other than for the noise protected side. Effectively, this means that the maximum noise level can be significantly higher, due to for example lots of heavy traffic, as long as the requirement for equivalent noise is achieved. The requirements for indoor noise levels are still in affect though, which needs to be addressed when dimensioning facade noise insulation.

3.7. EFFECTS ON PUBLIC HEALTH

The Public Health Agency of Sweden has put together *"General Advice on Indoor Noise"* (FoHMFS 2014:13), which details the requirements for noise levels where there is no inconvenience for public health, set forth in the Environmental Code, chapter 9, §3 (SFS 1998:808). The General Advice applies to noises originating both inside and outside of the apartment.

Regarding noise from external sources, the General Advice refers to the Swedish Environmental Protection Agency, who in turn refers to the Traffic Noise Regulation. The Public Health Agency interprets, in the publication *"Guidance regarding noise indoors and high sound levels"*, the General Advice to mean, in general, that if the requirements for equivalent and maximum traffic noise levels outside are met, there is a low risk of disturbance indoors as the requirements indoors would have subsequently also been met (Public Health Agency 2019).

Special care has to be taken with regards to low frequency noise when looking at disturbance and health effects. For this purpose, the Public Health Agency have developed guidelines regarding the frequencies from 31,5 to 200 Hz (FoHMFS 2014:13). Because the A-weighting dampens low frequencies, the sound pressure levels in table 3 is given in unweighted L_{eq}, which better corresponds to the resulting disturbance.

Table 3. Guidance noise levels regarding low frequencies (FoHMFS 2014:13)

1/3 octave band [Hz]	31,5	40	50	63	80	100	125	160	200
Sound pressure level, L_{eq} [dB]	56	49	43	42	40	38	36	34	32

The Public Health Agency writes in the report *"The Effects on Health from Noise and High Sound Levels"* that disturbance from frequencies below 31,5 Hz can't be ruled out, but that the sound pressure levels needed in order for someone to perceive such low frequencies makes it a lesser concern under normal circumstances (Public Health Agency of Sweden 2019).

Background noise is one of several factors that influences the ability to apprehend speech. The World Health Organization (1999) recommends that the background noise is at least 15 dB below the spoken word, which would mean a maximum background noise level of 45 dBA. In order to secure maximum speech intelligibility, a background noise level om maximum 35 dB is recommended (WHO 1999). These recommendations correspond to the requirements for traffic and external noise indoors set in Boverket's Building Regulations.

Low speech intelligibility has a direct effect on memory and concentration, since more energy has to be divided to deciphering what is being said. In addition to this, higher energy expenditure means lower performance and higher fatigue over time (WHO, 1999). Especially low frequency noise can be highly fatiguing and lead to increased stress. However, even if some studies show that noise levels can be tied to psychic- or general wellbeing, it is not to the same degree as with fatigue and concentration loss (WHO, 1999).

One of the most severe effects of environmental noise is the disturbance of one's sleep. People that are subject to loud noises during nighttime have a harder time falling asleep, wake up more times during the night and earlier in the morning, and are more prone to increased movement during their sleep cycle. This is shown in a review made by the WHO, which also states that the adverse effect of indoor noises starts to show at maximum noise levels of about 33-38 dBA and increase with 30% per 10 dB level increase (Public Health Agency of Sweden, 2019).

The Environmental Health report of 2017 (Public Health Agency of Sweden, 2017) presents the result of the national health survey performed in 2015. About 40 000 people in the ages of 18 to 84 were asked about several health-defining parameters, including noise. The report states that 20% of the participants live in a building subjected to traffic noise above the stipulated 55 dBA, 29% of them with one or more windows on the noise-subjected side. The possibility to open one's window is considered a "quality of life"-factor, and 16% of the participants sleep with the windows open (51% in the summer).

The report shows that 8% of the participants considers themselves to be disturbed, or much disturbed, by noise from traffic, and 2,3% experiences sleep disturbances daily or every week. 0,5% have cardiovascular diseases that can be contributed to high stress because of noise. The good news however is that the number of people experiencing noise disturbances have dropped with 12% since 2007, and that the number is significantly less in single-family housings (Public Health Agency of Sweden, 2017).

WHO also states that noise can lead to physiological stress reactions such as raised blood pressure and higher pulse, partly due to the added fatigue during the day and partly because of the lack of recuperation due to sleep disturbance. The lack of recuperation, as well as repeated awakenings, can also lead to increased risk of cardiovascular disease, weight gain, diabetes and impaired immune system (WHO, 2009).

However, in a review by the WHO in 2018, it was stated that there is a need for a greater number of qualitative studies regarding the health effect of noise in order to draw any definitive conclusions (Public Health Agency of Sweden, 2019). The Public Health Agency of Sweden however has adopted the view that even if the increase in individual health risk is low, there is such a great number of noise exposed people that the results are significant to the public health (Public Health Agency of Sweden 2019).

3.8. ACOUSTICAL STANDARDS

Acoustical requirements for dwellings have been developed by the Swedish National Board of Housing, Building and Planning (Boverket) and is presented, along with other regulations, in *"Boverket's building regulations – mandatory* *provisions and general recommendations"* (BBR). BBR is updated regularly, and its latest version, BBR 29, has been established with BFS 2020:4.

Requirements regarding protection against noise is presented in section 7 of BBR, and the defining text for dwellings can be found under 7.21:

> *"Buildings containing dwellings, their installations and lifts shall be designed to ensure noise from these and from adjacent premises and outside sound is attenuated. This shall be achieved to the extent required by the intended use and to ensure building residents are not disturbed by the noise."*

The requirements for sound insulation from traffic and other external sources (7:21c) are divided between "spaces for sleep, rest or daily socializing" and "spaces for cooking or personal hygiene", with the latter allowing for slightly higher levels of disturbance. Requirements for each type of space is further divided into equivalent sound pressure level ($L_{pAeq,nT}$) and maximum sound pressure level ($L_{pAFmax,nT}$).

Equivalent sound pressure level means the average sound pressure level over a period of time, 24 hours in the case of traffic noise. Maximum sound pressure level in turn means the noise levels from the noisiest sound source that can be expected during a standard night. The requirements should not be exceeded more than five times per night. For a bedroom the equivalent sound pressure level is allowed to be up to 30 dB, with a maximum level of 45 dB, according to BBR.

As a complement to BBR the Swedish Standards Institute (SIS) has published the Swedish Standard SS25267:2015 *"Acoustics – Sound classification of spaces in buildings –Dwellings"*. The standard specifies the sound classes A to D, where A is the highest and the requirements stated in BBR corresponds to sound class C.

Sound class B (Swedish Standards Institute, 2015) is designed to

> *"correspond to a dwelling with a significantly better sound environment than society's minimum requirements and is suitable for homes where a good sound environment is a priority."*

With this in mind, the equivalent sound pressure level allowed for a bedroom is changed to 26 dB, with a maximum level of 41 dB. Sound class B also adds a requirement for nightly equivalent sound pressure level of no more than 22 dB.

It should be noted that the requirements from BBR (sound class C) or sound class B is considered the norm for new dwellings. Sound class A is seldom used, other than for buildings with special acoustical needs, and sound class D is mostly used for refurbished dwellings where old constructions can't be adjusted in a way that satisfies requirements from BBR (Swedish Standards Institute, 2015).

3.9. WOODEN CONSTRUCTIONS

Wall constructions can be divided into two major groups of construction concepts – The single wall construction, and the double wall construction (Andersson, 2017).

A single wall construction is a homogenous wall construction, consisting of only one building material. A typical example of a single wall construction is the concrete wall. Sound reduction in a single wall depends on the frequency and can be divided into three areas (Andersson, 2017):

- Area controlled by the stiffness of the construction
- Area controlled by the mass of the construction
- Area controlled by the critical frequency of the construction

Lindbäcks façade constructions are a prime example of the other kind of wall, the double wall construction. Here you can get the same sound reduction index, but with a lighter and cheaper construction (Andersson, 2017).

A single wall construction usually has better sound reduction in the lower frequencies than a double wall construction, due to its larger mass, but are in turn more expensive and harder to assemble.

A double wall consists of two separate wall panels, separated for the most part with an airgap. Sound does therefore propagate in three ways (Andersson, 2017):

- Through the airgap, where the wall panels are fully separated
- Through the studs, where the wall panels are connected
- Through the edges, where the wall connects to floor, ceiling or another wall

The sound reduction of a double wall will increase with a bigger air gap and heavier wall panels. Sound will also propagate easier through solid objects than through air, meaning more sound reduction with less connection points (studs, edges) (Andersson, 2017).

This means that an ideal double wall construction is devised without connections, both between wall segments and at the edges. This is a utopia, as most walls will have to be connected in some way, but there are solutions with staggered studs, weak metal studs (called acoustic studs) and different kinds of vibration isolators to minimize sound propagation this way (Andersson, 2017).

Many façade constructions incorporate a window or a ventilation intake. Especially windows are problematic, as they are a relatively heavy construction, prompting for more studs to be used in the wall. Thick windows can also work as a new connection between the wall panels.

Due to the increased cost, and more difficult assemblage, of windows with higher sound reduction index prompts acousticians and developers to dimension compounded façades using wall constructions with a higher sound reduction in order to compensate for a window with lesser sound reduction. This is done in accordance with the formula for compounded sound reduction index:

$$R = 10\log\frac{\Sigma S_i}{\Sigma S_i^{-R_i/10}} \qquad \text{[dB]}$$

where S_i is the area of the sub-element (for example the window), and R_i is the reduction index of the sub-element.

4. Method

This project consists of a theoretical and a practical part.

The theoretical part includes a context analysis, a literature review and the concept ideation phase. The goal of the theoretical part has been to produce a number of construction concepts to be fabricated by Lindbäcks Bygg AB for testing.

The practical part includes the assembly of the façade constructions on a free-standing testing module and the acoustical measurements of the sound insulation of each construction. During the measurements the construction has been altered in order to determine how different materials and construction details influence the sound reduction of the constructions as a whole.

The measurement results have then been analyzed and evaluated with the goal of determining how different factors affect the result. The façade construction has then been iterated together with the engineers at Lindbäcks Bygg AB, and new measurements have been taken and evaluated.

The ultimate goal has been to determine which construction has the best prerequisites to achieve sound class B regarding noise from traffic and other external sources, as well as being a feasible option both financial and with regards to the production line in the factory.

4.1. PROCESS

The master thesis project has used a modified version of the Engineering Design Process, detailed in *"How do you design? - A compendium of models"* (Dubberly, 2004) after Michael J. French (1985). French's model works with iterations during the conceptualization and selection of ideas, going back to the analysis of the problem in order to verify that the statement of the problem keeps being relevant. The modified process used in this project is shown below in figure 2.

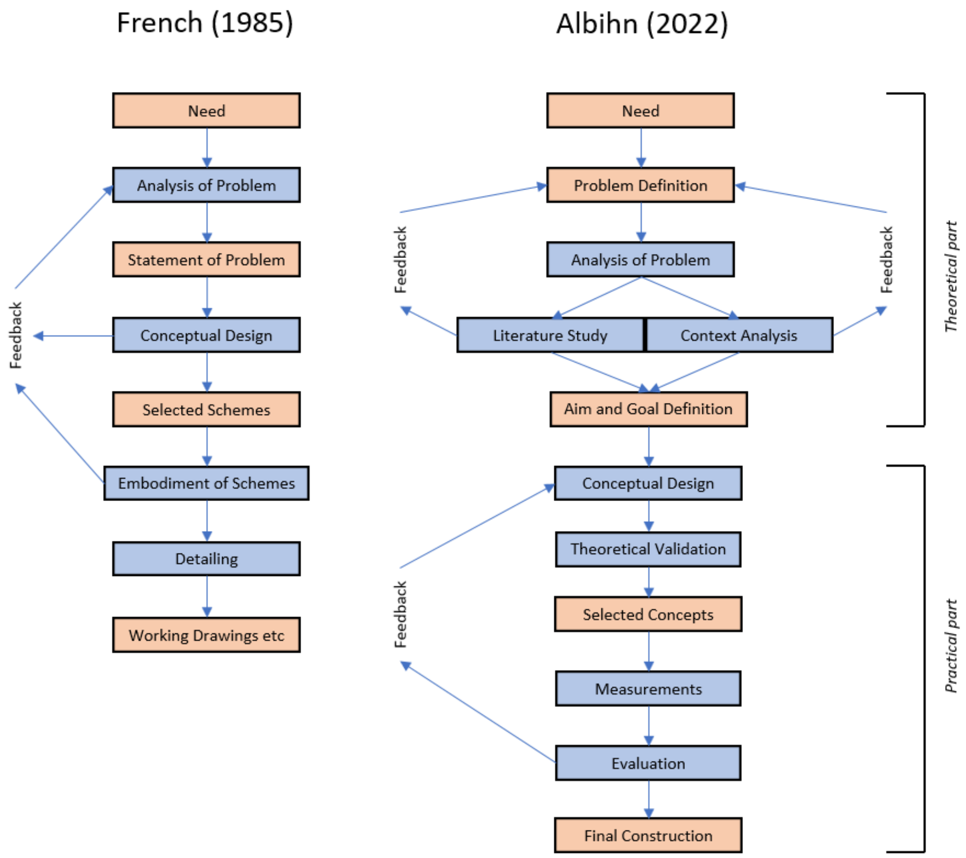


Figure 2. Adapted process used in this master thesis project.

The master thesis project started with a theoretical part, where a context analysis and literature study were conducted in order to further understand why the acoustical standards, regulations and methods that shape the industry looks as they do, what impact deviations or changes has on public health and the tenants of residential buildings in noisy areas, and how modular construction has become what it is today.

The theoretical part started out with the standards and regulations and worked outwards through their sources. More areas of research were added through the practical part of the project, as new theoretical concepts had to be explained or evaluated for relevance to the final result. The problem statement and the research questions were iterated through the theoretical part, as the information gathered revealed new uncertainties and different angles to the initial problem. Feedback was gathered regularly from the acousticians of Tyréns Sverige AB and the engineers of Lindbäcks Bygg AB, to make sure that the project was kept on track.

The aim of the theoretical part was to verify that the perceived problem with the sound reduction in wooden façade constructions are a real problem for the end user as well. With this cleared, the next step was to increase the understanding of the regulations, and the impact that these, especially the changes in the traffic noise regulation, have on the public health as well as the acoustical choices made when building housing. Lastly, the theoretical part had to determine the defining factors for façade wall constructions as a basis for the ideation and concept creation that led into the practical part of this master thesis project.

For the practical part of this project, a semi-iterative process has been chosen. The measurements and analysis started with making a baseline – measurements on the original construction to compare with Tyréns experience from field measurements. From the theoretical part was taken the findings regarding important factors for façade noise insulation, which lay the ground for the proposed tests. Together with Lindbäcks Bygg AB, the construction that was deemed the easiest and most economical to adapt were chosen as the first to test. After the measurements and analysis of the first concept, and after each subsequent concept, a new discussion took place to evaluate if the next construction still were a justifiable option, in the light of the results.

In the end, extra focus was devoted to "the next step" in discussions with Tyréns Sverige AB and Lindbäcks Bygg AB, as the results had to be implemented in upcoming module systems and tested in the field. The results were also adapted and included in Tyréns upcoming study on the wall constructions for corridors, another problem area for Lindbäcks Bygg AB.

The aim of the practical part was to test the proposed construction concepts against the theoretical models and against the baseline. The results were evaluated continually in order to catch deviances and possible improvements. The final constructions were brought before Tyréns Sverige AB and Lindbäcks Bygg AB and analyzed from a dimensioning and manufacturing viewpoint, to ensure that the result would really benefit the end user – the tenants of future modular houses.

4.2. PROJECT PLANNING

The planning of this master thesis project was done in close collaboration with Lindbäcks Bygg AB and the acousticians of Tyréns Sverige AB.

Tyréns had a number of ongoing projects taking up time and equipment, and early on it became important to coordinate the upcoming measurements. The same went for Lindbäcks Bygg, as production slots had to be allotted in the factory for manufacturing of the wall constructions. The measurements, and the subsequent manufacturing time, was therefore scheduled first, and the other stages of the project had to adjust to this timetable.

It became apparent early on that the theoretical part would have to be quite extensive, in order to build a knowledge base to start from when ideating wall construction concepts. Since the slot for the practical part of the project would coincide with the halftime presentation of the master thesis course, the decision was made to plan for most of the report writing to occur before the practical part of the project, except for the result and conclusion chapters.

During the project time regular checkups were planned with Tyréns Sverige AB and Lindbäcks Bygg AB, both to keep track of the timetable and to brainstorm, discuss and validate the theoretical findings and the resulting constructions.

A rough estimate of the timetable for the master thesis project is shown below in figure 3.

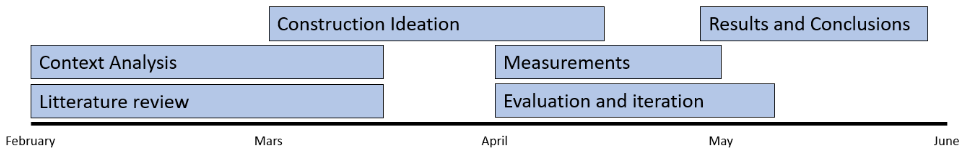


Figure 3. Rough timetable of this master thesis project.

4.3. CONTEXT ANALYSIS

In order to perform a context analysis of lightweight façade constructions and their challenges, several different methods were used.

First off, the initial problem had to be verified. As a part of a different development project, Tyréns Sverige AB has collected the results of acoustic measurement done on Lindbäcks building modules. The results were organized in a result matrix, which made it possible to evaluate the façade insulation of the modules in the field as a base for this master thesis project.

The measurement results were then compared to theoretical results for the existing façade constructions. The theoretical models were made with the use of the software Insul (ver. 8.0.9) by Marshall Day Acoustics, which is a standard software used by acousticians as an aid in building acoustic predictions. Insul makes it possible to add the different "layers" of, for example, a wall construction one by one to see how they affect the sound insulation of the construction. The software was later used to test the new façade constructions theoretically in the ideation and iteration phase.

Next up, the problem had to be validated against existing research. In conjunction with the literature review, the requirements set forth in the traffic noise regulation and their connection to public health was researched. With a start in the regulation itself and its sources the goal was to determine what negative health effects not reaching the requirements of the traffic noise regulation would have. Subsequently that would mean determining what effect not reaching the requirements in Boverket's building regulations, would have, respectively what health benefits there would be in reaching sound class B.

4.4. LITERATURE REVIEW

A literature review was conducted in order to gather information about traffic noise and disturbance, and to identify the factors that influence the effective sound insulation of lightweight façade constructions. For those readers who are not practicing acousticians, a section about sound in general was added for clarification.

The review leaned heavily on the Swedish Standards and the Swedish Building Regulations, which form the basis of the requirements for traffic noise inside residential buildings, and the Planning and Building Act and the Traffic Noise Regulation which detail the requirements on traffic noise outside the buildings. This was done to further understand the need for façade constructions with a good sound insulation, and to anchor the thesis and its results firmly in the non-flexible bedrock of Swedish law.

4.5. IDEATION

The ideation process started with Lindbäcks standard façade wall construction. Lessons from the context and theory phases identified the defining factors that could influence the sound reduction index of the wall, mainly by eliminating "dips" in the sound reduction in lower frequencies or shifting the coincidence frequency into a frequency area where high noise levels isn't perceived disturbing in the same way.

Through the literature review, research was made into the practical dimensioning of lightweight facades, with a start in the standards used by acousticians and their sources. Discussions with acousticians at Tyréns formed a basis for how they reason when they dimension walls, windows and vents for new buildings, backed up by praxis and years of experience.

A brainstorming session was conducted with engineers from Lindbäcks Bygg AB and the acousticians from the Acoustics Department North of Tyréns Sverige AB. Brainstorming is a popular method of generating a vast number of ideas over a broad body of knowledge, as described by IDEO.org (2015).

The ideas from this session, together with the information found in the context analysis and the literature review, made for a first draft of ideas for the ideation phase, which was subsequently discussed with the engineers and the acousticians.

The acousticians from Tyréns Sverige AB contributed with insight about which ideas had been tested before and which constructions doesn't perform as well in the field as in theory. The feedback from Lindbäcks was about which concepts were feasible from a structural strength point of view, and about the parameters for manufacturing a wall in the factory.

From the ideas that were left, a couple of initial concept series were made. Each of the series was designed to test one defining factor, and theoretically tested both increases and decreases of the factor. The theoretical models were validated by Tyréns acousticians and then finally taken back to Lindbäcks Bygg AB for a discussion on which ones to manufacture.

The manufacturing concepts were prepared for fabrication digitally, and after each measurement and evaluation, the decision was made whether to manufacture and assemble the next, or if any adjustments were needed.

4.6. IMPLEMENTATION

The construction concepts were sent to the engineers at Lindbäcks Bygg AB who finalized the designs into construction blueprints for Lindbäcks semi-automated factory at Haraholmen, Piteå.

As a part of an ongoing research and development project between Lindbäcks Bygg AB and Tyréns Sverige AB, a free-standing building module have been manufactured and mounted in a storage garage in Piteå.

Figure 4. Free-standing module for measurements.

The module is built with one larger room, to which the different outer wall constructions have been attached during the measurements, and a small room that are unaltered since leaving the factory.

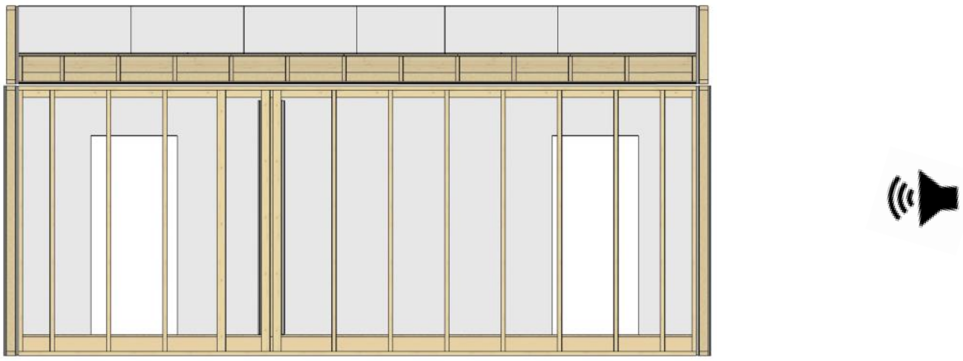


Figure 5. Cross section of the module construction.

The module is fabricated with Lindbäcks standard constructions. In order to simulate another module on top of the test module, short wall sections have been mounted on the top floor and an iron frame has been placed on top of them for weight. This makes sure that the pressure on the vibration insulators, as well as other connectors and insulators, between the modules, and therefore their compression or insulation rate, is similar to the conditions in the field.

The façade constructions are mounted on one of the short sides of the module using the same techniques as in the field. The standard façade was mounted in the factory, the rest with the help of personnel from Lindbäcks Bygg AB. Wooden panels were screwed on after assembly and was disassembled as a part of the measurements to be reused with each construction.

4.7. ACOUSTICAL MEASUREMENTS

Acoustic measurements were conducted on the façade constructions in accordance with Swedish Standard SS-EN ISO 16283-3:2016 *"Acoustics – Field measurement of sound insulation in buildings and of building elements – Part 3: Façade sound insulation"*. This is the measurement standard specified in SS 25267:2015 to be used to verify the acoustic requirements in buildings.

ISO 16283-3 details a couple of different setups regarding the equipment used and the measurement setup. The sound-source can be either a loudspeaker, which is the most common, or direct traffic noise. The measurement taken outside the building can be done either with the element method or the global method, and the measurements inside the buildings either in fixed positions or using microphone sweeps.

Using a loudspeaker as the sound-source, the loudspeaker should be positioned in a way that the incidence of the sound on the façade is 45° on at least one axis, and no nearer than 3,5 m from the façade (5 m radius between loudspeaker and measurement point). This distance is increased by 2 m if the global measurement method is used.

The element method means that the microphone is fastened, or held, directly on the outside of the building element that are being measured. The distance from the surface should be less than 10 mm if the microphone is held parallel to the surface, less than 3 mm if held normal to the surface. For the global method, the measurement is instead taken 2 m out from the façade of the building.

ISO 16283-3 states that the loudspeaker and element methods should be used as the preferred methods. Global and traffic methods is only to be used when the traffic noise levels are sufficiently high.

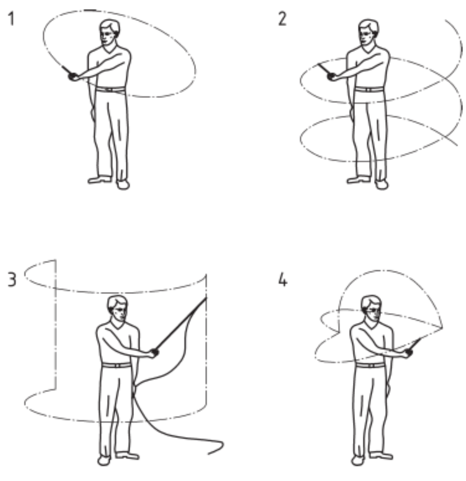
Indoor measurements taken in fixed positions means that the microphone is mounted on a stand, with the acoustician leaving the room during the measurement. A minimum of five microphone positions should be used, with a measurement time of at least 6 s. With the microphone sweeps, a minimum of two positions á 30 s sweep inside the building is used instead.

The measurements were taken using a handheld sound analyser from Norsonic, Nor140. The analyser records sound pressure levels for 1/3 octave bands ranging from 6.3 Hz to 20 kHz. The analyser can also be connected to a loudspeaker in order to send out pink noise, which is defined as noise which intensity has been adjusted to the A-weighted curve matching our ears. It is used to measure the reverberation time, the time it takes for the sound level to drop 30 dB when the noise is turned off, needed for building acoustic analysis. The analyser can then use this data to perform said analysis in the field.

Figure 6. Nor140 handheld sound analyzer for acoustic measurements.

The measurement files are transferred from the Nor140 to a computer and evaluated using the software NorBuild, also from Norsonic. NorBuild have the capacity to evaluate the measurement data for R'_w, R'_{45} as well as $D_{nT,w}$, and to present the result graphically.

The standard way for acousticians to take the measurements are with a microphone sweep in one or more positions in the room, depending on the room size. ISO 16283-3 details four different sweeping techniques, as seen in figure 7.



Key

1 circle
2 helix
3 cylindrical-type
4 three semicircles

Figure 7. Proposed techniques for microphone sweeps (copied from ISO 16283-3)

The cylindrical sweep was used in this project, as it was deemed to be the easiest to follow consistently. Two sweeps were done, in accordance with 16283-3, see figure 8.

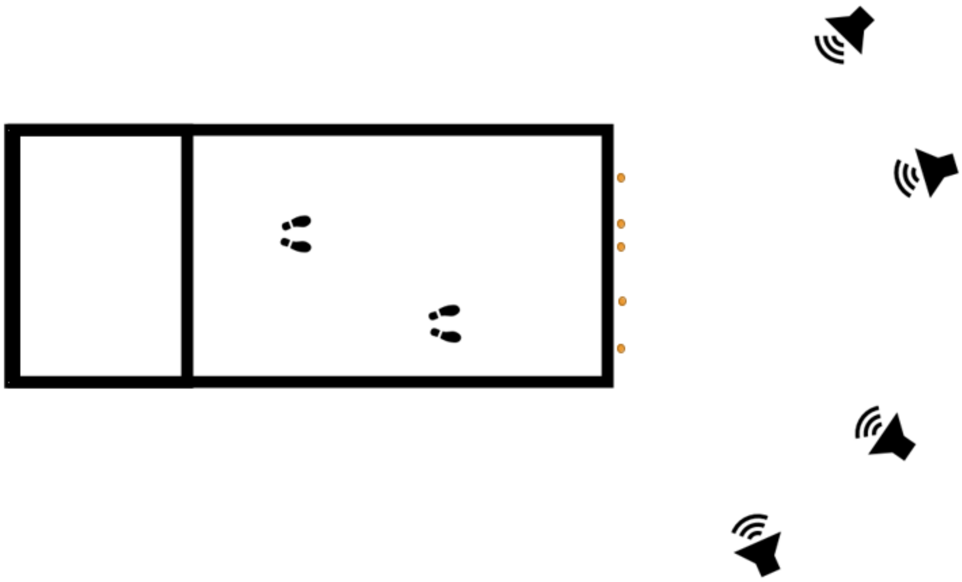


Figure 8. Measurement setup, ● = fixed position on the façade.

As the module was situated in a large storage garage, and not out in the open, it was decided to deviate from the measurement standard. The sound was bound to reflect of the garage's walls and ceiling, and therefore build up intensity in a more random sound field than is to be expected when using a loudspeaker with 45° incidence.

For the same reason, it was decided to use four loudspeakers instead of one. This generates a diffuse sound field at the façade, as is expected when measuring between two closed off rooms inside a building.

Figure 9. Loudspeaker setup for measurements.

A not fully unexpected benefit of this was a lesser risk of error in the measurement setup. In order to mount the new façade constructions on the module, the loudspeakers had to be moved. A loudspeaker is a fairly well-aimed contraption, small deviations can make big differences in the sound intensity at the façade, and the method with four loudspeakers made the setup less vulnerable to human error.

The result would now be the apparent sound reduction index of the wall (R'_w). It should however be noted that the measurement standard was followed regarding the microphone placement, as 5 positions directly at the façade were used instead of one or more sweeps in the diffuse sound field outside.

4.8. EVALUATION AND ANALYSIS

Since the results were to be presented as apparent sound reduction index (R'_w), the measurement was evaluated according to SS-EN ISO 16283-3:2016 *"Acoustics – Field measurement of sound insulation in buildings and of building elements – Part 1: Airborne sound insulation"*, instead of ISO 16283-3, and weighted according to SS-EN ISO 717-1:2020.

Evaluation was made using the software NorBuild (ver. 4.2) from Norsonic, and the results of each iteration were analysed against the baseline as well as similar constructions.

4.9. METHOD DISCUSSION

It is pertinent to discuss the fact that a large part of the theoretical studies was devoted to standards and regulations, diverting from the experience of the tenants of the buildings. This was mainly because of the way the project was initiated. The main partner for this master thesis project is Lindbäcks Bygg AB, who needed to improve their façade constructions in order to meet above mentioned regulations and standards. This made the study of the background and composition of those documents a main concern.

A more freely worded research question, such as "what is needed to make the majority of people living in buildings situated in areas with high traffic noise levels satisfied with the disturbance?", would probably yield a different result. It would maybe not however benefit Lindbäcks Bygg AB as a company.

For the same reason, this project has not looked into other types of solutions to lowering the indoor noise, such as noise barriers at the source, absorbers to lower the reverberation time, or noise cancelling technology.

The limitations are also found in the benchmarking. The factory at Haraholmen, Piteå, are customized to the constructions used today by Lindbäcks Bygg AB. It would therefore be a costly and time-consuming activity to build façade walls for some projects that deviate too far from the standard. This limits the possibilities to take too much from the book of other companies, and the benchmarking subsequently became more of a verification of how many companies that think in the same way.

Regarding the measurements and evaluation. Because of the pressure maximum that occurs when a microphone is placed against a surface, façade noise measurements are generally adjusted with 3 dB, if the microphone are within 2 m of the surface, and 6 dB if the microphone are placed against the surface. Evaluation using ISO 16283-3 would do this adjustment automatically, but ISO 16283-1 are not adapted for such measurement conditions. The adjustments would have to be made manually when evaluating the results, leaving the analysis open to human error.

Therefore, it was decided to focus on performing the measurements as consistently as possible, and to evaluate the relative changes in sound reduction instead of absolute numbers, ignoring the adjustments in decibel. The relative changes in sound reduction were also seen as a more robust and educational value to be presented, less prone to misinterpretation.

5. Ideation and iteration

The ideation has been a semi-iterative process. It started out with Lindbäcks standard façade construction. The information gathered in the context analysis phase showed weak spots in the construction to focus on, and the literature study identified the defining factors to work on in the new construction concepts.

The defining factors led, through a brainstorming session, to a number of ideas for façade wall constructions that were run by the acousticians of Tyréns Sverige AB and the engineers of Lindbäcks Bygg AB. Limitations were drawn out, based on previous knowledge and construction engineering theory.

The ideas that made the cut were modelled using the software Insul and parameters were changed to see what impact they would have on sound reduction. Each model was made out to test a different defining factor.

One more round of feedback from the acousticians at the Acoustics Department North of Tyréns Sverige AB and the engineers of Lindbäcks Bygg AB decided the final construction concepts to be manufactured, based mainly on the possibilities of adjustments in the factory. It was also decided that even if the construction concepts were prepared to be manufactured right away, the actual assembly of each new construction would await the results from the previous one. This to make sure that the next iteration still was valid.

It should be noted that the ultimate goal of the ideation and testing phases has not been to find the perfect façade construction, but to test the impact of different changes and gather enough information for Lindbäcks Bygg AB to make necessary improvements on their construction with minimal cost- and labour increase.

5.1. DEFINING FACTORS

From the literature study the following defining factors for a double wall construction was gathered (Anderson, 2017):

- The airgap
- The studs
- The edge connections

It would also be of interest to look at the corresponding factors for a single wall construction (Anderson, 2017):

- The stiffness
- The mass
- The critical frequency

5.2. FIRST IDEAS

A brainstorming session took place, including acousticians from Tyréns Sverige AB and engineers from Lindbäcks Bygg AB. The focus of the session was to come up with ideas for how the defining factors from the literature study could be addressed in a façade construction. The results from the brainstorming were then concretized into a number of "first ideas", summarized below:

- Addressing the airgap
    - Disconnect the wall panels
    - Increase or decrease the airgap
    - Change the mineral wool that fills the air gap
- Addressing the studs
    - Change the number of studs
    - Change de dimensions of the studs
    - Replace wooden studs with metal or acoustic studs
    - Disconnect or isolate the studs (or laths) through the layers
- Addressing the edge connections
    - Increase or decrease the number of edge connections
    - Disconnect the outer layer from the edges
    - Isolate the edge connections from vibrations
- Addressing the stiffness
    - Increase or decrease the number of studs or laths
    - Change the dimensions of the studs or laths
    - Increase or decrease the numbers of gypsum layers
    - Replace the gypsum layers with other materials
    - Replace wooden studs with metal or acoustic studs
- Addressing the mass
    - Increase or decrease the numbers of gypsum layers
    - Change the mineral wool that fills the air gap
    - Change the dimensions of the studs or laths
    - Replace one or two wall panels with cross laminated timber
- Addressing the critical frequency
    - Change the double wall into a single wall
    - Increase or decrease the airgap
    - Change the mineral wool that fills the air gap
    - Increase or decrease the numbers of gypsum layers

5.3. LIMITATIONS

The first ideas were presented to the engineers of Lindbäcks Bygg AB and the acousticians of Tyréns Sverige AB. The ensuing discussion landed in the following feedback regarding the limitations for the construction concepts.

Using metal studs is not possible due to the fabrication process, and it would lead to façade walls having to be constructed off site. Using acoustic studs are not possible either, due to them being too weak to withstand external forces over time. The conclusion is that wooden studs and laths will have to be used.

The façade construction is fastened directly into the boundaries of the module and is therefore not supported by the floor or ceiling constructions. This means that there isn't much to do about the number of connection points at the edges, but there could possibly be something done about the mode of connection, for example vibration isolators or different screws.

Changing the number of gypsum layers or replacing them with other materials could be done. So could changing the mineral wool. It was believed to make minimal impact though, due to the placement of the gypsum boards and the mineral wool in the construction. Lindbäcks Bygg AB have however been looking at a new fibre board, called a "Västkustskiva", made from rockwool. Using one of these as the outmost layer under the panel would add a porous layer first in the construction that could absorb low frequencies from entering the rest of the construction.

It was also, naturally, not desirable to build the façade as a single wall construction, or to incorporate cross laminated timbre, as this would go against the design of Lindbäcks modular concept.

The limitations set by the factory and the design choices of Lindbäcks Bygg AB had a significant impact on the design of the façade wall concepts. The choice of lightweight wooden construction made by Lindbäcks Bygg AB meant that effectively no radically new materials could be introduced to the design. The limitations of the factory meant that the final dimensions of the studs, as well as the constructions as a whole, had to be maintained if possible. This would lead to fewer options to try out regarding the stiffness and weight of the construction.

Ultimately, the limitations set for the design led to the different construction concepts being variations or alterations of the initial façade wall construction, rather than new and shockingly innovative ones.

5.4. INITIAL CONCEPTS

In the meeting with Lindbäcks Bygg AB and Tyréns Sverige AB, it was decided which concepts to go forth with. The basis for the decision was the initial ideas and the result of the feedback. Strong factors were also the time limit – how many concepts can be manufactured and measured in the weeks of this project – and the resource management – each construction takes time and material away from the regular operations of the factory.

The idea was for each of the concepts to test one defining factor, and to, at least theoretically, test the influence of both increasing and decreasing the factor.

The module came with Lindbäcks standard façade construction, and it was decided to keep it as a baseline as well as an opportunity to test if the influence of the wooden panel would be the same in the field as in theory.

Changing the number of studs would be relatively easy. It is already done when installing a window in the façade wall, since the weight of the window calls for extra support.

It was also deemed possible to make a construction where the wall panels were separated, since this is routinely done for indoor walls with higher sound reduction. Using two thinner studs instead of one thick and separating them with an airgap could be done, as long as the studs were connected in the top and bottom of the wall. The method of using staggered studs were proposed but discarded. It would probably lead to a stiffer construction because of the possibility to use thicker studs, but would then use up more material, both studs and mineral wool, and deviate too far from the manufacturing process in the factory.

Finally, the idea of using a "Västkustskiva" were chosen, as it was seen as a relatively cheap and easy change to make. It could also be mounted on the previously used concepts, which called for no extra production time in the factory.

It was decided not to test concepts using vibration isolators between the wall panels, in the connection points or at the edges initially. The reason was the lack of previous experiences with this technique on wall construction, though they are sometimes used in floor constructions, and with the limited time of this master thesis project these tests would have to be done in the future if necessary.

5.5. THEORETICAL MODELS

Theoretical models of the proposed constructions were made using the software Insul (ver. 8.0.9) by Marshall Day Acoustic.

5.5.1. Changing stud distance

The standard construction model was changed with regards to the distance between the wooden studs. 600 mm is the standard used by Lindbäcks Bygg AB, and when a window is installed, that distance reportedly drops down to 300 mm. 900 mm distance was chosen as well, in order to test the effect of a larger distance.

The change in sound reduction is shown in table 4 below, with a comparative graph for the sound reduction for different frequencies in figure 10. The standard construction with distance 600 is the baseline for comparison.

Table 4. Change in sound reduction relative the standard construction with stud distance 600 mm.

[dB]	Dist. 300 mm	Dist. 900 mm
ΔR_w	-5	0
$\Delta D_{nT,w}$	-5	0
$\Delta R_w + C_{50\text{-}3150}$	-8	+2
$\Delta R_w + C_{tr,50\text{-}3150}$	-9	+4

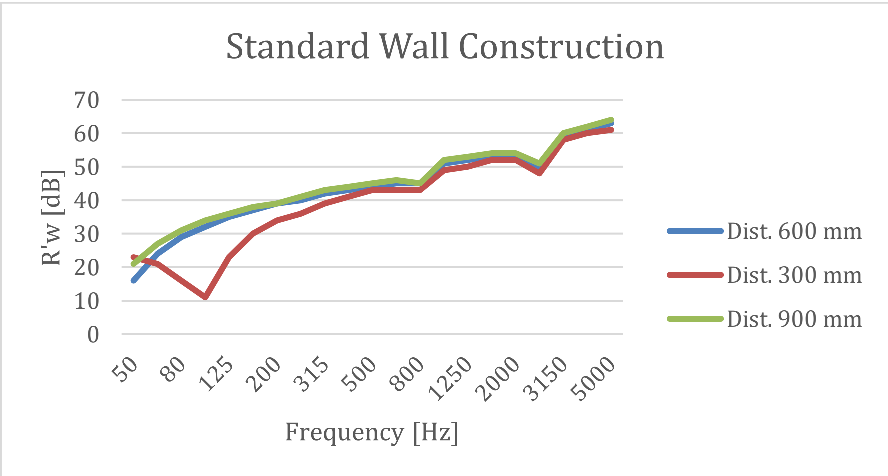


Figure 10. Sound insulation for the standard wall with different stud distance, depending on frequency.

5.5.2. "Soundwall" – Separated wall panels

The 220 mm studs of the standard construction were changed into two 95 mm wooden studs with a 30 mm air gap as a start, to keep the total thickness of the construction. In order to test the influence of the distance of the airgap, the construction (now named "The Soundwall" by Lindbäcks) was also modelled with 10 and 50 mm airgap respectively.

The change in sound reduction relative the standard construction is shown in table 5 below, with a comparative graph for the different frequencies in figure 11.

Table 5. Change in sound reduction for the "Soundwall" with different air-gap distances, relative the standard construction.

[dB]	Air gap 30 mm	Air gap 10 mm	Air gap 50 mm
ΔR_w	+2	+2	+2
$\Delta D_{nT,w}$	+2	+2	+2
$\Delta R_w + C_{50\text{-}3150}$	+3	+3	+3
$\Delta R_w + C_{tr,50\text{-}3150}$	+5	+5	+6

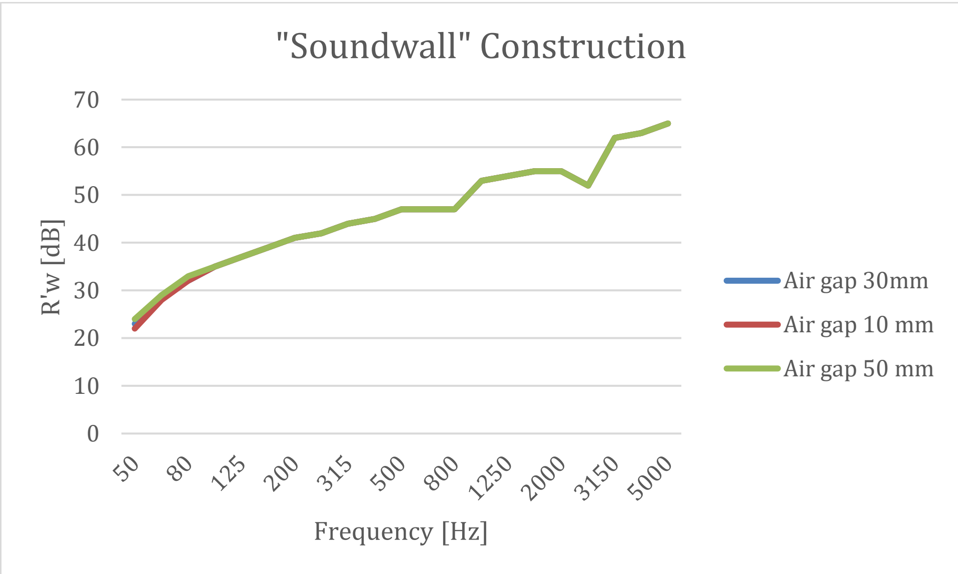


Figure 11. Sound insulation for the "Soundwall" with different air gap distance, depending on frequency.

5.5.3. Using a "Västkustskiva"

The modelling of the construction using the "Västkustskiva" were done in two versions, one with the standard construction as a base and one using the "Soundwall".

The "Västkustskiva" is made in three different dimensions; thickness 30 mm, 50 mm and 80 mm. The corresponding density is 110 kg/m^3, 80 kg/m^3 and 70 kg/m^3.

It should be noted that the "Västkustskiva" was not yet a part of Insuls database at the time, and the models were therefore made with the modified data of another similar product from Rockwool.

The change in sound reduction relative the standard construction is shown in table 6 and 7 below, with a comparative graph for the different frequencies in figure 12 and 13.

Table 6. Change in sound reduction for the Standard wall with "Västkustskiva" of different thickness relative the standard construction.

Standard construction with "Västkustskiva" (VKS)			
[dB]	VKS 30 mm	VKS 50 mm	VKS 80 mm
ΔR_w	-1	-1	-1
$\Delta D_{nT,w}$	-1	-1	-1
$\Delta R_w + C_{50\text{-}3150}$	-3	-3	-3
$\Delta R_w + C_{tr,50\text{-}3150}$	-4	-3	-3

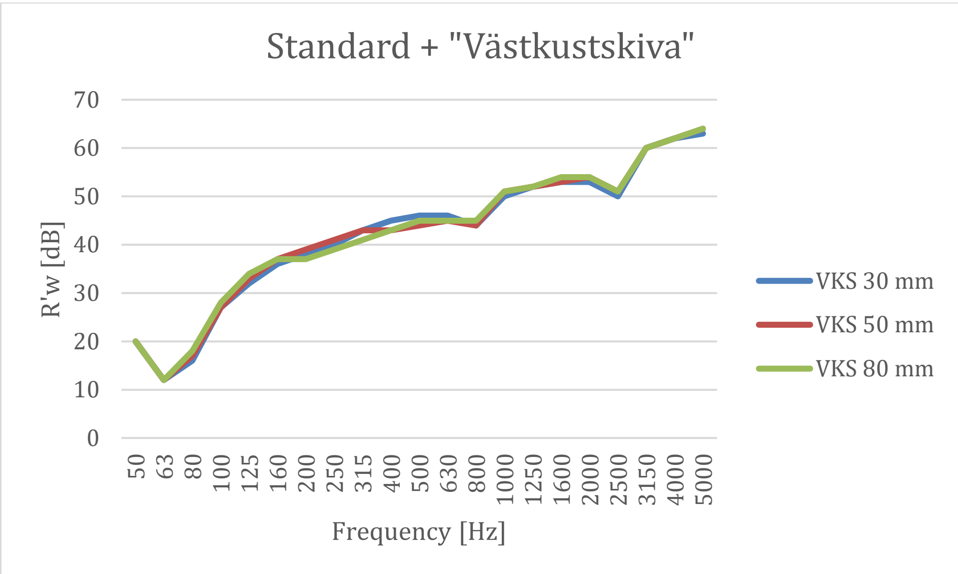


Figure 12. Sound insulation for the Standard wall with "Västkustskiva" of different thickness, depending on frequency.

Table 7. Change in sound reduction for the "Soundwall" with "Västkustskiva" of different thickness relative the standard construction.

"Soundwall" construction with "Västkustskiva" (VKS)			
[dB]	VKS 30 mm	VKS 50 mm	VKS 80 mm
ΔR_w	+2	+2	+2
$\Delta D_{nT,w}$	+2	+2	+2
$\Delta R_w + C_{50\text{-}3150}$	+4	+4	+4
$\Delta R_w + C_{tr,50\text{-}3150}$	+6	+7	+7

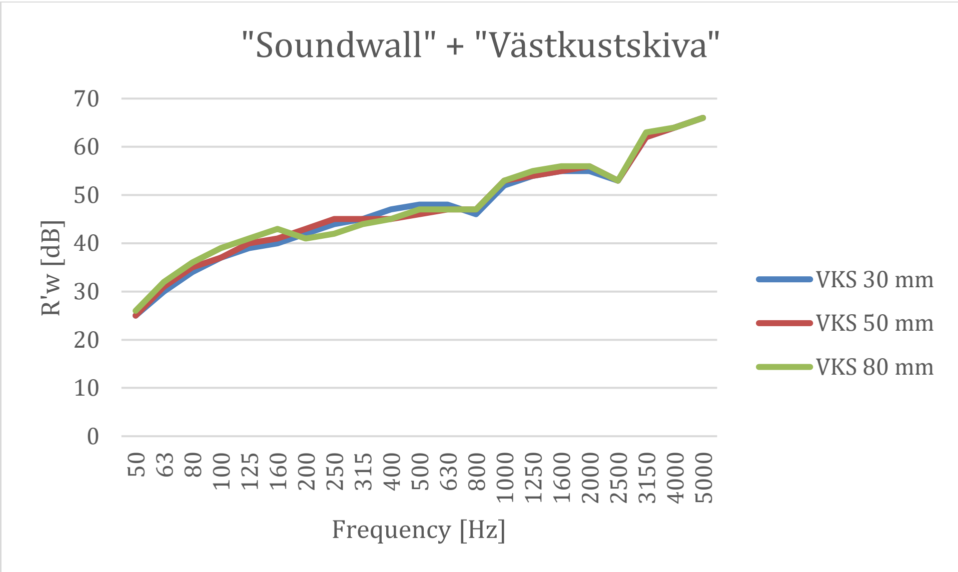


Figure 13. Sound insulation for the "Soundwall" with "Västkustskiva" of different thickness, depending on frequency.

5.5.4. Concept comparison

A comparative summary of the different concepts can be found in table 8 and figure 14 below. Since many construction variations perform about the same, the median variations were chosen to represent the construction.

Table 8. Comparative change in sound insulation for the different theoretical concepts.

[dB]	Dist. 300 mm	Air gap 30 mm	Standard VKS 50 mm	"Soundwall" VKS 50 mm
ΔR_w	-5	+2	-1	+2
$\Delta D_{nT,w}$	-5	+2	-1	+2
$\Delta R_w + C_{50\text{-}3150}$	-8	+3	-3	+4
$\Delta R_w + C_{tr,50\text{-}3150}$	-9	+5	-3	+7

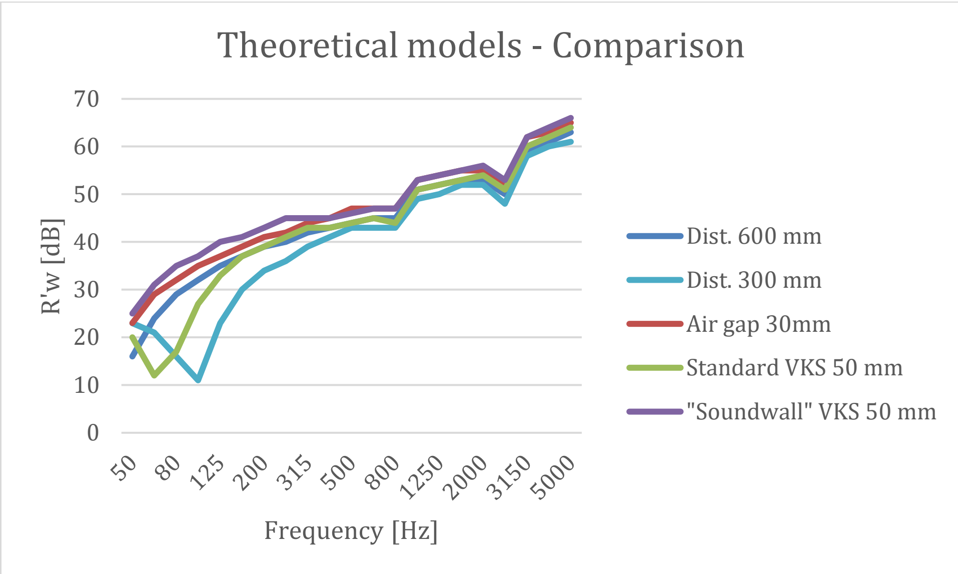


Figure 14. Comparative sound insulation for the different theoretical concepts, depending on frequency.

5.6. FEEDBACK

The most defining feedback from Lindbäcks Bygg AB was the need to, if possible, maintain the total thickness of the wall construction. This resulted in the final dimensions for the studs and the airgap in the "Soundwall" concept.

It was also decided to use the distance of 300 mm between the studs for that test, even though it performed worse theoretically. This because it is the normal distance used to strengthen the wall around a window, and it was deemed valuable to check the results with measurements.

5.7. CONSTRUCTION CONCEPTS

The series was validated by Tyréns acousticians and then finally taken back to Lindbäcks for the decision on which ones to manufacture.

In addition to the standard construction, two new wall constructions were sent for manufacturing by Lindbäcks Bygg AB – one with more studs and one with separated wall panels. Test with the "Västkustskiva" were made using the existing constructions, to save time and materials.

Below are the construction details, underlined text denotes changes from the standard construction.

5.7.1. Baseline – Standard construction

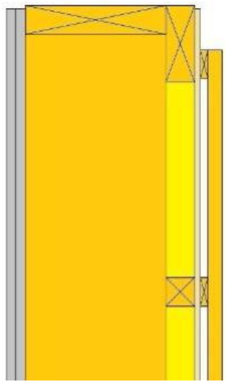


Figure 15. Standard facade construction.

2x15 mm gypsum board "Protect"
0,2 PE-foil
220 mm wooden studs, distance 600 mm, mineral wool between
45 mm wooden laths, mineral wool between
9 mm Glasroc composite board
28 mm wooden laths
22 mm standing wooden panel

The standard façade construction came with the module from the factory. It was measured as a baseline, to validate that the façade wall of the module performs in the same way as in the field.

The baseline construction was also dissembled in order to verify what impact the wooden panel has on the sound reduction, and if the result differ from the theoretical model and measurements in the field.

5.7.2. Phase 1 –More wooden studs

2x15 mm gypsum board "Protect"
0,2 PE-foil
220 mm wooden studs, distance 300 mm, mineral wool between
45 mm wooden laths, mineral wool between
9 mm Glasroc composite board
28 mm wooden laths
22 mm standing wooden panel

The standard façade construction was manufactured with a double amount of studs, in order to test if the added mass of the wall construction would compensate for the added number of connection points.

This construction was also disassembled in order to test the impact of the wooden panel, in the hope that the added stiffness of the underlying construction would mitigate the effect of the panel on the sound reduction.

5.7.3. Phase 2 – The "Soundwall"

2x15 mm gypsum board "Protect"
0,2 PE-foil
95 mm wooden studs, distance 600 mm, mineral wool between
30 mm airgap
95 mm wooden studs, distance 600 mm, mineral wool between
45 mm wooden laths, mineral wool between
9 mm Glasroc composite board
28 mm wooden laths
22 mm standing wooden panel

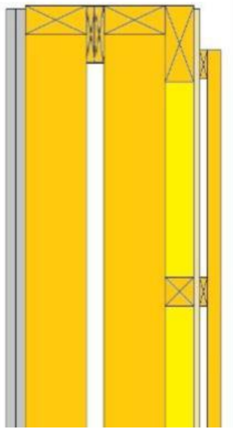


Figure 16. The "Soundwall" construction.

For the "Soundwall", the 220 mm wooden studs were exchanged for two 95 mm studs with an airgap of 30 mm. This was done to test how a minimum of connection points would change the noise propagation through the construction.

The "Soundwall" was not only made in order to test the impact of disengaging the two wall panels, but as with the other constructions the panel was disassembled in order to test if the sound reduction index is affected by it in the same way as with the standard construction.

5.7.4. Phase 3 – Adding a "Västkustsskiva"

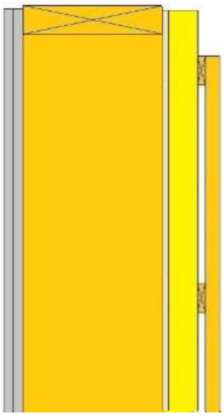


Figure 17. Standard with "Västkustskiva"

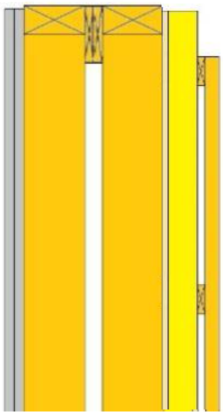


Figure 18. "Soundwall" with "Västkustskiva"

To test the effect of the "Västkustskiva", the previous constructions of the standard- and "soundwall" concepts were used again.

The change was instead that the outermost layers of

45 mm wooden laths, mineral wool between
9 mm Glasroc composite board
28 mm wooden laths
22 mm standing wooden panel

was changed to

9 mm Glasroc composite board
50 mm "Västkustskiva"
28 mm wooden laths
22 mm standing wooden panel

The setups with the "Västkustskiva" were done to test if a porous outermost layer (under the panel) would stop sound from propagating from the panel and into the rest of the structure.
Therefore, as with the other constructions concepts, the wooden panel were disassembled in order to measure its effect on the new constructions.

5.8. ITERATIVE CHANGES

As a result of the initial measurements, two alternative constructions were devised, manufactured and measured. The ideation process was done in collaboration with an upcoming project concerning the wall construction between apartment and corridor, as the experiences from the respective measurements and analysis could be combined.

5.8.1. Phase 4 – Slitted studs

In an attempt to improve on the "Soundwall" and make a façade that are easier to assemble in the factory, a construction was made where the studs were not separated, but instead slitted. The result was a construction with an in-built airgap.

5.8.2. Phase 5 – Vibration isolated studs

The previously discarded idea of using vibration isolators in the construction was made possible due to the collaboration with the corridor wall project. As the corridor wall was constructed in the factory, the existing 300 mm stud-distance façade wall was modified as well. The standard façade wall construction (600 mm stud-distance) could not be used due to the modifications done to it when measuring with the "Västkustskiva".

The change was instead that the outermost layers of

45 mm wooden laths, mineral wool between
9 mm Glasroc composite board
28 mm wooden laths
22 mm standing wooden panel

was changed to

10 mm vibration isolator (in the frame)
95 mm wooden studs, distance 600 mm, mineral wool between
9 mm Glasroc composite board
28 mm wooden laths
22 mm standing wooden panel

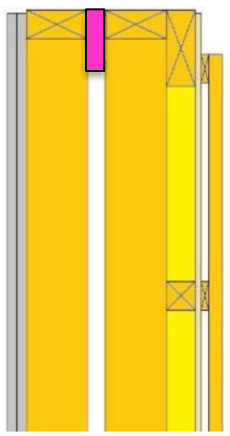


Figure 19. Construction with vibration isolated studs.

6. Results and Discussion

6.1. MEASUREMENT RESULTS

Presented below is the result of the measurements made on the different constructions mounted on the free-standing module. The results are given as change in sound reduction relative the standard construction, with spectrum adaption terms.

6.1.1. Baseline

The baseline measurements on the standard wall with 600 mm stud distance was made with and without panel and evaluated against the theoretical models.
The results are summarized in table 9 and figure 20 and 21 below.

Table 9. Standard wall construction – change in sound reduction relative to theoretical models.

[dB]	ΔR'w	ΔR'w +C	ΔR'w +C_{tr}	ΔR'w +$C_{50-3150}$	ΔR'w +$C_{tr,50-3150}$
Without panel	-2	-3	-3	0	+2
With panel	-4	-4	-4	-3	-3

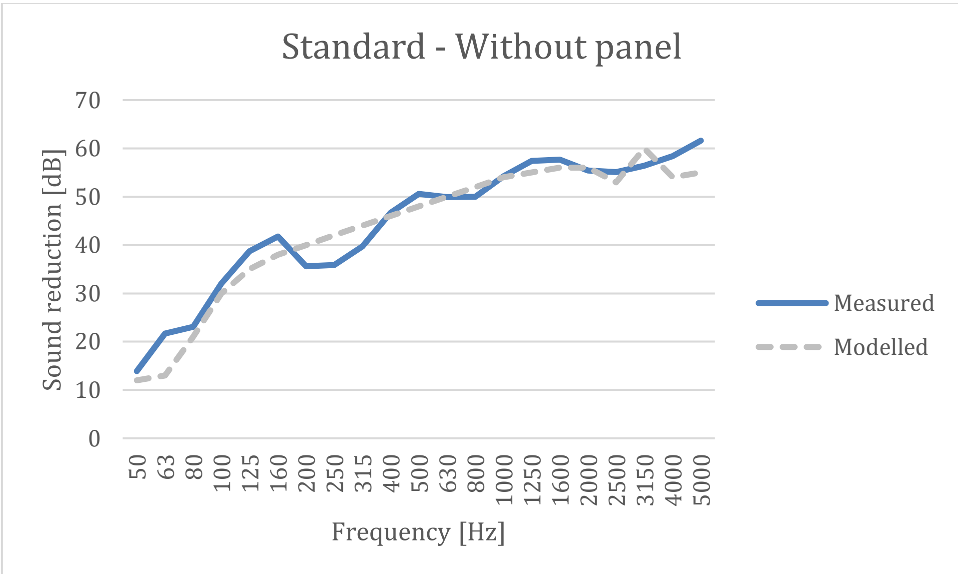


Figure 20. Standard wall construction - Without wooden panel.

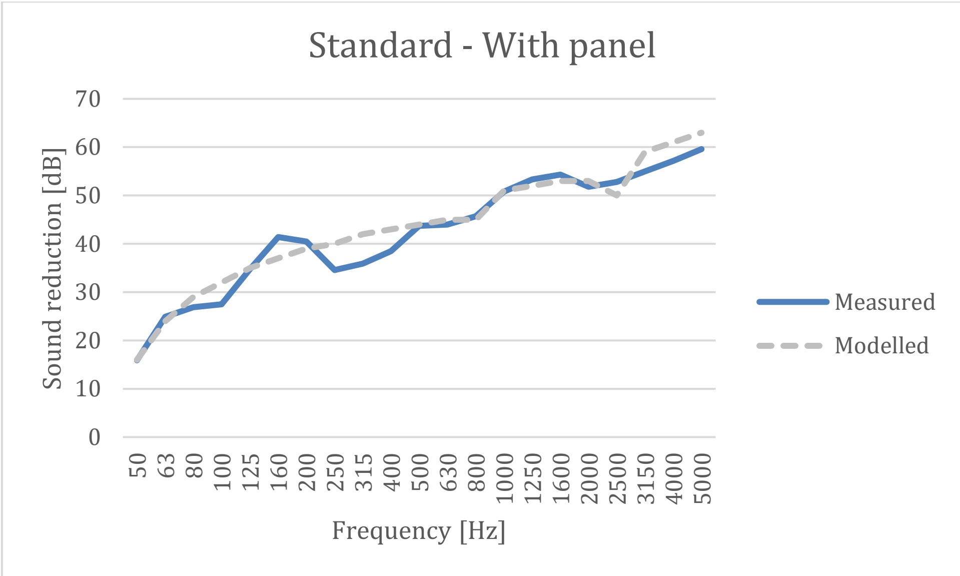


Figure 21. Standard wall construction - With wooden panel.

6.1.2. Phase 1

Measurements of the wall construction with 300 mm stud-distance were made without the wooden panel and evaluated against the theoretical model as well as the standard wall construction.
The results are summarized in table 10 and figure 22 below.

Table 10. Wall construction with stud distance 300 mm – change in sound reduction relative to the theoretical model and the standard construction.

[dB]	ΔR'w	ΔR'w +C	ΔR'w $+C_{tr}$	ΔR'w $+C_{50\text{-}3150}$	ΔR'w $+C_{tr,50\text{-}3150}$
Comp. to theory	*+3*	*+6*	*+8*	*+5*	*+1*
Comp. to standard	-1	-1	0	0	0

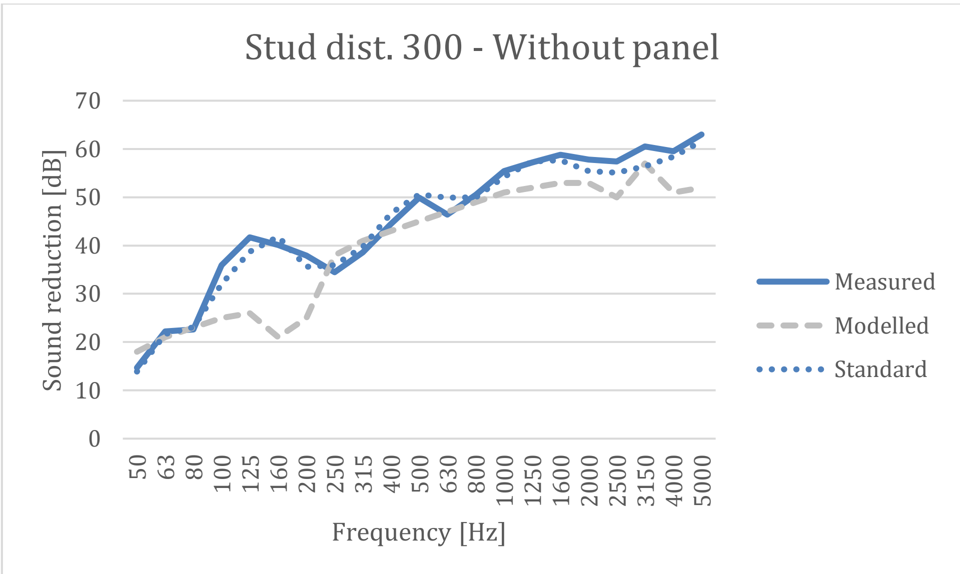


Figure 22. Stud distance 300 mm - Without wooden panel.

The “Soundwall” construction was made both with and without the wooden panel and evaluated against the theoretical models as well as the standard construction. The results are summarized in table 11 and figure 23 and 24 below.

Table 11. "Soundwall" construction - change in sound reduction relative to the theoretical model and the standard construction.

[dB]	ΔR’w	ΔR’w +C	ΔR’w $+C_{tr}$	ΔR’w $+C_{50\text{-}3150}$	ΔR’w $+C_{tr,50\text{-}3150}$
Without panel					
Comp. to theory	*-2*	*-2*	*-3*	*0*	*0*
Comp. to standard	+7	+7	+6	+6	+3
With panel					
Comp. to theory	*+1*	*+1*	*+1*	*+1*	*-1*
Comp. to standard	+3	+4	+5	+4	+7

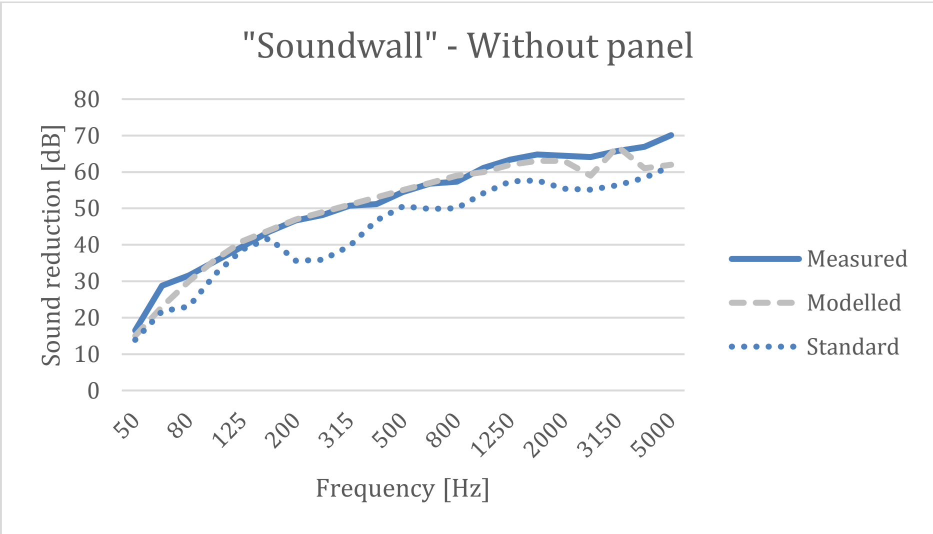


Figure 23. "Soundwall" - Without wooden panel.

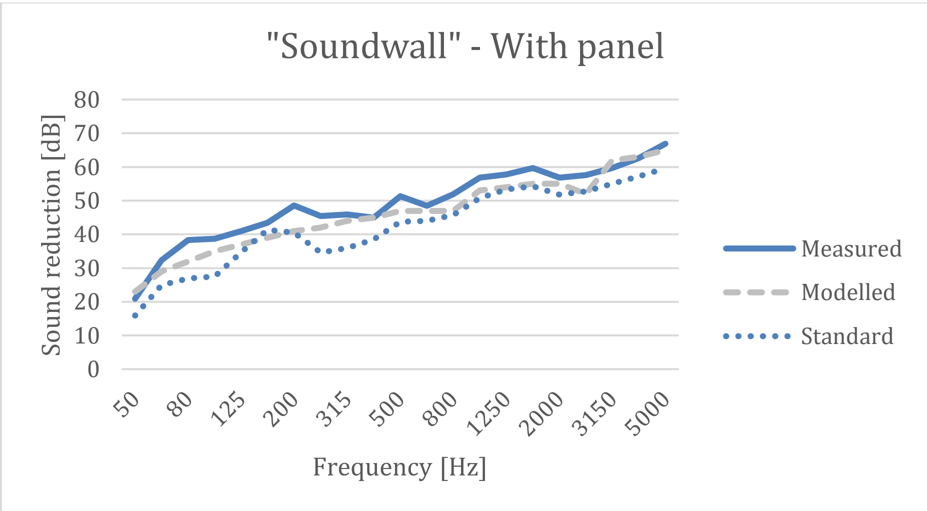


Figure 24. "Soundwall" - With wooden panel.

Measurements on the constructions using the "Västkustskiva" were made in two steps. First off was the modified standard construction. Results were evaluated against the theoretical model and the original standard construction and summarized in table 12 and figure 25 and 26 below.

Table 12. Standard construction with "Västkustskiva" - change in sound reduction relative to the theoretical model and the original standard construction.

[dB]	ΔR'w	ΔR'w +C	ΔR'w $+C_{tr}$	ΔR'w $+C_{50-3150}$	ΔR'w $+C_{tr,50-3150}$
Without panel					
Comp. to theory	*+17*	*+16*	*+14*	*+14*	*+4*
Comp. to standard	+2	+2	+2	+2	-1
With panel					
Comp. to theory	*0*	*-2*	*-1*	*+2*	*+5*
Comp. to standard	+3	+2	0	+2	+3

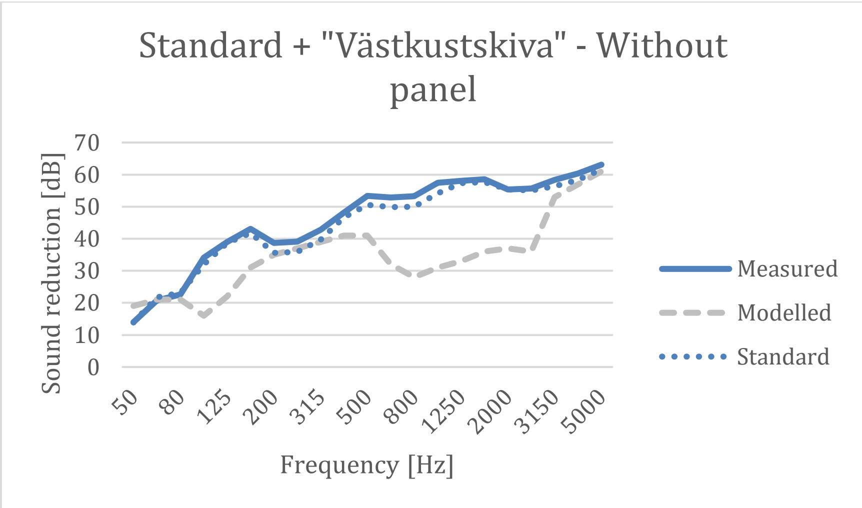


Figure 25. Standard wall construction with "Västkustskiva" – Without wooden panel.

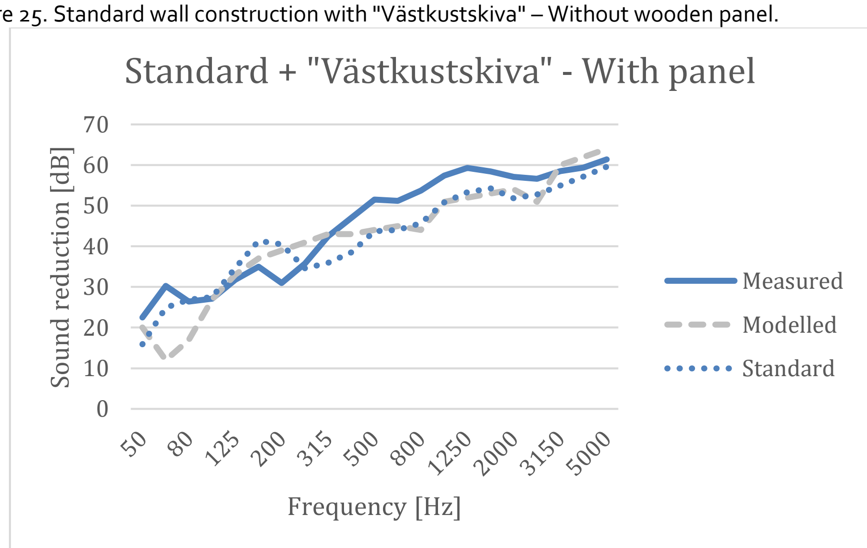


Figure 26. Standard wall construction with "Västkustskiva" – With wooden panel.

Then the modified “Soundwall” construction were measured and evaluated against the theoretical model as well as the original “Soundwall” construction. Results are summarized in table 13 and figure 27 and 28 below.

Table 13. "Soundwall" construction with "Västkustskiva" - change in sound reduction relative to the theoretical model and the original “Soundwall” construction.

[dB]	ΔR’w	ΔR’w +C	ΔR’w $+C_{tr}$	ΔR’w $+C_{50-3150}$	ΔR’w $+C_{tr,50-3150}$
Without panel					
Comp. to theory	*+4*	*+14*	*+12*	*+12*	*+2*
Comp. to ”soundwall”	-4	-3	-1	-2	0
With panel					
Comp. to theory	*+4*	*+3*	*+2*	*+2*	*-3*
Comp. to ”soundwall”	+3	+2	+1	+2	0

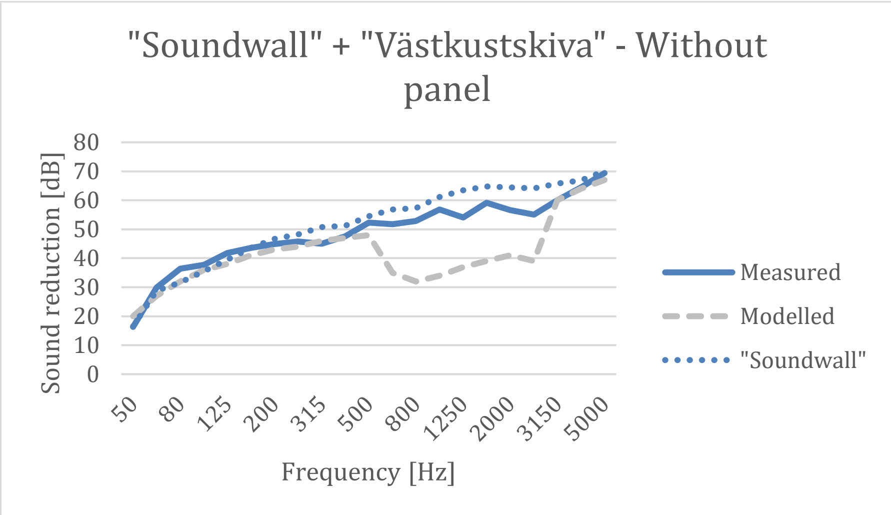


Figure 27. "Soundwall" construction with "Västkustskiva" – Without wooden panel.

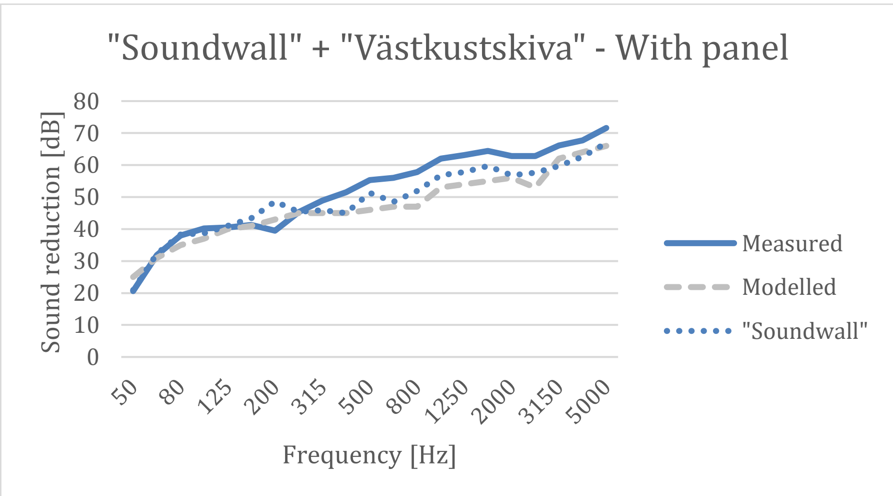


Figure 28. "Soundwall" construction with "Västkustskiva" – With wooden panel.

The wall construction with slitted studs proved not to be possible to theoretically model accurately using Insul and was therefore only evaluated against its “ancestor” – the “Soundwall” construction, as well as the standard construction, without the wooden panel.
Results are summarized in table 14 and figure 29 below.

Table 14. Construction with slitted studs - change in sound reduction relative to the original “Soundwall” construction and the standard construction.

[dB]	ΔR’w	ΔR’w +C	ΔR’w $+C_{tr}$	ΔR’w $+C_{50-3150}$	ΔR’w $+C_{tr,50-3150}$
Comp. to ”Soundwall”	-2	-1	+1	+1	+5
Comp. to standard	+5	+6	+7	+7	+7

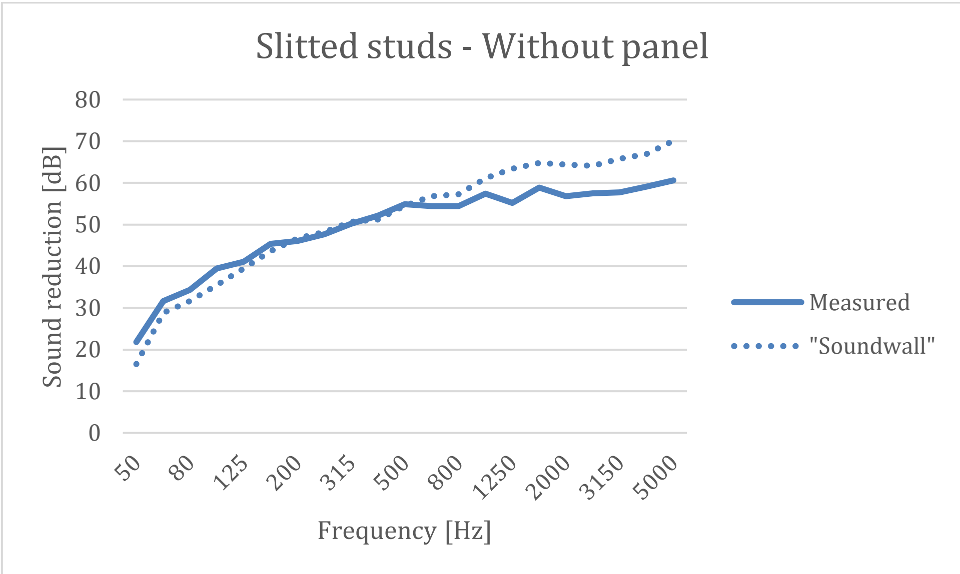


Figure 29. Construction with slitted studs - Without wooden panel.

Just as with the slitted studs, the wall construction using vibration isolators could not be accurately modelled in Insul and was therefore instead evaluated against the original construction with stud distance 300 mm, the "Soundwall" and the standard construction.

Results are summarized in table 15 and figure 30 below.

Table 15. Construction with vibration isolators - change in sound reduction relative to the original "Soundwall" construction, the standard construction, and the stud distance 300 mm construction.

[dB]	ΔR'w	ΔR'w +C	ΔR'w +C_{tr}	ΔR'w +$C_{50-3150}$	ΔR'w +$C_{tr,50-3150}$
Comp. to stud dist. 300 mm	+6	+7	+6	+6	+6
Comp. to "Soundwall"	-2	-1	0	0	+3
Comp. to standard	+5	+6	+6	+6	+6

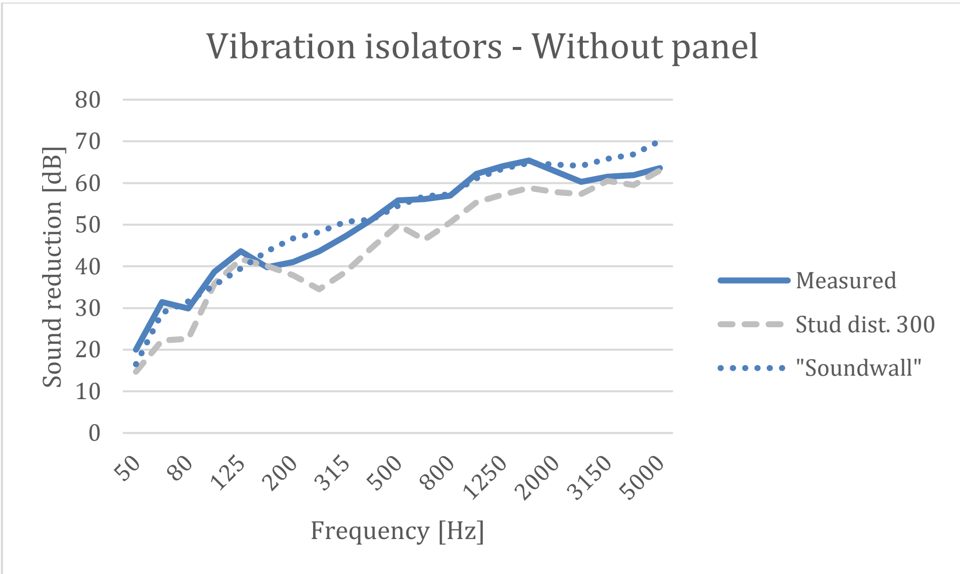


Figure 30. Construction with vibration isolators - Without wooden panel.

Table 16 features the compounded results of the measurements made. Figures 31 and 32 show a further comparison with and without panel, respectively, with the standard construction as a baseline.

Table 16. Summary of measurement results - change in sound reduction relative to the standard construction.

[dB]	ΔR'w	ΔR'w +C	ΔR'w $+C_{tr}$	ΔR'w $+C_{50\text{-}3150}$	ΔR'w $+C_{tr,50\text{-}3150}$
Dist. 300					
Without panel	-1	-1	0	0	+1
Soundwall					
Without panel	+7	+7	+6	+6	+4
With panel	+7	+8	+8	+7	+7
Standard + VKS					
Without panel	+2	+2	+2	+2	0
With panel	+3	+2	0	+2	+3
Soundwall + VKS					
Without panel	+3	+4	+5	+4	+4
With panel	+10	+10	+9	+9	+7
Slitted Studs					
Without panel	+5	+6	+6	+7	+8
Vibration Isolated Studs					
Without panel	+5	+6	+6	+6	+6

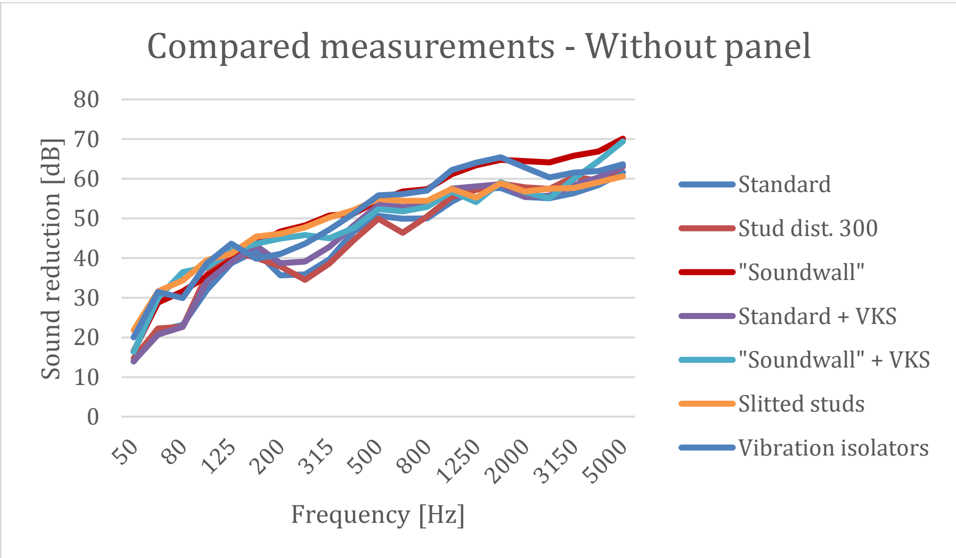


Figure 31. Comparison of measurement results - Without wooden panel.

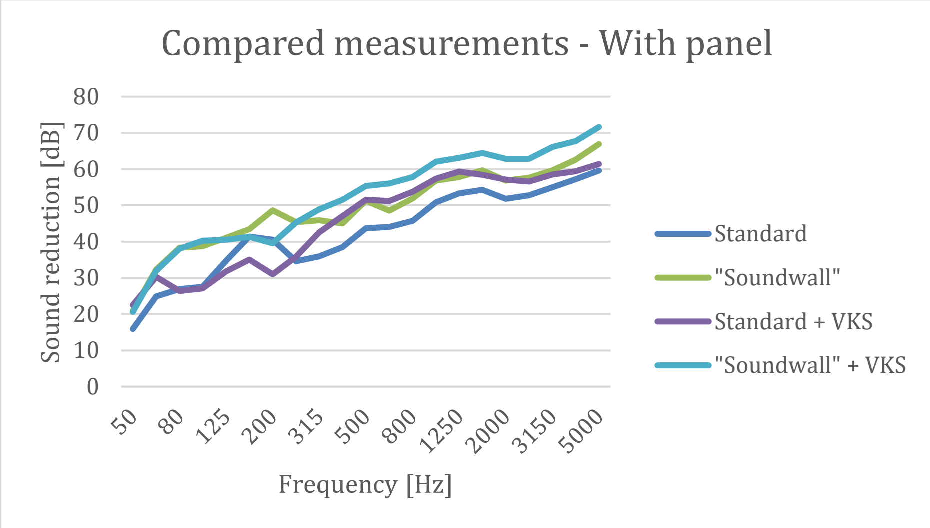


Figure 32. Comparison of measurement results - With wooden panel.

6.2. MEASUREMENT VERSUS THEORY

The results show that the measured results are in general as good as, or better than, anticipated from the theoretical models. The exception is the standard wall, where we see a dip in sound reduction around 200-250 Hz when measuring. This dip has been remedied in the "Soundwall", and we can also see that the results with wooden panels are better than calculated.

The biggest change in measurement versus theoretical result can be seen when using the "Västkustskiva" without the wooden panel. A possible explanation for this is that the outermost coating of the porous "Västkustskiva" impact the sound reduction more than the material database of Insul accounted for.

6.3. CHOICE OF FAÇADE CONSTRUCTION

In order to reach sound class B, a façade construction would need to have an improvement in sound reduction of at least 4 dB relative to the standard construction. This can be achieved with four of the construction concepts:

- The "Soundwall"
- The "Soundwall" + "Västkustskiva"
- The construction with slitted studs
- The construction with vibration isolators

The basic "Soundwall" construction is the most viable solution for mass production, since it is the concept that improve the sound reduction sufficiently with the least amount of modifications from the standard construction.

The construction with slitted studs were designed as an improvement on the "Soundwall", requiring less material and being easier to handle in the factory. The construction would however need to go through further testing to ensure that it for example are able to support a window, and that the acoustic results remain valid with such

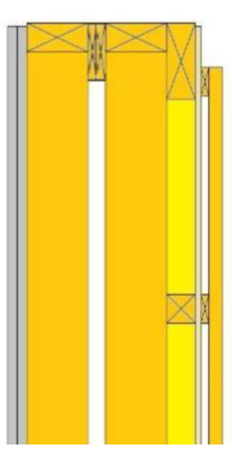


Figure 33. The "Soundwall" construction.

modifications.

The construction with vibration isolators is a more costly solution and will, according to Lindbäcks Bygg AB, therefore be viewed as a special case for demanding situations. The same goes for the solution with the "Västkustskiva", albeit not to the same degree.

It should be noted that the construction with slitted studs and the one with vibration isolators have not been measured with wooden panel. By basis on the measurement results this would mean that the increase in sound reduction for these constructions could be even greater. This would, however, have to be measured in order to validate the construction with wooden panel as well.

6.4. DISCUSSION

The theory section states that reducing noise in the low frequencies are a priority in order to counter stress and fatigue, as shown for example in table 3 (FoHMFS 2014:13). The low frequencies are reflected in the spectrum adaption terms, which makes it important that a new façade wall construction doesn't just fulfil the requirements for sound reduction index R'_w, but for $R'_w + C$ and $R'_w + C_{tr}$ as well. With the addition of the frequencies down to 50 Hz, the future façade wall construction has an extra layer of protection against low frequency disturbances.

The results show that the "Soundwall" construction increase the sound reduction of the façade with about 7 dB in the low frequencies ($\Delta R'_w + C_{tr,50\text{-}3150}$), which would greatly improve the sound environment for the tenants, and in the long run improve public health as well, as it will reduce the disturbance from low frequency traffic.

6.5. RELEVANCE

There is perhaps no doubt that the result presented in this master thesis is relevant to the stakeholders, albeit to different degrees.

Lindbäcks Bygg AB benefits from a more in-depth analysis of their existing and future façade wall constructions. The fact that there is a construction that satisfies the needs identified in housing projects being built in areas with higher-than-normal traffic noise levels is a comforting fact. Lindbäcks Bygg AB also projects that substituting the "Soundwall" for a wall with slitted studs is going to decrease production time and cost, as well as benefit the workers in the factory, as the slitted studs can be handled automatically by machines instead of being put together and transported manually.

Tyréns Sverige AB has gained an increased understanding of the acoustical workings of wooden façade constructions, both generally and specifically those of Lindbäcks Bygg AB. This adds to the knowledge base of the group and adds a layer of safety to the dimensioning of future housing projects, both modular and traditional.

Last, but not least, the tenants of the modular houses that Lindbäcks Bygg AB are about to build. The densification of our urban areas means that the houses are going to be built, one way or another. With the result of this master thesis project, wooden façade constructors have taken steps towards improving the sound environment for the people living in areas with high traffic noise levels, both objectively through the fulfilment of the standards, as well as subjectively through a better noise reduction in the disturbing low frequencies.

6.6. REFLECTION

Early in the project, the decision was made to evaluate the measurements using the standards for general sound reduction for walls, R'_w, instead of the ones for façade noise insulation, R'_{45}. The reason for this, and for not choosing the sound level difference, D_{nTw}, used as a simplified method when verifying constructions in the field, has been addressed earlier in this report. It has, in short, to do with the measurement setup and reproducibility. Measuring using only one loudspeaker, or with the module situated outside, and evaluating strictly according to the standard for façade noise insulation, could yield a different result, though it is believed to be on the marginal scale.

It also raises the question of the usefulness of the results to practicing acousticians. The result, as they are now, are a comparison between different constructions, and are helpful to Lindbäcks Bygg AB because of the knowledge Tyréns Sverige AB has about the standard construction, the baseline that everything is compared against. This makes the raw results hard to replicate for external stakeholders.

The measurements were made on only one construction of each type, on only one module, under very controlled conditions. This means that the results are vulnerable to flaws due to fabrication mistakes, assembly blunders and the general human factor. It should therefore be seen as a guideline, not an actual rule, and would have to be statistically validated, preferably in the field.

Because of the time limit many of the later measurements were done without the wooden panel. One of the initial questions for this master thesis was why the façade constructions with panel performed worse in the field than predicted. Measurements proved however that the "Soundwall" and subsequent constructions performed better than their theoretical models both with and without panel, leading to the decision to maximize number of constructions to be measured rather than testing the importance of the panel.

On a more general note, a bit of reflection about traffic noise is in order.

This master thesis has focused on solving the problem that comes from changing the traffic noise regulation, allowing for higher noise level at the façade of the building. By choosing to ignore the underlying problem with disturbances from traffic, the master thesis work is rounding a lot of resulting complications. This has been intentional, to narrow the scope and fit into the time frame but may still be addressed here.

A high noise level outside your window limits the desirability of opening said window, which in turn could be said to impact quality of life for the tenants. The same goes for balconies. According to the traffic noise regulation the tenants have the right to a quiet side and/or a protected patio however, which mitigates the situation somewhat. But one still has to leave the house sometimes and walking the dog or waiting for a taxi in an environment with sound levels of up to 85 dB is simply not desirable.

Sound is in some ways a subjective thing. As is stated in the theory section of this report, we tend to label undesirable sounds as noise. But the definition of undesirable is a harder one and will differ from person to person. The same goes for the more diffuse kind of noise. Some people are more sensitive to low frequencies and are more disturbed by the droning of traffic noise. Other have no problem with this but are instead disturbed by the children playing on the quiet side of the building. This thesis project has focused on the low frequency disturbance, mainly from traffic, in some areas at the expense of the higher frequencies. The conclusion is that even if we solve the objective problem of high noise levels inside from traffic and other external sources, we still have a long way to go to solve the subjective disturbance for everybody.

When this master thesis project began, there was an idea of testing the subjective experience of the different façade construction. This is done on similar projects focusing on for example the noise from walking feet on different floor constructions. Time limits, and limitations on the use of the module for measurements, made it hard to get the proper recordings made in order to set up a listening test. Hopefully this is something that can be done in a future project, as the end users experience of traffic noise disturbance using different façade constructions is a sorely neglected area of acoustic research.

6.7. CONCLUSIONS

6.7.1. Project objective and aims

The objective of the project has been to raise the quality of the acoustic environment for the tenants in modular apartments built by Lindbäcks Bygg AB.

As a baseline, the effects of traffic noise disturbance were researched. It was established that noise disturbance, specifically in the lower frequencies, impact the health of the tenants in apartments situated in areas with a high traffic load. Therefore, the improvement of the sound reduction in the lower frequencies were identified as the defining goal in order to improve of the acoustic environment of the modular apartments built by Lindbäcks Bygg AB.

Through research the master thesis project has identified the defining parameters for lightweight façade constructions in general, and the wooden constructions used by Lindbäcks Bygg AB in particular. The impact of the parameters has then been tested theoretically, and six construction concepts have been designed.

The construction concepts have been measured in order to determine the validity of the theoretical calculations, and to test the adequacy of each concept as a possible substitute to the façade construction used by Lindbäcks Bygg AB today.

Four of the proposed constructions proved to increase the sound reduction enough to reach sound class B in heavily trafficked areas. The constructions were then evaluated with the manufacturing process in focus, and the construction using slitted studs were deemed the most promising for future evaluation, due to its ergonomic and economic benefits.

As a sidenote, the master thesis project has also contributed to the parallel work of improving the sound insulation for the walls between apartment and corridors, which will further improve the acoustic environment of the apartments built by Lindbäcks Bygg AB in the future.

6.7.2. Research questions

What impact does the sound environment have on public health and residential?

Research, compiled in the literature review section of this report, show that background noise is one of the factors that influence the ability to apprehend speech, and therefore effect memory and concentration. Especially low frequency disturbances lead to increased fatigue and sleep disturbances, and by extension to stress and an increased risk for cardiovascular diseases (WHO, 2009).

The shown importance of low frequencies led to the inclusion of the spectrum adaption terms that include frequencies down to 50 Hz for the measurement results.

The 2017 revision of the traffic noise regulation raises the approved equivalent noise level at the façade of a building from 55 dBA to 60 dBA. An exception was also added for apartments smaller than 35 m^2, where an equivalent noise level of 65 dBA is allowed at the facade. The literature study shows that the adverse effects of indoor noise increase with 30% per 10 dB level increase (Public Health Agency of Sweden, 2019).

This increase means that the demand for sound insulation in façade wall constructions increase as well, since the approved levels indoors remain the same. The traffic noise regulation does not deal with the maximum traffic noise level either, other than at a noise protected side, which raise the stakes for façade wall constructions even more.

Analysis of the current façade wall construction used by Lindbäcks Bygg AB show that the sound reduction would have to be increased by at least 4 dB in order to counter the added traffic noise load that is the result of the 2017 changes in the traffic noise regulation.

What parameters affect the acoustic properties of a façade construction and what weaknesses can be identified in the constructions used today?

The literature review show that the sound reduction depends on the frequency and can for a single wall construction be divided into three areas controlled by the stiffness, the mass, and the critical frequency, respectively. In a double wall, in turn, sound propagates through the airgap, the studs and the edges (Anderson, 2017).

To test the different defining parameters above, the different construction concepts were theoretically modelled. The models showed that the use of an airgap increased sound reduction, as well as adding a layer of porous material to the construction. The number of studs in the wall had minimal effect on the sound reduction, only their composition, and the edges proved to be hard to influence due to the mode of assembly of the façade wall onto the module.

The results of the theoretical models led to the construction concepts sent to the factory for manufacturing, later to be measured.

How could a lightweight façade for modular housing be constructed in order to meet the requirements for sound dass B in areas with heavy traffic, and therefore improve the acoustical environment for the tenants?

The results of the measurements show that a façade wall construction would have to, in order to the increase sound reduction by at least 4 dB relative todays construction, be constructed either with an airgap between the studs, a layer of porous material directly under the wooden panel, slitted studs or vibration isolated studs.

The "Soundwall", with an airgap between the studs, are the easiest to implement, followed by the addition of a "Västkustskiva", a porous outer layer. Slitted or vibration isolated studs perform even better, but will need more testing, both acoustically and when it comes to other loads.

6.8. FURTHER WORK

The measurements have been made on a free-standing module. This partly isolates the results to the façade construction and does not test any problems that might occur during fabrication or assembly. More measurement would have to be made in the field, on finished buildings, in order to statistically verify the results.

A façade seldom exists without a window. The inclusion of the wall construction with stud distance 300 mm were made to test the sound reduction of the wall element when modified to support a window. The contribution of the window itself to the sound reduction of the whole façade wall has not been addressed, however. Parallel to this master thesis project, a window was installed in the different wall constructions and measured. The analysis would have to be done in a future project, in order to determine if the weight of the window, as well as different modes of installing the window, would influence the sound reduction of the new wall constructions.

As a parallel project, Tyréns Sverige AB has worked to improve the module walls between apartment and corridor. Knowledge from this project was integrated into the façade constructions, and vice versa. The corridor project has a greater possibility to test the assembling of the modules, and the mounting of a separate wall construction on the module. By continuing this project, important information can be carried over to continue the work with façade wall constructions.

Finally, the results of this master thesis project are focused on wooden panel as the outermost façade layer. Lindbäcks Bygg AB utilizes other materials as well for their buildings, and it is a recommendation to test the new constructions with these materials as well. This to verify that the results are valid throughout all Lindbäcks buildings.

7. References

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