

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**A SYSTEM PROPOSAL FOR FAÇADE APERTURES
TO PREVENT ACOUSTIC PROBLEMS OF
NATURALLY VENTILATED BUILDINGS**

M.Sc. THESIS

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Department of Architecture

Environmental Control and Construction Technologies Programme

JANUARY 2012

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

**DOĞAL HAVALANDIRMA OLAN BİNALARDA
AKUSTİK PROBLEMLERİN ÖNLENMESİ İÇİN
BİR CEPHE SİSTEMİ ÖNERİSİ**

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December 2011

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ABBREVIATIONS

SPL	: Sound Pressure Level
D	: Level Difference
RT	: Reverberation Time
P	: Root-mean-square Sound Pressure
P_{ref}	: Reference Pressure
TL	: Transmission Loss
Ms	: Surface Density
ρ_w	: Material Density
R	: Apparent Sound Reduction Index
R_w	: Weighted Sound Reduction Index
α	: Sound Absorption Coefficient
λ	: Wavelength
C	: Spectrum Adaptation Term (A-weighted pink noise)
C_{tr}	: Spectrum Adaptation Term (A-weighted urban traffic noise)
L	: Average Sound Pressure Level
L_{eq}	: Equivalent Sound Level During the Time Period of Interest
R_{1,2,3,4,5}	: Receiver Points
S_{1,2,3,4,5}	: Source Points
A	: Equivalent Sound Absorption Area
S	: Area of the Separating Element
V	: Volume
BNL	: Background-noise Level

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A SYSTEM PROPOSAL FOR FAÇADE APERTURES TO PREVENT ACOUSTIC PROBLEMS OF NATURALLY VENTILATED BUILDINGS

SUMMARY

The depletion of fossil energy resources and the damages of CO₂ emissions leads architects to design energy efficient systems. One of these passive systems is natural ventilation, which needs openings on the façade in order to have a way for air flow during the ventilation through these holes, also outdoor noise comes inside the building. Research about façade openings and their acoustic effects has been done in former years. Since these studies are mainly focusing on an existing building element like window and analyze it concerning design parameters, there aren't any system proposals which deal with concurrent natural ventilation and noise control.

The subject of this study is to propose a specialized double façade system which enables natural ventilation and noise control concurrently. By changing the position of openings in this system, it is intended to analyze the relationship between the distance of openings and the sound attenuation which is provided by the façade system.

The thesis is composed of four main sections.

In the first chapter, general concepts are explained and the aim of the study is defined.

In the second chapter, physical comfort requirements and importance of energy efficiency are mentioned. The terms indoor acoustic quality and annoyance due to noise are explained. Buoyancy and wind as main principles of natural ventilation are described and general terms of energy efficiency are stated. Background information and literature review about façade openings and their acoustic performance are explained. Regulations, as well as former and recent studies about the topic are presented.

In the third chapter, firstly, the proposed double façade system and stages of laboratory measurements are explained. Information about room properties of the laboratory, construction of the double façade with removable elements, standards related with measurement equipments and laboratory, terminology for the results, source and receiver positions are given respectively. The proposed system consists of particleboard panels and aluminium structure where each of the particleboard walls include twenty five removable grid elements that create façade openings. With the omni-directional source in the source room and the microphone in the receiver room, sound pressure levels in both rooms are measured and the sound reduction caused by the façade is calculated for each determined position. Secondly, the same setup is modeled in the room acoustics simulation program Odeon and finally the results of laboratory measurements and simulation calculations are compared. The results of laboratory measurements yielded that when the distance between the openings of the

façade system increases, the sound reduction of the façade increases as well. Although the materials and reverberation times were calibrated accordingly, the simulation results underestimated the sound reduction levels of the façade when compared to the measurements.

In the fourth chapter, the reasons of these differences are summarized and it is stated that current results are not reliable to continue the study by only simulation model calculations; therefore suggestions for future are given.

DOĞAL HAVALANDIRMA OLAN BİNALARDA AKUSTİK PROBLEMLERİN ÖNLENMESİ İÇİN BİR CEPHE SİSTEMİ ÖNERİSİ

ÖZET

Günümüzde fosil enerji kaynaklarının tükenmekte oluşu ve karbon salınımının doğaya verdiği zararlar sebebiyle pasif enerji sistemlerinin bina tasarımında önemi artmaktadır. Pasif sistem tasarımında en önemli değişkenlerden biri olan doğal havalandırmanın yapılarda uygulanması sırasında hava akışının sağlanacağı bir cephe boşluğuna ihtiyaç vardır. Bu durum, havalandırma açıklıklarından hava ile beraber dış mekan gürültüsünün de içeri girmesine neden olmaktadır. Cephedeki açıklıkların cepheye oranla boyutlarına bağlı olarak azalttıkları ses miktarı ve ortaya çıkan akustik problemlerin çözümüne yönelik olarak ilgili mevcut bina elemanı tipolojileri üzerinden yapılmış çalışmalar bulunmaktadır. Ancak, doğal havalandırma ile ses yalıtımını birlikte sağlayan cephe sistemi tasarımına yönelik çalışmalar henüz gelişme aşamasındadır ve araştırmanın bu konuya yenilikçi bir çözüm sunacağı öngörülmüştür. Bu bağlamda, çalışmanın amacı, doğal havalandırma sırasında iç mekana iletilen dış gürültünün azaltılmasını sağlayacak çift cidarlı yeni bir cephe tasarımı önerisi sunmak ve bu prototip üzerinden cephe sistemindeki boşluklar arası mesafenin değişiminin toplam ses azaltımını ne yönde etkilediğini saptamaktır.

Bu amaca yönelik olarak yapılan tez çalışması dört ana bölümden oluşmaktadır.

Bölüm 1’de, tezin genel hatları açıklanmış ve incelenecek konular hakkında bilgi verilmiştir.

Bölüm 2’de fiziksel konfor şartları ve enerji verimliliği kavramları hakkında bilgiler verilmiştir. İç mekan akustik kalitesinin insanlar üzerindeki etkileri anlatılmış, gürültünün kullanıcılara verdiği rahatsızlıklardan bahsedilmiştir. Daha sonra doğal havalandırmanın temel ilkeleri açıklanmış, rüzgar ve hava sıcaklıkları farkının nasıl taze havanın içeri girmesini sağladığı konularına kısaca değinilmiştir. Dünyadaki enerji tüketimi, havalandırma ve soğutmanın bu tüketimdeki payı ve bunun azaltılması için kullanılacak yöntemlere bağlı olarak enerji verimliliği konusu özetlenmiştir. Cephe açıklıkları ve bunların sebep olduğu akustik problemlerle ilgili literatür taraması yapılmış, bu konuda daha önce yapılan çalışmalar incelenmiştir. Konu ile ilgili yönetmelikler ve daha önce yazılan araştırma makaleleri ilgili detaylar verilmiştir. Doğal havalandırma ve bunun akustik performans üzerindeki etkisi anlatılmış, sonrasında ise yakın zamanlarda konu ile ilgili yapılmış araştırmalara yer verilmiştir. Bu araştırmalar genel olarak cephe sisteminde hangi elemanların nasıl ses azaltım etkisi yapacağına ve hangi özelliklere sahip cephe açıklıklarının nasıl ele alınması gerektiğine dair bilgiler içermektedir. İçinde konu ile ilgili detaylı araştırma bulunduran kaynaklardan Nanr116 proje raporunda ise hangi tip pencerelerin ses azaltımında ne rol üstlendiği konusunda bilgi vermektedir.

Bölüm 3'te, ilk olarak, projenin ana konusunu oluşturan yeni çift cidarlı akustik cephe sisteminin tasarımı, tasarım sürecinde öne çıkan parametreler, laboratuarda bire bir ölçekli duvar modelinin kurulumu, akustik ölçüm süreci ve sonuçların anlatılmasında kullanılan terminoloji açıklanmıştır. Ölçümlerde deneylerde gerçekçi sonuçlara ulaşmak için yeterli birim kütleye sahip olan ahşap yonga levhalar ve onları taşıyan alüminyum bir grid strüktür ile inşa edilen cephe, her iki tarafta yirmi beşer eşit boyutlu kare parçadan oluşturulmuş, bu parçaların parametrelere göre seçilen bazılarının yerlerinden çıkarılması ile çift cidarlı cephenin her iki tarafında cephe boşlukları yaratılmıştır.

Kaynak odasına yerleştirilen her yönde ses gönderen (omni-directional) hoparlör ve alıcı odasındaki mikrofondan sağlanan değerlere göre her iki hacimdeki ses basınç seviyeleri ölçülmüş ve bu bilgilerden yararlanılarak araştırmada önerilen çift cidarlı cephenin farklı cephe / cephe boşluğu oranlarında sahip olduğu akustik ses azaltım değerleri hesaplanmıştır. Örneğin alıcı odası tarafındaki duvardan 6 no'lu ve kaynak odası tarafındaki duvardan 16 no'lu grid parçaları çıkarılmış ve ölçüm sonucunda bu tip cephenin $R_w (C; C_{tr})$ değeri 28(0;0) olarak bulunmuştur. Alıcı odası tarafındaki 6 no'lu parça açık tutulmaya devam edilmiş, kaynak odası tarafındaki duvarda boşluk olarak açılan parçalar her seferinde birer kez yana kaydırılmak üzere sırayla 17, 18, 19 ve 20. parçalar çıkarılmış ve bu durumlar için ölçümler yapılmıştır. Gözlemlendiği üzere, duvarın iki tarafındaki boşlukların birbirine olan mesafesi arttıkça cephenin ses azaltım değeri de artmaktadır. $R_w (C; C_{tr})$ değerleri 17 no'lu parça çıkarıldığında 30(0;-1), 18 no'lu parça çıkarıldığında 31(-1;-1), 19 no'lu parça çıkarıldığında 31(0;-1) ve 20 no'lu parça çıkarıldığında ise 31(0;-1) olmaktadır. R_w değerleri son ölçümlerde benzer olsa bile, frekanslara göre ses azaltım değerleri incelendiğinde yine boşlukların arasındaki uzaklık arttıkça frekans bazında ses azaltımının arttığı gözlemlenecektir. Bir diğer ölçüm serisi de her iki duvardan bu kez ikişer parça çıkarılarak yaratılan boşluklarla yapılmıştır ve benzer değerlendirme sonuçlarına ulaşılmıştır.

Daha sonra bu deney prosedürlerinin aynısı bilgisayar ortamında modellenmiş, Odeon hacim akustiği programında ölçümlerin bir dijital temsili yapıp, laboratuvar sonuçları ile kıyaslanmıştır. Laboratuvar ortamı ile bilgisayar programında modellenen ortamların kalibre edilmesi amacıyla, kullanılan malzemelerin ses yutuculuk değerleri hesaplanmış ve bulunmuş, laboratuvardaki odalarda ölçülen reverberasyon süreleri baz alınarak en yakın sonuçlar elde edilecek biçimde Odeon verileri düzenlenmiştir. Buna rağmen Odeon, birçok durumda sonuçları laboratuvar ölçüm sonuçlarına göre ya daha yüksek ya da daha alçak olarak hesaplamaktadır. Bu durum, bilgisayar ortamının gerçek hayattaki ses fenomenlerini birebir yansıtamıyor oluşundan kaynaklanabilir.

Bölüm 4'te, tez çalışması kapsamında ele alınan konular ve önerilen cephe sisteminin sonuçları ortaya konmuş ve değerlendirilmiştir. Laboratuvar ölçümlerinden elde edilen sonuçlara göre, öngörüldüğü gibi çift cidarlı cephenin iç ve dış katmanlarındaki boşlukların birbirine olan uzaklıklarının artması durumunda cephenin ses azaltım değeri yükselmektedir. Bazı frekanslarda küçük sapmalar olmasına karşın sonuçlar beklenen yönde olmuştur. Bilgisayarda Odeon programında hesaplanan değerler incelendiğinde ise laboratuvar ölçüm sonuçları ile Odeon verileri farklılıklar taşımakta olduğundan, laboratuvar çalışmaları olmaksızın yalnızca bu programın kullanılarak çalışmanın devam ettirilmesinin sağlıklı olmayacağı gözlenmiştir. Çalışma, bu yenilikçi cephe sisteminin geliştirilmesi ve çalışmanın

devam ettirilmesi için öneriler belirtilerek sonuçlandırılmıştır. İleride yapılacak çalışmalarda, farklı açıklık kombinasyonları oluşturularak laboratuarda bunların akustik açıdan değerlendirilmelerinin yapılabileceği, en verimli biçimde çalışacak açıklık aralığının belirlenebileceği düşünülmüştür. Malzemede farklılıklara gidilip, çift cidarlı deney duvarının arasında kalan duvarların iç kısımlarının poliüretan köpük gibi yutucu bir malzeme ile kaplanıp, iki duvar arasında ses geçişi sırasında yansıyacak sesin yutularak ses azaltımının arttırılabileceği öngörülmüştür.

1. INTRODUCTION

Energy saving is an important issue by designing buildings today. Ecologic approaches lead architects to behave more carefully about protecting natural resources and therefore to design energy efficient buildings. Also the depletion of non-renewable resources makes it necessary to use green energy forms, especially in buildings where 80 % of the total energy of Turkey is consumed (Yılmaz, 2006).

Technology brought houses many comforts mostly by using extra energy. Thus, some conventional physical environment methods come out to solve this problem, but with modern materials and techniques this time. Natural ventilating, heating and cooling systems, solar shading devices, green roofs and day lighting systems are integrated into new structures in order to conserve energy. By using modern technology, energy can be produced with photovoltaic panels and wind turbines in the form of electricity. Also with the help of green algae, bio fuel can be produced and solid wastes from daily life can be turned into biomass.

Natural ventilation is an ecological solution for indoor air quality which has also economic benefits since no additional mechanical systems would be necessary. Since mankind has started building homes, it has been one of the main designing parameters because there should be fresh air inside houses. Today, natural ventilation can be achieved in different kind of methods like double facades, specialized facade - roof ventilation systems with air canals or chimneys. Also background trickle vents on windows are commonly used.

Acoustic comfort is one of the main building performance issues. It affects the living standard of users and therefore the value of the building directly. Especially in cities, undesired outdoor sounds like road traffic noise influence human psychology in a negative manner. Noise lowers the working performance efficiency in offices and also disturbs the habitants in residences. In order to prevent these kind of undesired cases, necessary acoustic precautions should be taken.

However, natural ventilation and sound insulation have contradictory principles to each other because natural ventilation requires openings on buildings' facades and openings reduce the acoustic insulation rate of the facade. This study starts with a background of basic information about open windows and provides a summary of recent research about natural ventilation and acoustic performance. The aim of this study is to propose a new double facade system which would provide natural ventilation with open windows and noise control at the same time. In order to test the performance of this structure, laboratory measurements and computer models are carried out. Laboratory measurements and simulation model calculation results are compared and analyzed in order to check the conformity of the simulation program to continue the study without measurements. In conclusion, suggestions and recommendations for future studies are given.

2. BACKGROUND OF THE STUDY

In this part of the study, the terms natural ventilation, acoustic comfort and energy efficiency will be defined according to literature sources and former researches about these topics will be represented. Since natural ventilation is one of the generally used traditional design techniques, its properties and its relevance to acoustic quality is to find in literature with a large date range.

2.1. Physical Comfort Requirements and Energy Efficiency

Building performance is dependent on subjects like thermal and acoustic comfort, energy efficiency, stability of the construction, fire resistance, safety, affordability, durability, legality and many other requirements. Besides visual and artistic design, architecture contains main topics like physical comfort issues. While fulfilling these requirements, buildings should also be energy efficient, as fossil fuel resources are getting depleted and carbon emissions threaten the nature of the world. Indoor acoustic quality and natural ventilation are two main topics which intersect on the point energy efficiency, as they must be treated concurrently to prevent undesired situations.

2.1.1. Indoor acoustic quality and annoyance due to noise

Indoor acoustic quality is one of the most essential building performance issues, as it influences human psychology in a direct manner. Due to technologic improvements, the quantity of machines and vehicles increase, which causes noisy environments. In modern times, noise is considered as a serious health problem (Ouis, 2001). Noise has always been a problem since ancient years but with increasing number of transportation vehicles in recent years, the noise control issue became necessary especially in cities.

Sound is the result of the propagation of a disturbance from a vibrating source in a medium, usually air. Every acoustic problem is composed of three main elements: a

sound source, a transmission path and a receiver. The best way to prevent noise would be to control the noise emission at the source itself. But for most cases, sound can firstly be attenuated on the transmission path (Ouis, 2001).

Outdoor noise affects the inner area of buildings, the transmitted sound depends on the buildings' façade properties. The difference between the average sound pressure level outside and inside determines the acoustic quality of the façade and other building elements in between. Human reaction to changes in level can be seen in Table 2.1.

Table 2.1: Human reaction to changes in level (Long, 2006).

Change in Level (dB)	Reaction
1	Noticeable
3	Very Noticeable
6	Substantial
10	Doubling (or Halving)

The former research paper states that inhabitants are mostly annoyed by road traffic as noise source (Kuerer, 1997). Figure 2.1 shows other annoying sources for residents.

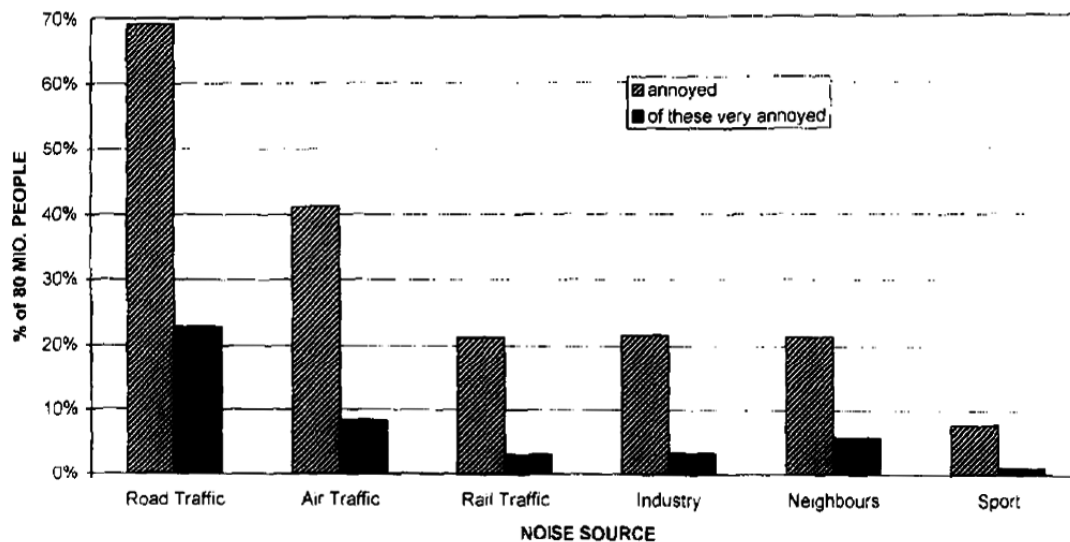


Figure 2.1: Noise complaints by German population in 1994 (Kuerer, 1997).

The same research continues by stating that people are unsatisfied with their neighborhoods mostly because of noise problems. Other discomfort reasons are also indicated in the Figure 2.2.

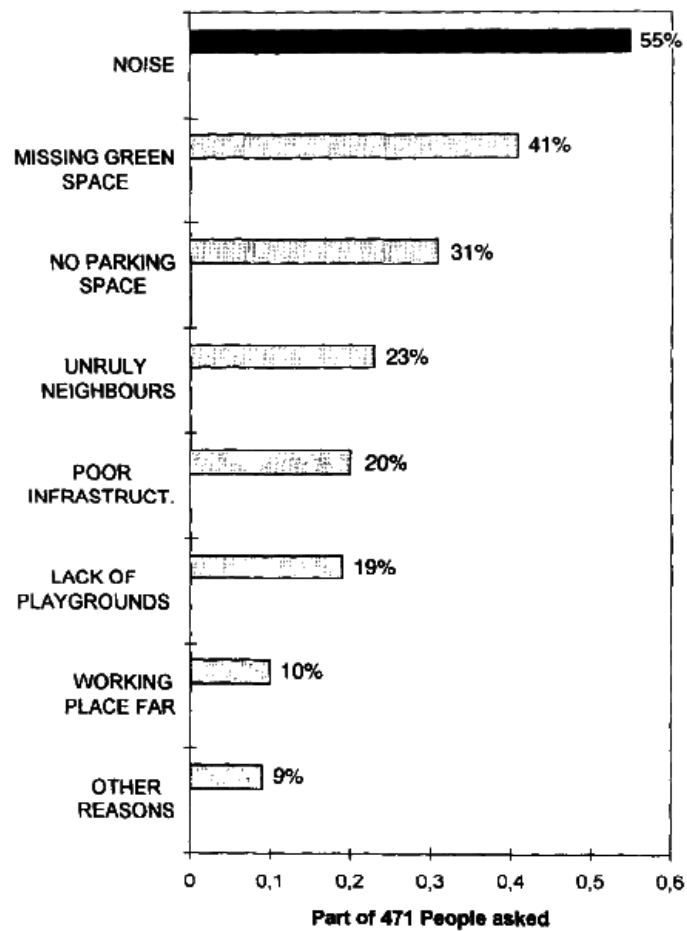


Figure 2.2: Dissatisfaction with neighborhood because of noise and other factors (Kuerer, 1997).

Traffic noise consists of cars' and heavy trucks' engine noises. The noise spectra for these vehicles can be seen in Figure 2.3. It can be inferred from the frequency spectra curve of a typical car that there is a heavier frequency content at around 1000 Hz. Therefore, noise control strategies should mainly focus on that frequency area. It can also be derived from the graph that heavy trucks create a noise which includes more lower frequencies.

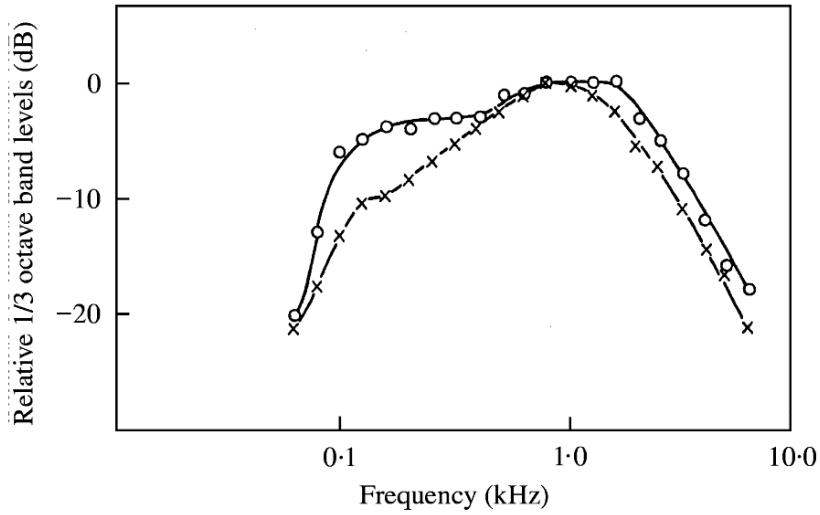


Figure 2.3: Normalized noise spectra for cars and heavy trucks. (-o- heavy trucks / -x- cars, both A-weighted) (Hayek, 1990).

Sound pressure level (SPL) is the most commonly used indicator of the acoustic wave strength (Long, 2006). It correlates well with human perception of loudness and can easily be measured. The reference sound pressure is set to the threshold of human hearing at about 1000 Hz for a young person. When the sound pressure is equal to the reference pressure the resultant level is 0 dB. The sound pressure level is defined as:

$$\text{SPL} = 10 \log \frac{p^2}{p_{\text{ref}}^2} \quad (2.1)$$

where:

p is the root-mean-square sound pressure [Pa];

p_{ref} is the reference pressure [2×10^{-5} Pa].

Figure 2.4 shows usual noise sources with their typical frequency content and their position on a sound level scale. It can be observed from the graph that traffic noise has a high sound pressure level which can be annoying for people.

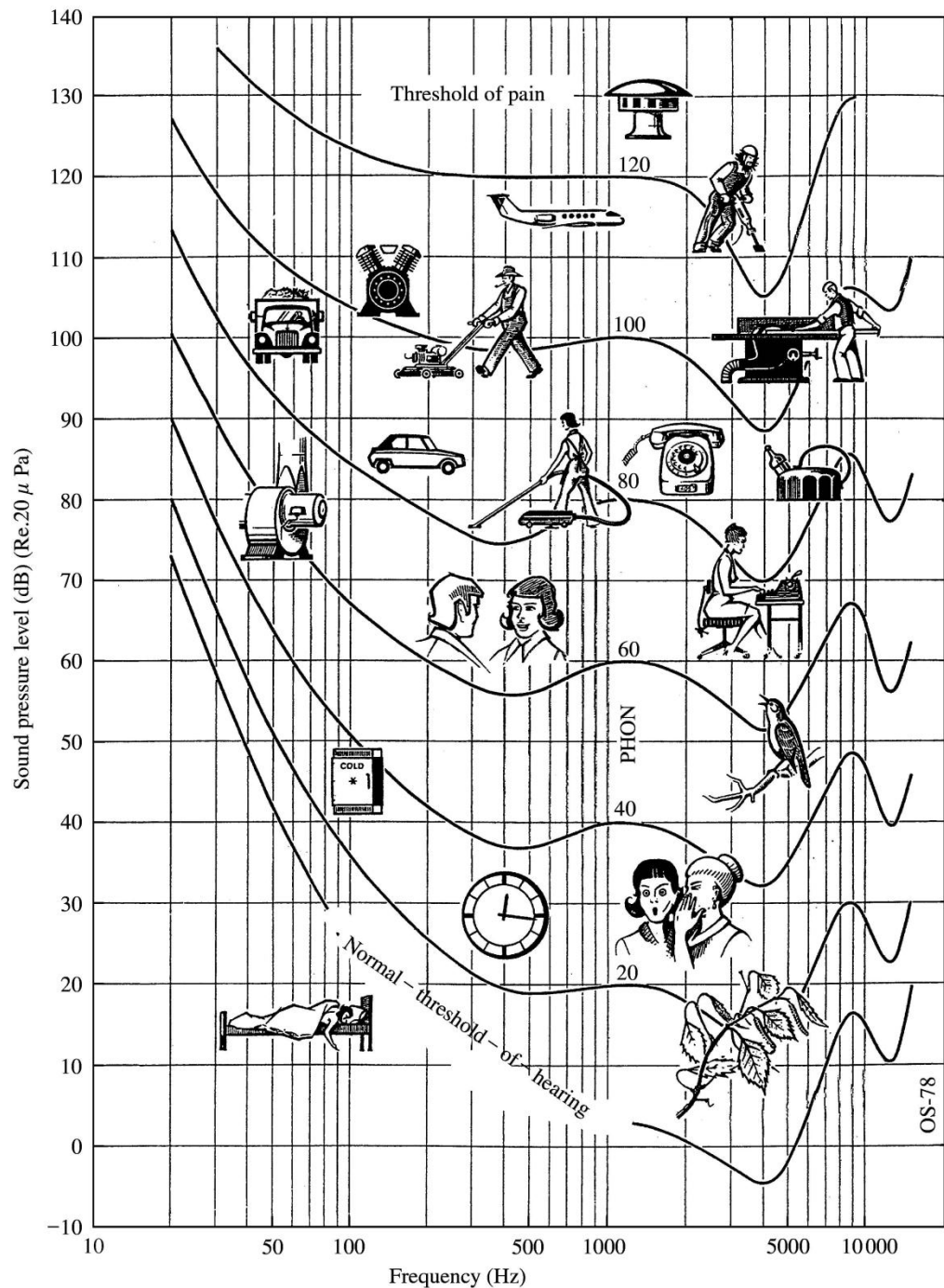


Figure 2.4: Sound levels and frequencies of common noise sources (Ouis, 2001).

The phon curves show for each frequency the perceived equal loudness. Human ear is less sensitive at low frequencies as it can be seen from the Figure 2.5. As it becomes harder to attenuate noise with barriers due to the longer wave length when frequencies get lower, this characteristic of human ear simplifies the situation by sound insulation.

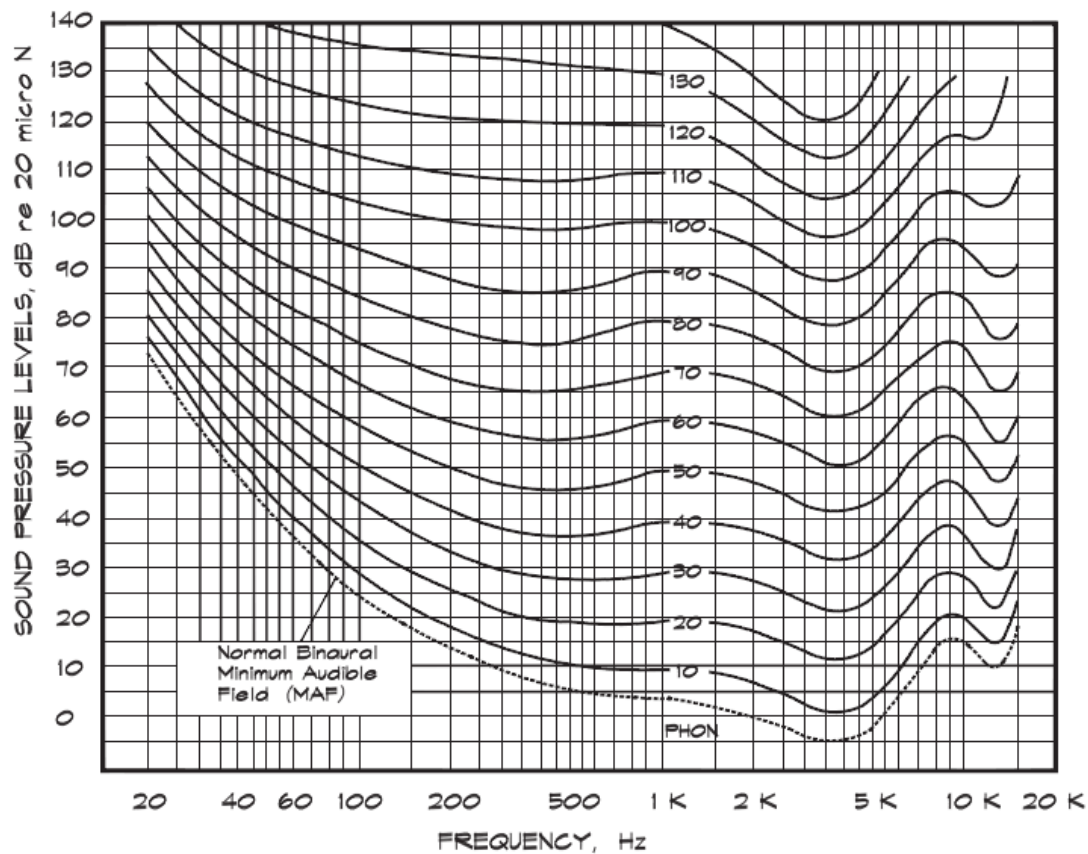


Figure 2.5: Normal loudness contours for pure tones (Long, 2006).

2.1.2. Natural ventilation

In warm periods of the year, indoor temperature may rise due to gains which would make the inhabitants physically uncomfortable. There are different ways to handle this problem like preventing sun rays from entering the building by solar control elements, preventing increases in heat due to conduction through the building skin by thermal isolation and replacing the hot inner air by fresh external air at a suitable temperature by natural ventilation as shown in the Figure 2.6 (Goulding, Lewis, & Steemers, 1992).

Natural ventilation is a conventional method used for providing fresh air and cooling inner space of buildings. It is also applied by modern architecture works in terms of being ecologically efficient. Naturally occurring differences in wind or air pressure enables cooler fresh air to come inside the building. The rate of heat loss by convection from the building envelope can be accelerated by the wind. This procedure is generally recommended for hot and humid climates.

There are two main types of natural ventilation: Cross and single sided ventilation. The driving forces for natural ventilation are wind and thermal buoyancy (Allocca, Chen, & Glicksman, 2003). Differences in wind pressure along the façade and differences between indoor and outdoor temperatures create a natural air exchange between indoor and outdoor air.

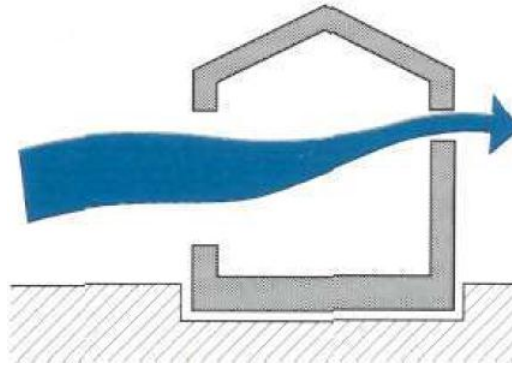


Figure 2.6: Drawing representing cross ventilation (Goulding, Lewis, & Steemers, 1992).

By buoyancy-driven flow, temperature difference between indoor and outdoor environment causes a density difference because warm air is less dense than colder air. A pressure difference occurs as a result. If two windows are open, one at the top and the other at the bottom of the space, cool air will flow into the lower opening and warm air will flow out of the upper opening. If there is a single opening in the space, the same air distribution will occur in borders of that opening. Figure 2.7 explains the air flow phenomena for these cases (Allocca, Chen, & Glicksman, 2003).

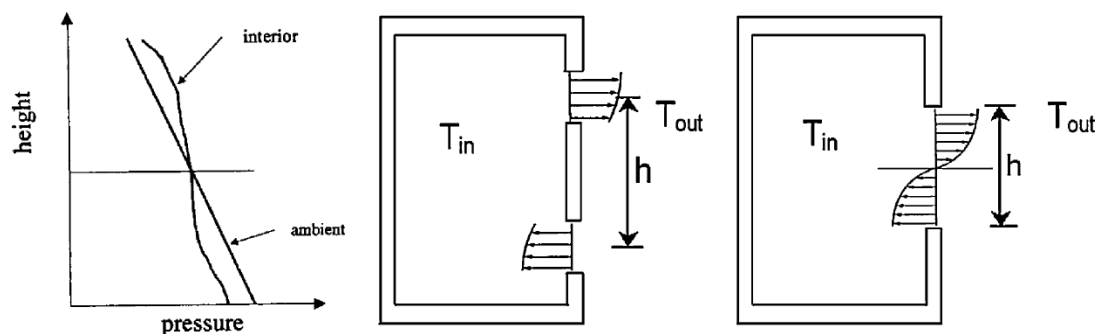


Figure 2.7: Indoor and outdoor pressure distribution for buoyancy-driven flow, causing flow through an upper and lower opening, or a single opening (Allocca, Chen, & Glicksman, 2003).

Wind driven flow's physical processes are complex because of the variability in wind conditions. Turbulence in the airflow along an opening causes simultaneous

positive and negative pressure fluctuations of the inside air. In most cases, buoyancy and wind-driven flow occur concurrently.

If the building is in a silent environment, choosing mechanical ventilation would be noisy due to engine sounds while natural ventilation has no additional sound except outdoor noise. Besides all the technical reasons, natural ventilation is also preferred by inhabitants because they appreciate having windows which they can open and have under control, instead of using air conditioning units. (Gratia & De Herde, 2007).

2.1.3. Energy consumption

Buildings account for 40% of the world's primary energy consumption and are responsible for about one-third of global CO₂ emissions (Eicker, 2009). Concerns about global warming and depletion of energy resources lead architects to make energy efficient designs.

More than half of the running costs of commercial buildings are accounted for by energy and technical services. A large part of the energy costs is due to ventilation and air conditioning (Eicker, 2009). Naturally ventilated buildings save energy which makes them more preferable to buildings with active systems. Typically, the energy cost of a naturally ventilated building is 40% less than that of an air conditioned building (Allocca, Chen, & Glicksman, 2003).

2.2. Regulations and Former Studies About Façade Openings

Facades provide acoustic insulation besides their other functions like thermal insulation, water insulation, sun shading and providing visual privacy. Except the parameters like material density, thickness and layers of the facade, the transmission loss value of the facade depends on the openings and their sizes.

Table 2.2 shows the approximate transmission loss values of facades with openings, depending on the percentage of the opening to the whole facade wall (Rossing, 2007).

Table 2.2: TL values for different air opening percentages (Rossing, 2007).

Wall area having air opening (%)	Resultant wall TL (dB)
0,01	39
0,1	30
0,5	23
1	20
5	13
10	10
20	7
50	3
75	1
100	0

In order to provide a basic scientific guidance about acoustic performance of open and closed windows, series of research are done and regulations are established according to their findings. One of these studies shows that the expected sound insulation performance of an open window according to international and regional standards is approximately between 10-15 dB (Nunes, Wilson, & Rickard, 2010). A detailed summary information about former research, findings and regulations about open window acoustic performance is given in the Nanr116 – “Open – closed window research” report of Napier University as shown in the Table 2.3 (Napier University, 2007).

Table 2.3: Summary of open-window acoustic transmission literature (Napier University, 2007).

Information Source	Summary of Findings
PPG 24 (1994)	A reduction of 13 dB(A) from the facade level is assumed for an open window
WHO (1999)	A reduction of 15 dB from the facade level is assumed for a partially open window. (no reference)
BS 8233 (1999)	Windows providing rapid ventilation and summer cooling are assumed to provide 10 - 15 dB attenuation (no specific reference)
BRE Digest 338 (1988)	A partly open window has an averaged level difference, $D_{1m,av100-3150}$ of 15 dB
DoE Design Bulleting 26 (1972)	A reduction of 5 dB(A) with a window wide open
Nelson - Transportation Noise (1987)	Sound insulation of an open single window is 5 – 15 dB. (theoretical)

Table 2.3 (continued): Summary of open-window acoustic transmission literature (Napier University, 2007).

Mackenzie & Williamson DoE Report (1972–73)	A vertical sliding sash window open 0.027 m ² (summer night-time ventilation) and 0.36 m ² (daytime summer ventilation) provided a sound level reduction of 16 and 11 dB(A) respectively. (Lab Study)
Kerry and Ford (1973–74)	A horizontal sliding sash window open 25 mm and 200 mm provided averaged sound reduction indices, R_{av} of 14 and 9 dB respectively. (Field Study)
Lawrence and Burgess (1982 – 83)	A vertical sliding sash open 9% of the total façade provided a sound reduction index R_w 10 dB. (Field study)
Hopkins (2004)	Road traffic noise reductions through window openings resulted in reductions of between $D_{2m,n,T}$ 8 and 14 dB. (Field Study)

According to former studies, while road traffic noise is attenuated 6,7 to 10,4 dB in a room with a facade with open windows depending on the room ceiling existence and material, the same room can have 26 to 29,9 dB of attenuation with closed windows as shown in the Table 2.4 (Buratti, 2002).

Table 2.4: Experimental results of Leq values with open and closed windows (Buratti, 2002).

	Mean Leq value emission room [dB(A)]	Mean Leq (0) value receiving room [dB(A)]	Mean Leq (1) value receiving room [dB(A)]	Mean Leq (2) value receiving room [dB(A)]
<i>Open window</i>				
Road traffic	83,5	76,8	75,9	73,1
Low speed railway traffic	86,2	80,0	79,1	76,2
High speed railway traffic	92,2	85,9	85,1	81,3
<i>Closed window</i>				
Road traffic	83,5	57,5	54,5	53,6
Low speed railway traffic	86,2	60,7	58,0	56,8
High speed railway traffic	92,2	63,5	62,0	58,8
Leq (0)= weighted A continuum equivalent level without false ceiling.				
Leq (1)= weighted A continuum equivalent level with panel no:1.				
Leq (2)= weighted A continuum equivalent level with panel no:2.				

Also regulations in Turkey mention the L_{eq} difference between closed and open windows (Turkish Ministry of Environment and Forestry, 2008). The “Limit values for indoors noise level” chart which is included in the “Regulation on the assessment and management of environmental noise” proposes L_{eq} values for rooms with different purposes (Table 2.5). Two different cases are defined for each function, which are called “closed windows” and “open windows” and 10 dBA differences between these two cases are called as acceptable.

Table 2.5: Limit Values for Indoors Noise Level (Turkish Ministry of Environment and Forestry, 2008).

Area of Use		Closed Windows L_{eq} (dBA)	Open Windows L_{eq} (dBA)
		Values while there is not any activity within the areas of use:	
Areas of Cultural Facilities	Theater halls	30	40
	Cinema palaces	30	40
	Concert halls	25	35
	Conference halls	30	40
Areas of Health Facilities	Inpatient treatment establishments and institutions, dispensaries, polyclinics, nursing homes etc.	35	45
	Lounges and treatment rooms	25	35
Areas of Educational Facilities	Classrooms at schools, private education facilities, kindergartens, laboratories etc.	35	45
	Gymnasium	55	65
	Dining hall	45	55
	Bedrooms in kindergartens	30	40
Areas of Tourism Facilities	Hotels, motels, holiday villages, guesthouses and similar bedrooms	35	45
	Restaurants at rest areas	35	45
Protected Areas	Archeological, natural, urban, historical, etc.	55	65
Commercial Buildings	Large offices	45	55
	Meeting rooms	35	45
	Large typewriter or computer rooms	50	60
	Game rooms	60	70
	Private offices (practical)	45	55
	General offices (accounting, clerical sections)	50	60
	Trade centers, shops, etc.	60	70
	Commercial storages	60	70
	Restaurants	45	55

Table 2.5 (continued): Limit Values for Indoors Noise Level (Turkish Ministry of Environment and Forestry, 2008).

Public Establishments and Institutions	Offices	45	55
	Laboratories	45	55
	Meeting rooms	35	45
	Computer rooms	50	60
Sports Areas	Gymnasia and swimming pools	55	65
Dwelling Areas	Bedrooms	35	45
	Living Rooms	45	55

2.3. Relationship Between Natural Ventilation and Acoustic Performance

Since machine industry and transportation technology started to develop and modern life became more and more unnatural, especially in cities, the demand for natural solutions has increased. Population growth has led to more crowded cities and the traffic noise produced by vehicles has become overwhelming by the time. For natural ventilation, systematic apertures on the buildings' facades were needed and facades should also provide an insulation against outdoor noise for acoustic comfort of users.

Using windows is a common and usual way of providing fresh air. In order to achieve natural ventilation through windows, facade openings must be designed which would provide enough air-flow for inside. While obtaining an ecologic and energy saving ventilation system, the indoor acoustic quality must also be considered as a design parameter in terms of sustainability.

There is the conflict that street and traffic noise comes inside when windows are open. Especially in residential buildings where people are supposed to rest and sleep or in offices where people need concentration for working, outside noise is a great problem for users' living quality. If this acoustical problem could be solved in a systematical way, naturally ventilated buildings would be more often preferred in noisy environments like on a busy road with traffic noise.

The research about the relationship between ventilation, air quality and acoustics in buildings has measurement results indicating that in naturally ventilated spaces, the main factor influencing the ventilation rate is the status of the windows - open or closed (Khalegi, Bartlett, & Hodgson, 2007). In that research it is observed that the air-flow rates become approximately zero when the windows are closed. Also in terms of acoustics, in naturally ventilated buildings, the acoustical conditions depend

completely on the window status. Background-noise level (BNL) was low when the windows were closed, but opening the windows to increase the ventilation rate led to higher mid- and high-frequency noise.

2.4. Recent Studies About Acoustic Properties of Façade Openings Providing Natural Ventilation

In order to provide sound attenuation while having natural ventilation, different kind of systems can be used. Recent studies show that acoustic louvres, elevated screens, balconies, courtyards and porous duct linings can be used for attenuating mid to high frequencies; quarter wave resonators and Helmholtz resonators for low to mid frequencies; panel resonators and active noise control for low frequencies; and closable apertures for all frequencies, as it can be seen from Figure 2.8 (De Salis, Oldham, & Sharples, 2002), (Oldham, De Salis, & Sharples, 2004).

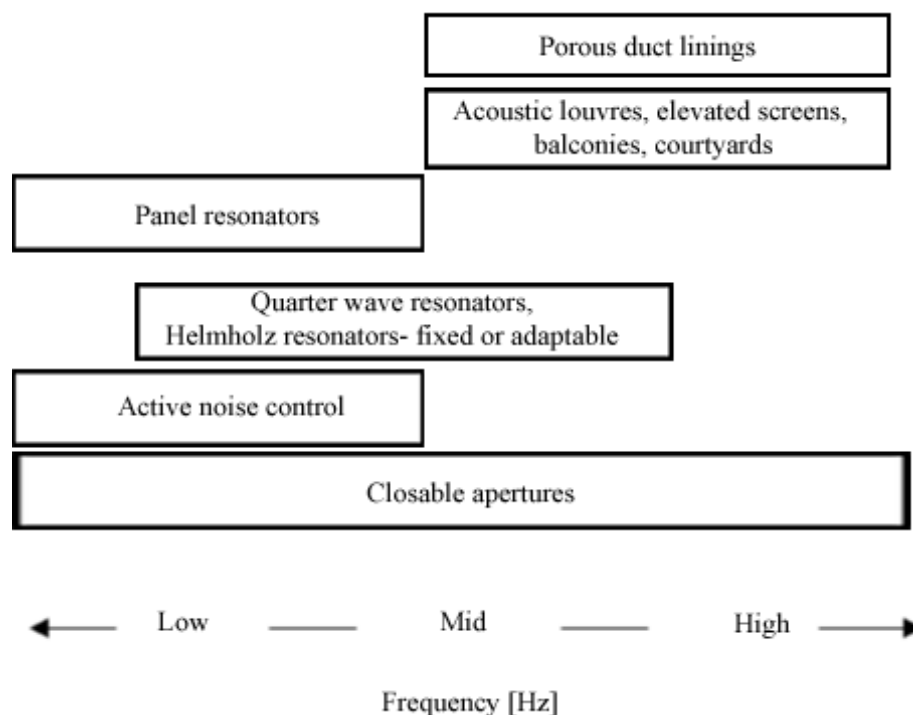


Figure 2.8: Frequency range of useful attenuation for noise control treatments (De Salis, Oldham, & Sharples, 2002).

Building barriers is a way of attenuating outdoor and also indoor noise. To provide any insertion loss, a barrier must break the line of sight between the source and the listener. Breaking this line of sight typically provides a minimum of 3-5 dBA of insertion loss, with insertion loss increasing as one goes further into the shadow zone

of the barrier. Because of diffraction, noise barriers are limited to 15 dBA of noise reduction capability, independent of the material (Rossing, 2007).

The scientific report of Napier University “Nanr116: ‘Open / Closed Window Research’ Sound insulation through vented domestic windows” provides results of a series of measurements done with seven window models and with a total of twelve different opening types (Napier University, 2007). The aim of that study was to quantify the sound insulation provided by a variety of window types, opening styles, areas of opening and ventilator devices. The investigation also tested the effect of incident noise angle on noise reduction. Open window sound transmission is assumed to be through a 0,05 m² opening and the measured Dw values are between 14 and 20 dB. A summary conclusion of the attenuation values is given in Table 2.6. It is also found that increasing the open area on the façade reduces the level of acoustic insulation. The glazing specifications and frame materials did not affect the sound attenuation of open windows. It is also interpreted from measurement results that the sound attenuation of open windows tend to increase when the noise incidence angle is greater.

Table 2.6: Nanr116 results showing sound attenuation of different windows & opening types (Napier University, 2007).

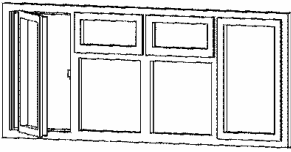
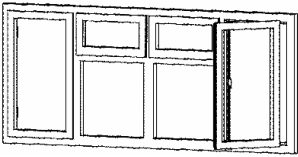
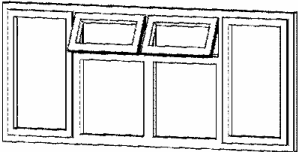
Window	Measurement	Opening	Comparative Level Difference (dBA)			
ID	Dw (C ; Ctr).	Illustration	D _{A,road}	D _{A,rail}	D _{A,air}	D _{A,music}
A-1	18(-1; -2)		17	17	18	16
A-2	18(-1; -2)		17	17	18	16
A-3	16(-1; -2)		14	14	16	16

Table 2.6 (continued): Nanr116 results showing sound attenuation of different windows & opening types (Napier University, 2007).

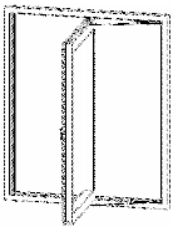
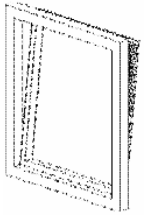
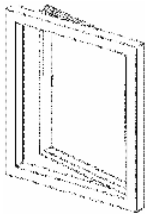
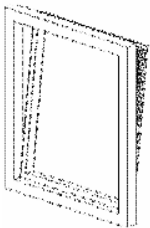
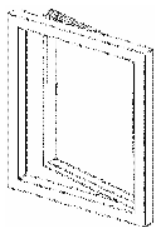
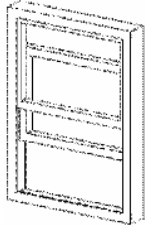
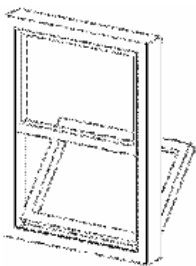
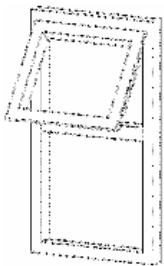
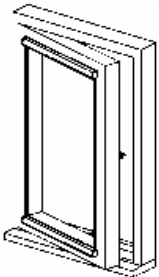
B	14(-1; -2)		12	12	14	15
C-1	17(-1; -1)		16	16	17	19
C-2	18(0; -1)		17	17	19	20
C-3	17(0; -1)		16	16	18	19
C-4	17(-1; -2)		15	15	17	18
D-1	18(-1; -2)		16	16	18	18
D-2	16(-1; -2)		14	14	16	17

Table 2.6 (continued): Nanr116 results showing sound attenuation of different windows & opening types (Napier University, 2007).

D-3	20(-3; -4)		16	16	18	18
E	17(0; 0)		17	17	18	18
F	18(0; -1)		18	18	18	18
G	15(0; 0)		15	15	15	17

From the results of Napier University's research report Nanr116, it can be inferred that no opening style shows significantly better insulating characteristics. It is also explained that an open slot ventilator within a window frame reduced the weighted closed window acoustic performance by 11 dB and this value decreased to 6 dB when the slots were closed. By open windows, the slot vents have a negligible effect on sound attenuation.

3. A NEW DOUBLE FAÇADE SYSTEM PROPOSAL

Taking these former studies into consideration, a double facade system model is proposed in order to have natural ventilation and indoor acoustical comfort at the same time. During the design stage of the façade system following sound phenomena are taken into consideration:

- Diffraction effect of barriers,
- Sound absorption by reflection,
- The attenuation due to the distance.

In this system, two particle board walls which are carried by an aluminium structure are designed. Each wall consists of twenty five removable parts, which are considered as windows of the façade system. By organizing these walls and the apertures on both walls according to parameters like “size of the openings”, distance between inner and outer facade”, “materials” and “dependence on frequency”, it is expected to have optimized sound attenuation against outdoor noise.

By arranging the openable windows *vertically reverse* situated on the inner and outer side of the double facade, direct sound paths from the lower side (e.g. traffic road) are prevented geometrically. Similarly, using a *shifted irregular aperture arrangement* on the inside and outside in the horizontal direction provides sound attenuation due to the diffraction effect of closed parts. As a potential problem in the lower frequency range, it can be foreseen that low frequencies would not be effectively attenuated because of their long wavelengths which enables them to pass through the smaller barriers. Regarding this potential problem, this research model could be improved and developed by using Helmholtz resonators around the apertures afterwards. Figure 3.1 represents the main principles of this system on a schematic plan diagram.

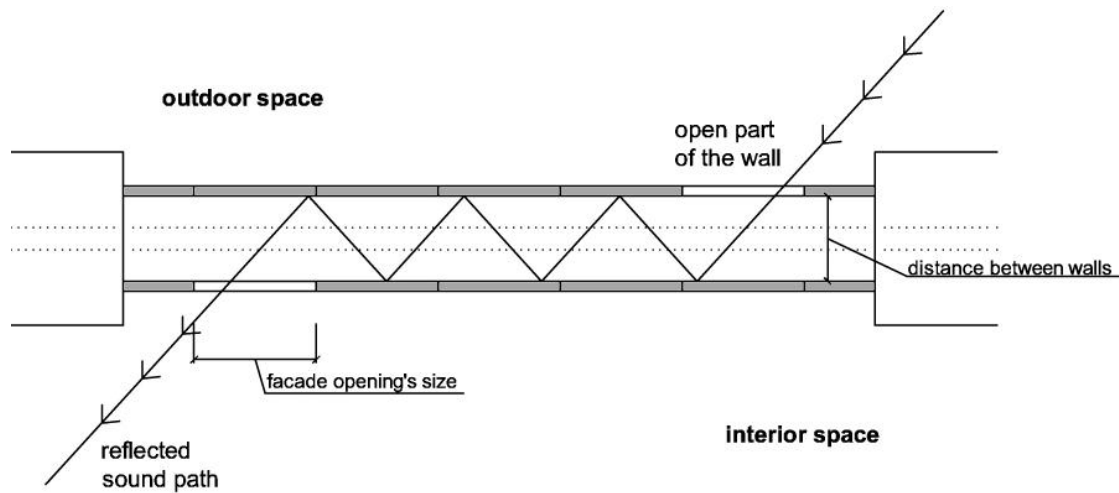


Figure 3.1: Schematic plan diagram showing the main principles of the proposed facade system.

3.1. Experiments In The Laboratory

A full scale model of the proposed double façade system is built up in the laboratory between two rooms. The source room represents outdoor space and the receiver room is considered as inner space of the building. The scale model represents the façade of a building's storey. It is aimed to build the model and to do acoustic measurement for different possibilities by removing or adding some of the grid panels of the walls, which would represent a different façade opening arrangement each time.

3.1.1. Room properties

Acoustic measurements are done in the Building Science and Technology Laboratory of Vienna University of Technology. The laboratory has two rooms with an opening between them which has the dimensions of 3,08 to 3,08 meters. These rooms' wall surfaces are highly reflective due to the concrete screed material. Due to this property, they are regarded as reverberation chambers by other measurements. Figure 3.2 shows the dimensional properties of the laboratory.

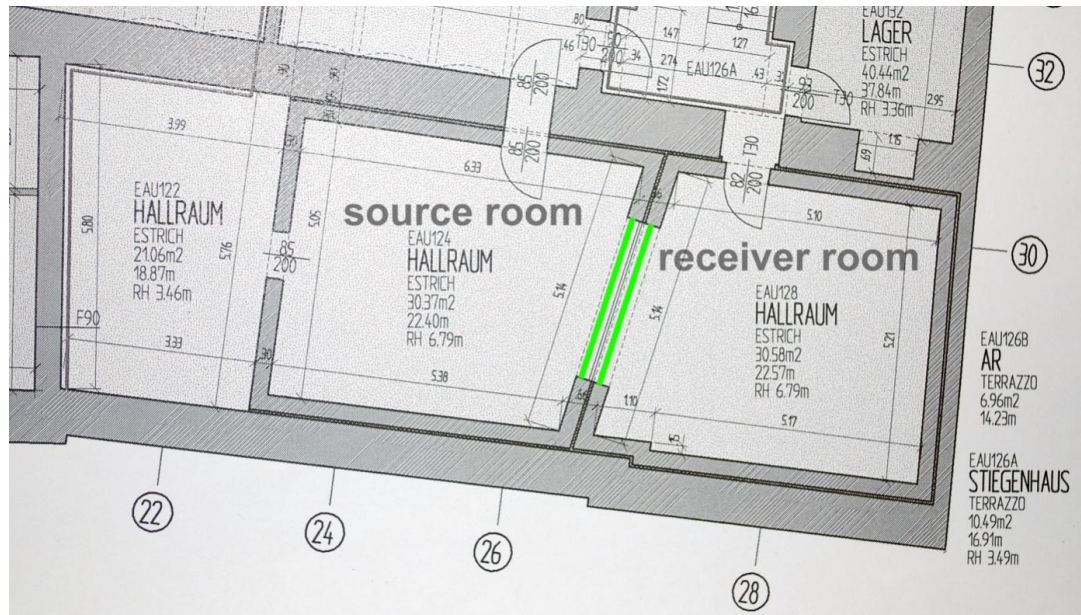


Figure 3.2: Existing drawings of the laboratory showing connections to other rooms.

Each room has a height of 6,79 m. The rooms' plans have the form of a trapezoid. The receiver room has the area of 30,58 m² and the volume of 207,64m³. The source room has the area of 30,37m² and the volume of 206,21m³. The wall between these two rooms, which has an opening inside, is 5,14 m long in total.

3.1.2. Construction of the walls with removable parts for acoustical measurements

A grid aluminium frame structure is designed for building up a double facade model in the opening between two reverberation chambers in the laboratory. The opening is 3,08 m high and 3,08 m wide. The distance between two walls of this double facade model is 35 cm. Each wall has a fixed frame part outside with the width of 29 cm. The five to five grid structure inside this frame consists of square divisions with the dimensions 50 x 50 cm. The dimensions of the structure are shown in the Figure 3.3.

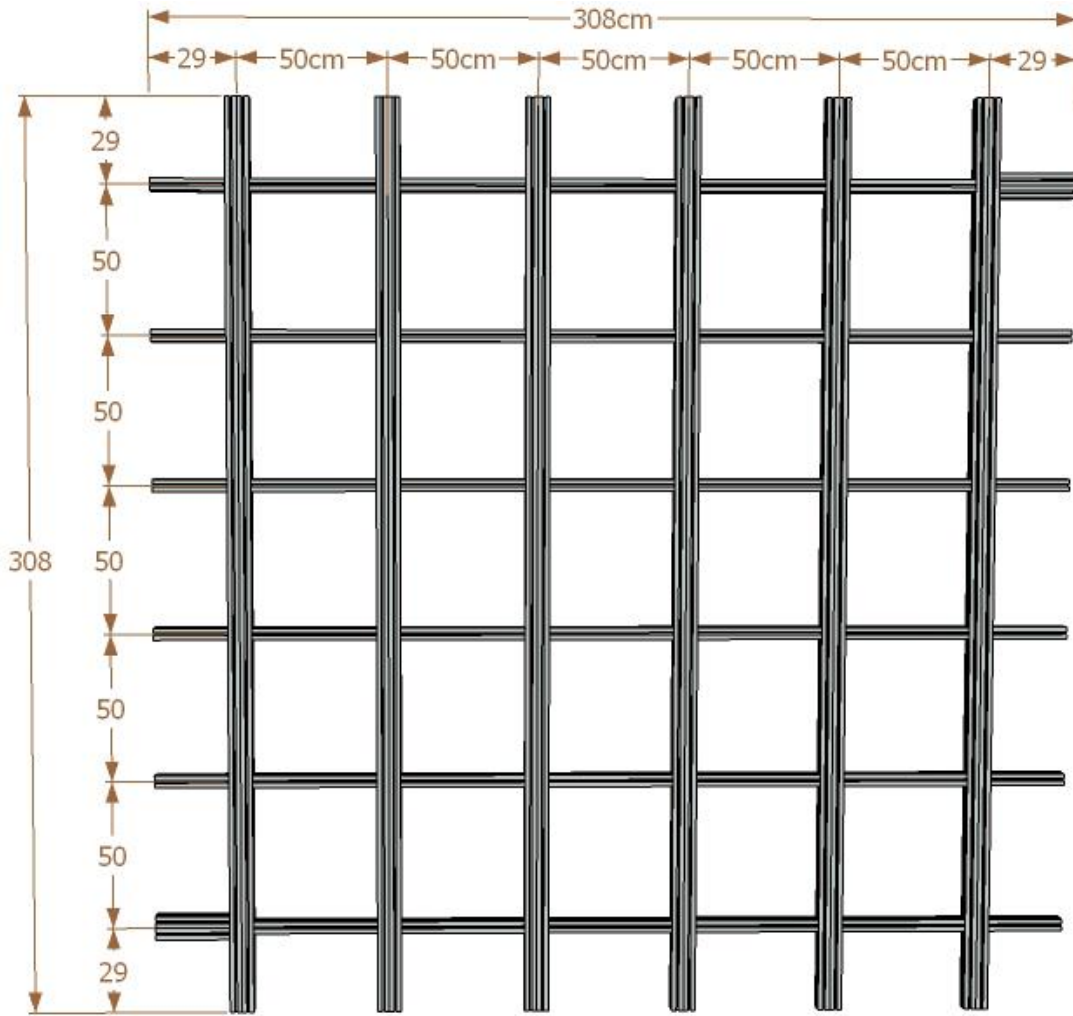


Figure 3.3: The proposed aluminium grid structure and its dimensions.

The structure is built up in the hole between the rooms, as shown in Figure 3.4, with aluminium profiles which were selected from the catalogue of the company (Item, 2011). The long columns are selected as “Profil 8 80x40mm leicht” in order to have the opportunity to mount two wooden square panels to each profile as this product has two opening bands for screws to be screwed in. The profiles between the columns to combine them are “Profil 8 40x40mm leicht”. All of these profiles are not solid and have air gaps inside, in order to be easier. In our case, to prevent the unintended sound transmission, materials must have enough unit mass (mass per square meter). In order to fulfill this requirement, the profiles’ internal spaces are filled with sand which makes the profile heavier at the probable sound transmission lines.



Figure 3.4: Test opening in the laboratory between two rooms.

After filling the column profiles with sand and mounting all profiles on the floor with screws to each other, the structure is lifted up and placed in the opening on the laboratory wall. The adjustable foots on the ending points of profiles are used to fix the structure to the existing laboratory wall. All surfaces where the aluminium structure and wooden panels will touch each other are sealed with an insulation material as it can be seen from Figure 3.5.



Figure 3.5: Insulation material between the aluminium structure and particle board panels.

The same procedure is applied for the second wall of the double facade model. The corrections of the verticality and horizontality are done by a bubble level. A distance

of 35 cm is left between these two wall structures. The panoramic view of the laboratory and the construction equipment can be seen in the Figure 3.6.



Figure 3.6: Finished aluminium structure inside the test opening.

For creating a solid facade, particle board (*Spanplatte*) panels are chosen because of their satisfying unit mass in order to increase sound attenuation. The surface density $M_s = \rho_w h$ of a 40mm thick particle board is 30 kg/m^2 , as its material density ρ_w is 750 kg/m^3 (Barron, 2003). The panels are pre-drilled on the exact points where they are going to be screwed to the aluminium frame. Outer frame components are mounted on the grid, the small gap lines are closed with a foam sealing material and then it is supported with silicon against any mistakes as shown in the Figure 3.7.

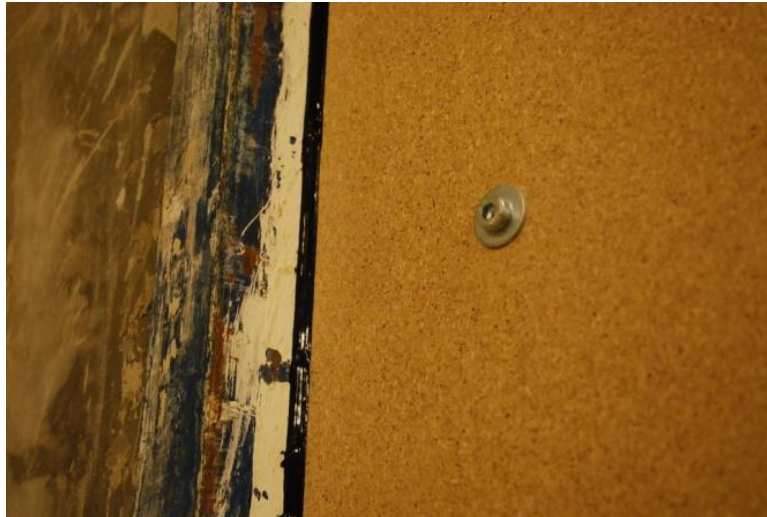


Figure 3.7: The combination lines which are filled with silicon.

The combining lines of the existing wall and the new elements are again closed with an additional wooden beam. After the fixed outer frame work is finished, twenty five removable square parts of the 5x5 grid wall are mounted on the aluminium structure.

These particle board elements and the aluminium profiles have sealing material between them to hinder undesired sound transmission. After all panels are mounted on the structure, a measurement is done with only one wall which has no open parts, in order to compare it with the following experiment results. Figure 3.8 shows the completed front wall in the laboratory.



Figure 3.8: Completed double façade experiment wall.

All these procedures are applied again for the second wall. Fixed outer frame and the structure of the removable parts can be seen from the Figure 3.9. R_w value of two closed walls is measured with an omni-directional speaker as point source and two microphones which are placed in the source room and the receiver room with different combination of places in order to have reliable results.



Figure 3.9: Fixed outer frame and the structure of the removable parts.

3.1.3. Standards about source and receiver rooms

According to the European Standard ISO 10140-5, the volumes of test rooms shall be at least 50 m³ and this requirement is fulfilled in this research (ISO10140-5, 2010). The reverberation time in the receiving room should not be too long or short and it can be calculated with the formula:

$$1 \leq T \leq 2(V/50)^{2/3} \quad (3.1)$$

which is in our case $1 \leq T \leq 5,17$ seconds.

In order to provide this requirement, four “Tectorock 035 VS” rockwool plates with dimensions of 100 x 62,5cm are placed in the receiving room which are 16 cm thick. The reverberation time in the receiving room is measured on five microphone positions for two source positions. Table 3.1 shows the final measured average reverberation times in receiving room with rockwool inside, for octave band frequencies.

Table 3.1: Reverberation Times in seconds for receiver and source rooms.

(measured by two walls closed case)	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
Reverberation Times for receiver room (with rockwool)	3,80	2,63	2,37	2,48	2,16	1,50
Reverberation Times for source room (empty room)	4,90	4,53	3,66	3,48	3,50	2,31

Figure 3.10 shows one of the hanging rockwool plates and the omni-directional sound source in the receiver room, which is placed for measuring the reverberation time in the receiver room.



Figure 3.10: The omni-directional source and a rockwool panel.

3.1.4. Measurement equipment, procedures and standards

The measurements are done according to terms of the European Standards (ISO10140-4, 2010). The equipment consists of two microphones, an omni-directional source (Nor270 Dodecahedron Loudspeaker) and a power amplifier (Nor280), which are wirelessly connected to a laptop including softwares “CtrlBuild (vers. 2.2)” , “Pulse (Brüel & Kjaer – Pulse LabShop vers. 15.1.0)” and “NorBuild (vers. 2.2)” through the Norsonic wireless central control unit. The omni-directional source is connected to the system through the “Norsonic power amplifier Nor280” which is connected to microphone control station. The whole system can be controlled over the laptop in the control room which is placed outside the measuring

rooms. The software “Pulse” is used for measuring the reverberation times, “CtrlBuild” is used for measuring and recording the sound pressure level data and the other software “NorBuild” is necessary to combine and analyze this data in order to find out the sound reduction indexes and compare the results.

The main process which is done by the softwares is to determine the sound pressure levels L_1 and L_2 in both source and receiver rooms, to calculate the difference (ΔSPL), to convert these values to sound reduction index R with the reverberation time correction factor for each frequency and at the end to find a single number quantity R_w (weighted sound reduction index) which is derived from all frequencies' R values.

3.1.5. Terminology for the measurement results (ISO140-4, 1998)

Average sound pressure level in a room, L (or SPL).

Ten times the logarithm to the base 10 of the ratio of the space and time average of the sound pressure squared to the square of the reference sound pressure, the space average being taken over the entire room with the exception of those parts where the direct radiation of a sound source or the near field of the boundaries (wall, etc.) is of significant influence; it is expressed in decibels. In practice, usually the sound pressure levels L_j are measured. In this case L is determined by:

$$L = 10 \lg \left(\frac{1}{n} \sum_{j=1}^n 10^{L_j/10} \right) \text{ dB} \quad (3.2)$$

where:

L_j are the sound pressure levels L_1 to L_n at n different positions in the room [dB].

Level difference, D (or ΔSPL).

Difference, in decibels, in the space and time average sound pressure levels produced in two rooms by one or more sound sources in one of them:

$$D = \Delta SPL = L_1 - L_2 \text{ dB} \quad (3.3)$$

where:

L_1 is the average sound pressure level in the source room [dB];

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

Apparent sound reduction index (apparent sound transmission loss) R .

In general, the sound power transmitted into the receiving room consists of the sum of several components. Also in this case, under the assumption that there are sufficiently diffuse sound fields in the two rooms, the apparent sound reduction index is evaluated from:

$$R = D + 10 \lg S/A \text{ dB} \quad (3.4)$$

where:

D is the level difference [dB];

S is the area of the separating element [m²];

A is the equivalent sound absorption area in the receiving room [m²].

3.1.6. Converting the values from 1/3 to octave band

1/3 octave sound pressure levels are derived from the laboratory measurements as results. For converting the SPL values from 1/3 to octave bands, the following formulas are used:

$$SPL_{oct} = 10 \lg(\sum_{n=1}^3 10^{-R_{1/3oct,n}/10}) \quad (3.5)$$

$$SPL_{oct} = 10 \lg (10^{L_{1/10}} + 10^{L_{2/10}} + 10^{L_{3/10}}) \quad (3.6)$$

The 1/3 octave sound reduction index (R_i) values for each wall type are derived from the measurements. When calculating the values of $D=(\Delta SPL)$ or R in octave bands from the values in one-third-octave bands, the following equations shall be used (ISO140-4, 1998), (Long, 2006):

$$\Delta SPL_{oct} = D_{oct} = -10 \lg(\sum_{n=1}^3 \frac{10^{-D_{1/3oct,n}/10}}{3}) \quad (3.7)$$

$$R_{oct} = -10 \lg(\sum_{n=1}^3 \frac{10^{-R_{1/3oct,n}/10}}{3}) \quad (3.8)$$

3.1.7. Source and receiver positions

Two source positions and five receiver positions for each source point according to the standard ISO 10140-4 are determined as shown in the Figure 3.11 (ISO10140-4, 2010).

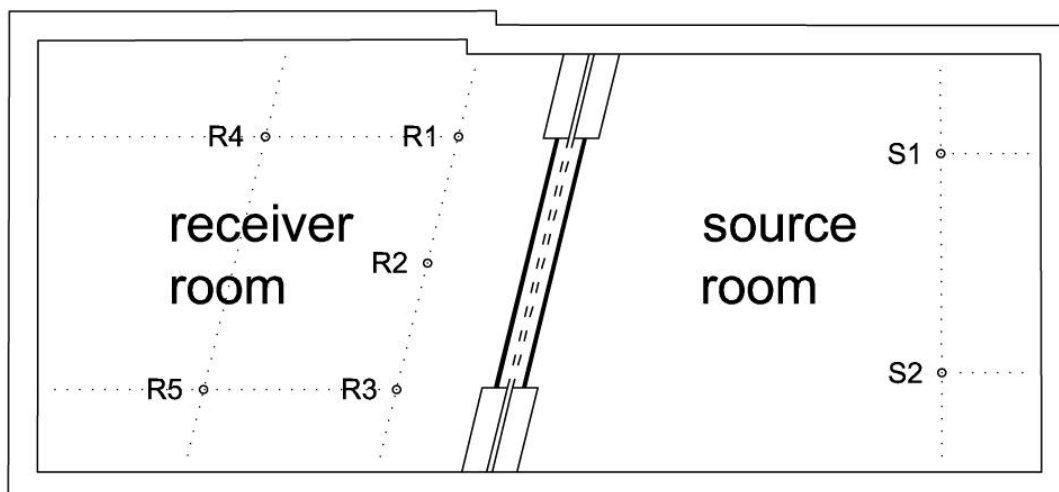


Figure 3.11: Source and receiver positions in the laboratory.

The distances are determined according to the principles which are defined in the standard (ISO10140-4, 2010). “The following separation distances are minimum values and shall be exceeded where possible:

- 0,7 m between fixed microphone positions;
- 0,7 m between any microphone position and the room boundaries;
- 0,7 m between any microphone position and any diffusers;
- 1,0 m between any microphone position and the test element;
- 1,0 m between any microphone position and the sound source.

Sound shall be generated in the source room using loudspeakers in at least two positions or a single loudspeaker moved to at least two positions or a moving loudspeaker.”

These requirements are fulfilled with the following positioning distances, which are shown in the Figure 3.12. A single omni-directional loudspeaker is used in two positions for the measurements.

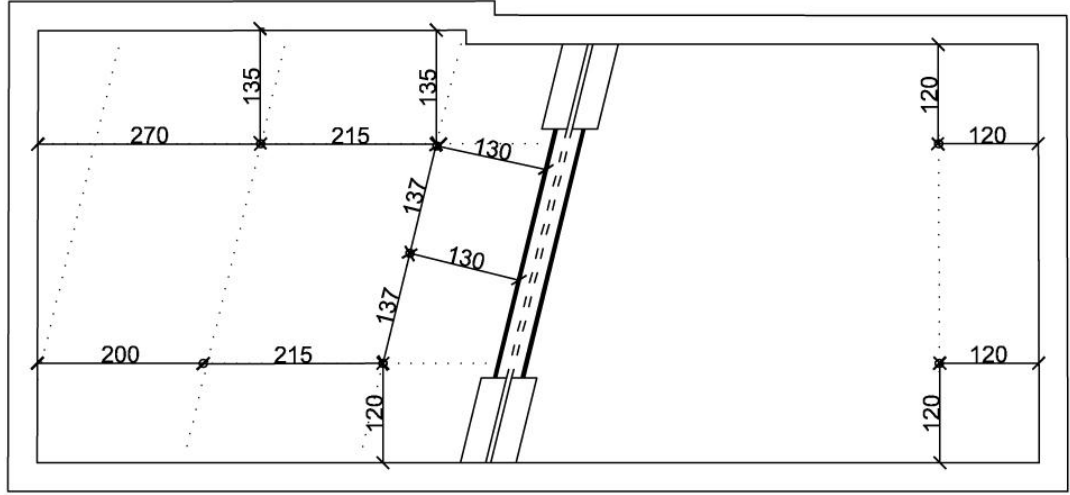


Figure 3.12: The microphone and source distances in two rooms.

According to the standard (ISO10140-4, 2010), in order to calculate the average sound reduction index derived from the values of five microphone positions for each source position, this formula should be used:

$$R = -10 \lg \frac{1}{n} (\sum_{i=1}^n 10^{-R_i/10}) \quad (3.9)$$

The software NorSonic calculates the final R values regarding also the background noise and the reverberation time in the rooms by doing corrections. By each measurement, microphones are calibrated with “Norsonic sound calibrator type 1251” which is used for adjusting the SPL value to 114 dB on the frequency 1000Hz. Microphones are 150 cm high from the floor. Measurements are done with pink noise as noise signal.

3.1.8. Parameters and first measurements

It is aimed to compare different parameters and properties of the double facade in this research. By analysing the potential sound reduction of the system, material properties like absorption coefficient (α), geometrical variables like facade opening's length (a_{out}), height (b_{out}) for outside and (a_{in}), (b_{in}) for inside facade, the quantity of openings, the distance between inner and outer double facade (n) which is 35 cm by the laboratory model, the width of the inner and outer facade (m_{in}), (m_{out}) which is 4 cm regarding the thickness of the particleboards; and sound wave properties like frequency (f) and wavelength (λ) gain importance.

In order to define all parts of the grid clearly, each element is given a certain number on each side of the double facade. The numbers are written in an increasing order from left to right and from top to bottom in the receiver room. In the source room, the numbers are mirrored and they have an increasing order from right to left and from top to the bottom that they have the same opening name with the other wall when they overlap by the front view. There are twenty five openable elements on each wall in total as it can be seen from Figure 3.13.

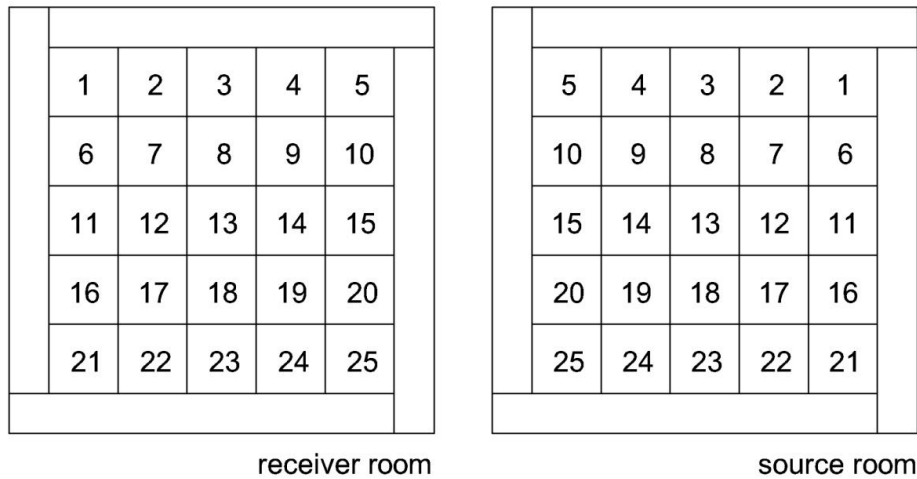


Figure 3.13: Numbering the removable grid parts of both walls.

In order to clarify the sound attenuation of the facade model without any apertures, first measurements are done with one closed wall and two closed walls. Reverberation times, sound levels in the source and the receiver rooms and the sound reduction of the double facade are measured and calculated each time. The sound reduction index is finally given out in $R_w (C;C_{tr})$ format as it is defined in the standard (ISO717-1, 1996).

One closed wall has the weighted sound reduction index R_w value of $R_w(C;C_{tr}) = 34 (-1;-2)$ dB. According to measurements, **two closed walls** provide $R_w(C;C_{tr}) = 51 (-2;-6)$ dB. The sound reduction index R values depending on frequencies are given in the Table 3.2.

Table 3.2: R values [dB] of closed walls taken from laboratory measurements.

R values [dB] - Lab. Measurements	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
one closed wall	25,1	29,3	34,0	33,5	32,8	35,7
two closed walls	32,1	41,1	46,8	51,8	58,0	62,8

The graphical comparison between the cases with one closed wall and two closed walls is shown in the Figure 3.14.

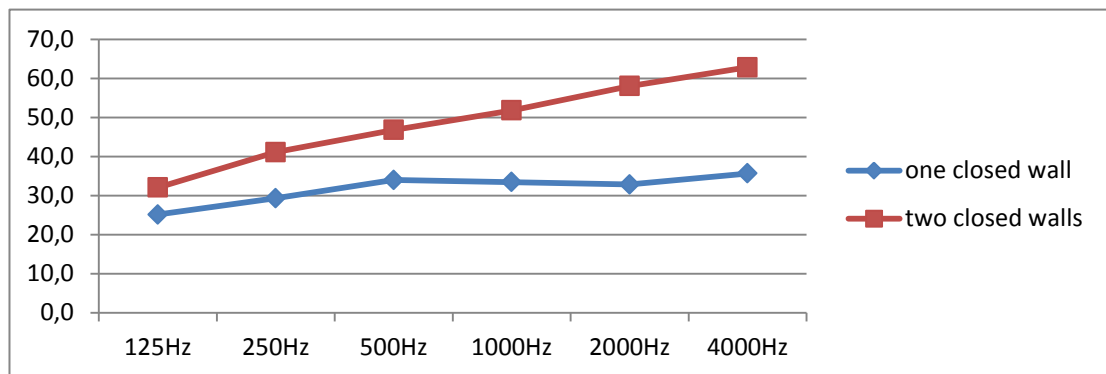


Figure 3.14: R values [dB] of closed walls taken from laboratory measurements.

From the graphs, it can be inferred that the sound attenuation at higher frequencies increases more than the lower frequencies when the wall layers are doubled.

For the following part of measurements, **one** 50 x 50 cm part of each wall is left open. The grid element with the number “6” on the receiver room side is kept constantly open. On the source room side, the elements “16-17-18-19-20” are taken out one by one and measurements are done. The R values depending on frequencies for all cases are shown in the Table 3.3.

Table 3.3: R values [dB] from lab. measurements with one open part on each wall.

R values [dB] - Lab. Measurements	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
receiver room 6 / source room 16	22,9	31,5	27,0	27,5	29,5	30,3
receiver room 6 / source room 17	25,2	31,0	27,7	28,8	30,9	32,3
receiver room 6 / source room 18	25,7	32,2	28,2	29,5	32,1	34,5
receiver room 6 / source room 19	27,2	33,9	28,5	30,4	33,3	35,5
receiver room 6 / source room 20	25,4	33,2	26,7	30,8	34,2	37,0

The graphical comparison between different cases are shown in the Figure 3.15.

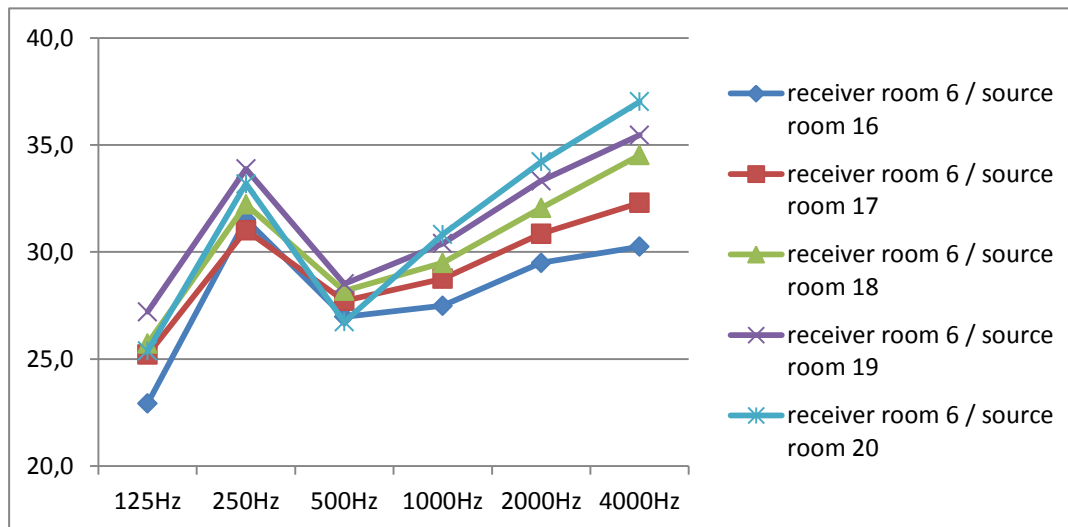


Figure 3.15: R values [dB] from lab. measurements with one open part on each wall.

It would have been expected that the sound reduction were greater due to diffraction effect when the distance between the inner and outer wall apertures increased. The laboratory measurements show similar results to this prediction with some differences. At high frequencies like 1000 – 2000 – 4000 Hz the order of the graphs is as it was expected, in other words, the sound reduction indexes increased when the distances between the apertures were increased. But at **500 Hz**, the case “receiver room 6 / source room 20 open” has lowest sound attenuation compared to the other cases, while the other cases’ graphs continue the right order (Figure 3.16). At 125 and 250 Hz there are also some slight changes in the order of sound reduction values.

It is also recognizable that all cases’ R values, in general, have the tendency to increase especially at the frequency **250 Hz**, while they mostly have a regularly raising graph line at other frequencies.

	1	2	3	4	5
6	7	8	9	10	
11	12	13	14	15	
16	17	18	19	20	
21	22	23	24	25	

Figure 3.16: Graphic showing the open parts on the walls (receiver room - element 6 is constantly open).

Single number quantity R_w values for the cases with one opening on each wall are shown in the Table 3.4.

Table 3.4: Single number quantity R_w values for one panel on each wall missing cases from lab. measurements (element 6 on receiver room is constantly open).

Open part on source room (while part 6 on receiver room is constantly open)	16	17	18	19	20
$R_w (C;C_{tr})$	28 (0;0)	30 (0;-1)	31 (-1;-1)	31 (0;-1)	31 (0;-1)

Next step is to leave **two** 50 x 50 cm parts of each wall open. The elements 6 and 16 on the receiver room's wall stay constantly open and the elements on the source room's wall 6-16, 7-17, 8-18, 9-19, 10-20 are opened in an order. The R values depending on frequencies for all cases are shown in the Table 3.5.

Table 3.5: R values [dB] from lab. measurements with two open parts on each wall.

R values [dB] - Lab. Measurements	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
receiver room 6&16 / source room 6&16	19,5	24,4	18,8	17,4	19,0	17,6
receiver room 6&16 / source room 7&17	21,4	26,0	21,8	22,0	22,4	22,8
receiver room 6&16 / source room 8&18	23,9	27,0	23,0	23,4	25,5	26,1
receiver room 6&16 / source room 9&19	26,0	27,8	23,3	24,7	27,4	27,5
receiver room 6&16 / source room 10&20	23,4	27,8	22,4	24,9	28,5	28,1

The graphical comparison between cases with two openings on each wall are shown in the Figure 3.17.

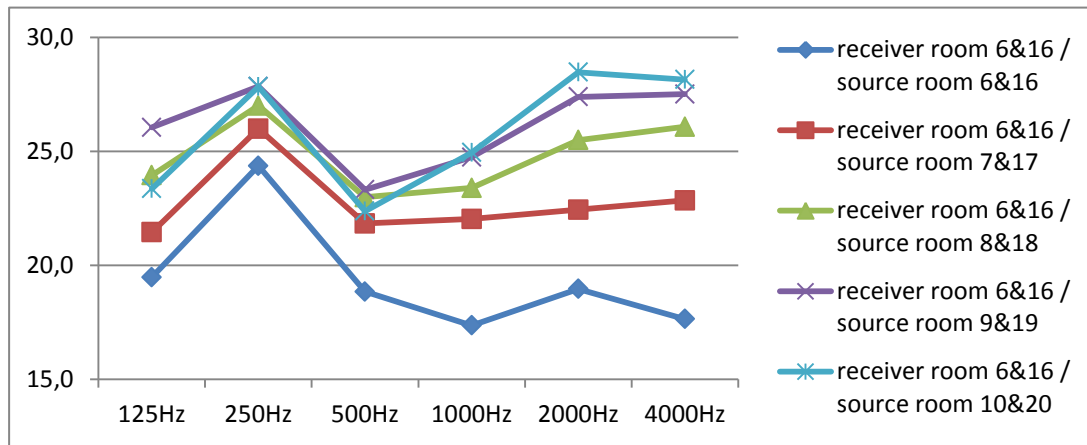


Figure 3.17: R values [dB] from lab. measurements with two open parts on each wall.

In these cases with two open parts on each wall like shown in Figure 3.18, at higher frequencies like 1000 – 2000 – 4000 Hz the order of the graphs is again as it was expected, in other words, the sound reduction indexes increased when the distances between the apertures were increased, similarly to the measurement results with one aperture on each wall. Although the case “receiver room 6&16 / source room 6&16 open” does not change its position at being the less sound attenuating case according to the other ones, other four cases have some slight changes in their order at lower frequencies. The reason for the case “receiver room 6&16 / source room 6&16 open” having the lowest sound reduction values, can be based on the fact that the aperture positions by this case have the greatest opportunity to leave the direct sound waves from the source room into the receiver room.

It can also be observed from the graphs that there is an increase of R values at 250 Hz and a slight decrease at 500 Hz according to the general tendency of every case’s graph line.

	1	2	3	4	5
6	7	8	9	10	
11	12	13	14	15	
16	17	18	19	20	
21	22	23	24	25	

Figure 3.18: Graphic showing the open parts on the walls (receiver room - elements 6 and 16 are constantly open).

Single number quantity R_w values for the cases with two openings on each wall are shown in the Table 3.6.

Table 3.6: Single number quantity R_w values for two panels on each wall missing cases from lab. measurements (elements 6 and 16 on receiver room are constantly open).

Open part on source room (while part 6 and 16 on receiver room is open)	6 and 16	7 and 17	8 and 18	9 and 19	10 and 20
$R_w (C;C_{tr})$	18 (0;0)	22 (0;0)	24 (0;0)	26 (0;-1)	26 (0;-1)

Figure 3.19 shows a case where two parts on each wall are open.



Figure 3.19: Photograph showing the case “receiver room 6-16 and source room 10-20 opened”.

3.2. Computer Model Of The Façade System In The Program ODEON

A computer model with the same room dimensions and settings is prepared in order to check the possibility to get near results to the laboratory measurements. A *.dxf file is created with layers according to materials and this file is imported into the program “Odeon (vers. 9.2 combined)”. In order to make a reasonable decision about the sound absorption coefficients (α) of each material in the room, the reverberation times according to laboratory measurements and the Odeon results have been calibrated. Table 3.7 shows the α values of the room materials derived from different references.

Table 3.7: Sound absorption coefficients of room materials.

	Absorption coef. (α)	125	250	500	1000	2000	4000	Reference
C1	Concrete (smooth unpainted)	0,01	0,01	0,02	0,02	0,02	0,05	Odeon Material Library
C2	Concrete	0,02	0,02	0,03	0,04	0,05	0,05	(Fasold & Veres, 1998)
C3	Concrete	0,01	0,02	0,02	0,02	0,02	0,03	(Mahdavi & Orehounig, 2011)
C4	Concrete (poured- unpainted)	0,01	0,01	0,02	0,02	0,02	0,03	(Barron, 2003), (Beranek, 1993), (Long, 2006)
C5	Concrete (smooth)	0,10	0,05	0,06	0,07	0,09	0,08	(Rossing, 2007)
C6	Concrete (rough)	0,02	0,03	0,03	0,03	0,04	0,07	(Cox & D’Antonio, 2009), Odeon Material Library
C7	Concrete floor	0,01	0,01	0,01	0,02	0,02	0,02	(Beranek, 1993), (Bies & Hansen, 2003)
C8	Concrete floor	0,01	0,01	0,015	0,02	0,02	0,02	(Everest, 2001), (Long, 2006)
P1	Particle board (unsanded) [humidity:30%]	0,04	0,04	0,04	0,07	0,08	0,11	(Godshall & Davis, 1969)
P2	Particle board (sanded) [humidity:30%]	0,04	0,04	0,06	0,06	0,04	0,08	(Godshall & Davis, 1969)
P3	Particle board	0,04	0,04	0,05	0,06	0,06	0,06	(Mahdavi & Orehounig, 2011)

Table 3.7 (continued): Sound absorption coefficients of room materials.

P4	Particle board (unsanded) [humidity:50%]	0,04	0,04	0,04	0,06	0,04	0,07	(Godshall & Davis, 1969)
P5	Particle board (sanded) [humidity:50%]	0,04	0,04	0,04	0,06	0,06	0,09	(Godshall & Davis, 1969)
R1	Rockwool	0,68	0,84	0,82	0,78	0,75	0,77	(Mahdavi & Orehounig, 2011)
R2	Rockwool or fiberglass blanket	0,65	1,00	1,00	1,00	1,00	1,00	(Bies & Hansen, 2003)
R3	Rockwool	0,53	0,99	0,99	0,97	0,99	0,98	Lab. Measurements

3.2.1. Measurements of sound absorption coefficient α for rockwool

The sound absorption coefficient of rockwool for each frequency is measured in the source room. First, the empty room's reverberation times are measured. Secondly, 8 rockwool boards are placed in the room and the reverberation time is measured again. Each plate has the dimensions of 1 x 0,625 x 0,16 meters. The source room has the volume of $V = 206,21\text{m}^3$. α_{rockwool} is calculated with following formulas:

$$RT = 0,163 \cdot \frac{V}{A} \quad (3.10)$$

$$A = \sum \alpha_i \cdot S_i \quad (3.11)$$

where:

α_i is the absorption coefficient of each material;

S_i is the area of each material in receiver room [m^2].

A_1 is for the empty source room and A_2 for the source room with rockwool boards. The top surface of total rockwool is 5m^2 and S_{rockwool} which is visible is $6,44\text{m}^2$.

$$A_1 = \alpha_{\text{conc.}} \cdot S_{\text{conc.}} + \alpha_{\text{part.b.}} \cdot S_{\text{part.b.}} + \alpha_{\text{wood}} \cdot S_{\text{wood}}$$

$$A_2 = \alpha_{\text{conc.}} \cdot S_{\text{conc.}} + \alpha_{\text{part.b.}} \cdot S_{\text{part.b.}} + \alpha_{\text{wood}} \cdot S_{\text{wood}} + \alpha_{\text{rockw.}} \cdot S_{\text{rockw.}} - \alpha_{\text{conc.}} \cdot 5\text{m}^2$$

$$A_2 = A_1 + \alpha_{\text{rockw.}} \cdot 6,44\text{m}^2 - \alpha_{\text{conc.}} \cdot 5\text{m}^2$$

Sound absorption coefficients α of rockwool for each frequency are calculated and shown in the Table 3.8. The rockwool plates which are placed on the floor can be seen in Figure 3.20.

Table 3.8: Calculation of the sound absorption coefficient for rockwool from lab. measurement results.

Laboratory Measurements			Calculations			
Freq.	Reverberation Time in Source Room				C2	calculated
	Empty	with Rockwool	A1	A2	α_{concrete}	α_{rockwool}
125	4,90	3,30	6,86	10,19	0,02	0,53
250	4,53	2,34	7,42	14,36	0,02	1,09
500	3,66	2,02	9,18	16,64	0,03	1,18
1000	3,48	2,14	9,66	15,71	0,04	0,97
2000	3,50	2,12	9,60	15,85	0,05	1,01
4000	2,31	1,63	14,55	20,62	0,05	0,98



Figure 3.20: Rockwool plates and the measurement equipment in the laboratory.

3.2.2. Sound absorption coefficient decisions

After a series of simulation result comparisons according to reverberation times with several sound absorption coefficient values from different sources, most reasonable values are chosen for the following model calculations.

Table 3.9 shows the α values which are used for the computer simulations. With the aid of properly selected materials, a great agreement is reached between the laboratory measured reverberation times and simulated values (Table 3.10).

Table 3.9: Absorption coefficient values which are used in computer models.

Absorption coef. (α)	125	250	500	1000	2000	4000
Concrete [for walls]	0,02	0,03	0,04	0,04	0,04	0,04
Rockwool	0,53	0,98	0,98	0,97	0,97	0,97
Particle board (sanded)	0,04	0,04	0,06	0,06	0,04	0,04

The reverberation times from laboratory measurements and simulations can be seen in the Table 3.10 and the graphical comparison is shown in the Figure 3.21.

Table 3.10: Reverberation time comparisons of lab. measurements and Odeon results.

Reverberation Times (seconds)						
Source Room (Empty)-ODEON	6,63	4,64	3,34	3,19	2,88	1,96
Source Room (Empty)-Lab. measurements	4,90	4,53	3,66	3,48	3,50	2,31
Source Room with rockwool-ODEON	3,54	2,36	2,02	1,96	1,81	1,42
Source Room with rockwool-Lab. measurements	3,30	2,34	2,02	2,14	2,12	1,63
Receiver Room with rockwool-ODEON	3,65	2,84	2,22	2,14	1,96	1,52
Receiver Room with rockwool-Lab. measurements	3,80	2,63	2,37	2,48	2,16	1,50

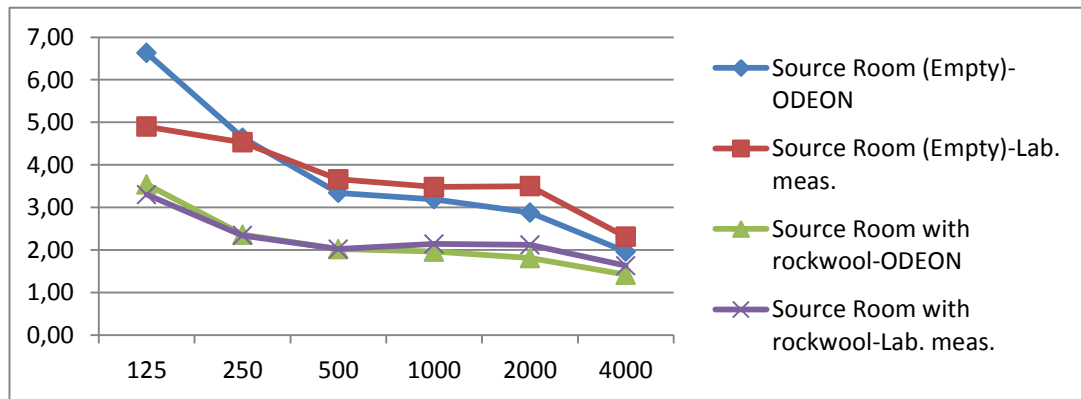


Figure 3.21: Reverberation time comparison graphs for lab. measurements and Odeon.

3.2.3. Δ SPL results from simulations for different cases

Δ SPL values for certain cases are calculated in the computer modeled environment according to the instructions given by the Odeon User's Manual with sound absorption coefficients which are mentioned before (Christensen, 2008). After the material assignment to the surfaces in the model, the experiment walls are defined as "transmission walls" which allow sound transmission according to their R values for each frequency. Odeon requires 1/3 octave R values for transmission walls. The values from the case "one closed wall" are shown in the Table 3.11.

Table 3.11: Third octave R values for one closed wall taken from lab. measurements.

Freq. [Hz]	R [dB]	Freq. [Hz]	R [dB]	Freq. [Hz]	R [dB]	Freq. [Hz]	R [dB]
50	28,2	100	22,3	200	28,4	400	33,2
63	22,9	125	26,6	250	29	500	34
80	28,1	160	29,4	315	30,9	630	35

Freq. [Hz]	R [dB]	Freq. [Hz]	R [dB]	Freq. [Hz]	R [dB]
800	33,3	1600	32,9	3150	35
1000	34	2000	32,4	4000	37,7
1250	33,1	2500	33,2	5000	34,8

For the room setup, in order to have the same conditions with the laboratory, the temperature and the humidity are measured in the lab. The results 20,5°C for the temperature and 35% for the humidity are used for the Odeon calculations. The defined signal source has an overall gain of 120 dB at all frequencies.

The cases “one closed wall” and “two closed walls” are examined firstly. The Δ SPL values for the facade structure derived from computer models are given in the Table 3.12 and the graphical comparison is shown in the Figure 3.22.

Table 3.12: Odeon Δ SPL results for one closed wall and two closed walls.

Δ SPL values [dB] from Odeon	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
one closed wall:	24,7	29,8	35,3	34,8	34,4	38,2
two closed walls:	38,8	48,2	60,0	58,9	56,5	63,3

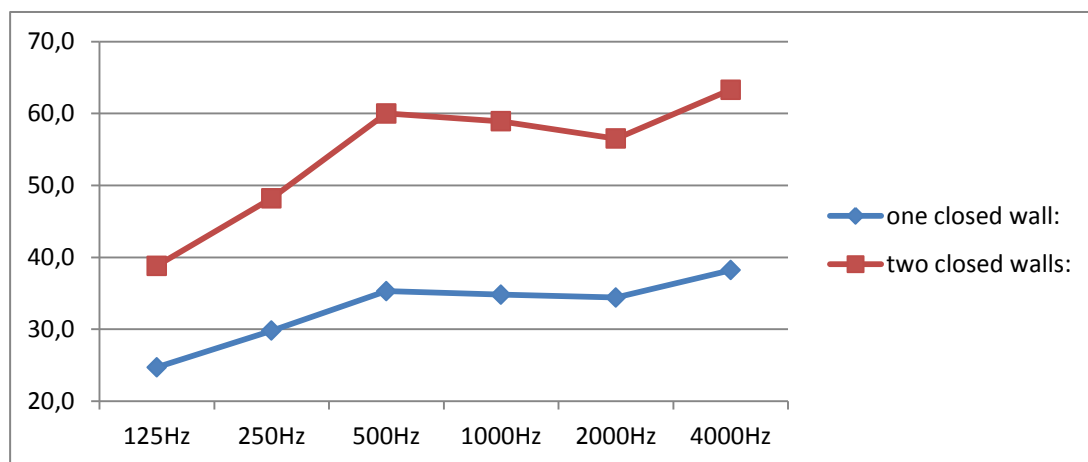


Figure 3.22: Odeon Δ SPL results for one closed wall and two closed walls.

For further steps, comparisons are made for the cases where **one** 50 x 50 cm part of each wall is open. The grid element with the number “6” on the receiver room side is kept constantly open. On the source room side, the elements “16-17-18-19-20” are erased in the simulation one by one and calculations are done. The Δ SPL values depending on frequencies for all cases are shown in the Table 3.13.

Table 3.13: Δ SPL values [dB] from Odeon with one open part on each wall.

Δ SPL values [dB] from Odeon	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
rec.room6/source room16 open	23,1	25,0	27,0	27,1	27,1	28,6
rec.room6/source room17 open	22,5	24,6	27,2	27,3	27,0	29,0
rec.room6/source room18 open	21,6	23,1	25,9	26,1	24,8	26,8
rec.room6/source room19 open	22,3	23,9	26,4	26,4	25,3	26,4
rec.room6/source room20 open	23,8	26,3	29,2	29,4	28,9	30,7

The graphical comparison of the cases with one opening on each wall according to simulation results is shown in the Figure 3.23.

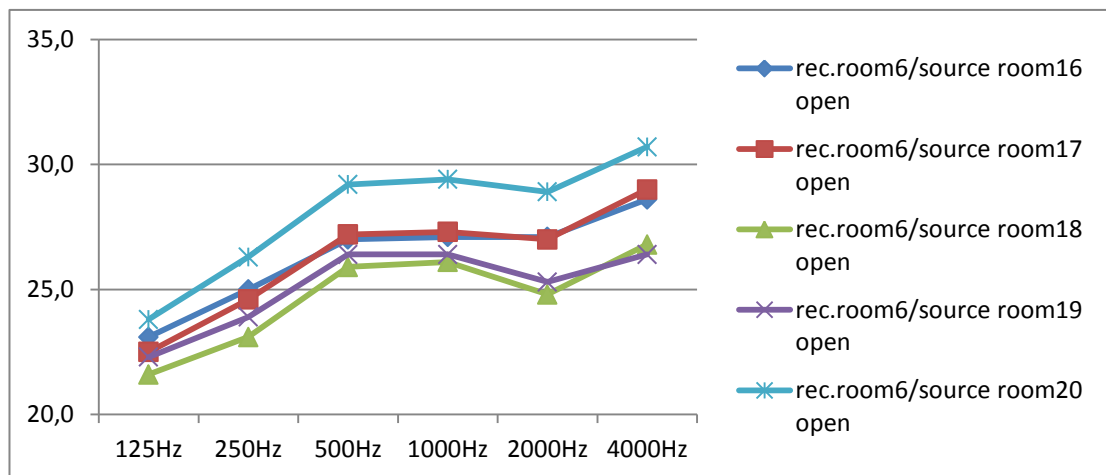


Figure 3.23: Δ SPL values [dB] from Odeon with one open part on each wall.

As it was by the laboratory measurements, it would have been expected that the sound reduction were greater due to diffraction effect when the distance between the inner and outer wall apertures increased. The simulation calculations show quite different results to this prediction. The case “receiver room 6 / source room 20 open”

has the highest sound attenuation at all frequencies as it was expected, but all other cases' graphs have a different order than it was foreseen. The case “receiver room 6 / source room 18 open” has the lowest sound attenuation in all the other cases, according to simulation results.

3.3. Comparison of Laboratory Measurements and Odeon Results for Δ SPL

As the Δ SPL from the laboratory measurements and simulations are known, they can be compared in order to test the ability of Odeon to estimate the sound attenuation of this specialized facade system. The first case is “one closed wall” with no openings and the values to be compared are given in the Table 3.14.

Table 3.14: Δ SPL comparison of Odeon and lab. measurements – “one closed wall”.

Δ SPL values [dB]	125	250	500	1000	2000	4000
one closed wall - Odeon	24,7	29,8	35,3	34,8	34,4	38,2
one closed wall - Lab. Measurements	25,4	28,3	33,1	31,9	32,0	37,6

The graphical comparison of results from laboratory measurements and simulations for one closed wall is shown in the Figure 3.24.

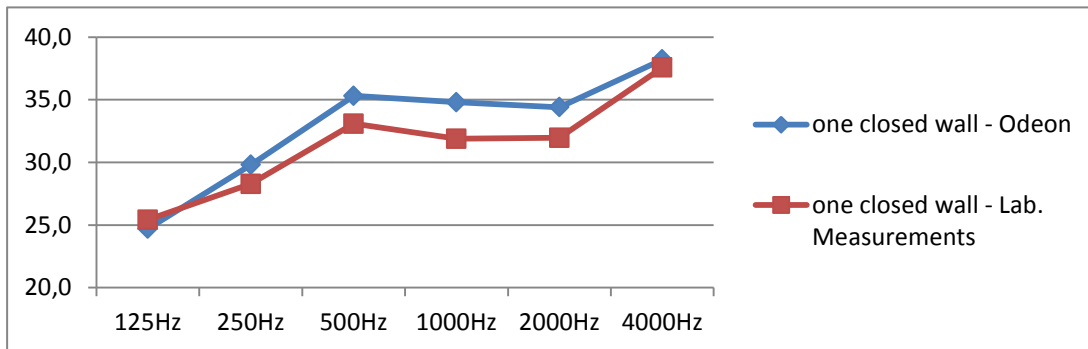


Figure 3.24: Δ SPL comparison of Odeon and lab. measurements – “one closed wall”.

In the case “one closed wall”, simulation and laboratory measurement results tend to be quite similar to each other even though they have some small differences.

The next case is “two closed walls” and the values to be compared are given in the Table 3.15.

Table 3.15: Δ SPL comparison of Odeon and lab. measurements – “two closed walls”.

Δ SPL values [dB]	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
two closed walls - Odeon	38,8	48,2	60,0	58,9	56,5	63,3
two closed walls - Lab. Measurements	34,4	40,9	48,8	53,1	59,8	66,0

The graphical comparison of results from laboratory measurements and simulations for two closed walls is shown in the Figure 3.25.

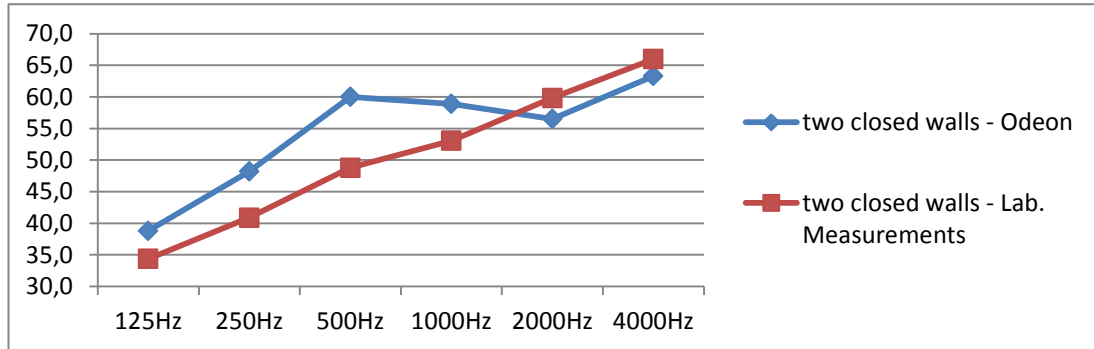


Figure 3.25: Δ SPL comparison of Odeon and lab. measurements – “two closed walls”.

In the case “two closed walls”, Odeon *overestimates* the sound level difference between the rooms at lower frequencies between 125 and 1000 Hz, where it slightly *underestimates* at high frequencies like 2000 and 4000 Hz. Especially at 500 Hz there is a major difference between laboratory and Odeon results.

The next case is “receiver room 6 / source room 16 open” and the values to be compared are given in the Table 3.16.

Table 3.16: Δ SPL comparison of Odeon and lab. measurements – “receiver room 6 / source room 16 open”.

Δ SPL values [dB]	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
rec.room6/source room16 - Odeon	23,1	25,0	27,0	27,1	27,1	28,6
rec.room6/source room16 - Lab. Meas.	23,3	30,9	30,2	29,0	31,5	34,2

The graphical comparison of results from laboratory measurements and simulations for the case “receiver room 6 / source room 16 open” is shown in the Figure 3.26.

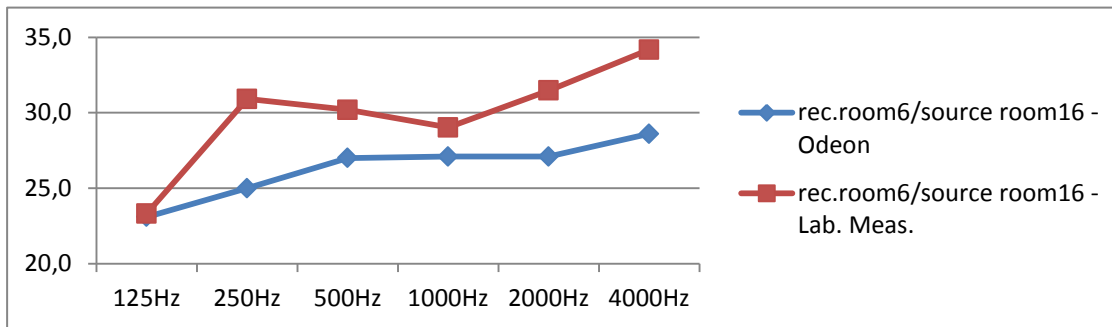


Figure 3.26: Δ SPL comparison of Odeon and lab. measurements – “receiver room 6 / source room 16 open”.

The next case is “receiver room 6 / source room 17 open” and the values to be compared are given in the Table 3.17.

Table 3.17: Δ SPL comparison of Odeon and lab. measurements – “receiver room 6 / source room 17 open”.

Δ SPL values [dB]	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
rec.room6/source room17 - Odeon	22,5	24,6	27,2	27,3	27,0	29,0
rec.room6/source room17 - Lab. Meas.	25,8	30,8	31,0	30,2	32,7	36,2

The graphical comparison of results from lab. measurements and simulations for the case “receiver room 6 / source room 17 open” is shown in the Figure 3.27.

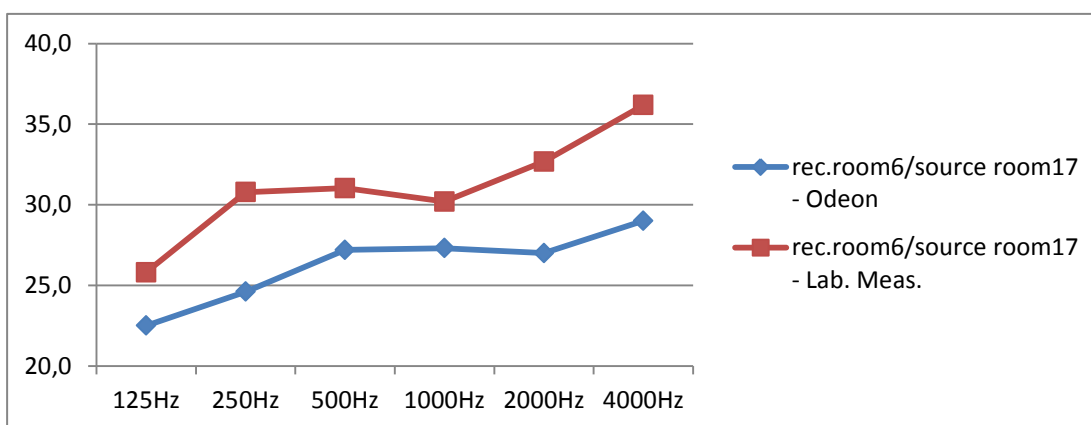


Figure 3.27: Δ SPL comparison of Odeon and lab. measurements – “receiver room 6 / source room 17 open”.

The next case is “receiver room 6 / source room 18 open” and the values to be compared are given in the Table 3.18.

Table 3.18: Δ SPL comparison of Odeon and lab. measurements – “receiver room 6 / source room 18 open”.

Δ SPL values [dB]	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
rec.room6/source room18 - Odeon	21,6	23,1	25,9	26,1	24,8	26,8
rec.room6/source room18 - Lab. Meas.	27,2	32,2	31,3	30,9	33,8	38,4

The graphical comparison of results from lab. measurements and simulations for the case “receiver room 6 / source room 18 open” is shown in the Figure 3.28.

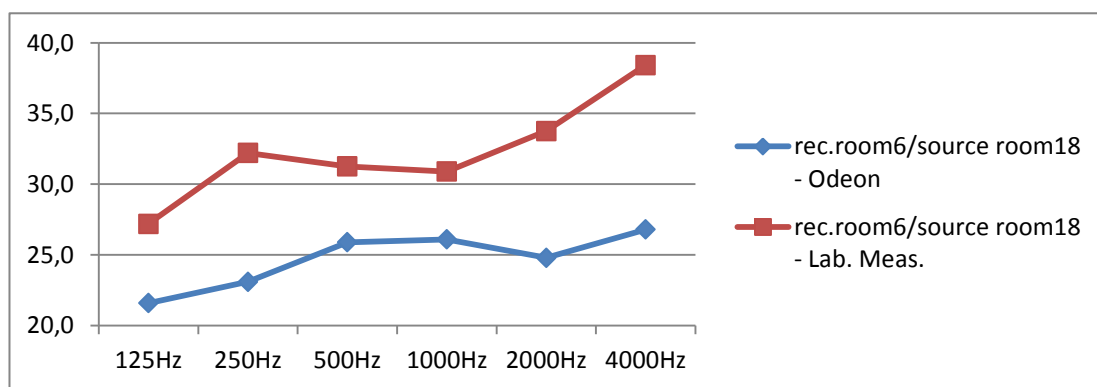


Figure 3.28: Δ SPL comparison of Odeon and lab. measurements – “receiver room 6 / source room 18 open”.

The next case is “receiver room 6 / source room 19 open” and the values to be compared are given in the Table 3.19.

Table 3.19: Δ SPL comparison of Odeon and lab. measurements – “receiver room 6 / source room 19 open”.

Δ SPL values [dB]	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
rec.room6/source room19 - Odeon	22,3	23,9	26,4	26,4	25,3	26,4
rec.room6/source room19 - Lab. Meas.	28,4	34,0	31,8	31,9	35,2	39,4

The graphical comparison of results from lab. measurements and simulations for the case “receiver room 6 / source room 19 open” is shown in the Figure 3.29.

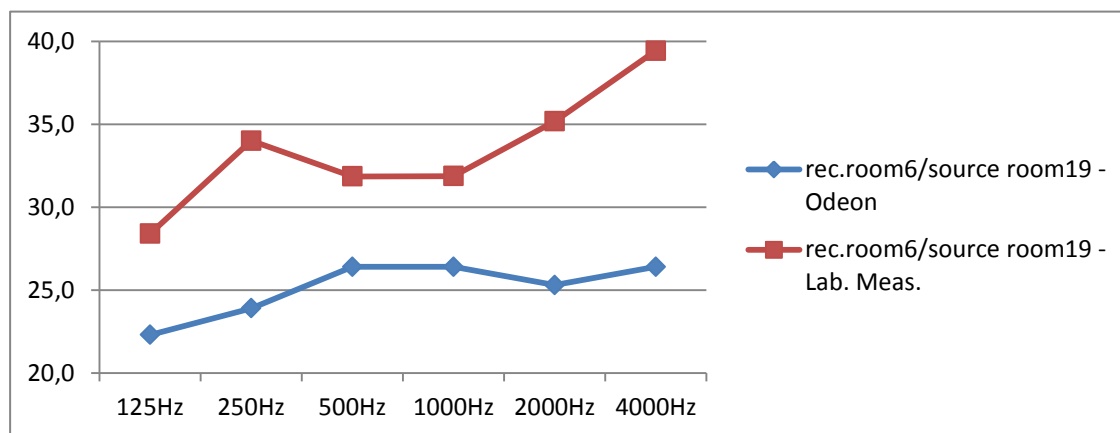


Figure 3.29: Δ SPL comparison of Odeon and lab. measurements – “receiver room 6 / source room 19 open”.

The next case is “receiver room 6 / source room 20 open” and the values to be compared are given in the Table 3.20. The graphical comparison is shown in the Figure 3.30.

Table 3.20: Δ SPL comparison of Odeon and lab. measurements – “receiver room 6 / source room 20 open”.

Δ SPL values [dB]	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
rec.room6/source room20 - Odeon	23,8	26,3	29,2	29,4	28,9	30,7
rec.room6/source room20 - Lab. Meas.	26,5	34,1	30,3	32,1	35,9	40,9

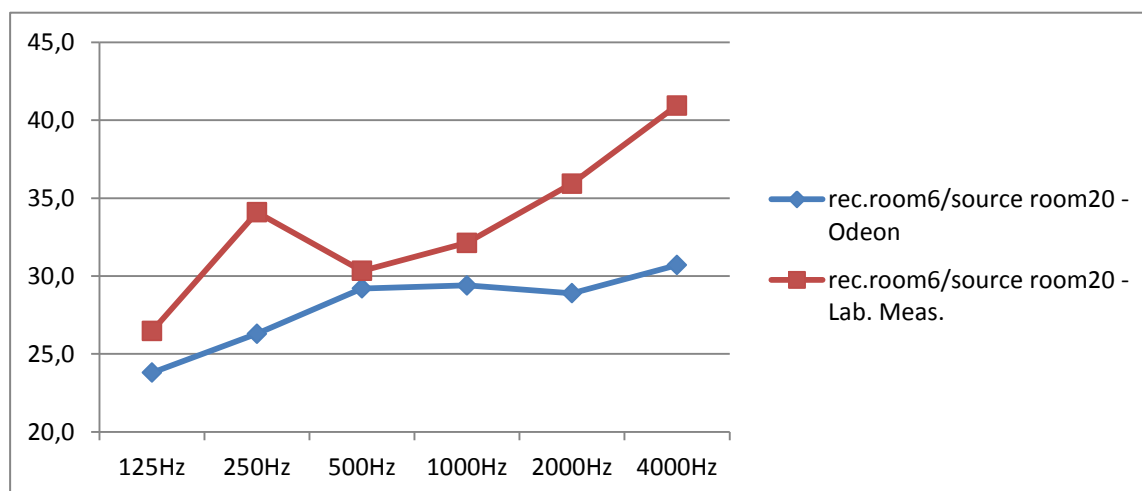


Figure 3.30: Δ SPL comparison of Odeon and lab. measurements – “receiver room 6 / source room 20 open”.

Screenshot pictures from simulations during the preview of the option 3D Billiard for demonstrating sound scattering from surfaces and sound transmission through the experiment wall are shown in the Figure 3.31. By all these five cases where the sixth panel of the receiver room wall stays constantly open, it can be inferred from the graphs that Odeon *underestimates* the sound level difference between the rooms every time. While the graph shapes of the cases derived from Odeon usually seem to have a constantly and regularly rising tendency, the actual laboratory measurements' graphs have generally an instant rise at 250 Hz and a higher rising slope at higher frequencies like 2000 and 4000 Hz. Based on these comparison results, it can be told that it is not sufficient enough to continue this research with only computer model estimations.

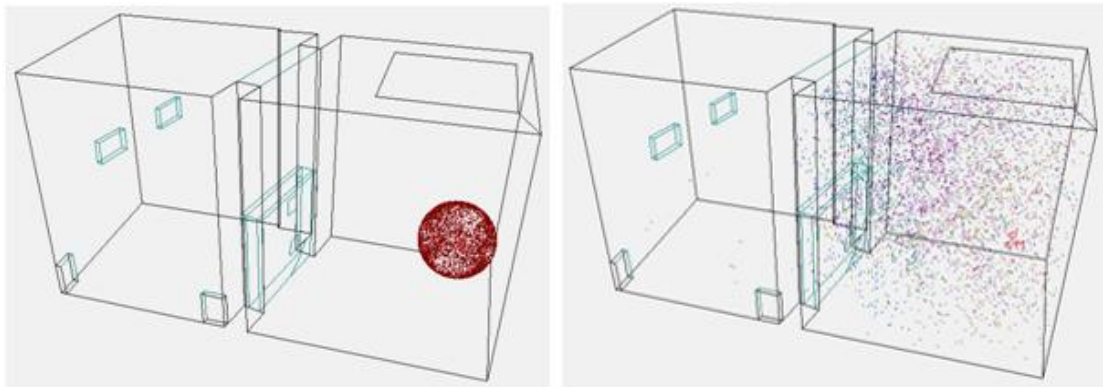


Figure 3.31: Screenshots from the simulations.

4. CONCLUSION AND FURTHER SUGGESTIONS

In order to determine the sound reduction values of the proposed acoustic double façade system by natural ventilation, laboratory measurements and computer simulation model calculations have been done for different opening combinations and results are given in the previous chapter. Taking laboratory measurement results into consideration, the sound reduction increased when the distance between the openings on the inner and the outer side of the double façade increased, as it was expected. This is mainly due to the diffraction effect of the particleboard panels which work as noise barriers on soundwaves' way through the openings. Also by each reflection of the soundwaves between two walls during the measurements, the particleboards' surfaces absorb a part of the sound depending on their absorption coefficients for each frequency, which makes the transmission loss greater.

The same processes were carried out by the simulation program Odeon. Although the materials and reverberation time values were calibrated according to laboratory measurements, the results were not meaningful when compared to laboratory measurement results. By all the cases, Odeon underestimates the sound level difference between the rooms, which can be caused by underestimating the diffraction effect of the panels.

The materials, which are used during this study, are selected concerning their sound transmission efficiency by measurements. In real building constructions, they will be replaced with different kinds of materials, which may lead to different numeric results. The material properties may vary but the main result, that the distance between openings affects the sound attenuation with a direct proportion, would remain the same.

As next steps of this research, different opening combinations can be applied and measured in the laboratory. It is foreseen that the proven fact, that sound reduction values of the façade increases when the distance between the openings on the outer and the inner wall of the double façade increases, will also occur by the future study

measurements. One wall can be removed and installed again with a different distance to the other wall so that the distance between two walls can be changed and that the effect of the distance between walls can be interpreted.

As further research, in order to improve the sound reduction by preventing reflection between the walls, an efficiently absorbing material with a high absorption coefficient α can be used between two walls. Polyurethane foam panels can be placed on the back side of each wall in the following steps of laboratory work.

Also the use of electric cars should be encouraged in terms of noise control and ecology. Besides their ecologic approach, electric cars have no engine noise like standard car motors which use petrol based fuel. In that way, traffic noise can be lowered especially in lower frequencies and that would affect the indoor acoustic quality in a positive manner.

As mentioned at the beginning of this research, as a potential problem in the lower frequency range, it can be foreseen that low frequencies would not be effectively attenuated because of their long wavelengths which enables them to pass through the smaller barriers. Regarding this potential problem, this research model could be improved and developed by using Helmholtz resonators around the apertures afterwards.

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APPENDICES

A. OBJECTIVE LABORATORY MEASUREMENT RESULTS

Table A.1: Reverberation Times in source room measured with 5 different receiver positions (measured twice for each position) without rockwool.

Frq [Hz]	Primary T30	Secondary T20	Primary T30	Secondary T20	Primary T30	Secondary T20	Primary T30	Secondary T20	Primary T30	Secondary T20
50	5,29	4,42	5,36	4,7	6,5	6,35	4,98	3,95	6,21	5,21
63	4,91	4,33	3,35	3,27	7,24	7,18	6,16	5,97	4,06	3,16
80	4,52	4,45	5,45	5,05	6,23	6,18	5,69	5,04	5,55	5,02
100	6,01	5,93	6,74	6,74	5,51	4,75	5,29	5,12	4,43	4,34
125	4,85	3,67	4,96	5,14	4,53	4,08	5,26	4,97	4,8	5,2
160	4,14	3,46	4,66	3,96	4,62	4,43	5,15	4,58	4,66	4,05
200	4,48	4,32	4,86	3,77	3,85	3,69	4,6	3,87	4,55	4,73
250	4,74	4,5	4,98	4,86	4,95	4,96	4,74	4,72	5,32	5,33
315	4,57	3,96	4,39	3,97	4,99	4,93	4,87	4,26	5,08	4,43
400	3,79	3,79	4,03	4,34	3,95	3,94	3,82	3,96	3,47	3,64
500	3,71	3,83	3,68	4,12	3,65	3,59	3,69	3,52	3,58	3,6
630	3,47	3,38	3,54	3,62	3,29	3,97	3,35	3,27	3,52	3,8
800	3,41	3,69	3,21	3,5	3,46	3,8	3,28	3,28	3,35	3,27
1000	3,32	3,42	3,37	3,43	3,68	3,53	3,35	3,48	3,55	3,56
1250	3,54	3,67	3,59	3,48	3,48	3,44	3,69	3,68	3,7	3,78
1600	3,83	3,88	3,68	3,52	3,62	3,66	3,66	3,59	3,78	3,74
2000	3,48	3,58	3,55	3,55	3,46	3,3	3,45	3,43	3,56	3,77
2500	3,31	3,29	3,25	3,29	3,29	3,32	3,22	3,16	3,28	3,34
3150	2,93	2,77	2,82	2,76	2,81	2,78	2,8	2,89	2,82	2,87
4000	2,25	2,28	2,24	2,21	2,26	2,17	2,13	2,12	2,2	2,19
5000	1,87	1,78	1,87	1,88	1,96	1,89	1,81	1,85	1,88	1,96
6300	1,54	1,66	1,54	1,48	1,59	1,64	1,52	1,55	1,59	1,59
8000	1,82	1,59	1,71	1,38	1,71	1,45	1,75	1,46	1,83	1,5

Table A.1 (continued): Reverberation Times in source room measured with 5 different receiver positions (measured twice for each position) without rockwool.

Frq [Hz]	Primary T30	Secondary T20	Primary T30	Secondary T20	Primary T30	Secondary T20	Primary T30	Secondary T20	Primary T30	Secondary T20
50	6,41	6,46	5,5	5,24	6,51	6,53	5,13	3,96	6,16	6,41
63	5,44	5,41	5,24	5,21	6,91	6,49	5,32	5,41	5,62	5,89
80	5,6	5,24	5,63	5,49	5,61	4,8	5	4,89	5,84	5,93
100	6,31	6,69	4,38	4,63	5,5	5,81	4,7	4,44	5,38	5,03
125	4,23	3,6	4,14	4,41	3,9	3,04	4,61	4,52	4,92	4,57
160	4,57	4,4	4,85	4,91	3,97	3,61	4,88	4,84	4,95	4,59
200	4,12	3,42	3,98	4,07	3,94	3,21	3,5	3,53	3,8	3,62
250	4,5	3,85	4,54	4,43	3,84	4,52	4,21	3,57	4,42	3,83
315	5,6	5,13	4,85	4,8	4,09	4,17	4,69	4,49	4,97	4,56
400	4,2	4,13	4,01	3,82	3,73	3,99	3,96	3,99	4,03	4,08
500	3,83	3,75	3,7	3,84	3,76	3,86	3,53	3,28	3,58	3,45
630	3,33	3,47	3,49	3,7	3,52	3,51	3,13	2,79	3,52	3,16
800	3,21	3,53	3,4	3,38	3,47	3,6	3,27	3,25	3,24	3,18
1000	3,57	3,4	3,4	3,37	3,59	3,69	3,68	3,53	3,47	3,56
1250	3,62	3,52	3,61	3,5	3,65	3,9	3,58	3,52	3,72	3,49
1600	3,76	3,6	3,59	3,49	3,65	3,85	3,66	3,64	3,69	3,71
2000	3,57	3,44	3,57	3,51	3,66	3,83	3,69	3,55	3,51	3,59
2500	3,28	3,29	3,28	3,3	3,24	3,25	3,32	3,33	3,2	3,31
3150	2,78	2,62	2,82	2,67	2,8	2,68	2,9	2,75	2,92	2,85
4000	2,18	2,21	2,27	2,06	2,2	2,16	2,14	2,12	2,23	2,1
5000	1,8	1,82	1,85	1,8	1,85	1,82	1,87	1,79	1,9	1,81
6300	1,57	1,57	1,58	1,52	1,53	1,58	1,53	1,49	1,57	1,5
8000	1,75	1,45	1,7	1,47	1,67	1,53	1,73	1,46	1,82	1,51

Table A.2: Average third octave and octave RT values in source room measured with 5 different receiver positions (twice for each position) without rockwool.

Frequency	RT Average	RT Octave
50	5,805	
63	5,425	5,58
80	5,512	
100	5,425	
125	4,62	4,90
160	4,645	
200	4,168	
250	4,624	4,53
315	4,81	
400	3,899	
500	3,671	3,66
630	3,416	
800	3,33	
1000	3,498	3,48
1250	3,618	
1600	3,692	
2000	3,55	3,50
2500	3,267	
3150	2,84	
4000	2,21	2,31
5000	1,866	
6300	1,556	
8000	1,749	

Table A.3: Reverberation Times in source room measured with 5 different receiver positions (measured twice for each position) with rockwool.

Frq [Hz]	Primary T30	Secondary T20	Primary T30	Secondary T20	Primary T30	Secondary T20	Primary T30	Secondary T20	Primary T30	Secondary T20
50	5,52	4,77	6,4	4,72	5,01	4,19	4,51	4,48	4,46	4,03
63	6,07	5,25	3,96	4,14	5,7	4,84	3,61	3,72	5,91	5,25
80	4,2	3,84	3,34	2,97	4,6	4,36	3	2,99	4,62	4,02
100	4,16	4,02	3,99	4,17	4,03	3,66	4,13	4,04	4,73	4,62
125	3,4	3,3	2,34	2,24	2,63	2,28	2,45	2,17	3,57	3,11
160	3,03	2,92	2,63	2,95	2,57	2,7	3,34	2,78	2,62	2,41
200	2,45	2,49	2,52	2,76	2,22	1,96	2,6	2,28	2,3	2,28
250	2,74	2,36	2,29	2,15	2,39	1,8	2,62	2,46	2,24	2,1
315	2,19	1,86	2,16	1,64	2,41	2,17	2,37	1,89	2,2	2,05
400	2,16	2,4	2,1	1,8	1,89	1,56	2,15	2,01	2,47	2,16
500	1,86	2,02	1,88	1,85	1,9	1,8	1,89	1,91	1,9	1,86
630	2,06	1,93	1,8	1,76	1,91	1,71	2,11	2,02	2,09	2,01
800	2,06	2,08	1,92	1,84	1,93	1,99	1,92	1,79	2,14	2,23
1000	2,03	2,09	2,09	2,19	2,04	1,99	2,22	2,12	2,16	2,03
1250	2,21	2,14	2,17	1,98	2,27	2,34	2,19	2,19	2,33	2,42
1600	2,23	2,14	2,19	2,17	2,2	2,17	2,18	2,09	2,2	2,32
2000	2,17	2,03	2,15	2,19	2,19	2,15	2,17	2,21	2,16	2,24
2500	2	1,96	2,08	2,1	2,07	1,99	2,18	2,12	2,01	2,18
3150	1,88	1,88	1,94	1,93	1,79	1,88	1,86	1,75	1,93	1,96
4000	1,59	1,61	1,52	1,5	1,56	1,66	1,63	1,65	1,58	1,62
5000	1,41	1,3	1,43	1,36	1,41	1,47	1,46	1,47	1,41	1,37
6300	1,21	1,2	1,23	1,16	1,22	1,17	1,23	1,2	1,18	1,17
8000	1,26	1,2	1,15	1,16	1,16	1,12	1,15	1,19	1,16	1,1

Table A.3 (continued): Reverberation Times in source room measured with 5 different receiver positions (measured twice for each position) with rockwool.

Frq [Hz]	Primary T30	Secondary T20	Primary T30	Secondary T20	Primary T30	Secondary T20	Primary T30	Secondary T20	Primary T30	Secondary T20
50	6,22	6,09	4,51	3,45	5,51	4,66	6,01	5,81	5,29	4,37
63	4,95	4,15	4,05	4,23	4,44	4	5,69	4,27	5,12	5,34
80	3,78	3,47	2,96	2,49	3,52	3,3	3,97	3,88	3,96	3,89
100	4,62	4,23	3,37	3,32	4,54	4,29	4,51	4,3	4,74	4,33
125	3,58	3,13	2,43	2,51	3,16	2,62	3,37	3,07	2,74	2,54
160	2,6	2,49	2,41	2,27	2,29	2,1	2,54	2,68	2,42	2,23
200	2,36	2,48	1,91	1,77	2,69	2,16	2	2,08	2,13	2,19
250	2,66	2,26	2,41	2,34	2,66	2,52	2,83	2,74	2,12	2,21
315	2,15	2,14	2,12	2,12	2,02	1,73	2,34	2,09	2,22	2,24
400	2,32	1,92	2,03	2,11	2,04	1,92	2,14	1,92	2,25	2,01
500	1,95	1,96	1,84	1,81	2,01	2,04	2	2,02	1,79	1,82
630	1,91	2,14	1,97	1,82	2,02	1,96	2,02	1,86	2,1	2,15
800	2,03	1,98	1,91	2,1	2,12	2,13	2,01	1,82	2,14	1,85
1000	2,29	2,41	2,12	2,39	2,21	2,11	2,19	2,19	2,19	2,08
1250	2,28	2,35	2,43	2,21	2,16	2,12	2,16	2,18	2,22	2,3
1600	2,25	2,17	2,19	2,15	2,08	2,07	2,21	2,08	2,08	1,97
2000	2,08	2,04	2,15	2,15	2,16	2,13	2,12	2,13	2,11	2,3
2500	2,07	2,09	2,07	1,99	1,9	1,9	2,06	1,93	1,99	1,93
3150	1,94	1,99	1,95	1,92	1,95	1,88	1,87	1,88	1,84	1,71
4000	1,59	1,54	1,58	1,57	1,58	1,6	1,56	1,51	1,53	1,43
5000	1,46	1,49	1,38	1,32	1,48	1,4	1,37	1,32	1,41	1,45
6300	1,25	1,25	1,18	1,23	1,2	1,12	1,23	1,19	1,26	1,24
8000	1,17	1,18	1,15	1,14	1,2	1,16	1,17	1,25	1,21	1,14

Table A.4: Average third octave and octave RT values in source room measured with 5 different receiver positions (twice for each position) with rockwool.

Frequency	RT Average	RT Octave
50	5,344	
63	4,95	4,70
80	3,795	
100	4,282	
125	2,967	3,30
160	2,645	
200	2,318	
250	2,496	2,34
315	2,218	
400	2,155	
500	1,902	2,02
630	1,999	
800	2,018	
1000	2,154	2,14
1250	2,242	
1600	2,181	
2000	2,146	2,12
2500	2,043	
3150	1,895	
4000	1,572	1,63
5000	1,422	
6300	1,219	
8000	1,178	

Table A.5: Results table with third octave R values for studied cases.

Frq.	R						
[Hz]	[dB]						
	one layer closed	two layers closed	rec. room 6 source room 16 open	rec. room 6 source room 17 open	rec. room 6 source room 18 open	rec. room 6 source room 19 open	rec. room 6 source room 20 open
50	28,2	30,3	20	22,8	22,2	18,5	17
63	22,9	32,3	16,2	18,2	23,6	20	17,6
80	28,1	34,8	21,3	22,9	23,4	21,7	20,6
100	22,3	28,7	21,9	23,2	22,7	24,2	22,3
125	26,6	34,1	24,2	27,9	30,4	31,9	30,5
160	29,4	39,1	23	25,8	27,6	29	27,2
200	28,4	39,1	28,1	28,4	30	32	32,8
250	29	40,5	35,3	33,5	34,4	34,7	33,6
315	30,9	46,8	35,7	33,2	33,6	35,9	33,2
400	33,2	48,7	34,6	34,2	34	35,4	35,1
500	34	46,1	27,5	27,6	27,3	28,3	25,4
630	35	46,1	24,1	25,3	26,4	26,1	25
800	33,3	49	27,4	28,3	28,5	30,1	29,6
1000	34	53,3	26,9	29	29,8	30	31,4
1250	33,1	55,9	28,3	29	30,4	31,2	31,8
1600	32,9	58,1	29,3	30,4	31,3	33,1	33,7
2000	32,4	57,6	29,6	31	32,7	33,7	34,7
2500	33,2	58,4	29,6	31,2	32,3	33,2	34,3
3150	35	62,4	30,6	32,3	34,6	35,4	36,9
4000	37,7	65,5	30,4	32,4	34,8	35,8	37,5
5000	34,8	61,5	29,8	32,2	34,2	35,2	36,7

Table A.5 (continued): Results table with third octave R values for studied cases.

Frq.	R				
[Hz]	[dB]				
	rec. room 6&16 source room 6&16 open	rec. room 6&16 source room 7&17 open	rec. room 6&16 source room 8&18 open	rec. room 6&16 source room 9&19 open	rec. room 6&16 source room 10&20 open
50	16,9	17,6	21,1	12,8	10,6
63	10,2	14	18,9	18,3	14,4
80	12,5	16,2	20,4	25	17,9
100	19,7	20,6	22	24,4	21,8
125	17,9	20,2	25,7	26,8	22,5
160	21,6	24,9	25,1	27,6	27,9
200	25,1	26	27	27,1	28,9
250	24,9	25,6	26,8	27,5	27
315	23,3	26,4	27,2	29,2	27,8
400	20,3	25,8	28,5	28,6	27,8
500	18,9	20,9	21,8	22,7	21,1
630	17,7	20,5	21,5	21,4	21
800	17,2	22,2	23,2	24,4	24,3
1000	17,2	22,2	23,2	24,4	25,2
1250	17,7	21,7	23,8	25,5	25,4
1600	18,8	22,4	25,1	27	28,3
2000	19,3	22,4	25,9	27,8	28,4
2500	18,8	22,5	25,5	27,4	28,7
3150	18,7	23,3	27,2	29,1	30,4
4000	17,4	23	25,6	27,3	27,6
5000	17	22,3	25,6	26,5	27,1

CURRICULUM VITAE



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